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LIMIT LOAD ASSESSMENT OF HYDRAULIC ACTUATORS FOR MOVING APPLIANCES UNDER PROGRESSIVE BUCKLING

Emanuele Vincenzo Arcieri[1] **and Sergio Baragetti**[1]

[1] Department of Management, Information and Production Engineering, University of Bergamo
Viale Marconi 5, Dalmine 24044, Italy
e-mail: {emanuelevincenzo.arcieri,sergio.baragetti}@unibg.it

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Abstract. *Hydraulic actuators are key components in moving appliances, that enable large load-carrying capacities despite their compact dimensions. During operation, they are subjected to compressive forces and time-variable actions, such as vibrations and oscillations induced by moving payloads, which may significantly influence their stability. Under these conditions, actuators can be exposed to progressive buckling, which is affected by geometric imperfections, component slenderness, boundary conditions, straightness deviations, and the stiffness of wear rings. Accurate prediction of the limit load of hydraulic actuators (i.e., the maximum load that prevents buckling and material yielding) is essential for improving structural safety and obtaining optimized designs. The present work investigates the progressive buckling behavior of a hydraulic actuator through laboratory experiments, conducted with two boundary conditions and different wear ring materials. The analysis of bending stress vs. applied pressure curves enabled the identification of the critical load values for the analyzed actuator in the various loading configurations. The tested wear ring materials were found to have a negligible influence on both limit and critical pressures for pinned-pinned configuration, while a small influence can be noticed for fixed-pinned case. The obtained results contribute to a deeper understanding of the structural behavior of hydraulic actuators used in moving appliances and support the development of more reliable and efficient design methodologies.*

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1 INTRODUCTION

Hydraulic actuators are widely used in civil and industrial applications to generate forces and controlled displacements. Despite their compact size, they provide the high load-carrying capacities required to operate large structures and machinery. Since they typically operate under compressive loads, assessing their progressive buckling behavior is essential to ensure structural integrity. This response depends on several factors, including component slenderness, load eccentricity, wear ring stiffness, geometric imperfections, and boundary conditions. In real moving appliances, hydraulic actuators are subjected to time-variable actions, such as vibrations and oscillations induced by moving payloads, as well as dynamic disturbances transmitted through the supporting structure. These effects may significantly influence the buckling stability of the actuator system. Moreover, material yielding must be prevented throughout the service life, making the correct determination of an actuator's safe operating limits a fundamental design requirement.

The simplest way to estimate the critical buckling load of a hydraulic actuator is to apply Euler-type formulations to simplified representations of the rod-cylinder system, such as a single-beam model [1], a rigid-cylinder assumption [2], or a two-beam configuration [3]. The influence of internal pressure, actuator weight, misalignment, friction, and clearance at the rod-cylinder interface has been investigated in the literature [4-11]. Additional modeling approaches include the incorporation of seal and bearing effects [12] and analyses of telescopic cylinders accounting for eccentric loads and lateral forces [13]. Baragetti and Villa [14] further highlighted the influence of rectilinear imperfections and wear ring stiffness. These studies converged in the ISO/TS 13725 standard [15], which provides methods for evaluating cylinder buckling loads within the framework of elastic buckling theory.

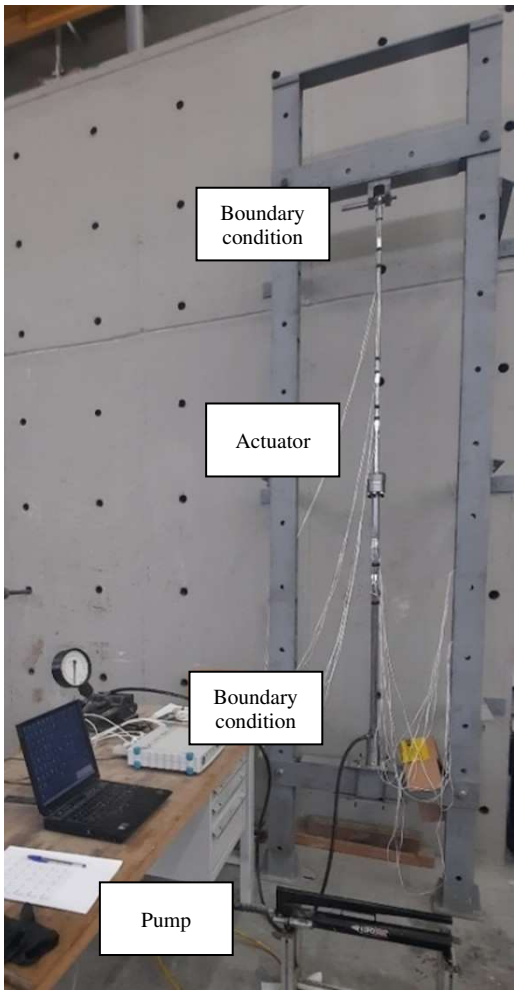
The objective of this work is to experimentally characterize the progressive buckling behavior of a slender hydraulic actuator under different boundary conditions and with wear rings made of various materials [16-18]. Experimental evidence showed that the stiffness of the tested wear rings has a negligible effect on the actuator buckling behavior in the pinned-pinned configuration, whereas a modest influence emerges in the fixed-pinned case. These findings enhance the understanding of the structural behaviour of hydraulic actuators and contribute to the development of more robust and efficient design methodologies.

2 MATERIALS AND METHODS

Experimental tests were conducted on a custom-made steel hydraulic actuator mounted on a test frame [16], as shown in Figure 1a. The actuator was manufactured from S235 steel, and its main dimensions and mechanical properties are summarized in Table 1. The cylinder was connected to the lower support of the frame, whereas the rod was connected to the upper support. The pinned connection shown in Figure 1b was used at the rod end in all tests and, in the pinned-pinned configuration, also at the cylinder end. In the fixed-pinned configuration, the cylinder end was instead restrained by means of the fixed connection shown in Figure 1c. The actuator consisted of a cylinder, rod, piston, intermediate disk, cap, O-rings, and four wear rings, as illustrated in Figure 1d. The examined wear rings were made of PLA, nylon, PA, and composite material. Each combination of boundary condition and wear ring material was tested three times and the corresponding average values were subsequently analyzed.

During each test, the internal oil pressure was gradually increased using a manual hydraulic pump until the stress state approached the onset of material yielding, which corresponds to the limit load condition. To monitor the evolution of the stress-strain state, uniaxial strain gauges aligned with the actuator axis were installed at selected axial sections along the cylinder and the rod. At each monitored section, four strain gauges were positioned around the cir-

cumference at angular intervals of 90°. The monitored axial sections were located at distances of 115, 815 and 965 mm from the rod end and 819 and 978 mm from the cylinder end. A half-bridge Wheatstone circuit with active and dummy strain gauges was adopted to ensure temperature compensation and suppress thermal effects in the acquired signals. The resulting dataset provides strain measurements for discrete pressure levels.



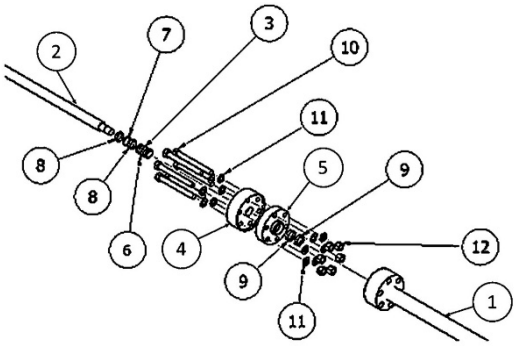
a)



b)



c)



1	Cylinder
2	Rod
3	Piston
4	Cap
5	Intermediate disk
6	O-ring
7	O-ring
8	Wear ring
9	Wear ring
10+11+12	Bolt components

d)

Figure 1: Experimental setup, adapted from [16]: a) overall view of the test apparatus; b) pinned-end connection; c) fixed-end connection; d) exploded view of the actuator assembly.

Parameter	Value	Parameter	Value
Rod diameter	20 mm	Material	S235 steel
Cylinder outer diameter	30 mm	Yield stress	235 MPa
Cylinder inner diameter	25 mm	Ultimate tensile strength	360 MPa
Rod length	1165 mm	Density	7850 kg/m^3
Cylinder length	1276 mm	Young's modulus	206,000 MPa
		Poisson's ratio	0.30

Table 1: Main specifications of the tested hydraulic actuator [16].

3 RESULTS

To interpret the experimental results, the bending stresses were obtained by subtracting the axial component from the measured total stresses and were then plotted as a function of the applied pressure (Figure 2). The experimental points exhibit clear asymptotic trends, enabling the identification of critical pressures for each combination of boundary condition and wear ring material. The data were fitted using an asymptotic function of the form shown in Formula 1:

$$\sigma = a/(b - p) \tag{1}$$

where a is a constant, b is the critical buckling pressure and p is the applied pressure.

For the pinned-pinned configuration, the stiffness of the tested wear ring materials shows negligible influence on the critical pressure, which falls within the narrow range of 81-83 bar. The fitting quality is excellent for all materials, indicating that the asymptotic model accurately captures the progressive buckling behavior. The maximum pressure applied in the experimental tests, which approximately corresponds to the limit pressure, i.e., the pressure associated with the onset of material yielding, is 80 bar and is therefore very close to the critical buckling pressure. This proximity confirms the actuator's significant susceptibility to buckling in the pinned-pinned configuration and is consistent with the experimental observations, where bending of the actuator was clearly detected during the tests.

For the fixed-pinned configuration, the results appear globally more scattered, with the exception of the composite material that shows an almost perfect fit. Critical pressures are significantly higher than in the pinned-pinned case, ranging approximately from 131 to 145 bar, as expected due to the presence of more restrictive boundary conditions. An increased variability in the bending response can therefore be observed, likely due to differences in wear ring stiffness and frictional interaction. As already shown in [18], wear rings made of PLA and nylon exhibit very similar behaviors. The present study, however, reveals a distinct trend for the composite wear ring, characterised by an initial phase in which the bending stress increases slowly with the applied pressure, followed by a second phase where the increase rate becomes markedly steeper. As regards the assessment of the limit load, all tests were conducted with a maximum applied pressure of 130 bar. By considering this value as an estimate of the limit pressure, it can be observed that the limit load is close to the critical buckling load for the different wear ring materials. In the case of the composite wear ring, the maximum pressure applied in the experiments is essentially coincident with the critical buckling load.

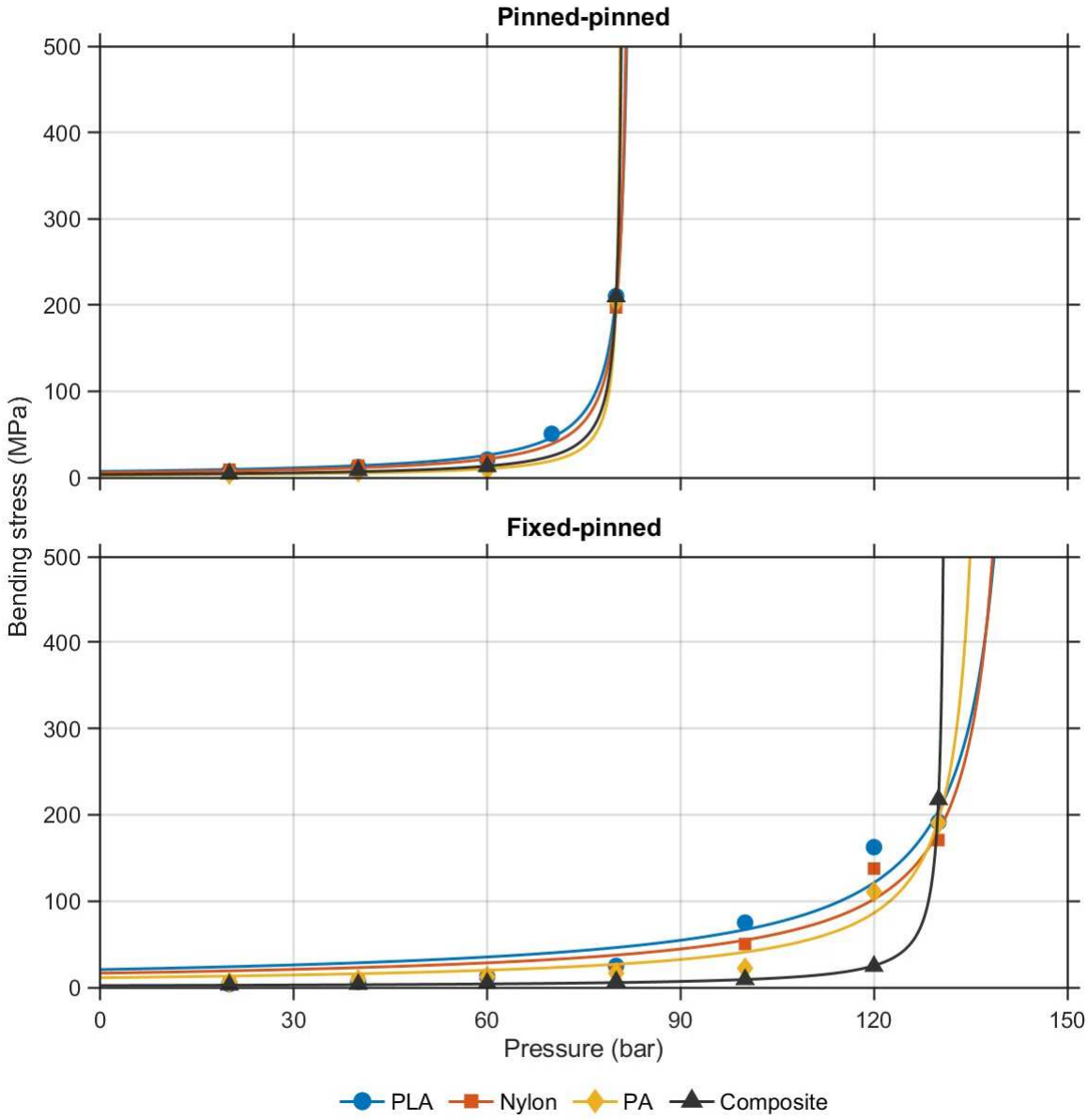


Figure 2: Bending stress vs. applied pressure curves [16-18].

4 CONCLUSIONS

In this work, the progressive buckling behaviour of a slender hydraulic actuator was investigated under different boundary conditions and using various wear ring materials. The results showed that the bending stress trends exhibit vertical asymptotes corresponding to the critical pressures for each configuration and wear ring material. The boundary conditions strongly influence the buckling response of the actuator: the fixed-pinned configuration reaches significantly higher critical loads than the pinned-pinned case. Wear ring material has negligible influence in the case of pinned-pinned configuration, whereas a slight influence is observed in the fixed-pinned case. Furthermore, the limit load, identified as the pressure at the onset of material yielding, was found to lie very close to the critical buckling pressure in the pinned-pinned configuration, indicating a narrow safety margin between yielding and instability. The experimental results contribute to a more accurate understanding of progressive buckling in hydraulic actuators and support the development of improved design methodologies for moving appliances.

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