Potential and application fields of lightweight hydraulic components in multi-material design

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Abstract

Hydraulic systems are used in many fields of applications for different functions like energy storage in hybrid systems. Generally the mass of hydraulic systems plays a key role especially for mobile hydraulics (construction machines, trucks, cars) and hydraulic aircraft systems. The main product properties like energy efficiency or payload can be improved by reducing the mass. In this connection carbon fiber reinforced plastics (CFRP) with their superior specific strength and stiffness open up new chances to acquire new lightweight potentials compared to metallic components.

However, complex quality control and failure identification slow down the substitution of metals by fiber-reinforced plastics (FRP). But the lower manufacturing temperatures of FRP compared to metals allow the integration of sensors within FRP-components. These sensors then can be advantageously used for many functions like quality control during the manufacturing process or structural health monitoring (SHM) for failure detection during their life cycle.

Thus, lightweight hydraulic components made of composite materials as well as sensor integration in composite components are a main fields of research and development at the Institute of Lightweight Engineering and Polymer Technology (ILK) of the TU Dresden as well as at the Leichtbau-Zentrum Sachsen GmbH (LZS).

KEYWORDS: Lightweight design, Lightweight hydraulic components, Carbon fibre reinforced plastic (CFRP), Composite, Multi material design, Sensor integration, Optic fibre sensors, structural health monitoring

1. Introduction

The increasing pressure for the development of energy-efficient systems requires the realization of economic lightweight structures. Therefore fiber reinforced plastics (FRP) are more and more used for highly stressed structures which are currently made of metals. The development of hydraulic components made of FRP is a particular challenge due to the very high mechanical loads and partial extreme environmental conditions like highly varying temperatures. Here, the outstanding mechanical properties of carbon fiber reinforced plastics (CFRP) can be advantageously utilized for cylindrical components with a well-defined state of stress like hydraulic actuators or accumulators.

Furthermore the application of FRP for hydraulic components offers new opportunities to integrate sensors or other elements into the composite structure to realize different functionalities like structure health monitoring (SHM) or heating. These sensors are integrated inside the FRP-structure during the primary manufacturing process. So these sensors can be already used for measuring of processing parameters to control the quality and to adapt the process parameters if required. Thus, new possibilities of interoperability and real-time monitoring regarding the so called “Internet of Things” (IoT) – one of the keywords of Industry 4.0 – can be realized.

The development and technological realization of lightweight hydraulic components in multi material design like lightweight bladder accumulators, hydraulic lightweight actuators or manifolds as well as the integration of sensors into composite structures a are main activities at the Institute of Lightweight Engineering and Polymer Technology (ILK) at the TU Dresden /1,2,3,4,5/.

2. Lightweight hydraulic components in multi-material-design

Following the development of lightweight hydraulic components are addressed in two examples, first a bladder accumulator in multi-material design and second a metallic lightweight manifold block. The bladder accumulator Type IV pressure vessel (bladder accumulator) and the hydraulic manifold block were designed for 315 bar operating and 1260 bar burst pressure /6/. Afterwards both components were manufactured and fully tested to reach the baseline for further industrialization (components are shown in **Figure 4**). Results showed that considerable potential in mass reduction are given compared to the given state of the art design (**Table 1**).

	Reference [kg]	ILK [kg]	**Reduction [%]**	Dimension
Manifold block	13,75	2,44	**-82**	15x13x10 cm
Bladder accumulator	28	11,84	**-57**	10 liter

Table 1: Achieved mass reduction of lightweight hydraulic components

2.1. Lightweight bladder accumulator

A comprehensive development specification for lightweight bladder accumulators was developed within an iterative chain of design, production, inspection and testing (**Figure 1**). The baseline is a design tool based on VASILIEV shown in /1/. Within this analytical tool the resulting dome architecture for an isotensoid deformation behavior is determined and the contour directly exported for 3D-CAD modelling. The laminate layup is then first determined by the vessel formula to aim the one to two ratio of axial to circumferential fibers and detailed with the help of finite element analysis (FEA).

Considering the manufacturing restrictions of the winding process, the laminate layup is adapted the way to reduce fiber accumulation at the boss sections by increasing the fiber angle in the cylindrical section. Mainly geodesic winding is chosen to avoid fiber slippage during the laminate build up. As the fiber deposition is mandatory for the resulting mechanical behaviour the manufactured vessel is inspected by computer tomographic (CT) scanning to identify the real laminate layup. By FEA and manufacturing iterations combined with CT inspection the winding architecture is optimized to the isotensoid deformation behavior to optimize the material effort and the incorporated lightweight potential.

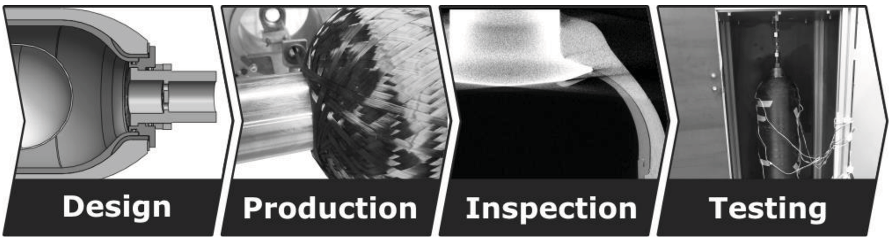

Figure 1: Development chain for lightweight bladder accumulators

The final design has been thoroughly tested. Static testing up to 710 bar was conducted without reaching a fatal bursting of the accumulator. Additionally a more important dynamic test cycle was performed. With a minimum working pressure of 100 bar and a maximum of 315 bar, the structure withstood 100,000 periodic load cycles without any sign of degradation (**Figure 2**).

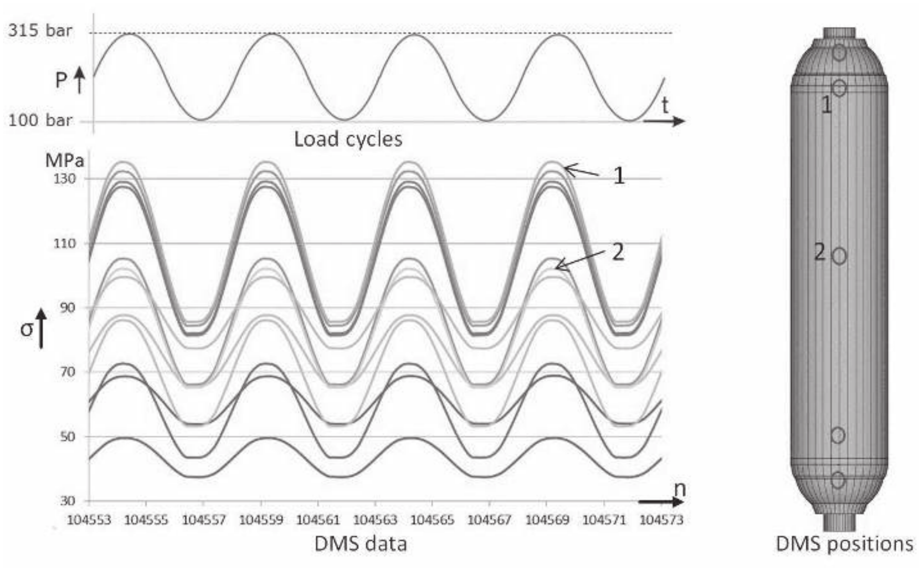

Figure 2: Test cycle of the bladder accumulator

2.2. Lightweight manifold block

Compared to the above shown design specification a point design (**Figure 3**) of a metallic lightweight manifold block is performed to prove general feasibility of near-net-shape manufacturing of manifold blocks in an aluminum casting design. To maintain the operating pressure and the sealing concept of the reference steel manifold block the pressure loads and tightening torques had to be sustained. Therefore an iterative design cycle of CAD design and FEA was performed. The manifold block is designed to a high and low cycle fatigue approach to reach the necessary fatigue strength for up to one million load cycles. Due to the use of the aluminum casting alloy AlSi7Mg0.3 and its reduced strength the threads' length as well as the wall thicknesses were redesigned. Additional casting requirements for wall thickness changes had to be addressed and to avoid blowholes, etc. form-filling simulations were performed showing a good casting behavior for the aluminum casting material utilizing it for near-net-shape manufacturing.

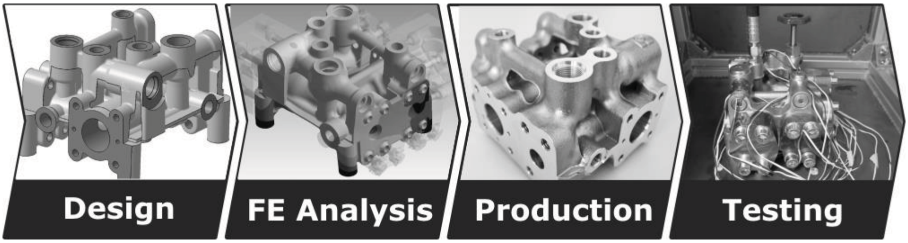

Figure 3: Development chain of a casted lightweight manifold block

The casting design of the manifold block was also verified through static and dynamic testing. For simplification all cavities had been loaded simultaneously with the same pressure level. In a first static test with 500 bar no critical stresses could be identified. Similar to the bladder accumulator test program a load cycle between 0 and 315 bar was chosen, as the manifold is either fully or non-pressurized during operation. The manifold block showed no damages after 100,000 load cycles.

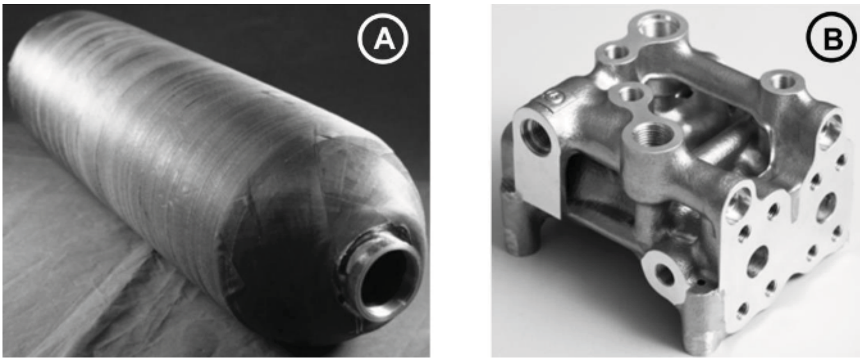

Figure 4: Lightweight hydraulic bladder (A) and aluminium casted manifold block (B)

3. Application fields for integrated sensors in FRP-lightweight structures

Lightweight hydraulic components made of fiber reinforced plastics (FRP) can be equipped with a smart integrated system for quality control during fabrication, for monitoring the component state – keyword industry 4.0 - and for structural health monitoring to estimate life time and to determine damages. Interesting parameters are temperature, pressure, position of the piston and the strain within the structure. A basic design for a smart integrated system is shown in **Figure 5**.

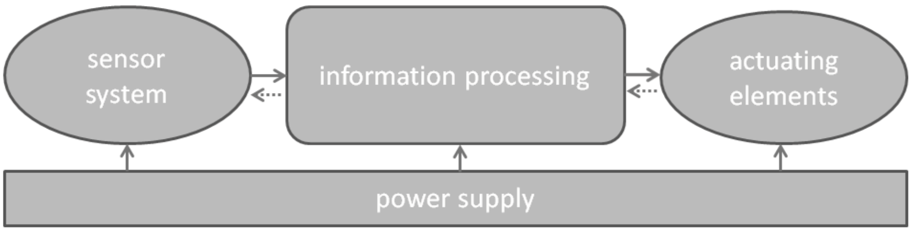

Figure 5: Principle of a monitoring system capable of being integrated

One or more sensor elements convert physical properties into electrical signals. Usually a conditioning unit is required. A processing unit computes the signals based on an adapted algorithm and deduce actions, for instance control an actuating element. For all these components a power supply is required.

The monitoring system can be usually realized in two different ways – either by external analysis or by fully integrated monitoring system. In the first way the power supply and the information process unit are external. An external analysis system has usually significant more performance but larger dimensions which cannot be integrated. Furthermore a more expensive analysis system can be used for many components.

The second application is the fully integrated monitoring and control system. With such an integrated system an online analysis by specific parameters of the whole structure can be provided. The integrated information processing unit can control integrated actuating elements, save data for a later evaluation or send a signal to an external system. For such a fully integrated system the costs relative to the component costs and the long-term stability are more important.

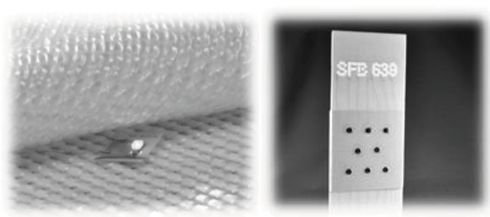

Figure 6: Example: LED before and after integration

For lightweight hydraulic components specific sensors and actuating elements are of interest:

- The position of the piston is determined by a strain. This strain can be detected by integrated strain gauge sensors or optical glass fiber sensors (figure 8).

Figure 7: Sensor node ready for integration

- The temperature can be measured with integrated sensors (NTC, PTC, Thermocouple, Platinum-sensor). These information can prevent temperature hotspots or give an indication of the viscosity of the oil.

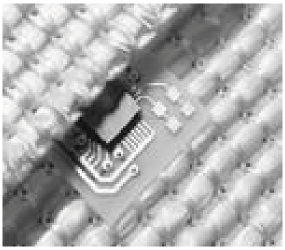

Figure 8: Temperature sensor in an ASIC-environment, ready for integration

- The dynamic pressure can be measured with integrated piezo ceramics. The deformation of the piezo ceramic by pressure will be converted into a voltage representing the dynamic pressure.

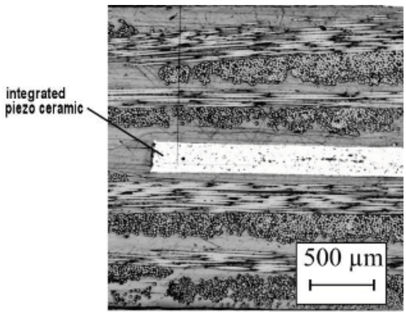

Figure 9: Integrated piezo ceramic

- With an above-mentioned integrated electronical control system enhanced with an integrated heating system composed of a copper wire or a carbon fiber an active temperature control for better performance of the oil can be integrated into lightweight hydraulic components made of composite material

4. High pressure vessels made of CFRP with integrated fiber-optic Rayleigh sensors

One application example for SHM in combination with hydraulics is the integration of high-resolution fiber-optic sensors (FOS) in high-pressure vessels. In terms of automation FOS are integrated in the composite structure during a braiding process (**Figure 10**). For that purpose a braiding wheel was supplemented with an appliance for automatic sensor application, which was used to manufacture preforms of high-pressure vessels with FOS-networks integrated between the fiber layers.

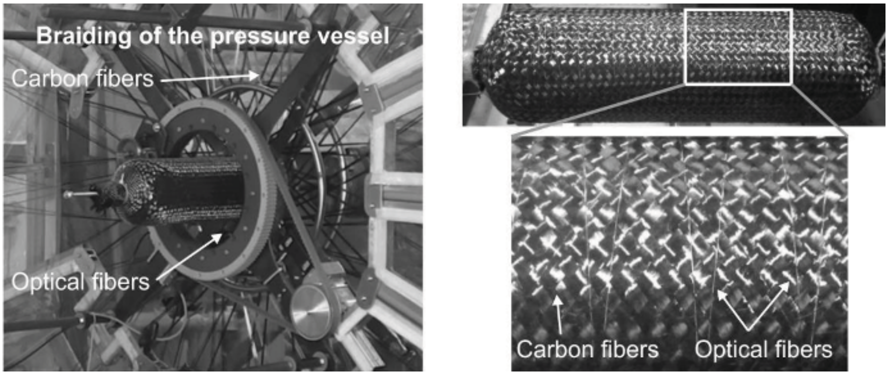

Figure 10: FOS integration during the braiding process /7/

The sensor network was then used in quasi-static pressure tests to monitor the load level until failure (**Figure 11**). Results showed reliable real-time tracking of the failure behavior /7/.

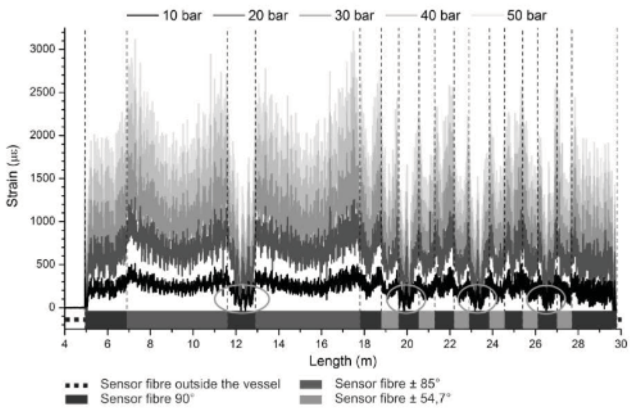

Figure 11: Stress state monitoring during quasi-static pressure test /7/

5. Summary

The successful realization and test of an innovative lightweight bladder accumulator made of CFRP and a casted lightweight aluminum manifold – both components with a mass reduction of more than 50 % compared to the metallic reference structure – show the enormous lightweight potential for hydraulic components. Furthermore lightweight hydraulic components made of FRP can be equipped with integrated sensor networks and other functional elements for (A) structural health monitoring (online and offline), (B) measurement and optimization of process parameters during manufacturing (Industry 4.0) and (C) other functions like heating or measuring the position of the piston. A CFRP-pressure vessel has been exemplarily equipped with a high resolution optic-fiber sensor systems, which was integrated during the braiding process of the CFRP-pressure vessel. This cost-efficient solution provides the possibility to measure the temperature during the curing process and to monitor the deformation (strain) during operation.

6. References

/1/ Helms, O.: *Konstruktion und technologische Umsetzung von hochbeanspruchten Lasteinleitungssystemen für neuartige Leichtbaustrukturen in Faserverbundbauweise*. Dissertation, Technische Universität Dresden, 2006.

/2/ Ulbricht, A.: *Zur Gestaltung und Dimensionierung von zylindrischen Leichtbaustrukturen in Faserkunststoffverbund-Metall-Mischbauweise*. Dissertation, Technische Universität Dresden, September 2011.

/3/ Ulbricht, A.; Hufenbach, W.: *Multi-Material-Design gefragt – Leichtbau-Hydraulikkomponenten für mobile Anwendungen*. fluid 03/2014, page 56-58, 2014.

/4/ Hufenbach, W.; Böhm, R.; Thieme, M.; Tyczynski, T.: *Damage monitoring in pressure vessels and pipelines based on wireless sensor networks*. Procedia Engineering 10 (2011), page 340 – 345, 2011.

/5/ Hufenbach, W.; Adam, F.; Fischer, W.-J.; Kunadt, A.; Weck, D.: *Mechanical behaviour of textile-reinforced thermoplastics with integrated sensor network components*. Materials & Design, Volume 32, Issue 10 (2011), pages 4931-4935, 2011.

/6/ Hufenbach, W.; Ulbricht, A. et al.: *Lightweight hydraulic components in novel multi-material-design for mobile applications*. 2014. 9th International Fluid Power Conference, Aachen, March 24-26, 2014.

/7/ Hufenbach, W.; Gude, M.; Czulak, A.; Kretschmann, M.: *Development and implementation of an automatic integration system for fibre optic sensors in the braiding process – with objective of online monitoring of composite structures*. Published in SPIE Proceedings Vol. 9061: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2014.