Numerical Evaluation of Material and Geometric Effects on Hydraulic Cylinder Rod Performance

KHALID FAIZA[1, *], MOURAD BENDIFALLAH[1], FARIS AISSAOUI[2]

[1]Center of Research in Mechanics (CRM), Constantine 25000, Algeria

[2]Laboratry of Materials, Energy systems, Technology and Envirement, Faculté des sciences et de la technologie, département d'automatique et électromécanique, Université de Ghardaïa 47000, Algeria

*Correspondence: faiza.a@crm-constantine.dz

Abstract

The study presents a parametric numerical investigation of the mechanical behavior of hydraulic cylinder rod subjected to high axial pressure, with direct application to heavy-duty compaction systems. Model analysis using MATLAB software to evaluate the effect of material properties and geometric measurements on the mechanical behavior of the rod. Solid cylindrical rods with diameters (50, 56, 63, 70, and 80 mm) are analyzed under an axial load generated by a hydraulic pressure of 150 MPa. Five commonly used engineering materials carbon steel, stainless steel 304, ductile cast iron, aluminum alloy 6061, and bronze copper alloy are considered. The model evaluates axial strain, axial displacement, Euler buckling load, yield safety factor, and buckling stability. The results show that, under pure axial loading, stress levels are controlled by rod geometry and applied force, whereas deformation and buckling resistance are primarily governed by material stiffness. Buckling capacity increases with the fourth power of the rod diameter, emphasizing the critical role of geometric optimization. High-modulus materials effectively reduce elastic deformation, while increased diameters are necessary to ensure buckling safety, especially for low-stiffness alloys. Overall, the developed MATLAB framework offers an efficient tool for preliminary design, material selection, and structural optimization of hydraulic cylinder rods subjected to high axial loads.

Keywords: Hydraulic Cylinder Rod, Axial displacement, Local Materials, Performance, Buckling Resistance.

1. Introduction

Hydraulic cylinders constitute essential actuating devices in industrial machinery, converting hydraulic pressure into controlled linear force across applications ranging from construction equipment to specialized manufacturing processes. The advancement of hydraulic system technology continues through innovations in materials and design methodologies. Composite hydraulic integration represents a transformative approach toward achieving lightweight hydraulic robots, where strategic material selection enables significant mass reduction without compromising structural performance [1]. Refractory brick manufacturing exemplifies a demanding industrial application requiring robust hydraulic systems capable of delivering high compaction forces consistently [2]. The service life and reliability of hydraulic cylinders are fundamentally influenced by seal material selection, as demonstrated through combined simulation and experimental investigations [3]. Performance enhancement of long-dimensional hydraulic cylinders for road and construction machinery presents unique engineering challenges related to geometric proportions and structural stability [4]. Friction forces generated by piston sealing elements in hydraulic cylinders directly affect operational efficiency and component wear, necessitating precise experimental characterization [5]. Failure analysis of hydraulic cylinder components provides critical insights into structural inadequacies and pathways for design improvement, as exemplified by investigations identifying end cap structural deficiencies in loader applications [6]. Hydroforming analysis of structural steel plates contributes to understanding material behavior under complex stress states relevant to pressure vessel design [7]. Advanced optimization methodologies applied to multi-layer compound cylinders demonstrate sophisticated approaches for achieving superior structural performance [8]. Theoretical and numerical analysis techniques enable comprehensive optimization of hydraulic cylinder system design, integrating classical mechanics principles with modern computational capabilities [9]. Established engineering references provide foundational knowledge supporting contemporary hydraulic system development [10]. Assessment of functional properties of ductile cast iron surfaces reveals material characteristics pertinent to hydraulic cylinder applications requiring favorable combinations of mechanical properties and manufacturability [11]. Design considerations for multiple-stage hydraulic cylinders encompass both structural safety requirements and sealing system performance [12]. Ratcheting and fatigue behavior of copper alloys under uniaxial cyclic loading with mean stress characterizes material performance under conditions representative of hydraulic cylinder operation [13]. Crack growth analysis and fatigue life estimation methodologies applied to piston rods in hydro turbine applications provide frameworks for predicting long-term structural durability [14]. Feasibility analysis of double-acting composite cylinders operating under high-pressure loading conditions explores opportunities for advanced material systems in fluid power applications [15]. Design optimization employing response surface methodology combined with computational fluid dynamics techniques offers systematic approaches for identifying optimal design configurations [16]. Analytical methods for evaluating maximum load-carrying capacity of pin-mounted telescopic hydraulic cylinders demonstrate the continued utility of classical mechanics approaches [17]. Hydraulic chip compactor systems illustrate practical industrial applications benefiting from optimized hydraulic cylinder design [18]. Metallurgical and mechanical characterization of dissimilar joints between low carbon steel and stainless steel addresses practical fabrication considerations in hydraulic cylinder construction [19]. Refractory material characterization establishes performance requirements for hydraulic equipment employed in refractory production processes [20]. Manufacturing quality requirements for hydraulic cylinder rods in mining machinery applications emphasize the importance of precision machining and surface finish specifications [21]. Failure analysis investigations of hydraulic cylinder rods employ advanced characterization techniques to identify failure mechanisms and contributing factors [22]. Corrosion analysis of stainless steel components in demanding service environments informs material selection decisions for hydraulic systems [23].

Previous research highlights the importance of structural optimization, fatigue analysis, and material selection for efficient hydraulic cylinder design. However, studies addressing high-pressure refractory brick compaction (>150 MPa) are limited, and research on using locally available materials remains scarce, despite its relevance for cost-effective production in developing industrial contexts.

This work addresses this gap by investigating a hydraulic jack system for refractory brick compaction at 150 MPa. A numerical analysis compares five rod diameters (50, 56, 63, 70, 80 mm) and five materials-carbon steel, stainless steel (SS 304), ductile cast iron, aluminum alloy (AA6061), and bronze–copper alloy. the work evaluates the effects of rod geometry and material on displacement, von Mises stress, and buckling behavior, providing practical guidelines for selecting optimal material–geometry combinations for reliable, cost-efficient hydraulic presses.

2. Theoretical and Analytical method

2.1 Axial Displacement Response

The axial deformation of the hydraulic cylinder rod under compressive loading is governed by the classical one-dimensional elasticity relationship:

$$\delta = \frac{FL}{AE} \tag{1}$$

Where:
F: Applied axial load.
L: Rod length.
A: Cross-sectional area.
E: Young's modulus of the material.

2.2 Yield Safety Factor Analysis

The yield safety factor is defined as the ratio between the material yield strength and the induced axial stress:

$$\mathrm{SF} = \frac{\sigma_y}{\sigma} \tag{2}$$

For axially loaded rods, the stress σ depends solely on the applied load and the cross-sectional area. Consequently, variations in the yield safety factor among different materials are exclusively governed by differences in yield strength.

2.3 Critical buckling load

The stability of slender hydraulic rods under compressive loading is governed by Euler's buckling criterion:

$$\mathrm{P_{cr}} = \frac{\pi^2 \mathrm{EI}}{(\mathrm{KL})^2} \tag{3}$$

Where:
I: Second moment of area.
L: Rod length.
K: Boundary condition factor.

2.4 Buckling Ratio Analysis

The buckling ratio, defined as the ratio of the critical buckling load to the applied axial force

$$B_R = \frac{F}{P_{cr}} \tag{4}$$

3. Geometry and materials

3.1 Hydraulic cylinder rod geometry

Consider a double-acting hydraulic cylinder (Figure 1) with a 125 mm bore, different piston rod diameters (50, 56, 63, 70, 80 mm) and a 250 mm stroke. The dimensional specifications of the cylinder were established in accordance with ISO and AFNOR standardization guidelines, based on the methodology of Faiza et al. (2025). Each rod is modeled as a uniform circular cross-section with constant area *A* and second moment of area I are given by:

$$A = \frac{\pi d^2}{4} \tag{5}$$

$$I = \frac{\pi d^4}{64} \tag{6}$$

These geometric parameters directly govern the axial stress, elastic deformation, and buckling resistance of the rod. End conditions are assumed to be fixed-free, which represents a conservative configuration for buckling analysis and is commonly adopted in preliminary design studies. The applied axial force is derived from a hydraulic pressure of 150 MPa acting on the piston area and is transmitted uniformly along the rod axis. This geometric modeling framework enables a systematic evaluation of the combined effects of rod diameter and material properties on structural performance.

Figure 1: 3D model of Hydraulic cylinder

The model captures the essential dimensional parameters of the rod, including its overall length and variable diameters. Functionally, the rod comprises a threaded section for piston connection, a bearing zone to resist axial loads, and a free end interfacing with the hydraulic system each designed to ensure efficient load transfer and structural stability during operation.

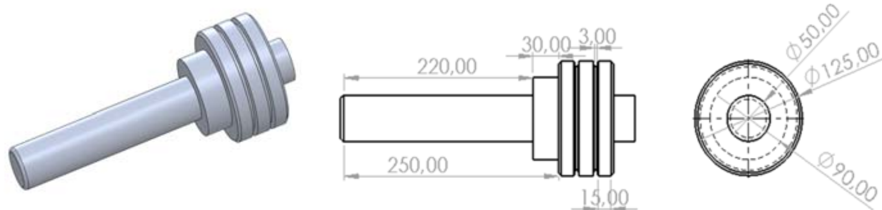

Figure 2: 3D model and detailed schematic of the hydraulic cylinder rod.

To evaluate the influence of geometry on mechanical behavior, five rod diameters (50, 56, 63, 70, 80 mm) were analyzed while maintaining a constant length of 220 mm. The rods were subjected to a uniform compressive pressure of 150 MPa, representative of refractory brick pressing conditions, with one end fully constrained and the opposite end axially loaded.

3.2 Material Properties

Five materials commonly available in local markets were selected for comparative analysis, representing different material classes with distinct mechanical characteristics. Table 1 summarizes the mechanical properties used in the finite element simulations.

Table 1. Mechanical properties of the hydraulic cylinder rod materials.

Materials	**Young's Modulus E (GPa)**	**Poisson's Ratio ν**	**Density ρ (kg/m³)**	**Yield Strength σy (MPa)**
Carbon Steel	200	0.30	7850	250
Stainless Steel (AISI 304)	193	0.29	8000	215
Ductile Cast Iron	169	0.28	7200	300
Aluminum Alloy (AA6061)	69	0.33	2700	240
Bronze–Copper Alloy	115	0.34	8800	200

4. Results and Discussions

4.1 *Effect of Material Selection*

Material selection significantly influences the mechanical behavior, durability, and performance efficiency of the hydraulic cylinder rod under high-pressure conditions. In this study, five candidate materials were examined C-Steel (Carbon Steel), SS304 (Stainless Steel 304), SGI (Ductile Iron), Al-6061 (Aluminum Alloy 6061), and Cu-Br (Copper–Bronze Alloy) to assess their comparative performance under a pressure of 150 MPa.

The simulation results revealed notable variations in axial displacement, yield safety factor, and buckling load among the selected materials due to differences in their elastic modulus, density, and yield strength.

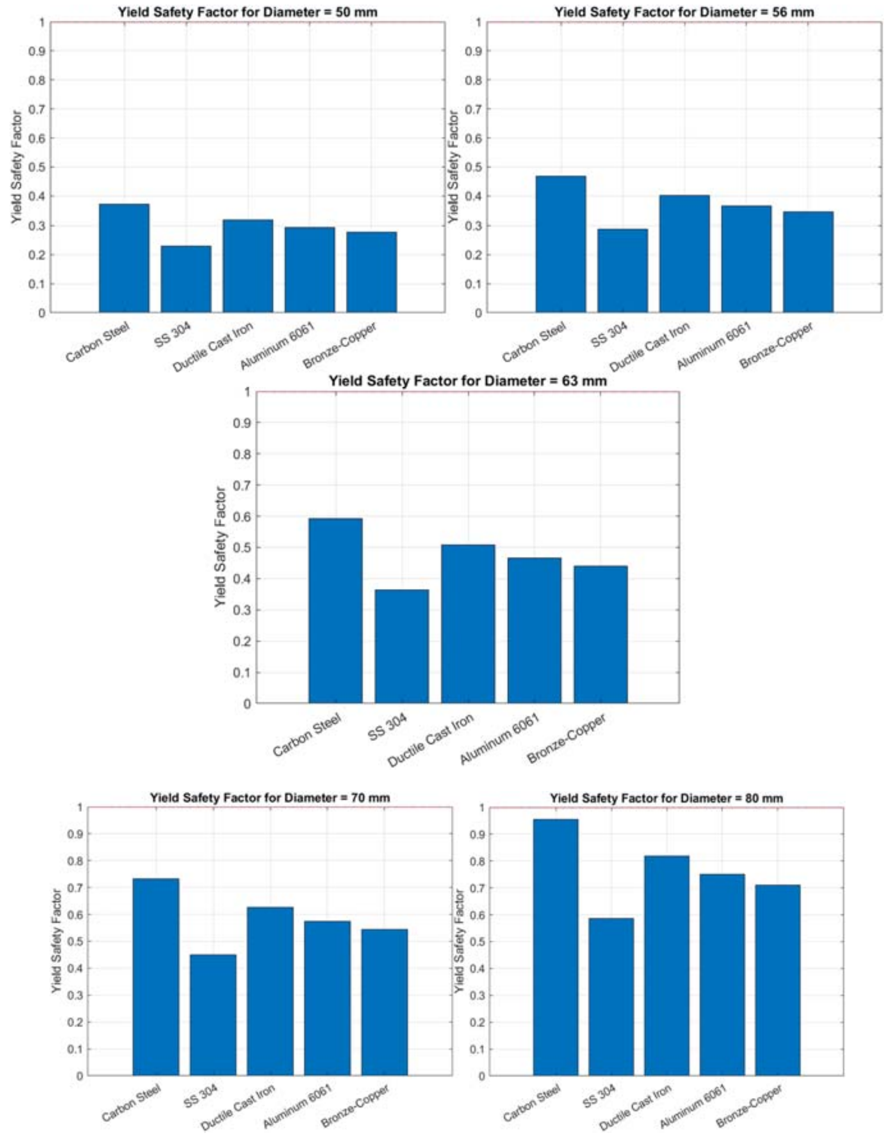

Figure 3: Comparison of yield safety factor for the hydraulic cylinder rod in different materials.

Figures 3 and 4 emphasize the combined roles of material strength and stiffness in rod performance. The yield safety factor is mainly governed by yield strength, with Carbon Steel providing the highest margin against plastic deformation, followed by Ductile Iron and Aluminum 6061, while Stainless Steel 304 shows the lowest margin, particularly critical at smaller diameters. Buckling behavior, in contrast, is controlled by elastic modulus: stiffer materials such as Carbon Steel and Stainless Steel 304 exhibit the highest critical buckling loads, whereas Aluminum 6061 shows the lowest stability. Overall, the results indicate that while yielding is secondary for large diameters, material stiffness is the key factor governing buckling resistance in slender hydraulic rods.

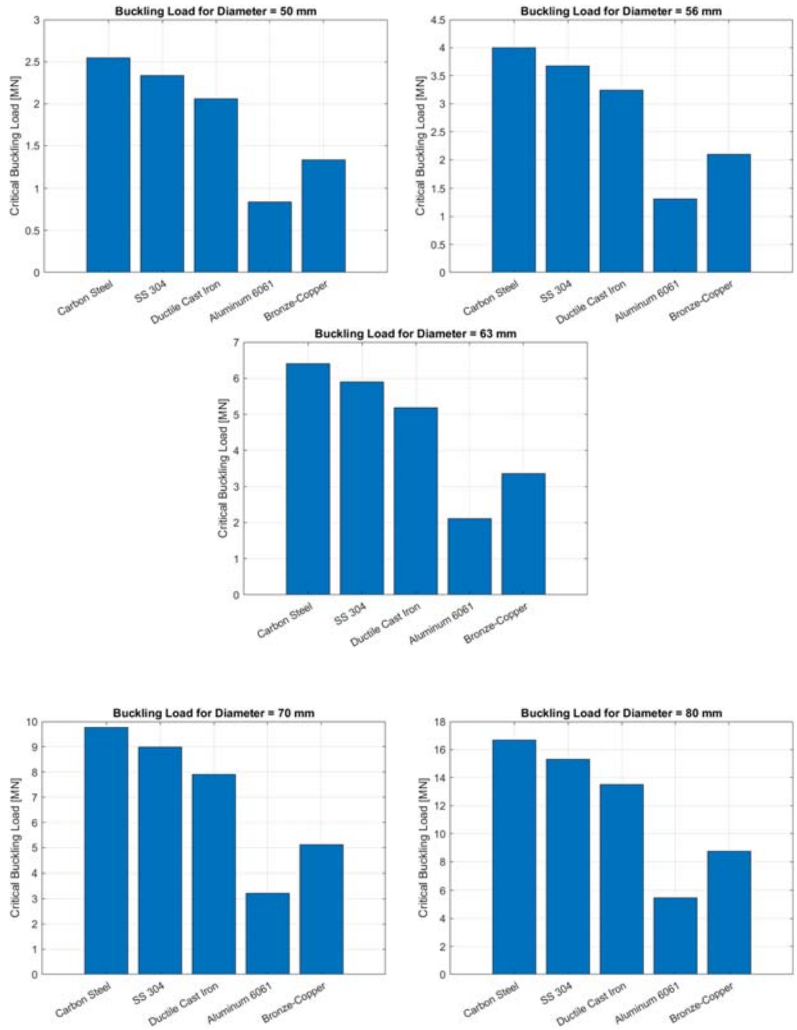

Figure 4: Comparison of buckling load for the hydraulic cylinder rod in different materials.

The axial displacement strongly depends on the material elastic modulus for a given rod diameter and applied load, as illustrated in Figure 5. Materials with lower Young's modulus exhibit higher deformation, with Aluminum 6061 showing the largest axial displacement due to its low stiffness. This increased deformation may adversely affect dimensional accuracy and operational performance in hydraulic systems. Conversely, Carbon Steel and Stainless Steel 304 display the lowest axial displacements owing to their high elastic moduli, while Ductile Iron (SGI) and Copper Bronze exhibit intermediate behavior. These results highlight material stiffness as a key parameter in controlling elastic deflection.

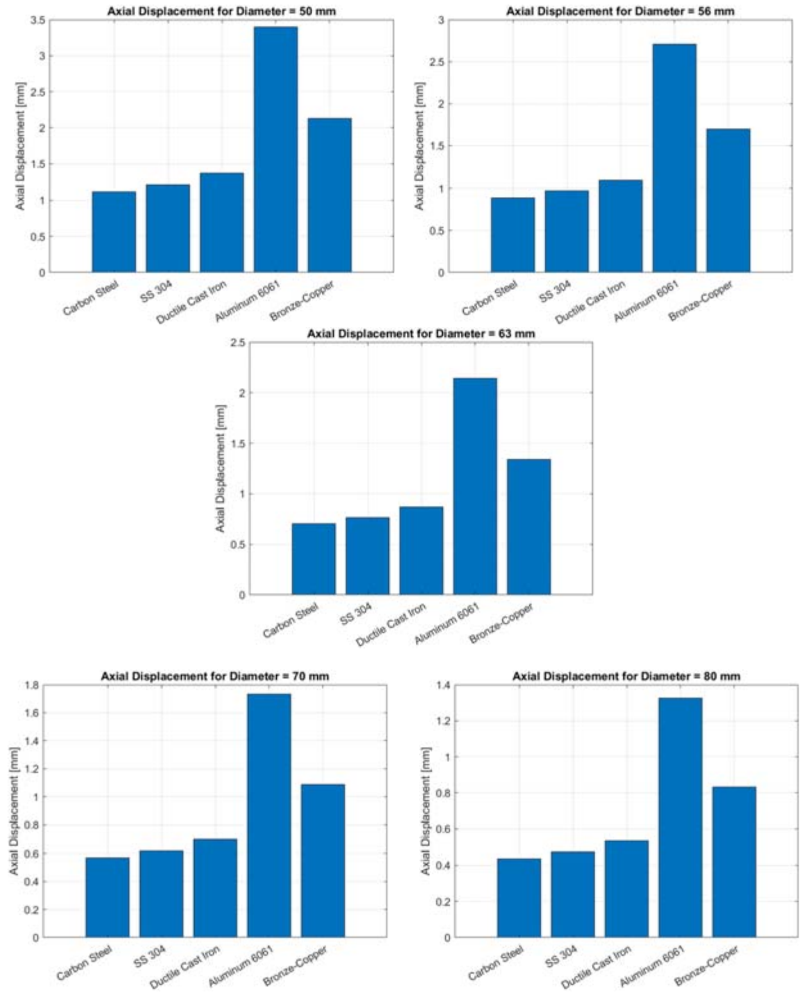

Figure 5: Comparison of axial displacement for the hydraulic cylinder rod in different materials.

4.2 Effect of geometric configurations

The rod diameter plays a critical role in controlling the stiffness, stress distribution, and buckling resistance of the hydraulic cylinder rod. Five diameters (50, 56, 63, 70, and 80 mm) were numerically evaluated under an internal pressure of 150 MPa using MATLAB. The results reveal a strong inverse relationship between diameter and axial deformation, with the maximum displacement reduced by more than 60% as the diameter increased from 50 mm to 80 mm. This improvement is attributed to the increased cross-sectional area and moment of inertia, which enhance the load-carrying capacity.

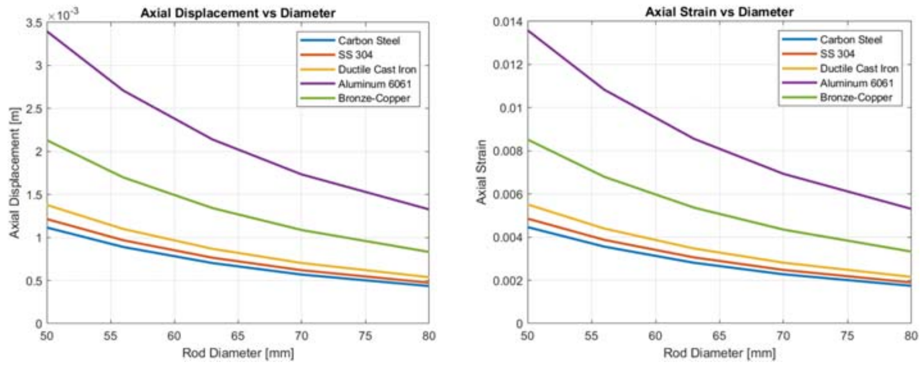

Figure 6: Comparison of axial displacement and strain for various rod diameters and material types.

Figure 6 shows the effect of rod diameter and material type on axial displacement and axial strain under a uniform compressive load. Larger diameters result in markedly lower displacement due to the increased cross-sectional area, which reduces overall deformation.

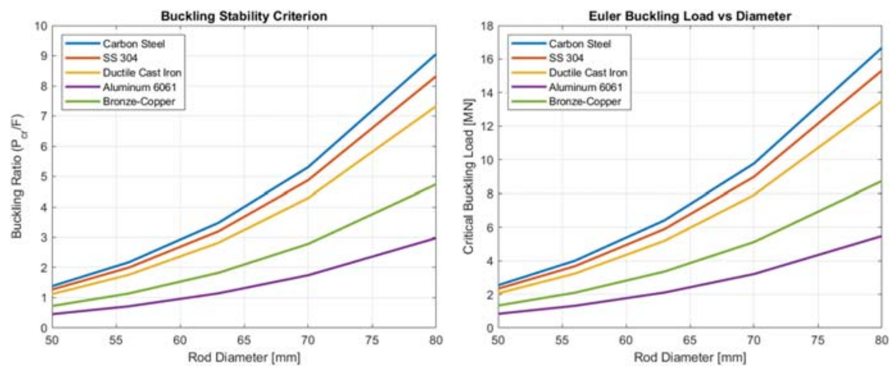

Figure 7: Comparison of buckling stability for various rod diameters and material types

Figure 7 illustrates the influence of diameter and material on the rods' critical buckling load. Rods with larger diameters exhibit greater buckling resistance, consistent with the cubic dependence of the moment of inertia on diameter according to Euler's buckling theory.

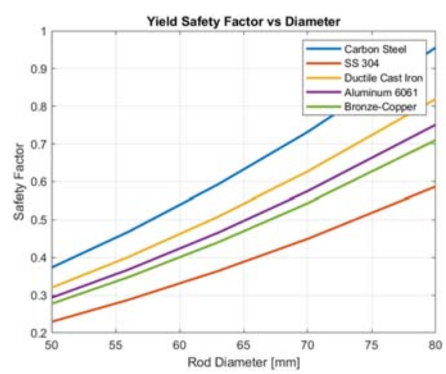

Figure 8: Comparison of yield safety for various rod diameters and material types.

Figure 8 depicts the yield safety factor for various rod diameters and materials. Carbon steel achieves the highest safety factor across all diameters, indicating superior resistance to plastic deformation, followed by ductile cast iron and stainless steel. Aluminum and bronze rods show lower safety factors, particularly at smaller diameters, highlighting an increased risk of yielding under identical compressive loads. The figure demonstrates that, for slender rods, buckling dominates failure, while yield strength becomes increasingly critical for smaller-diameter rods to ensure safe operation.

Overall, the analysis confirms that C-Steel and SS304 offer the best performance in terms of stiffness, strength, and safety under high-pressure operation, making them the most suitable choices for the hydraulic cylinder rod used in high-pressure compaction of refractory bricks.

5. Conclusion

The study presented a numerical investigation of a hydraulic cylinder rod used in refractory brick pressing applications, focusing on the influence of geometric configuration and material selection under a constant pressure of 150 MPa. Five rod diameters (50, 56, 63, 70, and 80 mm) and five materials C-Steel, SS304, SGI, Al-6061, and Cu-Br were analyzed using MATLAB to evaluate the axial strain, axial displacement, Euler buckling load, yield safety factor, and buckling stability. The results demonstrated that both diameter and material properties play a decisive role in the mechanical performance of the rod. Increasing the diameter from 50 mm to 80 mm led to a significant reduction in axial displacement and an increase in buckling resistance, confirming the critical effect of geometric optimization. Among the studied materials, C-Steel exhibited the highest stiffness-to-cost ratio, making it the most suitable for heavy-duty pressing operations. SS304 provided excellent corrosion resistance with acceptable rigidity, while SGI offered good damping but limited ductility. Al-6061 was advantageous for lightweight applications but less resistant to deformation, and Cu-Br proved ideal for wear-resistant and fatigue-prone environments.

The comparative analysis highlights that an optimized combination of geometry and material can substantially enhance the efficiency, reliability, and service life of hydraulic systems used in refractory brick production. The findings provide practical guidance for selecting cost-effective and durable rod configurations, particularly in regions relying on locally available materials for industrial applications.

References

[1] Abdellatif, A., El Asswad, M., Sleiman, M., Khalil, K., & Alfayad, S. (2025). Composite hydraulic integration: A new step toward lightweight hydraulic robots. *Malaysian Journal on Composites Science and Manufacturing, 16*(1), 150–166.

[2] Bennett, J. P., & Smith, J. D. (Eds.). (2001). *Fundamentals of refractory technology* (pp. 135–154). American Ceramic Society.

[3] Bui, T. A., & Tran, X. N. (2025). Analyzing pneumatic cylinder service life through seal material selection, simulation, and experimentation. *Tribology in Industry, 47*(1).

[4] Chukwunedum, O. C., Okeagu, F. N., Anyaora, C. S., & Anizoba, C. D. (2025). Increasing method performance of long-dimensional hydraulic cylinders for road and construction machinery. *Greenation International Journal of Engineering Science, 3*(1), 23–47.

[5] Cristescu, C., Dumitrescu, C., Radoi, R., & Dumitrescu, L. (2014). Experimental research for measuring friction forces from piston sealing at the hydraulic cylinders. *Tribology in Industry, 36*(4), 465.

[6] Ding, S., Li, G., Shi, Y., Ma, J., & Gao, M. (2023). Failure analysis of a loader hydraulic cylinder and its end cap structure improvement. *Engineering Failure Analysis, 152*, Article 107514. https://doi.org/10.1016/j.engfailanal.2023.107597

[7] ERUSLU, S. Ozmen. DALMIS, I. Savas (2018). Hydroforming analysis of structural steel plates . *Journal of the Technical University of Gabrovo, 56, 43-47.*

[8] Es-saheb, M. H., Alsubaie, A., & Fouad, Y. (2024). Advance optimum design of multi-layer compound cylinders. *AIP Advances, 14*(3).

[9] Faiza, K., & Bendifallah, M. (2025, April 27–29). Theoretical and numerical analysis for optimization of hydraulic cylinder system design. In *Proceedings of the First International Conference on Engineering and Advanced Technologies (ICEAT'2025)*. Mila, Algeria.

[10] Fanchon, J.-L. (2007). *Guide des sciences et technologies industrielles*. Nathan.

[11] Grochała, D., Jasiewicz, M., Filipowicz, K., Parus, A., Powałka, B., Grzejda, R., & Zmarzły, P. (2024). Assessment of the functional properties of the surfaces of ductile cast iron parts. *Applied Sciences, 14*(19), 9129.

[12] Haonan, Q., Brilianto, R. M., Choi, M., et al. (2025). Design of multiple-stage hydraulic cylinder for structural safety and sealing analysis. *Scientific Reports, 15*, 14429. https://doi.org/10.1038/s41598-025-99413-x

[13] Lim, C. B., Kim, K. S., & Seong, J. B. (2009). Ratcheting and fatigue behavior of a copper alloy under uniaxial cyclic loading with mean stress. *International Journal of Fatigue, 31*(3), 501–507.

[14] Liu, X., Presas, A., Luo, Y., & Wang, Z. (2018). Crack growth analysis and fatigue life estimation in the piston rod of a Kaplan hydro turbine. *Fatigue & Fracture of Engineering Materials & Structures, 41*(11), 2402–2417.

[15] Mantovani, S. (2020). Feasibility analysis of a double-acting composite cylinder in high-pressure loading conditions for fluid power applications. *Applied Sciences, 10*(3), 826. https://doi.org/10.3390/app10030826

[16] Nejadali, J. (2020). Design optimization of hydrodynamic coupling applying response surface method combined with CFD technique. *Journal of the Brazilian Society of Mechanical Sciences and Engineering, 42*(10), 509.

[17] Prakash, J., Gupta, S. K., & Kankar, P. K. (2020). An analytical approach to evaluate the maximum load carrying capacity for pin-mounted telescopic hydraulic cylinder. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 234*(19), 3919–3934.

[18] Rahim, N. A., Hasan, N. A., & Suhut, F. M. (2025). Hydraulic chip compactor. *Asian Journal of Vocational Education and Humanities, 6*(2), 74–79. https://doi.org/10.53797/ajvah.v6i2.7.2025

[19] Scutelnicu, E., Iordachescu, M., Rusu, C. C., Mihailescu, D., & Ocaña, J. L. (2021). Metallurgical and mechanical characterization of low carbon steel–stainless steel dissimilar joints made by laser autogenous welding. *Metals, 11*(5), 810.

[20] Sengupta, P. (2020). Refractory: Characterization. In *Refractories for the chemical industries* (pp. 1–29). Springer International Publishing.

[21] Sevagin, S. V., & Mnatsakanyan, V. U. (2020). Ensuring the required manufacturing quality of hydraulic-cylinder rods in mining machines. *IOP Conference Series: Materials Science and Engineering, 709*(4), 044095.

[22] Tavares, S. M. O., Viriato, N., Vaz, M. A. P., & de Castro, P. M. S. T. (2016). Failure analysis of the rod of a hydraulic cylinder. *Procedia Structural Integrity, 1*, 173–180. https://doi.org/10.1016/j.prostr.2016.02.024

[23] Xu, X., Liu, S., Liu, Y., Smith, K., & Cui, Y. (2019). Corrosion of stainless steel valves in a reverse osmosis system: Analysis of corrosion products and metal loss. *Engineering Failure Analysis, 105*, 40–51.