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Experimental investigation of a self-adjusting piston sealing system coupled with a GRE hydraulic cylinder barrel for high-load and long-stroke applications

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ABSTRACT

The rapid expansion of wind energy has highlighted the need for adaptive structural solutions to mitigate the visual and environmental impact of traditional fixed towers. This study presents the experimental validation of an innovative hydraulic lifting system designed for retractable wind towers. The proposed architecture overcomes the traditional manufacturing constraints of long-stroke metallic actuators by integrating a Glass Reinforced Polymer Epoxy (GRE) cylinder barrel with a novel radially self-adjusting piston sealing system. The cylinder barrel was constructed through the field-joining of standard commercial filament-wound pipes using an interlocking profile and external glass-fiber overwrap. To ensure hydraulic tightness despite the potential ovalization and geometric tolerances of composite structures, a specialized sealing assembly was developed. This system utilizes a double quad-ring configuration mounted on a self-adjusting Polytetrafluoroethylene graphite reinforced backup ring, designed to maintain continuous contact pressure against the internal resin surface of the GRE barrel. Experimental validation was conducted on a full-scale (1:1) test rig under a representative load of 200 kN. The system underwent 515 lifting cycles, simulating approximately one year of operational life, including over 1000 crossings of the pipe joints. Results demonstrated stable performance with no observed leakage or significative wear of the sealing elements.

1. Introduction

The rapid expansion of renewable energy sources over the past few decades has become a cornerstone of global strategies to mitigate climate change and reduce reliance on fossil fuels. Among these technologies, wind power has emerged as one of the most cost-effective and scalable solutions, with global installed capacity increasing from less than 18 GW in 2000 to over 900 GW by 2023 [1]. Wind turbines now contribute a significant share of electricity generation in many countries and are projected to continue substantial growth in the coming decades [2], supported by recent research focused on prefabricated foundation solutions and the use of recycled materials for foundation construction [3,4], with the aim of reducing construction costs. Despite of the environmental benefits of wind energy, concerns remain regarding the landscape impact and visual intrusion of wind turbine towers, particularly in regions of high ecological or touristic value. Traditional fixed-towers, with height typical range from 30 m to over 100 m, are permanent structures, that often conflict with aesthetic, ecological, or cultural priorities [5]. While careful siting and design guidelines can mitigate some visual impacts, there is increasing interest in adaptive structural concepts that would allow turbine towers to be temporarily removed or lowered when wind sources are too low or during peak tourism seasons. One potential pathway to such adaptability lies in the integration of lifting systems that enable towers to retract, tilt, or be otherwise stowed with minimal residual visibility.

To this aim, hydraulic lifting systems based on the sliding of telescopic pipes, are among the most studied, due to their high force density and controllability [6], but at present they do exhibit a fundamental limit: the cost of the strict tolerance required between the internal diameter of the outer pipe and the external diameter of the inner pipe dramatically increases along with the stroke diameter and length. In the specific range of the typical wind-tower lengths (30 m–100 m) the use of

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steel pipes, required by the high occurring stress, provide large additional costs that make unproductive the overall investment.

A consortium of companies and research institutions based in Sicily (Italy), including the University of Palermo and the VED s.r.l. company, carried out an industrial research project named P.E.R.I.M.A. 2 (*Palo Eolico a Ridotto IMpatto Ambientale 2*), aimed to compare different lifting solutions for telescopic wind towers. Among them, one of the most promising ones is the hydraulic lifting system.

In this work, we propose a novel approach to overcome the above said limitations of the hydraulic lifting system. The approach is based on the use of fiberglass external piping and self-adjusting hydraulic seals, coupled to the traditional inner steel stroke. Fiberglass pipelines offer a favourable strength-to-weight ratio, corrosion resistance, and dimensional stability. Coupled with self-adjusting sealing technology that actively compensates for dynamic loads and misalignments, this integrated system could enable reliable, retractable wind towers with reduced environmental footprint. Furthermore, the present study goes beyond a purely conceptual or numerical investigation by including an experimental validation at full scale (1:1) of the proposed lifting system. The load provided by the 30 m high telescopic wind tower, equipped with a 55 kW wind generator, adopted in PERIMA 2 project, was used to assess the feasibility, structural behaviour, and operational reliability of the adaptive hydraulic lifting concept. The full-scale experimentation allowed direct evaluation of critical aspects such as dimensional tolerances, seal performance, composite pipe deformation, and system stability under realistic loading conditions. The results provide concrete evidence of the applicability of fiberglass-based hydraulic lifting systems for retractable wind towers and represent a significant step toward the practical deployment of environmentally adaptive wind energy infrastructures.

1.1. Hydraulic cylinders: state of the art

In heavy-duty applications requiring large-diameter and long-stroke hydraulic actuators, the increase in stroke length and bore diameter leads to significant structural and functional challenges, including susceptibility to buckling, rod bending, seal wear, and loss of positioning accuracy, which typically demand thicker cylinder walls, oversized piston rods, and robust guiding systems to ensure stiffness and reliability over the full operational range [7,8]. While conventional steel actuators remain the industrial standard due to their high load-bearing capacity and pressure resistance, their scalability to very large dimensions results in considerable mass penalties and manufacturing constraints, particularly for applications where installation, dynamic performance, or foundation loads are critical [8,9]. In recent years, the adoption of composite materials for hydraulic actuators, especially carbon fiber reinforced polymers (CFRP), has emerged as a promising solution to reduce weight, enhance corrosion resistance, and tailor directional stiffness through material anisotropy [10,11]. Composite hydraulic cylinders are commonly realized through filament-wound CFRP overwraps on metallic liners, achieving substantial mass reductions while maintaining adequate resistance to high internal pressures; however, these hybrid configurations introduce complex stress states, interfacial issues, and increased sensitivity to manufacturing defects [12]. Moreover, fatigue behaviour under cyclic pressure loading represents a critical design concern, as damage initiation and progression in multilayer composite structures differ significantly from those observed in isotropic metallic cylinders, requiring advanced failure criteria and fatigue models based on anisotropic strength theories, such as Tsai–Hill or Tsai–Wu formulations, for reliable life prediction [13,14]. Consequently, despite their clear potential advantages, large-scale composite hydraulic actuators still demand further research to address durability, inspection, and design standardization issues before widespread industrial adoption. The experimental work carried out aims to highlight how well-established production technologies in the formation of fiberglass tubes for pressurized fluids can also be adopted for the production of large-diameter, long-stroke hydraulic actuators.

1.2. The proposed hydraulic actuator

Within the framework of the industrial research project PERIMA 2, building upon the research activities developed in the previous PERIMA project, lifting solutions for a telescopic wind tower are currently under investigation. The tower consists of three concentric cylindrical segments and is designed to support two-bladed wind turbines. The main innovation of the PERIMA project lies in the capability of retracting the tower into itself under no-wind conditions or whenever a reduction of the environmental impact of wind turbines is required. In this configuration, the tower is accommodated within an underground shaft below ground level, leaving only the nacelle exposed above the ground surface (Fig. 1).

In this context, a fully underground hydraulic lifting system has been developed, to be entirely located beneath the tower housing shaft. The proposed concept calls for using the 30-meter well as a barrel for a site-built hydraulic system. In the new project, a constant-diameter cylinder barrel made of Glass Reinforced Polymer Epoxy (GRE), closed only at its base by an end cap and operating as a single-acting cylinder, is designed within this shaft. The adoption of GRE provides a cost-effective and corrosion-resistant solution, particularly suitable for direct contact with natural soil, where exposure to stray currents and saline environments may occur. A single access port for both the inlet and outlet of the working fluid is positioned slightly above the end cap (Fig. 2).

In the proposed configuration, the working fluid consists of non-additivity water. The use of water free of solutes or emulsified additives enhances the environmental compatibility of the system, especially considering its underground installation. Inside the barrel, a tubular rod shaft with a length of 30 m, a wall thickness of 10 mm, and an outer diameter of 350 mm slides axially. The rod shaft dimensions are identical to those adopted in the prototype designed and manufactured within the PERIMA project (Fig. 1), where the same component was employed in a jack-up lifting system. In contrast, in the proposed configuration, an adaptive hydraulic sealing system has been planned at the base of the strut, as described in the following sections.

Water stored in a reservoir located at ground level is pressurized by a hydraulic pump and injected at variable pressure near the end cap during the lifting phase. During the descent of the tower, the water flow is conveyed back to the reservoir under the combined gravitational action of the tower and the wind turbine, with a controlled flow rate, as discussed in the subsequent section.

1.3. Loads acting on the lifting system and design of the hydraulic circuit

Assuming the same telescopic tower adopted for the PERIMA prototype [15,16], which was designed to support a 55 kW LIBELLULA-type wind turbine, the maximum load of the lifting system is 200 kN. Since the piston rod in the previous prototype had a diameter of 250 mm to prevent buckling, the diameter of the cylinder barrel was assumed to be 350 mm. Based on these assumptions, the minimum pressure required to lift the tower was calculated to be 20.4 MPa.

The wind tower lifting time of 20 min represents a reasonable compromise between the needs of a pumping system of limited size and of a small overall energy consumption. To this end a multistage electric pump was selected, characterized by a maximum head of 230 m of water column and a flow rate of 3 L/s.

During the movement of the designed telescopic tower the load varies during both the lifting and lowering phases due to the engagement of the second and third tower sections with the first section during ascent, and their contact with the foundation during descent. In addition to the load variation occurring during each lifting and lowering operation, the opposing hydrostatic pressure acting at the outlet of the pump delivery pipe also varies from 0 to 30 m of water column, thus shifting the pump operating point.

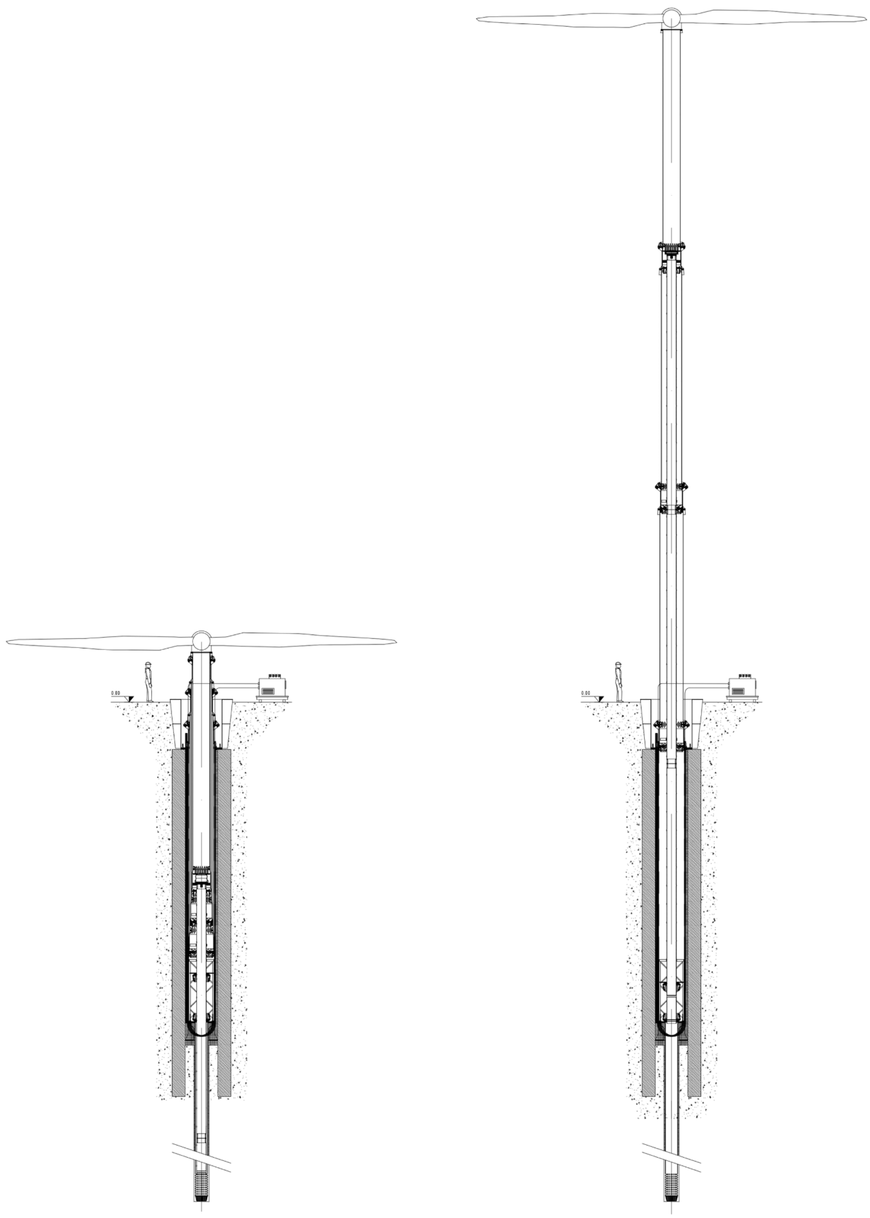

Fig. 1. Schematic section of the telescoping tower of the PERIMA project in its retracted position (on the left) and lifted position (on the right).

Previous studies on hydraulic seals in oleodynamic actuators [17] have shown that seal wear increases when the actuator is subjected to load fluctuations and variations in motion velocity. Therefore, in order to mitigate seal wear, it is advisable to implement a control system for regulating the piston rod velocity. The control of the upward and downward displacement of a single-acting hydraulic actuator requires different strategies due to the asymmetric actuation principle. The upward motion is actively driven by hydraulic pressure and is commonly controlled by regulating the inlet flow through proportional or servo-controlled valves, enabling accurate positioning and velocity tracking [18]. Conversely, the downward motion is typically induced by gravity or external loads and must be controlled indirectly by managing the exhaust flow to avoid instability and excessive descent velocity, often through throttle or counterbalance valves [19]. Reliable displacement control in both phases can be achieved by integrating position feedback sensors within a closed-loop control architecture, while accounting for load variability and valve nonlinearities [20]. In the proposed lifting system, a control system for the piston rod motion velocity has been planned (and implemented in the test bench) for both the lifting and lowering phases. The piston rod position is monitored through a PLC and dedicated sensors at 500 ms intervals. The opening or closing of the ball valve located downstream of the pump is regulated during the lifting phase, and the ball valve located in the bypass pump line is regulated during the lowering phase. A PID regulation has been implemented in the Programmable Logic Controller (PLC) for the movement of both valves.

1.4. GRE cylinder barrel

The cylinder barrel was manufactured using a GRE tube produced with an epoxy matrix through a filament winding process on a collapsible cylindrical mandrel. In this process, resin-impregnated glass fibre roving is wounded onto a rotating mandrel and subsequently cured, enabling the fabrication of cylindrical composite structures with high dimensional accuracy and repeatability. The use of a precision collapsible mandrel allows the achievement of particularly uniform internal diameters and improved geometrical regularity of the barrel. Furthermore, the internal surface quality is enhanced because the inner lining

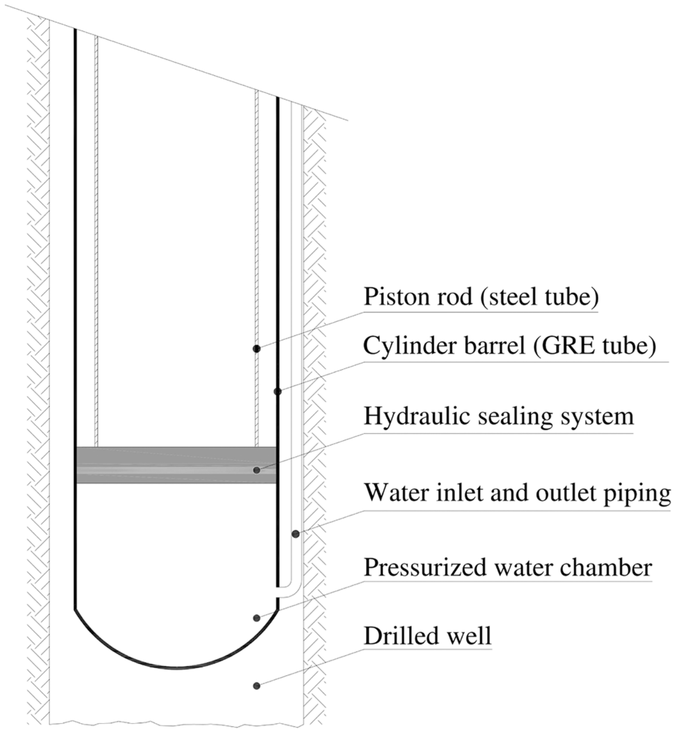

Fig. 2. Well and barrel schematic section of the in-site hydraulic lifting system.

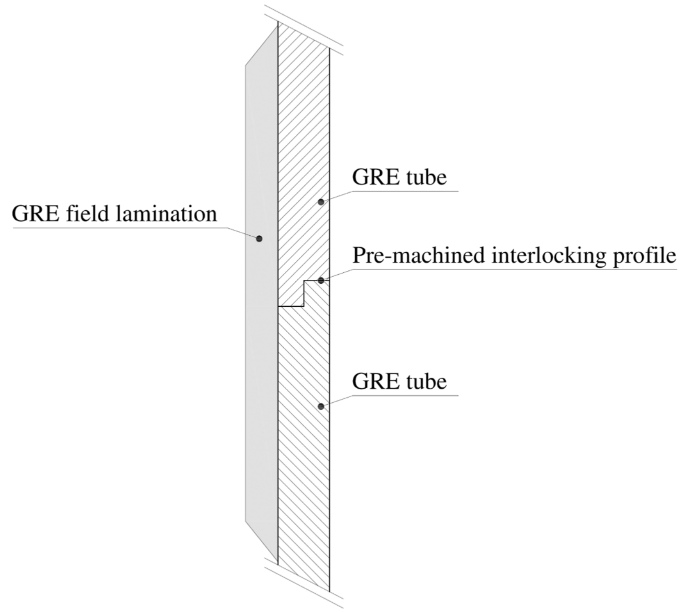

Fig. 3. Detail of the butt joint between two GRE cylinder barrel tubes.

consists of a thin layer of pure epoxy resin formed during the winding and curing process, resulting in a nearly mirror-like surface finish. This characteristic minimizes surface roughness and potential friction effects at the internal interface. Filament-wound GRE tubes have been widely investigated for structural cylindrical components such as pipes, pressure vessels, and hollow structural members due to their high specific strength, corrosion resistance, and manufacturing reliability [21–23]. Previous studies confirmed the suitability of epoxy/glass filament-wound cylinders for applications requiring controlled geometry and high-quality internal surfaces [21–23].

In the specific case study, a commercial GRE pipe was adopted, characterized by a nominal diameter of 350 mm and a nominal pressure rating of 25 bar, corresponding to a wall thickness of 15 mm. Commercial GRE pipes with this diameter are typically manufactured in standard lengths of about 6 m. Consequently, the joints between pipe sections become a critical aspect of the system design, as they must ensure resistance to the operating pressure while simultaneously avoiding any surface irregularity. This requirement is essential to both maintain the hydraulic sealing during the crossing of the pipe joints and to reduce the effects of seal wear. In the present configuration, a butt joint between two pipe sections was implemented. The joining process involves the pre-machining of an interlocking profile at the pipe ends to ensure precise alignment and concentricity. The actual joining operation is performed on-site (field lamination) by means of an external glass-fibre overwrap impregnated with epoxy resin, with a thickness specifically designed to withstand the operating pressure (Fig. 3).

1.5. Self-adjusting piston seal

Due to the manufacturing characteristics of filament-wound GRE tubes and the possible deviations from perfect circularity associated with composite structures, a good design of the piston sealing system is essential to guarantee reliable hydraulic tightness. The hydraulic sealing of a piston is a key requirement in systems involving pressurized fluid and relative motion between the piston and the cylinder barrel. Effective sealing requires a stable contact pressure between the sealing element and the internal surface of the barrel while maintaining low friction and limited wear during operation. For this reason, piston sealing systems must be capable of accommodating small geometric deviations, such as dimensional tolerances, surface irregularities, and local deviations from perfect circularity of the cylinder [24,25]. In the present case study, a sealing system based on a double four-lobe seal (quad-ring configuration) was adopted to improve sealing reliability and stability during piston motion. Quad-ring seals are commonly used in reciprocating applications because their four-lobe geometry provides multiple sealing lips, improved lubrication retention, and reduced risk of twisting compared with conventional O-rings. To further ensure reliable hydraulic tightness in the presence of possible ovalization of the GRE tube, the sealing assembly was mounted on a self-adjusting backup ring (Fig. 4). The sealing system incorporates a self-adjusting support element made of PTFE-reinforced graphite, which allows the sealing elements to adapt locally to variations in the internal geometry of the barrel. Thanks to the mobility of the PTFE ring on its support, enabled by the presence of a dimensional gap with respect to the internal diameter (Fig. 4), the seals are able to compensate for minor deviations in the regularity of the pipe cross-section, maintaining a continuous contact pressure along the circumference and preserving hydraulic tightness during piston motion [25]. This sealing configuration was therefore selected to ensure stable hydraulic performance under the expected operating conditions. The effectiveness of the adopted solution was subsequently assessed through the experimental tests described in the following section.

1.6. Experimental test bench

The experimental campaign was conducted using a dedicated test rig developed and assembled in the Hydraulic Laboratory of the University of Palermo. The assembly features a DN350 GRE cylinder barrel coupled with a DN250 steel piston rod, which integrates a specialized adaptive seal holder and lobe-type seals (Fig. 5 and Fig. 6). Hydraulic power is supplied by a 9 kW multistage pump delivering pressurized pure water, avoiding the use of lubricants or additives within the barrel. To replicate the operational conditions of a wind tower, a static load of 200 kN is simulated via a Y-shaped reaction frame connected to three hydraulic contrast actuators. These actuators operate within a closed water circuit integrated with a 1000-liter pressurized air-water vessel. This significant volume ensures that the pressure fluctuations remain negligible during

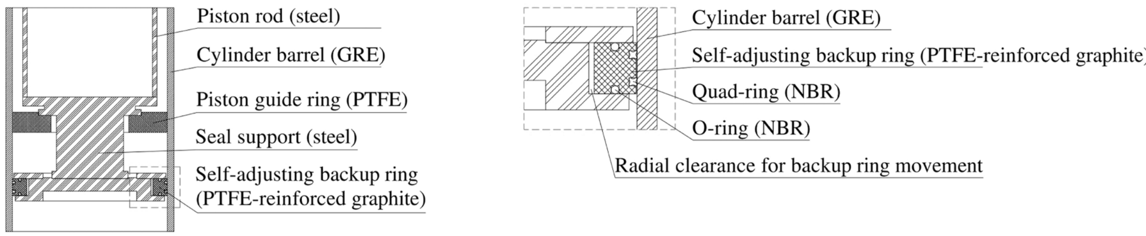

Fig. 4. The sealing system incorporates a self-adjusting backup ring.

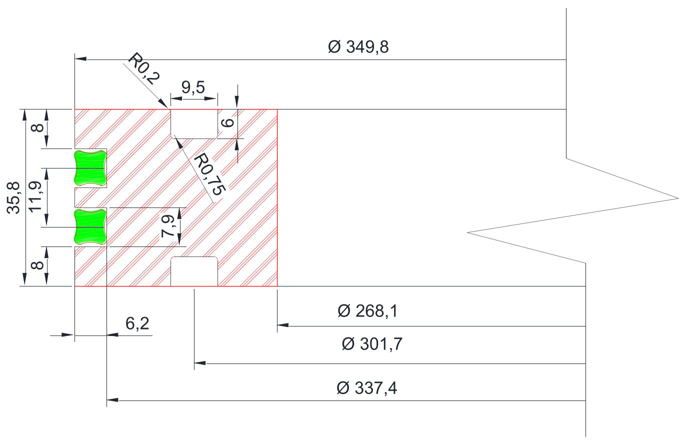

Fig. 5. Dimensions of the prototype sealing system.

the 1000 mm test stroke, thereby maintaining a near-constant contrast load. The force exerted by each actuator is precisely monitored through dedicated tension load cells. Notably, the 1200 mm length cylinder barrel was sectioned and reassembled using the previously described joint configuration; this setup allows for a detailed investigation into the system's durability and the structural response of the seals as they repeatedly cross the joint interface. The entire facility (Fig. 7) is instrumented with high-precision water pressure transducers, displacement sensors for rod positioning, and flow meters. A PLC manages the continuous load cycles, enabling an automated assessment of hydraulic seal wear and long-term reliability under realistic loading scenarios.

2. Tests and results

To evaluate the reliability of the proposed lifting system, to test the hydraulic seal integrity, and to assess the long-term durability of the seal under operational conditions, the sealing system has been tested in both the University Lab and in the VED plants. A static test has been carried out first in the VED plants by using a short part of the GRE pipe, with nuts and bolts linking the upper flange of the pipe with that of the sealing system. A pump raised the pressure inside the GRE pipe through a small inlet high-pressure pipe, up to the final value of 20 bars. A valve finally disconnected the pump from the GRE pipe and the initial pressure of 20 bars was observed to remain constant for several hours. The device has been then mounted in the experimental test bench described in the previous section, where a series of cyclic lifting and lowering tests was performed. The experimental setup maintained a nearly constant contrast load of 200 kN. The stroke for each cycle was set to 700 mm for both the ascent and descent phases, with the piston velocity fixed at 2 cm/s. A total of 515 lifting cycles were completed, resulting in 1030 crossings of the pipe welds by the hydraulic sealing system. When scaled to the real-world application, considering a tower height of 30 m, these tests simulate approximately one full lifting and lowering operation per month over one year. Upon completion of the first test cycle, the system demonstrated excellent performance with no recorded water leakage through the hydraulic seal. Subsequent disassembly and detailed inspection of the used seal revealed that visual (Fig. 8 and Fig. 9) and dimensional inspections (Fig. 10) of the double quad-ring seal showed only small signs of wear.

Initial measurements of the seals show a manufacturing dimensional tolerance of less than 0.1 mm. Post-service measurements reveal a width variation ranging from 0.17 to 0.51 mm for seal n.1, and from 0.38 to

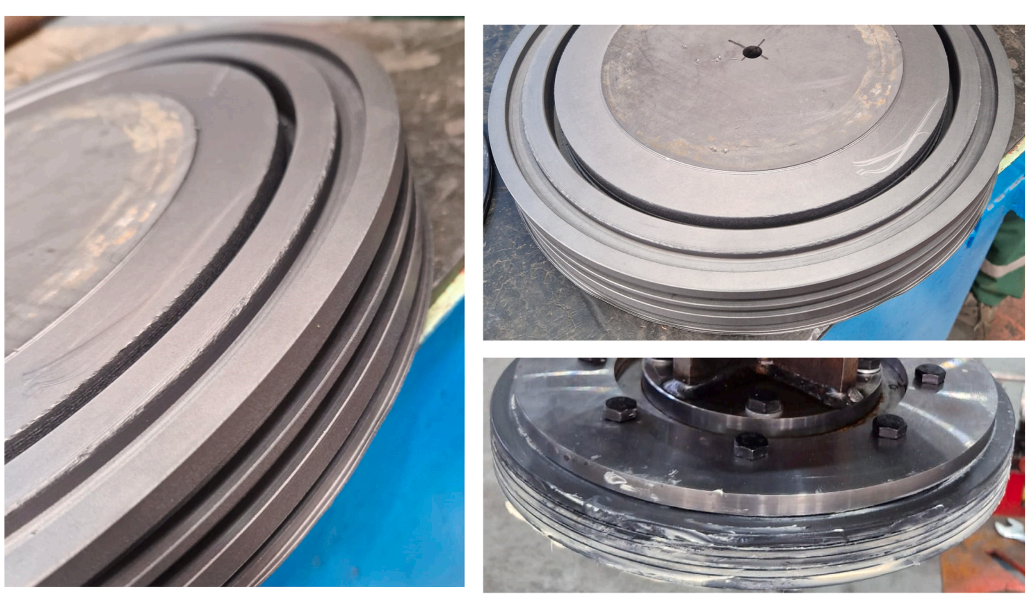

Fig. 6. Sealing system of the prototype.

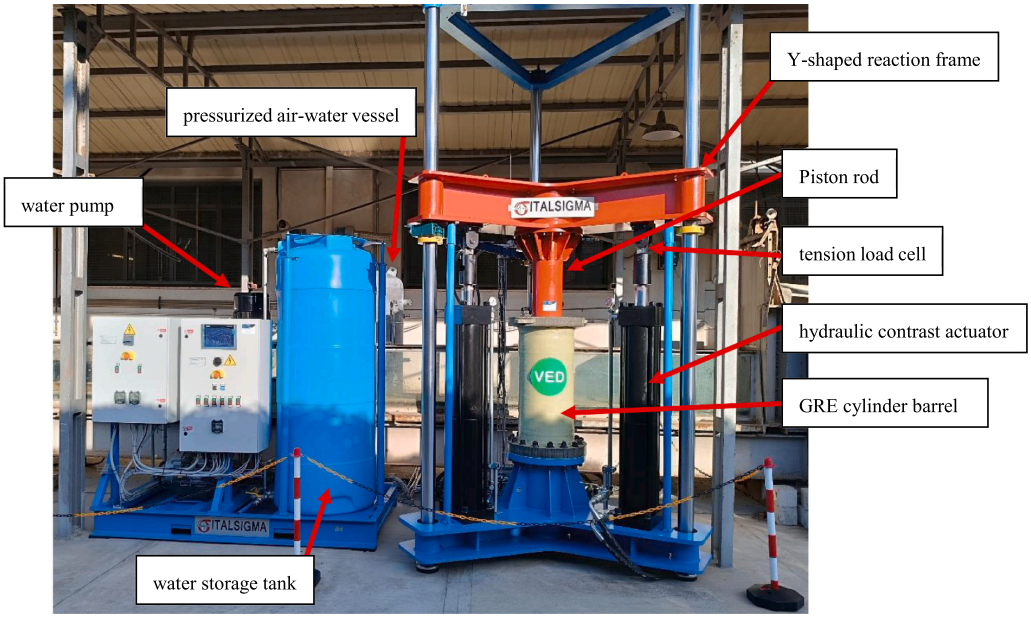

Fig. 7. The test rig.

Fig. 8. Sealing system of the prototype after testing.

Fig. 9. Detail of the sealing system showing quad-rings.

0.56 mm for seal n.2. Given that elastic deformation is expected during assembly and disassembly, these width variations can be attributed to sliding-induced wear. Nevertheless, the implementation of a self-adjusting backup ring ensured that width variations exceeding 0.5 mm did not result in water leakage, even at maximum operating pressure. It should be highlighted that the seals operated dynamically within a closed-loop system where the fluid shortly became contaminated with suspended solids from the uncoated steel support. This created a highly demanding operating environment. Despite that, the self-adjusting backup ring and the Quad-ring seals prevented any leakage at maximum pressure.

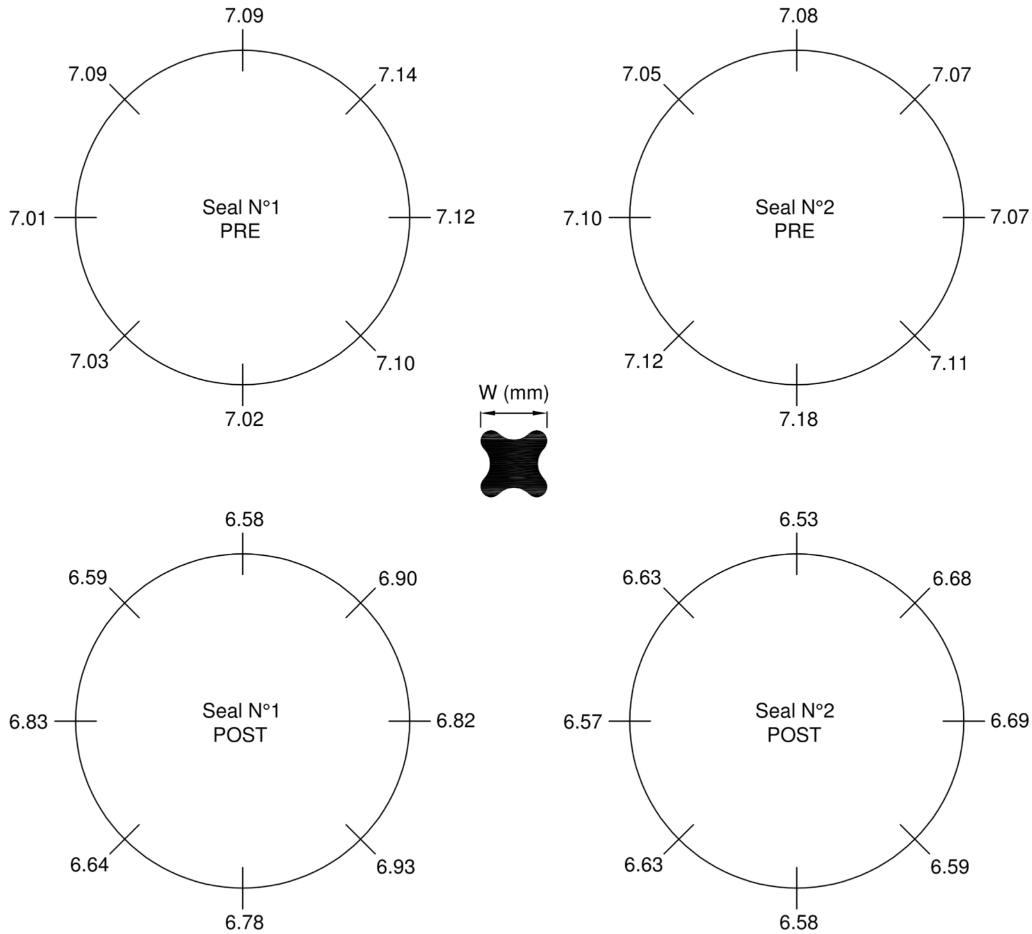

Fig. 10. Comparison of seal width measurements: (upper) pristine condition and (lower) post-use state.

2.1. Uncertainties on the long-term field performance of the sealing system

Even if experimental results fully satisfied our expectations, it is very important to underline that the sealing system prototype is part of a larger PERIMA project, where the tower optimal design is sought after by means of incremental optimization and testing of single components and their connections. With this research we shifted the TRL of the sealing system from 4 to 6 (*Technology model or prototype demonstration in a relevant environment*), but a detailed optimization of its components, along with a detailed monitoring of all the parameters relative to the suspended solids in the power fluid, to the wear and the deformation of both the plastic and the GRE material components, still remains for the next levels of the PERIMA design.

One fundamental question, that has been only partially investigated in this research, is the frequency required for the replacement of the double quad-rig seal, which strongly depend on the motivation of the PERIMA tower. This motivation can be a) Tower installation in a small island or other place with a strong touristic vocation in the summer period, (b) Tower installation in sites with relevant landscape, but high potential production also during the night, (c) small return period times of occurring wind forces, in geographic areas with frequent hurricanes, due to the possibility to contract the structure even with an event anticipation of few minutes.

The required durability of the sealing system depends on: 1) the specific motivation of the PERIMA system, among the previous (a,b,c) mentioned ones, 2) the cost of the seal replacement. For point (2) the envisioned telescopic tower geometry allows to replace the seal, in contracted tower condition, by simply temporarily remove the generator with the blades and the rod, which is designed to be easily sectioned and reassembled in several parts. No cranes for high loads are required and few hours of operations should be sufficient for one seal change.

This implies that, if case (b) applies, the expected duration of one seal must cover at least the experimentally simulated cycles (12), but a larger number would be probably better. If case (a) or (b) applies the cost of the seal change is probably negligible with respect of the value of the energy production.

A second fundamental question is the risk of rock displacement around the shaft. To avoid the risk of a consequent GRE deformation, a careful geologic analysis is in order. It is also important to protect the GRE pipe inside the shaft with reinforced concrete or other rigid and resistant material.

3. Conclusions

This study presented the experimental validation of an innovative hydraulic actuation system designed for high-load and long-stroke applications, with specific focus on retractable wind tower systems. The proposed solution integrates a GRE cylinder barrel, constructed in situ through the field-joining of standard commercial pipes, with a radially self-adjusting piston sealing system based on a double quad-ring configuration. The experimental campaign, conducted under severe loading and operating conditions, demonstrated the effectiveness of the proposed concept. The hydraulic system exhibited stable performance throughout cyclic testing, with no observed leakage and small wear upon post-test inspection. The presence of a thin water film between the internal resin surface of the cylinder barrel and the seals provided sufficient lubrication, contributing to reduced friction and enhanced durability. These results confirm that the synergy between composite materials and adaptive sealing technology can overcome traditional limitations associated with large-diameter and long-stroke hydraulic cylinders, particularly regarding manufacturing tolerances and seal reliability. In this context, the proposed approach represents a new paradigm for hydraulic actuators, enabling the on-site construction of large-scale systems while maintaining high performance and reliability. From an application perspective, this technology opens new opportunities for the development of environmentally adaptive wind energy systems. Specifically, retractable wind towers with reduced visual impact can be realized, allowing structures to be lowered or concealed during specific periods to improve integration into sensitive landscapes. Furthermore, the experimental findings and the materials adopted suggest promising implications for offshore wind applications. The use of GRE components and in-situ construction techniques has the potential to significantly reduce installation, transportation, and maintenance costs in marine environments, where corrosion resistance and ease of assembly are critical factors.

CRediT authorship contribution statement

Francesco Cucè: Methodology, Investigation, Conceptualization. **Silvia Cosentino:** Writing – original draft, Methodology, Investigation, Conceptualization. **Tullio Tucciarelli:** Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition. **Marco Sinagra:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Armando Falla:** Writing – original draft, Methodology, Funding acquisition, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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