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COMPOSITE HIGH PRESSURE HYDRAULIC ACTUATORS FOR LIGHTWEIGHT APPLICATIONS

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During the last decades, the market share of products made of reinforced plastics increased rapidly. The low density, corrosion resistance and high fatigue performance of such materials provide a wide range of benefits for different applications. Parker Hannifin has developed fully composite hydraulic cylinders for 380 bar applications which are up to 60 % lighter than their standard steel cylinder equivalents. The fully composite cylinders were tested extensively under various mechanical and environmental influences to verify the robustness of the products. The results confirmed that the new composite barrel technology for hydraulic actuators is competitive to standard metal solutions while providing further benefits in terms of weight and corrosion resistance.

Keywords: Composites, Hydraulic Actuators, Lightweight, Robustness

Target audience: Military, Marine, Oil & Gas, Mobile Hydraulics

1 Introduction

Industrial demand on products with low density in combination of outstanding mechanical properties requires continuous R&D effort. While for metals the development of new lightweight alloys /1/, /2/, /3/ and their joining technologies /4/, /5/ is the common approach, developments and production of composite materials moved into the focus as a reasonable alternative. Compared to metal matrix composites /6/, /7/ fiber reinforced plastics offer additional weight savings by the low density of the matrix material.

For high pressure hydraulic cylinders, accumulators and pressure vessels typically high strength ste-

el alloys are chosen. Such materials are not suitable for lightweight applications. Depending on the level of weight efficiency of the original design, utilization of high performance metal alloys, typically based on aluminium or titanium, is the current state-of-the-art lightweight solution. Because an increase in strength typically results in low ductility and, correspondingly, reduced fatigue performance, their benefits for actuators are rather limited. Incorporation of fibre reinforced plastics can overcome the conflict of reduced fatigue at higher strength. Ideally, the load-bearing structure of the products would be made entirely out of composite, thus without a metallic liner, and without a metallic barrel that supports the axial loads applied on the end caps. Parker has developed an ultra-lightweight high pressure fully composite hydraulic cylinder series called Lightraulics®. Figure 1 shows an example of a Lightraulics® composite hydraulic cylinder with a bore diameter of 200 mm that is rated for 380 bar.



Figure 1: 380 bar Fully Composite Hydraulic Cylinder (Example 200mm bore dia., 125mm rod dia.).

The design concept follows the approach of separation of duties. The barrel consists of two parts, an inner liner and an outer barrel. The design concept of the fully composite barrel is shown in Figure 2. While the fully composite inner liner with integrated diffusion barrier is carrying the hoop loads of the internal pressure, the fully composite outer barrel is responsible for the axial loads. The interface between the outer composite barrel and the metal end caps is realized by metal parts with inner threads that are integrated in the outer barrel.

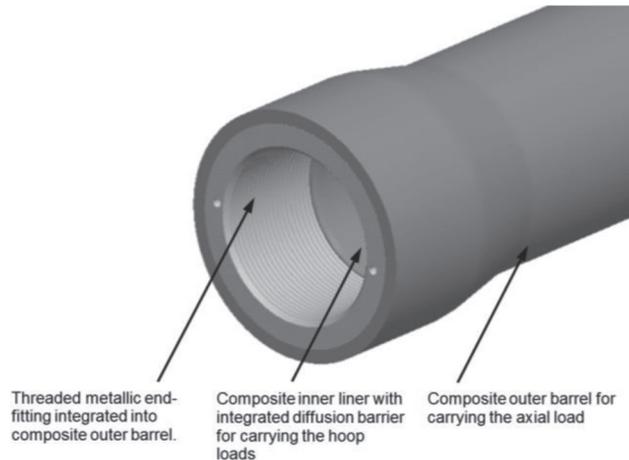


Figure 2: Fully Composite Design Concept.

During the development phase Parker carried out several tests to demonstrate the outstanding performance of the product. These investigations were accompanied by additional requirements that were demanded by the customers for specific application. Because for fully composite piston accu-

mulators /8/, the same barrel design is considered, some tests are related to CE-requirements for piston accumulators /9/, too.

2 Experimental

Depending on the properties to be proven, test specimens consisted of either composite liners components, composite barrels subassemblies, or complete hydraulic cylinder products. To capture all design and manufacturing variations expected across the catalogue range, a wide range of sample dimensions were tested. A summary of the dimensions is given in Table 1. In Figure 3 - Figure 5 examples of different specimen types and sizes are shown.

Table 1: Specimen Dimensions.

Specimen	B75	C75	L110	B150	B200	C200
Type	Composite Barrel	Complete Cylinder	Composite Inner Liner	Composite Barrel	Composite Barrel	Complete Cylinder
Bore Ø [mm]	75	75	110	150	200	200
Total barrel length [mm]	840	840	290	1280	1946	1946
Rated no. of cycles	500,000 @ 380 bar	500,000 @ 380 bar	1,000,000 @ 380 bar	1,000,000 @ 380 bar	250,000 @ 380 bar	250,000 @ 380 bar



Figure 3: Example of Composite Liner Specimen.

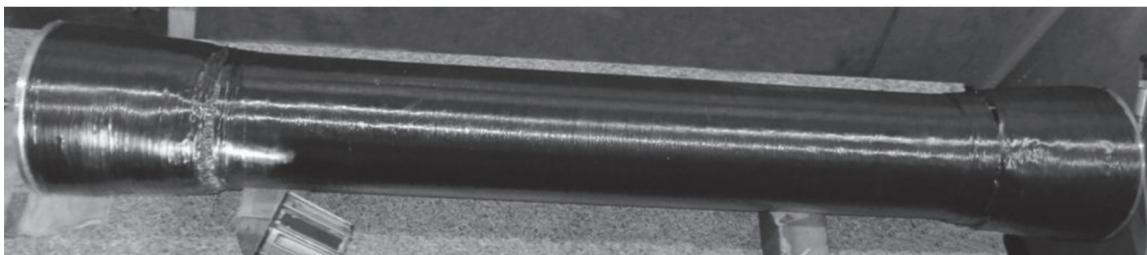


Figure 4: Example of Composite Barrel Specimen.



Figure 5: Example of Composite Cylinder Specimen.

2.1 Pressure testing

2.1.1 Static test

Static pressure tests were carried out to prove the burst strength of different fully composite barrel specimens, in particular, specimens B150-1 and B200-1. The pressure was increased at a controlled rate until the specimens ruptured (catastrophic failure) or were no longer able to hold pressure. The pressure was measured directly at the ports of the specimens.

2.1.2 Fatigue test

Cyclic pressure tests were carried out to prove the fatigue resistance of different fully composite liner and barrel specimens. In the fatigue resistance tests, premature catastrophic failure or loss of pressure holding ability would constitute failure. Table 2 provides an overview of the test parameters.

Table 2: Parameters of cyclic testing.

	Specimens B75-1	Specimens L110-1	Specimens B150-2
Type	Composite Barrel	Inner Liner	Composite Barrel
Cyclic Pressure [bar]	20 - 450	20 - 420	100 - 380
No. of cycles	1,600,000	5,850,000	1,800,000

2.2 Wear behaviour

2.2.1 Short stroke test

In many hydraulic applications, cylinders are operating in environments where low frequency vibrations will be applied to the cylinder. Unless suitably remedied, such vibrations could result in local wear of the piston or liner surfaces. This situation was simulated by a short stroke test. Specimen C75-1 was mounted in test frame as shown in Figure 6.

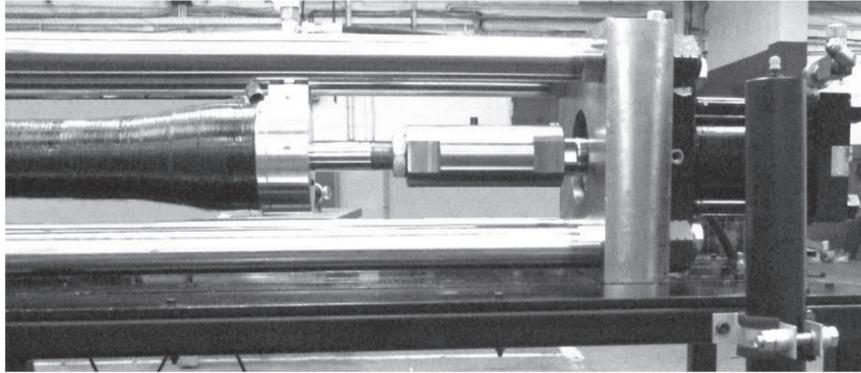


Figure 6: Test set-up for short stroke test of specimen C75-1.

The cylinder was cycled with 5 mm double strokes (10 mm travel) for 1,000,000 cycles with precharge pressures of 115 bar on the rod side and 94 bar on the piston side, respectively. Subsequently, the inner surface of the composite liner was inspected for signs of excessive wear.

2.2.2 Side load test

Specimen C75-2 was tested for 1,000,000 cycles at full stroke while a side load of 72 kg was applied perpendicular to the cylinder axis via the rod gland. This test was performed to determine the wear behaviour between piston and inner composite liner surface under eccentric load conditions. The test set-up is shown in Figure 7. Pressure levels were chosen to achieve a cycle time of 5.4 seconds. After testing, the inner surface of the composite liner was inspected.

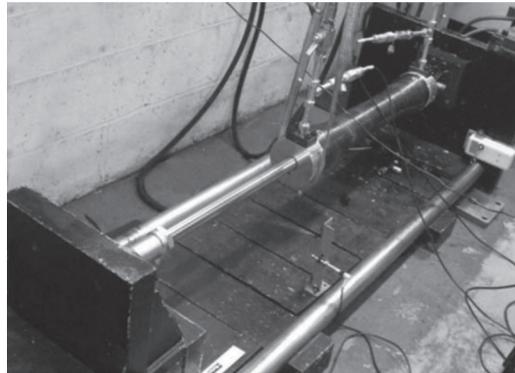


Figure 7: Test set-up for side load test of specimen C75-2.

2.3 External resistance

2.3.1 Drop test

In some applications the actuators will not be handled with appropriate care. Especially during installation or maintenance procedures, it might occur that the cylinder is dropped to the ground. Based

on Norm DIN EN 12245 for CE-approval of pressure vessels /9/, 50 % of the volume of specimen B200-2 was filled with oil and it was dropped twice from each of five different positions as shown in

Figure 8. Subsequently, the barrel specimen was statically tested up to 1.5 x the design operating pressure (DOP) to confirm the structural integrity of the product.

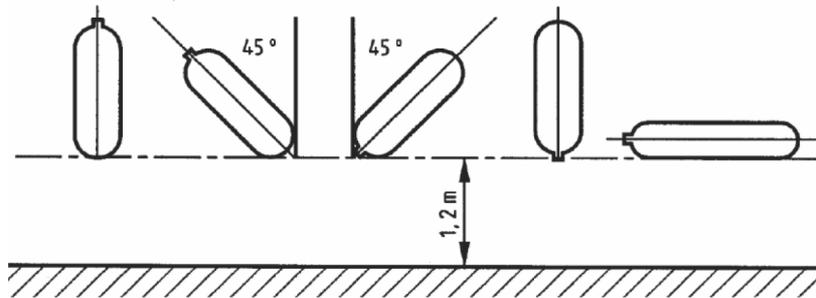


Figure 8: Falling positions for drop testing of pressure vessels /9/.

2.3.2 Impact test

Particularly in rough environments, such as mobile construction machinery, it may occur that a cylinder barrel will accidentally come in contact with flying debris such as falling stones. Due to the separating of duty design shown in Figure 2, leakage would occur if the inner liner would be affected by the impact. Therefore impact tests were performed with liner specimens L110-2, -3, -4 and -5 without considering the outer barrel structure. The test was performed based on the specifications given in aerospace norm ASTM D7136 /10/. In this norm the impact energy E_{impact} is calculated depending on the wall thickness s in mm as given in Equation (1):

$$E_{\text{impact}} \triangleq 6,7 \cdot s \quad (1)$$

According to Equation (1) an impact energy of

$$E_{\text{impact}} \triangleq 6,7 \cdot 10 \text{ mm} \triangleq 67 \text{ J} \quad (2)$$

was applied for the specimens of type L-110. This was realized by a 1,25 m free drop of an impact body of 5.46 kg.

The tip of the impact body is half-spherical with a diameter of 16 mm as shown in Figure 9 a). Static pressure tests at 570 bar (1,5 x DOP) were performed with all specimens before and after the impact. While specimen L110-2 was tested unprotected, the specimens L110-3, L110-4 and L110-5 were covered with different protection materials, as listed in Table 3 and shown in Figure 9 b).

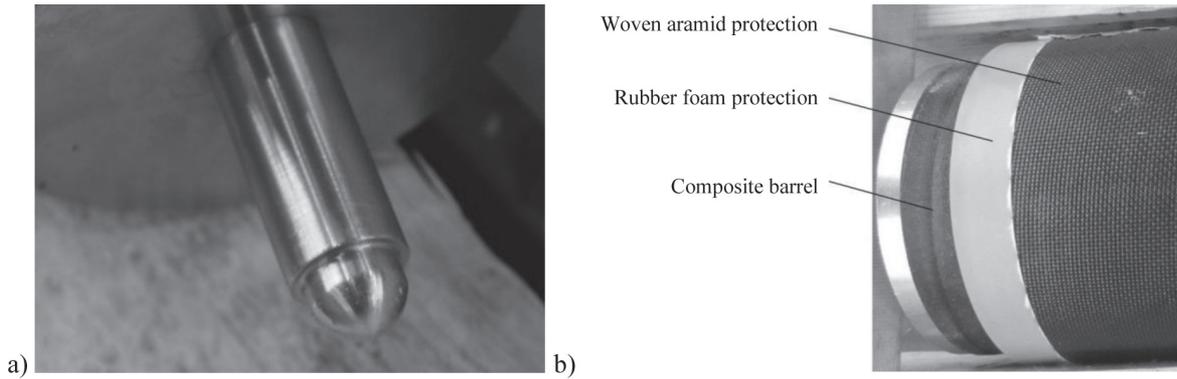


Figure 9: a) Tip of impact body, b) impact protection lay-up.

Table 3: Tested impact specimens and impact protection materials.

Specimen	Protection Material
L110-2	No protection
L110-3	2 sheets of woven aramid
L110-4	Woven aramid + 4 mm rubber foam
L110-5	Woven aramid + 6 mm rubber foam

The specimens were clamped on a solid table. The weight was dropped freely through a downpipe. The test set-up is given in Figure 10. All specimens were statically pressure tested with 570 bar (1.5 x DOP) before and after impact. Specimen L110-5 was additionally tested for 600,000 pressure cycles at 20-380 bar.

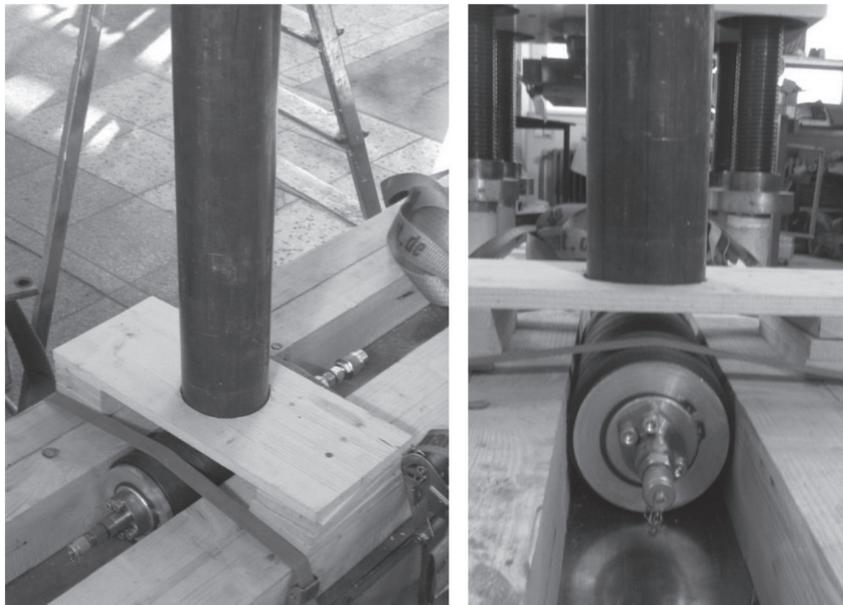


Figure 10: Test set-up of impact test.

2.3.3 Buckling test

To prevent premature buckling of actuators under compression loads, the relevant actuators must be selected or designed to have a sufficient safety factor between operating conditions and the expected buckling condition limits. The buckling test was carried out on Specimen C200-1. Prior to the buckling test, the specimen was proof tested to 570 bar with the piston rod fully extended and subsequently fully retracted.. The specimen was fixed in a test frame with its piston rod almost fully extended, as shown in Figure 11. While increasing the applied pressure at a controlled rate, deflections at the guiding end cap and strains on the piston rod surface were measured continuously. In the first step, the pressure was increased to 380 bar (DOP) and decreased again to 0 bar (gauge) to check for pure elastic deformation. Subsequently, the cylinder was pressurized to progressively increasing pressure levels, depressurizing at each cycle, until sudden buckling occurred. According to theoretical calculations, buckling was expected in the test specimen at 610 bar.

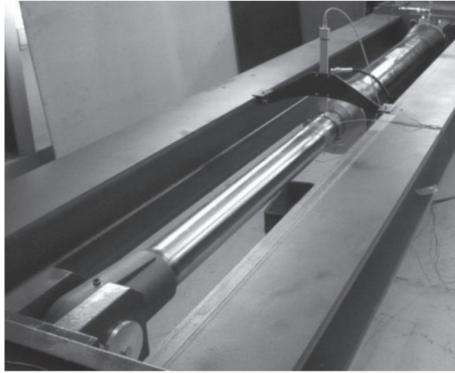


Figure 11: Specimen C200-1 in test frame before buckling test.

3 Results

3.1 Pressure testing

3.1.1 Static test

Due to the intentional “leak-before-burst” functionality of the fully composite barrel design, both test specimens B150-1 and B200-1 reached a pressure level far exceeding DOP without catastrophic structural failure. Leakage occurred through the end cap seals as shown in Figure 12 at such a rate that further pressurization was not possible. In Figure 13, the corresponding pressure curve is given. Table 4 summarizes the static pressure results of both specimens.

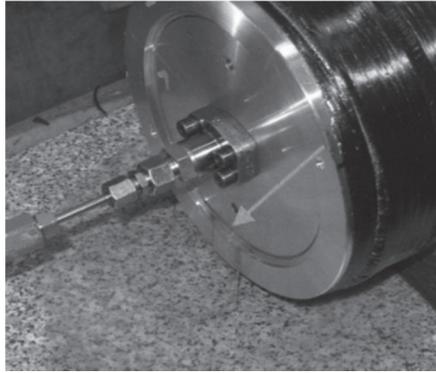


Figure 12: Leakage through the end cap seals of specimen B150-1 at 1272 bar.

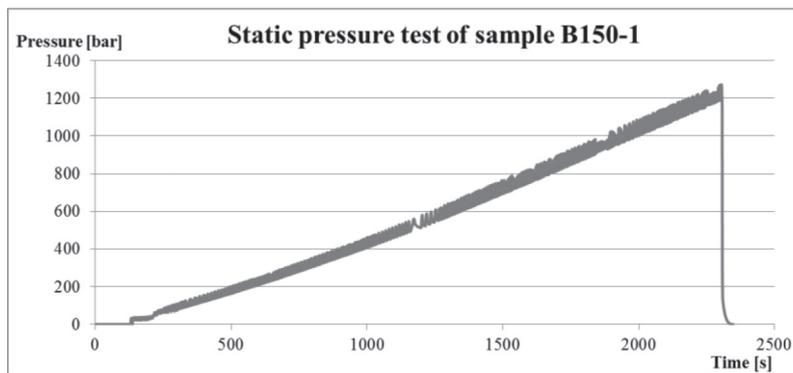


Figure 13: Static pressure test of specimen B150-1.

Table 4: Static pressure results.

	Specimen B150-1	Specimen B200-1
Maximum pressure [bar]	1272	930
Factor against standard operating pressure	3.35	2.45
Failure mode	Leakage through end cap seals	Leakage through end cap seals

The pressure at which leakage occurs can be customised, but both specimens first leaked with an overpressure factor of at least 2x DOP. Furthermore, specimen B150-1 confirmed that rupture will not occur even at 3x DOP.

3.1.2 Fatigue test

All fatigue tests were stopped at the numbers of cycles stated in Table 5, when the target fatigue life cycle count was reached. There was no specimen failures detected during testing.

Table 5: Results of cyclic testing.

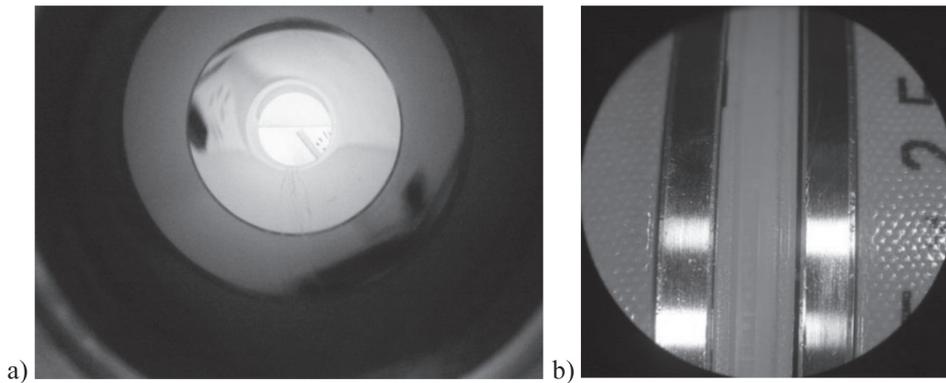
	Specimen B75-1	Specimen L110-1	Specimen B150-2
Cyclic Pressure [bar]	20 - 450	20 - 420	100 - 380
Factor against standard operating pressure	1.2	1.1	1.0
No. of cycles	1,600,000	5,850,000	1,800,000
Factor against rated no. of cycles	3.2	5.85	1.8

These results confirm the superior fatigue resistance properties of fibre reinforced composites, which typically can withstand a larger cycle count at a higher stress level than conventional metals.

3.2 Wear behaviour

3.2.1 Short stroke test

After 1,000,000 short stroke cycles, specimen C75-1 showed no loss of functionality and no evidence of leakage. Figure 14 a) shows the inner surface of the cylinder liner of specimen C75-1 after short stroke testing. The piston sealing system in Figure 14 b) as well as the inner surface did not show any signs of unusual wear damage and were in good condition.


Figure 14: a) Inner liner surface and b) piston seals after 1,000,000 short stroke cycles.

3.2.2 Side load test

The cylinder specimen C75-2 was operated under side load for 1,000,000 cycles. After the test, the cylinder did not demonstrate any loss of functionality or signs of damage. The inner liner surface of specimen C75-2 after testing is shown in Figure 15 a). There was no evidence of wear detected inside the liner. The axial wear marks of the piston seal system were increased by the side load as shown in Figure 15 b). These observations confirmed that the composite liner is more wear resistant than typical piston seals and guiding elements.

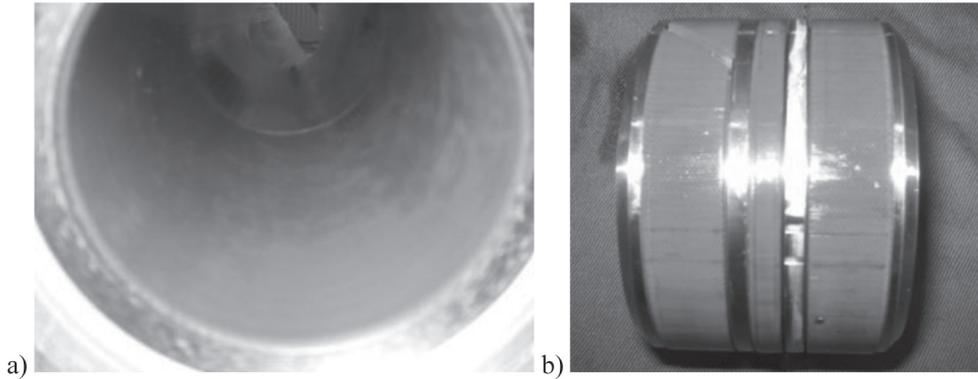


Figure 15: a) Inner liner surface and b) piston seals after 1,000,000 side load cycles.

3.3 External resistance

3.3.1 Drop test

At each falling position, the specimen hit the ground with the impact zones on or near the end caps due to the larger outer diameter at the ends of the barrel. Figure 16 shows the resultant damage of specimen B200-2 after drop testing. Subsequently the specimen was successfully pressurized up to 570 bar without failure or leakage. These results prove that the fully composite barrel is able to withstand 1.5 x DOP after the dropping scenarios defined in DIN EN 12245 /9/.

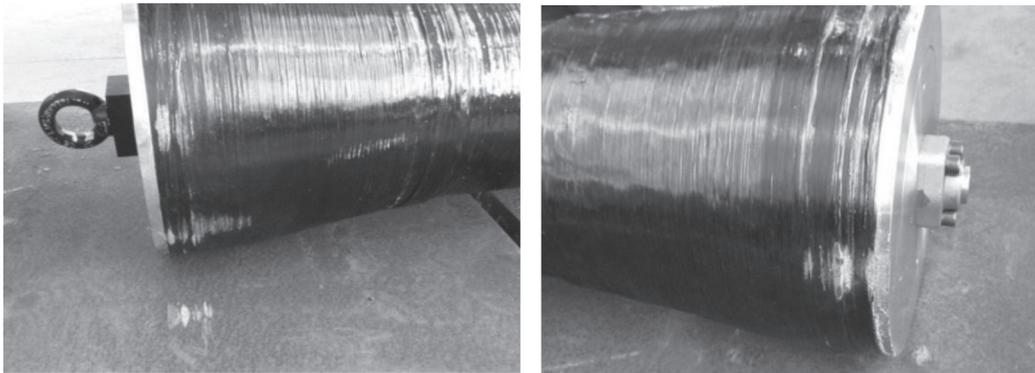


Figure 16: Impact zones of specimen B200-2 after drop testing.

3.3.2 Impact test

After impact testing, the specimens L110-2 and L110-3, without impact protection, were no longer able to hold the applied pressure. The specimens sweated locally at the impact zone. Cross sectional inspection confirmed that the liner structure of the specimens was damaged by the impact. No rupture or catastrophic failure occurred.

In contrast, specimens L110-4 and L110-5, with additional impact protection, withstood the pressure test without any evidence of leakage. L110-5 was subsequently pressurized for 600,000 cycles from 20 to 380 bar without failure. Cross sectional inspection later revealed that even these protected specimens had impact cracks, however their intensity was reduced significantly and the specimens passed the subsequent pressure test due to the impact protection.

The liner outer surfaces after impact testing are shown in Figure 17 and Figure 18. Table 6 summarizes the results and observations. These tests prove that fully composite actuators can meet demanding impact resistance requirements through suitable impact protection.

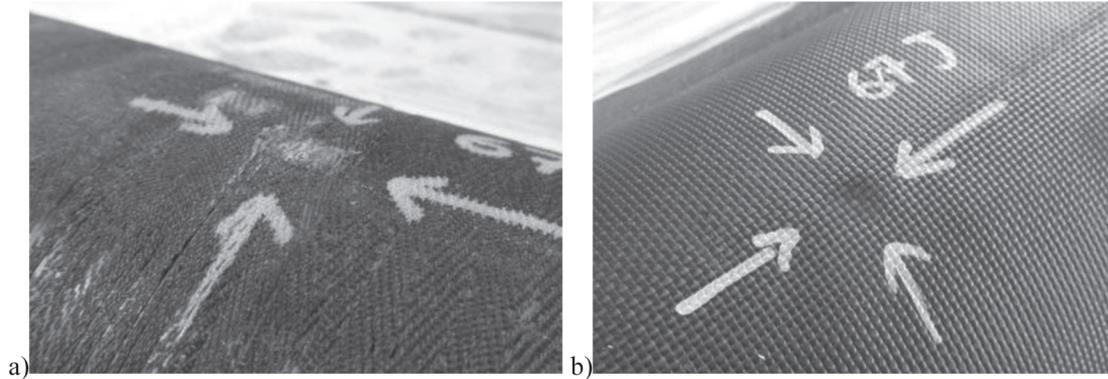


Figure 17: Impact zone of a) specimen L110-2 and b) specimen L110-3.

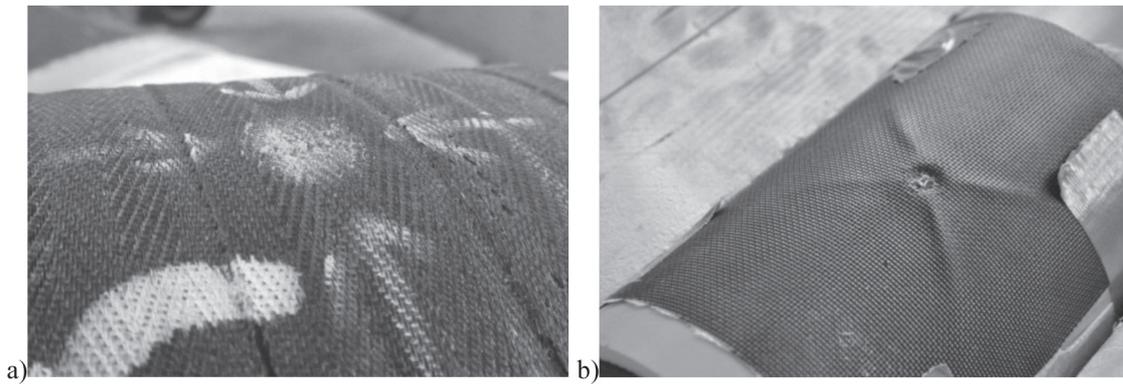


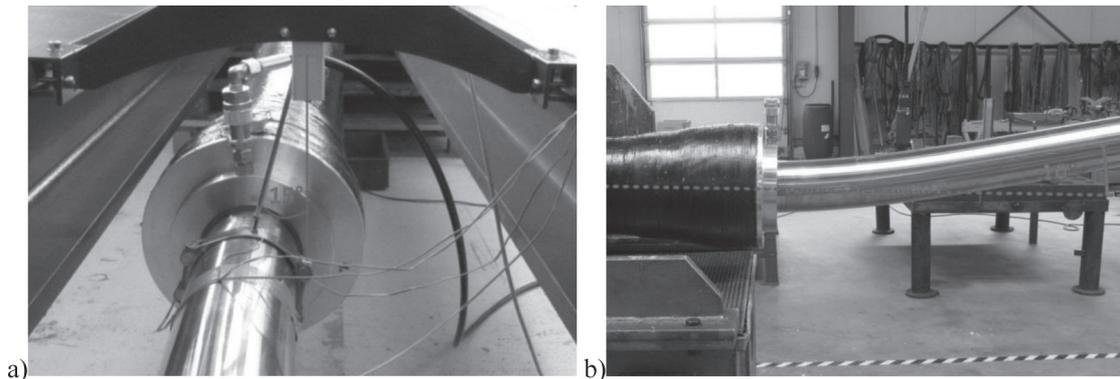
Figure 18: Impact zone of a) specimen L110-4 after removing the protection layers and b) specimen L110-5 with protection layer in place.

Table 6: Impact test results.

Specimen	L110-2 No protection	L110-3 2 sheets aramid	L110-4 Aramid + 4 mm rubber foam	L110-5 Aramid + 6 mm rubber foam
Static pressure test at 1,5 x DOP	passed	passed	passed	passed
Impact Test 67 J	completed	completed	completed	completed
Static pressure test at 1,5 x DOP	failed	failed	passed	passed
Cyclic pressure test 20 – 380 bar	---	---	---	600,000 cycles without any evidence of leakage
Cut to inspect cross section	Impact cracks over the whole circumference of the barrel		Minor impact cracks	Minor impact cracks, lesser extent than with 4 mm protection

3.3.3 Buckling test

During the process of stepwise pressure increases, plastic deformation was first detected at 650 bar. At this pressure level, the position sensor indicated a permanent deflection of 0,3 mm unloaded. A finer stepwise pressure increase may have revealed the true onset of buckling to be closer to our expected buckling pressure of 610 bar. Figure 19 shows the cylinder specimen C200-1 after testing. Figure 20 shows the measured buckling curve. Subsequent inspection confirmed that buckling occurred due to plastic deformation of the piston rod while the composite structure remained intact. These results confirm the robustness of the fully composite actuator design against buckling to be no lower than of an equivalent steel design.

**Figure 19:** Composite cylinder specimen C200-1 after buckling test.

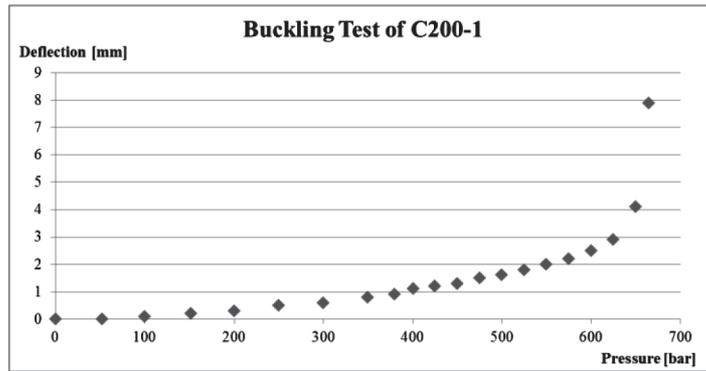


Figure 20: Buckling curve of composite cylinder specimen C200-1.

4 Summary and Conclusion

Parker Hannifin has developed a new generation of lightweight hydraulic actuators to fulfil the increasing demand on high performance hydraulic components with reduced weight. In addition to lightweight metal components, fibre reinforced plastics were used to develop a fully composite cylinder barrel without the need for a metallic liner. An extensive test programme was carried out across a wide range of hydraulic actuator sizes to demonstrate the robustness and resilience of this novel design. In particular, resilience against rupture and high cycle fatigue, seal wear behaviour, and robustness against external influences like impact and buckling were proven to ensure longlife operation without extensive maintenance effort. It was confirmed that the new actuator design performs superior to standard metallic roundline designs and also provides further benefits in terms of corrosion resistance and significant weight reduction. It should also be noted that this fully composite barrel technology is equally applicable to piston accumulators.

Nomenclature

<i>Variable</i>	<i>Description</i>	<i>Unit</i>
DOP	Design Operating Pressure	[bar]
Eimpact	Impact Energy	[J]
s	Wall thickness	[mm]

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