High Pressure Lightweight Hydraulic Fully Composite Piston Accumulators

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Abstract

High pressure hydraulic products require high strength structural components. High strength steels are traditionally used for common industrial applications, while more expensive lower density alloys are used for lightweight applications. Composites are an ideal reinforcement material for hydraulic products, but reinforced designs are still limited by the strength of the remaining metallic components. Therefore, a better solution would be to remove all metallic components and fully utilise composite materials to support both the hoop and axial loads in the product. Parker has developed a fully composite piston accumulator which offers dramatic weight savings potential and exceptional burst and fatigue strengths.

KEYWORDS: composites, lightweight, piston accumulators, cylinders

1. Background

1.1. Market Situation

Hydraulic accumulators can be considered hydraulic "batteries", analogous to electrochemical batteries, which can store and deliver hydraulic energy at higher rates than even the best pumps. Accumulators are therefore often added to hydraulic circuits in order to store energy, boost the power of a hydraulic system, or dampen out transient pressure fluctuations /1/. They are sometimes also supplemented by pressure vessels that store gas in order to increase the total volume of the accumulator.

Parker Hannifin Corporation, the world leader in motion and control solutions, offers a comprehensive range of hydraulic components in various sizes and construction types that can operate under virtually any condition experienced on (or off) the Earth. The total global market worth of hydraulic equipment has been estimated at around 20 billion Euros per annum in the year 2006 /2/, and is predicted to reach around 50 billion US dollars by 2017 /3/.

1.2. Current State-of-the-Art

High pressure hydraulic cylinders, accumulators, and pressure vessels are traditionally constructed from high strength steel alloys. When standard hydraulic component masses (inertias) are too high and "lightweight" solutions are required, the typical approach of mass optimisation consists of removing material contributing insignificantly to the overall structure's performance (e.g. stiffness and strength). As the volume of material in the structure is reduced, stresses are consequently increased, which must be compensated for by using higher strength materials. Alternatively, lower density materials with could be used as a substitute for the original material when their strengths are equivalent.

Depending on the level of mass efficiency of the original design, significant mass savings can sometimes be obtained simply by removing unnecessary material, often at additional manufacturing cost, without even changing materials. However, further along the spectrum of mass optimisation, one will find designs which utilize high performance alloys, typically based on aluminium or titanium, as the current state-of-the-art lightweight solution /4/.

One significant disadvantage of high strength metallic alloys is that their high ultimate strength typically comes at the cost of decreased ductility and, correspondingly, reduced fatigue strength. This makes designing with high strength metallic alloys challenging for hydraulic components that must withstand a large quantity of high pressure loads, as discussed in chapter 2 below. It is for this reason that most lightweight alloy hydraulic products are rated for lower operating pressures and/or shorter operating lifespans than their steel equivalents. Furthermore, it is important to note that high strength materials are particularly expensive to procure and to process into the finished product. This is especially true of low density high strength materials such as Ti-6Al-4V (Grade 5) titanium alloy, where procurement prices vary dramatically based on market supply and demand fluctuations /5/. Carbon steel, on the other hand, is far more commonly available on the market and therefore enjoys lower procurement prices.

1.3. Increasing Popularity of Composite Materials

Composite materials have been used since the dawn of mankind, as evident in the first mud-straw bricks /6/. Rapid developments in recent decades have brought about composite materials that utilise various matrix and reinforcement materials with extremely useful properties and incredibly low densities. This paper focuses on fibre-reinforced plastic composites that consist of a polymer matrix reinforced with *continuous*-fibres. Unless explicitly stated otherwise, they shall herewith be simply referred to as “composites”.

Much of the intense development of composite materials was motivated by military, aerospace, or sports racing (e.g. Formula One, America’s Cup, etc.), where performance advantages outweighed higher manufacturing and material costs /7/. However, as a result of these more specialised developments, design experience and manufacturing technologies have been gradually maturing, increasing the availability of high performance composites at ever reducing costs. Not only can more reliable and robust designs be developed more rapidly and with increased confidence, but new raw material and production equipment suppliers are entering the market, providing designers and manufacturers with more options to meet a wider range of applications. This trend is making composite materials available to a wider range of more cost sensitive applications, including hydraulic actuation systems using hydraulic cylinders, accumulators, and pressure vessels.

2. Technical Challenges

The idea of using composites to replace metallic components in hydraulic products is not a new one, but it confronts the design engineer with some technical challenges that must first be overcome.

2.1. Strength

This paper focuses on “high pressure” hydraulic components with operating pressures above 200 bar. Under internal pressure, the hydraulic components are placed under tensile stress in order to support the applied loads. Thus, material selection is typically dominated by tensile strength properties. Fortunately, continuous fibre-reinforced polymer composites have exceptionally high tensile strengths, which make them ideally suited to pressure vessel applications. To demonstrate the stress magnitudes involved, consider the hoop stress in a thin-walled pressure vessel (where bending and shear stresses are ignored), which can be estimated according to (1).

$$\sigma_{hoop} = \frac{P \cdot r}{t} \tag{1}$$

Thus, 300 bar gauge pressure in a pressure vessel with a bore diameter of 200 mm and a wall thickness of 10 mm would result in a hoop stress of around 300 MPa, which represents only one component of principle stress. If one then considers that, to compensate for the risk of dangerous rupture, pressure vessels have to implement generous safety factors, such that their minimum burst pressure is typically twice their rated maximum operating pressure, then the total stress levels quickly exceed the strengths of most medium strength materials.

2.2. Fatigue

In addition to withstanding their nominal pressure loads, accumulators and pressure vessels must be designed to also withstand the transient pressure fluctuations they are expected to absorb from the hydraulic system during normal operation. This means their structural components must be designed to support large static loads, as well as a large quantity or large magnitude of dynamic loads. Such products are therefore at risk of fatigue failure, which significantly reduces the maximum allowable stresses in their structure, as compared to products with low cycle count applications.

As mentioned in chapter 1.2 above, high performance lightweight metallic alloys are typically not well suited for high dynamic applications where a significant risk of fatigue failure exists. Fortunately, however, composites generally have superior fatigue properties, which implies that the more composite material can be used, the better. The application of this principle, however, is not as simple as it sounds. Simply adding composite material does not necessarily mean it will proportionally support more of the applied load. The challenge here lies in how effectively the composite material is utilised in supporting the applied pressure loads, and more precisely, how the loads are transferred from metal components into composite ones. This is critically important, as discussed in chapter 3, because although using *only* composite materials would be ideal for the pressure vessel, metallic components are at least required for mounting hydraulic fittings. This is especially true for cylinders, where threaded mechanical joints must also be accommodated.

2.3. Stiffness

So far only the beneficial strength and fatigue properties of fibre-reinforced components were considered, which owe almost all of their conglomerate properties to the extremely high tensile strength of the reinforcing fibres. However, it should be noted that most fibre-reinforced composites have a lower modulus of elasticity than common high strength metallic alloys. The modulus depends on, among other things, the fibre material and fibre dimensions, but is rarely comparable to that of steel. Unfortunately, as a general rule, the higher the modulus of the composite material, the more expensive it is to produce and procure.

The most significant consequence of this is that it makes load sharing more difficult between metallic structural components and composite ones. For example, if pressure is applied to a high modulus metallic component which is reinforced by a lower modulus composite material, then the metallic component may be allowed to experience excessively high strains before being supported by the surrounding composite. That is, the potential reinforcement of the surrounding composite will not be effectively realised.

A more subtle consequences of designing hydraulic cylinders and piston accumulators out of lower modulus materials, is that seal selection is made more difficult due to seal suppliers often implicitly assuming properties based on steel walled cylinders. The most important of these is pressure induced dilation, which is sometimes covered by extrusion gap limits being specified in seal catalogues. However, it should be noted that most sealing elements were designed and proven on steel liners, with sometimes implicitly assumed roughness, hardness, and friction properties.

2.4. Diffusion Barrier

Finally, and perhaps the most challenging, is the need for a diffusion barrier inside the high pressure hydraulic product in order to maintain an internal pressure without external leakage. This typically presents designers with the choice of using a metallic liner or a polymer liner. While many plastics are known to provide an effective leak-tight diffusion barrier for even small molecule gases, such plastics do not have nearly enough strength to support the high stresses resulting from the applied high pressures. In addition, non-metallic liners must also provide good tribology properties to allow effective seal performance without excessive wear.

3. Composite Solutions

3.1. Composite Overwrapped Cylinders

The most obvious method of incorporating composite materials is the modification of an existing metal design by reducing its wall thickness and replacing the removed material with fibre reinforced composites. When considering hydraulic cylinders, which have mechanical mounts (e.g. clevis, flange, etc.) extending beyond the ends of the pressurized cylindrical barrel, the most common implementation of this approach is to only remove material from the mid-section of the barrel. This is owing to the difficulty of wrapping the composite reinforcement around the ends of the barrel, such that they can support the axial loads on the end caps of the product. Without such axial reinforcement, the axial loads must still be supported by the metal barrel, and the composite supports only hoop stresses along the mid-section of the barrel. The amount of metal that can be removed and replaced with composite material is therefore limited, as the design still heavily relies on the strength of the metal in the structure. Thus, the potential weight savings of such designs are limited. This is especially true of fatigue critical or high cycle-life applications, where local stress concentrations in the metallic barrel (e.g. in threaded end caps) limit the product's overall burst pressure or fatigue life. Adding more composite material offers diminishing benefits to such stress concentrations, hence, such approaches also result in the reduction of safety factors while only offering modest weight savings relative to the original metal design.

3.2. Composite Overwrapped Accumulators

When considering hydraulic piston accumulators, it is possible to completely envelope the thinned-down metallic structure with composite reinforcement, except for the relatively small port openings. This allows the composites to support both the hoop stress resulting from the applied radial pressure loads along the cylindrical section, as well as the axial stress resulting from the pressure acting on the end caps. This allows the designer to remove more material from an existing metal accumulator design than from a metal cylinder design.

However, such designs still face two important shortcomings. Firstly, as discussed in chapter 2.3 above, such designs require high modulus composites in order to balance the load-sharing between the metal and composite structures. This often drives such designs to rely on more expensive composite materials, which tend to reduce their attractiveness as an alternative to traditional metal products. Alternatively, the load-sharing between metal and composite can also be improved by reducing the thickness of the metal structure until its higher modulus is offset by the relative thickness of the lower modulus composite. Ideally, the metal structure would be thinned down until it forms merely a diffusion barrier, or "liner", contributing almost nothing to the strength of the overall structure. Unfortunately, the manufacture of thin-walled metallic liners is a costly process, especially when tight tolerances are required for sealing against a moving piston, as in hydraulic cylinders and piston accumulators. Thus, once again, it is difficult to develop designs using such approaches which are price competitive to conventional metal products, and their success depends on the ratio of additional cost to the added value from the mass reduction of the product.

3.3. Ultra-Lightweight Fully Composite Piston Accumulator

Combining the shortcomings of the above approaches leads us to seek a design solution that fully utilizes the high tensile and fatigue strength properties of composites by minimising our reliance on metallic components. Ideally the load-bearing structure of the products would be made entirely out of composites, thus without a metallic liner, and without a metallic barrel that supports the axial loads applied on the end caps.

To meet this challenge, Parker has developed an ultra-lightweight high pressure *fully* composite piston accumulator. **Figure 1** shows an example of a 15 litre composite piston accumulator with a high-resolution full-length piston position measurement system. The yellow outer layer visible in Figure 1 is a Kevlar abrasion resistant composite layer which is integrated into the outer barrel and therefore more robust.

Figure 1: 15 Litre Fully Composite Piston Accumulator Example

The design concept underlying this product consists of a fully composite liner with integrated diffusion barrier, supported by a fully composite outer barrel that supports the entire axial load applied on the end caps. The only metallic components that remain are the end caps, their mating (threaded) components, and the piston. The design concept of the fully composite piston accumulator is shown in **Figure 2**.

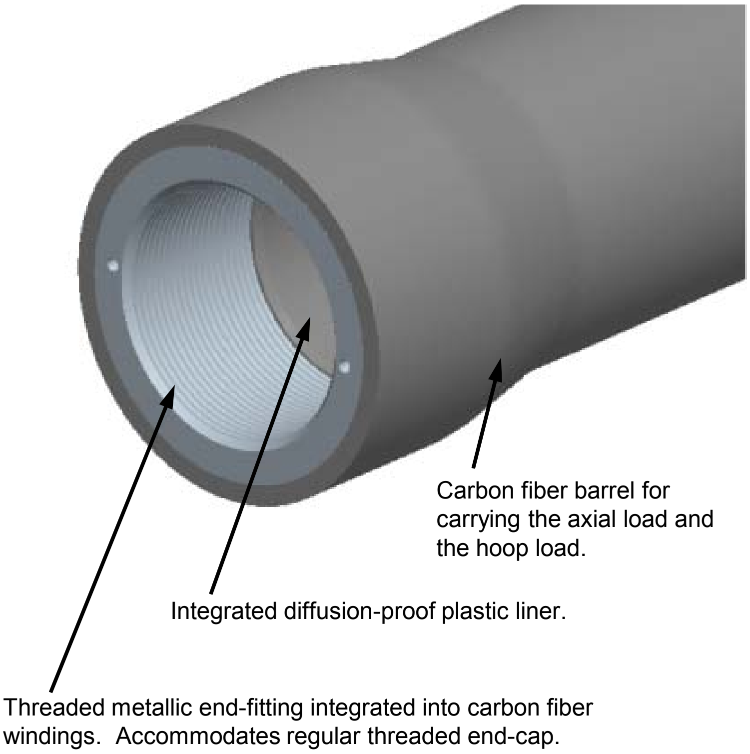

Figure 2: Fully Composite Design Concept

The fully composite liner is cheaper to manufacture, lighter, and offers higher burst and fatigue strengths than a composite reinforced metallic liner. Likewise, the fully composite outer barrel is lighter and offers outstanding burst and fatigue strengths, as demonstrated in chapter 4 below. Thus, Parker's design approaches the ideal solution and offers significant weight savings that are not achievable with the other designs discussed in chapter 3.

For example, some 15 years ago, the maximum weight savings expected even for a composite bladder accumulator with metallic liner was only 50% of a completely metallic equivalent /8/. In **Table 1** the mass of the example accumulator is compared with similar performance steel piston accumulators, using data published in several major hydraulic accumulator manufacturers product catalogues. Thus, from this example a weight saving of between 70% and 80% can be realised.

	Typical Steel Piston Accum.	Parker Composite Accum.
Volume [L]	15	15
Pressure [bar]	350-375	380
Weight [kg]	90-131	26

Table 1: Example of Piston Accumulator Mass Comparison

4. Experimental Validation

4.1. Cyclic Pressure Tests

To validate the fatigue strength and robustness of the diffusion barrier, the fully composite inner liner was separately tested with samples of bore diameter 110 mm and a length of 290 mm as shown in **Figure 3**. One liner sample was pressurised from 20 to 420 bar. **Figure 4** and **Figure 5** show the applied pressure profile. The test was stopped after the sample survived 5.850.000 pressure cycles, at which point the cycle count target was reached. There were no signs of fatigue or sample failure.

Figure 3: Composite Liner Sample Cycle Testing

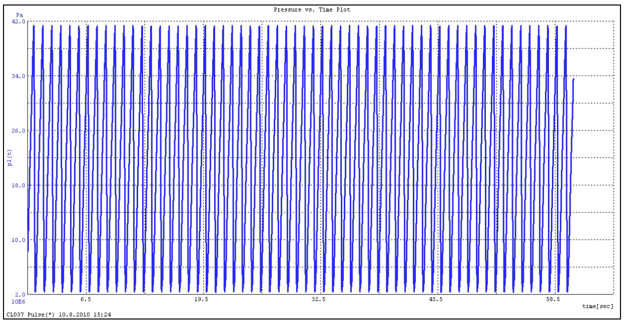

Figure 4: Cyclic Pressure Profile Sample

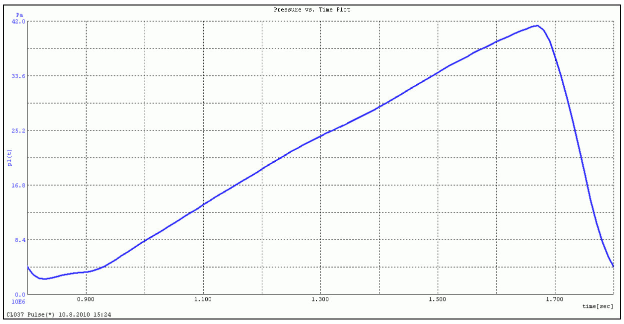

Figure 5: Single Pressure Cycle Shape

To equivalently validate the fatigue strength of the fully composite outer barrel, samples of outer diameter 170 mm and length 750 mm were tested as shown in **Figure 6**. The samples were pressurized from 140 to 630 bar (more than 1,5 times their rated operating pressure) for 1.000.000 cycles without any fatigue failures.

Figure 6: Fully Composite Outer Barrel Sample Cyclic Testing

To validate the strength of the fully composite outer barrel even after such a strenuous test, one of the samples was then pressurised to burst at 1275 bar, more than 3 times the rated operating pressure. The pressure profile from this burst test after 1 million pressure cycles from 140 to 630 bar is shown in **Figure 7**.

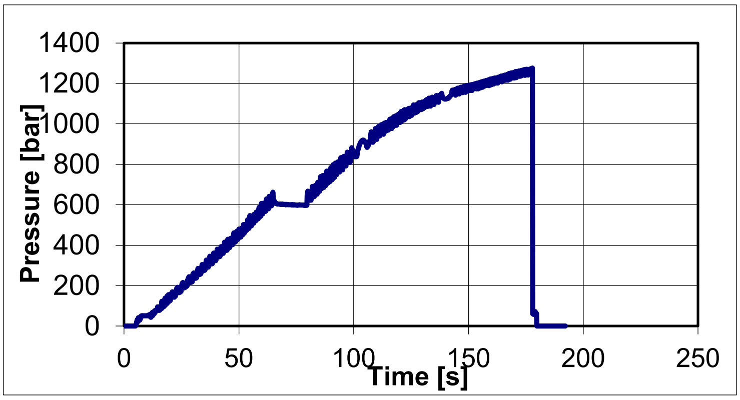

Figure 7: Pressure Profile of Burst Test of Fatigued Sample

4.2. Burst Pressure Tests

To validate the strength of the fully composite outer barrels in their virgin state, 3 samples were pressurised to burst at pressures well exceeding 3 times their rated operating pressure.

4.3. Functional Testing

The function, including sealing and diffusion barrier, of complete fully composite piston accumulator products were also tested using samples of outer diameter 170 mm and a length of 750 mm. The test configuration is shown in **Figure 8**. The samples were pressurized from 170 to 300 bar for 250.000 cycles, equating to over 55km of piston travel. At the time of writing, additional functional tests are ongoing with dimensional variants of the same fully composite piston accumulator product.

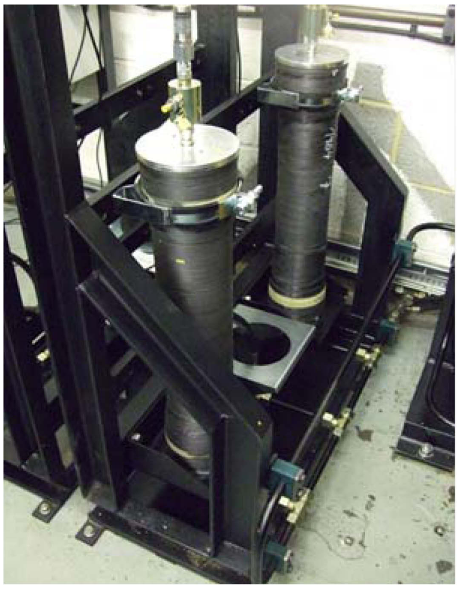

Figure 8: Test Samples in Functional Test Rig

The effectiveness of the diffusion barrier in the composite liner has been validated through several tests, including long-term static and pre-charge pressure monitoring during long-term functional tests.

4.4. Outlook

Parker is actively continuing the development of ultra-lightweight fully composite piston accumulators and high performance fully composite cylinders. Current development activities include:

- Integrated sensor in composite liner as piston position measurement system
- Design-for-Manufacture studies for large-volume serial production
- CE certification for industrial applications
- Type-Approval for automotive energy recovery applications

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6. Nomenclature

P	Internal guage pressure	MPa
r	Radius to inner surface	mm
t	Wall thickness	mm