Development of Lightweight Hydraulic Components in Innovative Fibre Composite Design

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Abstract

The increasing competition in the field of aerospace industry requires the development of innovative lightweight-hydraulic actuators made of fibre reinforced plastics (FRP) to reduce the direct operating costs. The usage of carbon fibre reinforced plastics (CFRP) with its outstanding specific strength and stiffness provide the opportunity to achieve significant weight reductions. Because of their well defined loads the shell-shaped cylinder tube and the piston rod of hydraulic actuators are especially predestined for the application of CFRP. Metallic materials are very well suited for the glands due to the possible space-saving integration of hydraulic connections and sealing grooves as well as the resistance to the hydraulic fluid. The realisation of such an advantageous multi-material-design requires the development of innovative load introduction systems to connect metallic flanges to the CFRP-cylinder tube and the piston rod respectively. Furthermore the different coefficients of thermal expansion (CTE) have to be considered for multi-materials design in order to avoid strength-decreasing residual stresses. A further challenge arises from the integration of a diffusion-resistant coating or liner on the inner side of the CFRP-cylinder tube to provide a diffusion barrier against the hydraulic fluid and a sliding surface for the piston seal.

Here a novel lightweight hydraulic actuator for aerospace applications serves as an example for innovative multi-materials design by advantageous application of different materials and joining technologies as well as the determination of residual stresses. Moreover the technical feasibility for different types of liners and coatings on the inner side of the CFRP-cylinder-tubes has been investigated.

KEYWORDS: lightweight design, fibre reinforced plastics (frp), composite, hydraulic actuator

1. Introduction

The current development of more efficient transportation systems concerning CO_2-emissions and energy consumption requires the realisation of economic lightweight solutions. High-strength metals are increasingly replaced by FRP as first-choice material for highly stressed structures. Thus, the application of FRP for hydraulic actuators used in aircrafts or automobiles provides new lightweight potentials. The usage of FRP with their outstanding specific strength and stiffness for nearly plane structures primarily subjected to in-plane loads like the cylinder tube allows the realisation of huge weight reductions. However, the different functional and structural requirements of hydraulic systems usually necessitate the additional use of metals. The determination of chemical resistant resins, the development of innovative joining technologies for different materials and the dimensioning of hybrid structures considering different CTE's are the main challenges arising from the realisation of multi-material design for hydraulic actuators.

2. Innovative lightweight design of hydraulic actuators

Innovative lightweight structures in multi-material design are characterised by an advantageous usage of different materials according to the structural and functional requirements. The usage of CFRP for shell-, tube- or beam-structures with one- or two-dimensional states of stress like the cylinder tube or the piston rod allows the achievement of significant weight reductions by adapting the fibre orientation to the prevailing stresses. Complex-shaped components with threedimensional states of stress like flanges for load introduction are preferably made of isotropic materials like metals.

The primary function of the cylinder tube and the piston rod during retraction and extension of a hydraulic actuator is the load transmission between the bearing points

(**Figure 1**). In contrast to the uniaxially loaded piston rod, the cylinder tube is partially subjected to a biaxial load because of the internal pressure. The piston rod and the cylinder tube are especially suited for the application of CFRP due to those well-defined loads and the stretched shape. In contrast to that, high loads are applied in different directions at the bearing lugs of the hydraulic actuator resulting in complex states-of-stresses. Due to this concentrated load-introduction the glands are preferably made of isotropic materials like high-strength metals. Moreover the functional surfaces and the grooves for seals and strips can be easier realized by using metals.

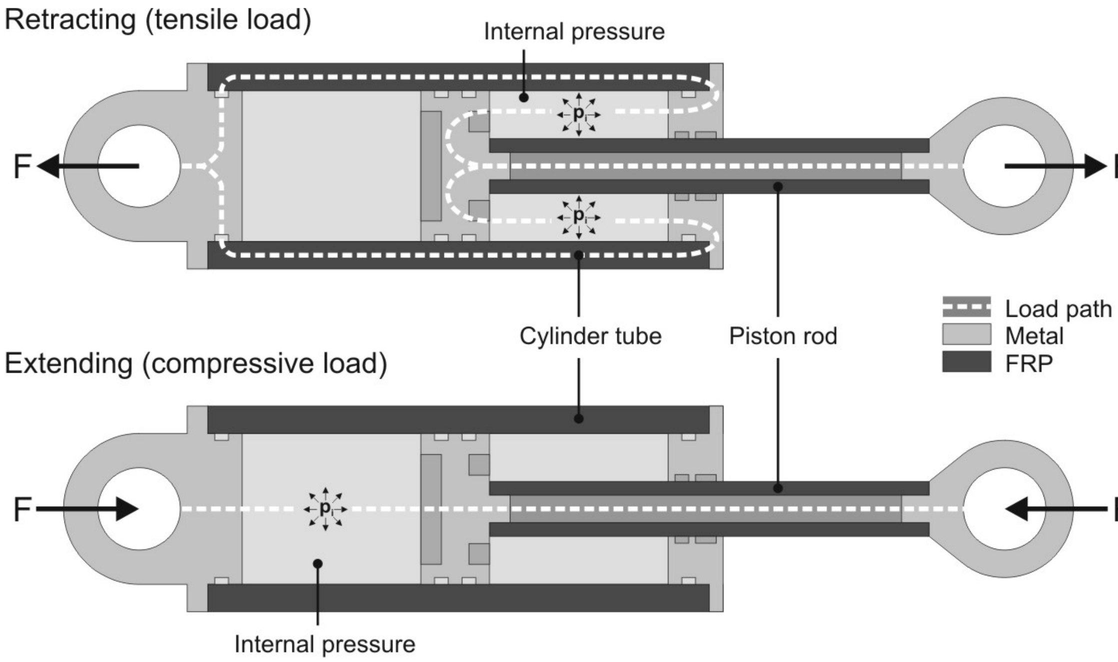

Figure 1: Load transmission in hydraulic actuators and preferable material selection

The realisation of those lightweight actuators in multimaterial design requires the development of innovative joining technologies to connect the metallic flanges with the CFRP-cylinder tube /3/. Positive joining technologies like loop-, bolt- or contour connections are predestined for transferring high loads into CFRP-structures. Non-positive joining technologies cannot ensure a comparable high joint strength over a long period of time due to the cyclic loading and the continuous exposure to fluids.

2.1. Cylinder tube in multi-materials-design

The piston and the piston rod are generally assembled by inserting them into the opening on the rod side of the CFRP cylinder tube. Hence, more design freedom is offered for innovative load-introduction systems on the other side of the lightweight hydraulic actuator. So an integrally formed CFRP-loop can be drafted, which allows the introduction of high tension loads into the CFRP-structure (**Figure 2 a**). The metallic glands of the CFRP-loop connection permit a space-saving design due to the comparatively short distance between the pressure chamber and the spherical bearing.

Another possibility to connect the CFRP tube structure with the spherical bearing is the structural integration of two coplanar areas where a cross hole is placed to assemble the bolt with the spherical bearing (**Figure 2 b**). Here a transition area is necessary to transform the annular cross section of the CFRP tube structure into a rectangular cross section. This transition area leads to an increased axial overall length of the hydraulic actuator compared to other load introduction system like the CFRP-loop connection. Furthermore the spherical bearing is not fixed inside the metallic gland of the hydraulic actuator but inside a metallic flange on the mounting side in contrast to other connections like the loop connection. This design allows the realisation of a rotation-symmetric layup inside the CFRP-cylinder tube at the sealing area compared to the non-rotation symmetric layup at the CFRP-loop connection. Hence hydraulic pressure inside the CFRP-cylinder tube nearly results in a uniform gap width between the cylinder tube and the metallic gland, which considerably simplifies the selection of a well-suited seal.

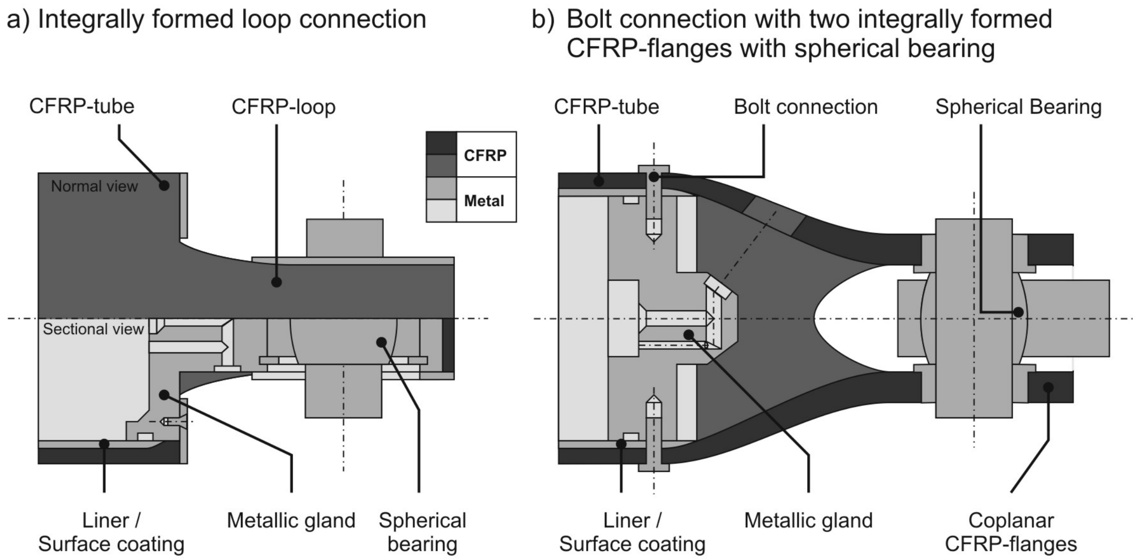

Figure 2: Load introduction systems for a cylinder tube in multi-material-design

Different prototypic lightweight-hydraulic actuators have been developed and manufactured at the ILK within several aeronautical research projects. The modular winding mandrel exemplarily shown in **Figure 3** allows manufacturing of different joining technologies on both ends of the CFRP-cylinder tube using the same middle section to form the cylindrical part of the CFRP-hydraulic actuator. Preliminary winding studies without resin have been made to guarantee a repeatable manufacturing process of the hydraulic actuator with the CFRP-loop connection, whose basic design is shown in Figure 2 a). The prototypic lightweight hydraulic actuator with the CFRP-loop connection has been successfully tested over 80.000 load cycles without any damages (Figure 3 b).

Figure 3: Preliminary winding test and final hydraulic actuator in multi-material design

2.2. Piston Rod in Multi-Material-Design

High axial loads at the ends of a piston rod can be advantageously introduced by a contour connection providing a high joint strength over a long period of time (**Figure 4**). A high joint strength of non-positive joints can not be ensured because of the thermal and cyclic loading as well as the continuous exposure to fluids /1/.

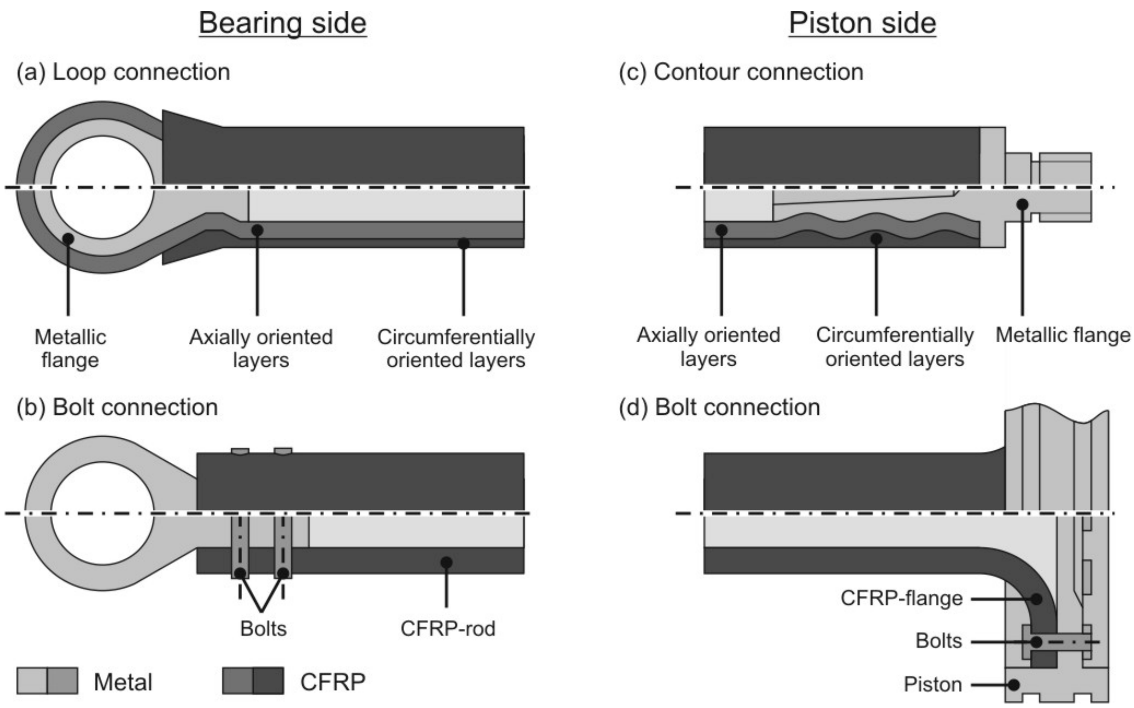

Figure 4: Load introduction systems for a piston rod in multi-material-design

One end of the lightweight piston rod has to be mounted through the flange of the hydraulic actuator. Thus, the outer diameter of one end of the piston rod should not be greater than the rod diameter. The exemplarily shown load introduction systems “bolt connection” (b) and “contour connection” (c) in Figure 4 fulfil this requirement.

Loop connections (a) can carry very high tensile forces, but the introduction of compression forces is very complicated. The axially oriented fibres of a FRP-piston rod can be shaped like circumferential corrugated contours, which can be used to fix a metallic flange with a positive connection (Figure 4 c). The circumferential fibres prevent the axially oriented fibres from stretching under tension load as well as kinking under compression load. The load carrying capacity of the contour connection (c) was determined by extensive tests under static and cyclic loading at the ILK.

3. Residual stress analysis of hybrid multilayer structures

The integration of a stainless steel liner on the inner side of CFRP-cylinder tubes is one possibility to ensure a wear-resistant bearing surface for the piston and to protect the load-bearing CFRP-structure against the aggressive hydraulic fluid (**Figure 5**). The non-load carrying metallic liner is usually made very thin to achieve higher levels of lightweight design. An additional interface layer made of glass-fibre reinforced plastic (GFRP) is usually placed between the CFRP-structure and the liner to prevent electrochemical corrosion, which results from the differing electronegativity of CFRP and steel.

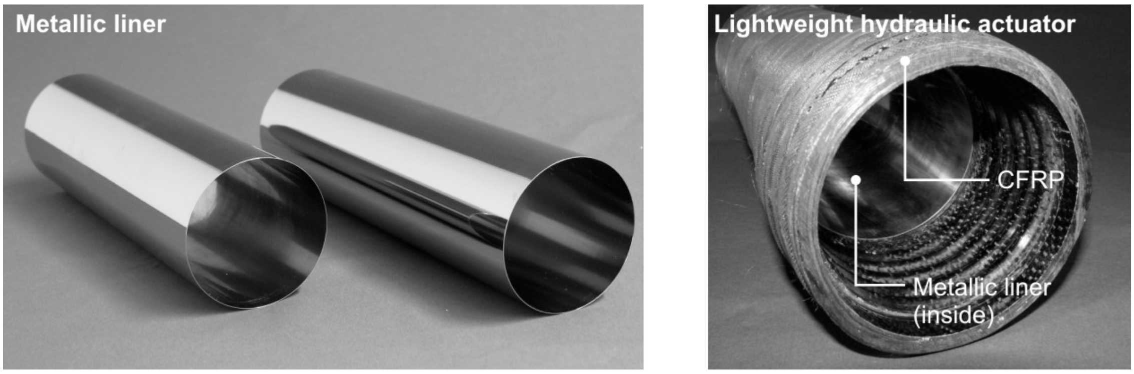

Figure 5: Metallic liner for the lightweight hydraulic actuator

Thermal induced residual stresses resulting from different CTE and temperature changes have to be considered during the dimensioning of such hybrid laminates /4/. The first significant temperature change occurs after the first curing cycle of the resin. It is assumed that stresses are not reduced by plastic yielding processes at temperatures below the glass transition temperature T_G of the resin. The metallic structure and the FRP-structure are perfectly joined together at temperatures below T_G, which is assumed as the stress-free temperature. Extensive Dynamic Mechanical Analysis (DMA) tests at specimen of the used resin have been performed to determine the glass transition temperature for the same curing cycle as the CFRP-cylinder and the CFRP-piston rod.

A geometrically nonlinear finite element model for the determination of residual stresses was calibrated by comparison of the simulation results with the optically measured deformation of hybrid plate-structures (**Figure 6**) /2/. Moreover the deformations of the plate-structures were analytically calculated by a software tool developed at the Institute of Lightweight Engineering and Polymer Technology (ILK) at the TU Dresden. The hybrid plate structures consist of a thin stainless steel sheet with a thickness of 0.5 mm and the one-sided CFRP-structure, which is nearly equal to the layup of the hydraulic actuator. The validity of the calibrated FE-model was further examined at plates with other layups.

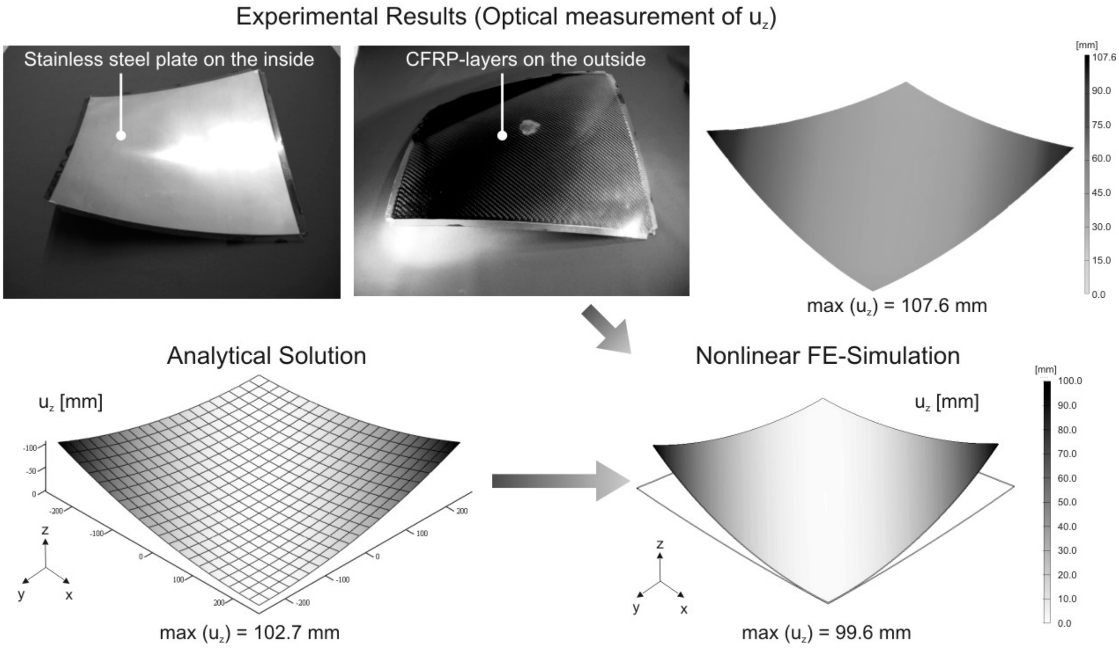

Figure 6: Calibration of a nonlinear FE-model by experimental and analytical results

The shear-strength at the interface in hybrid laminates has been experimentally determined in extensive single-lap- (SLS) and double-lap-shear tests (DLS) to estimate the material effort in this area (**Figure 7**).

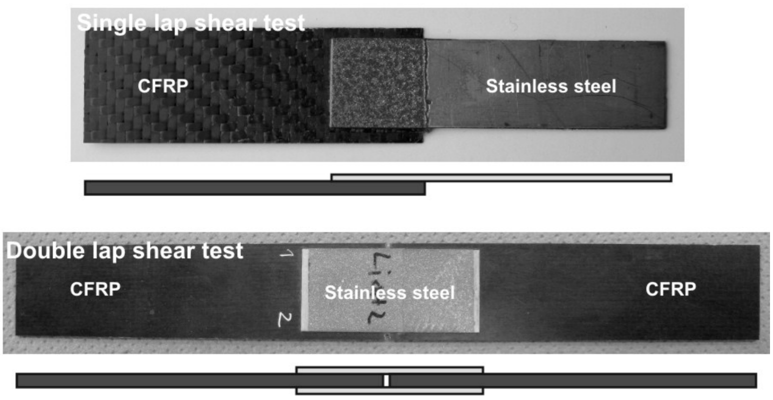

Figure 7: Hybrid specimen for single and double lap shear tests

Different surface treatments of the metallic liner like arc spraying and abrasive blasting were compared by the measured shear strengths. Furthermore the force-displacement curves served as a basis for the calibration of a more detailed finite-element-model for damage analysis at the interface.

Higher shear strengths at the interface can be usually achieved by increasing the joining area and roughness depth resulting in a microscopic positive join. The experimental results and polished cut images of the interface show the significant differences between arc spraying and abrasive blasting concerning the joining area (**Figure 8**).

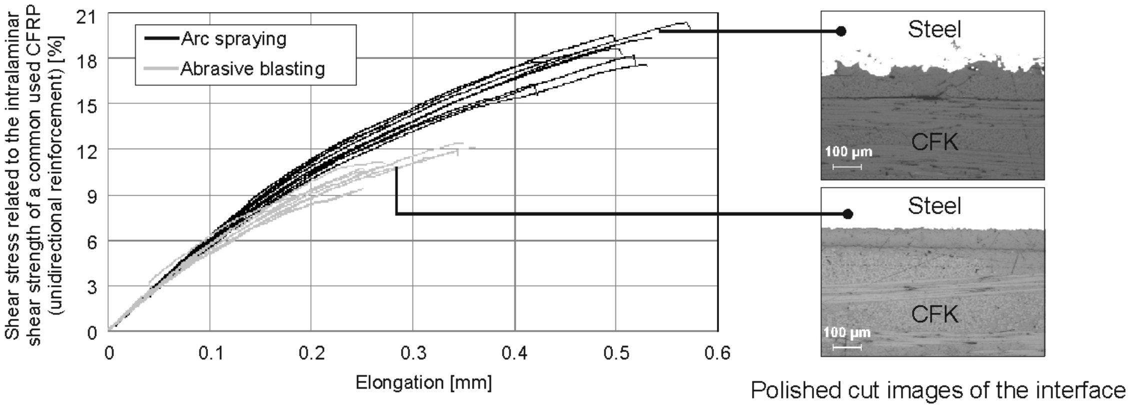

Figure 8: Results of the double lap shear test for different surface treatments

4. Plastic coatings as protective layers in composite hydraulic components

The application of thin steel liners on the inner side of CFRP-cylinder tubes is a well proven method for the realisation of protective layers with high wear- and temperature-resistance. However, the dimensioning of such multilayered composite structures is very complex for components with a wide range of operation temperatures due to residual stresses resulting from the different CTE of CFRP and steel. Moreover the differing electronegativity of CFRP and steel requires the integration of an additional GFRP-layer between the CFRP-structure and the liner to prevent electrochemical corrosion. Furthermore tubular steel-liners are usually manufactured by roller spinning on a cylindrical mandrel, which is a very cost-intensive process. Another expensive step during the manufacturing process is the necessary surface treatment of the metallic liner to achieve the required shear strength at the interface between the metallic liner and the FRP-structure.

The application of an additional coating made of a filled thermoset – commonly known as a gelcoat - is an alternative method for the cost-effective realisation of protective layers inside of tubular CFRP-structures manufactured by winding. The gelcoat is applied to the winding-mandrel and precured before winding the carbon fibres (**Figure 9**). Compared to a metallic liner no additional interface layers have to be provided between the CFRP-structure and the protective layer, because electrochemical corrosion can not occur.

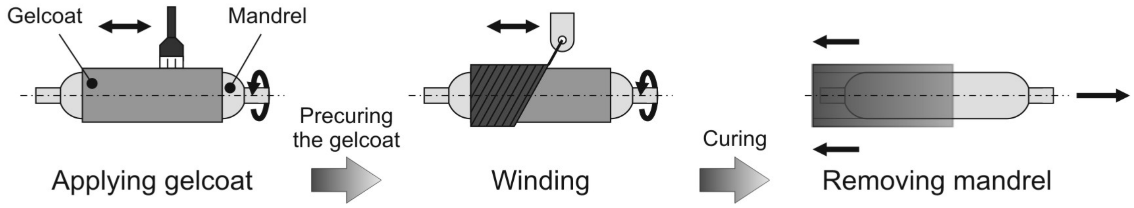

Figure 9: Manufacturing process of CFRP-cylinder tubes with a gelcoat

The successful application of gelcoats as a diffusion barrier against hydraulic fluids and a gliding surface for seals within CFRP-cylinder tubes requires the experimental determination of the wear resistance of gelcoats under realistic test conditions. Therefore tubular CFRP-specimens with different gelcoats on the inner surface have been manufactured at the ILK (**Figure 10**). All specimens have the same layup of the laminate like in the hydraulic actuator (Figure 3).

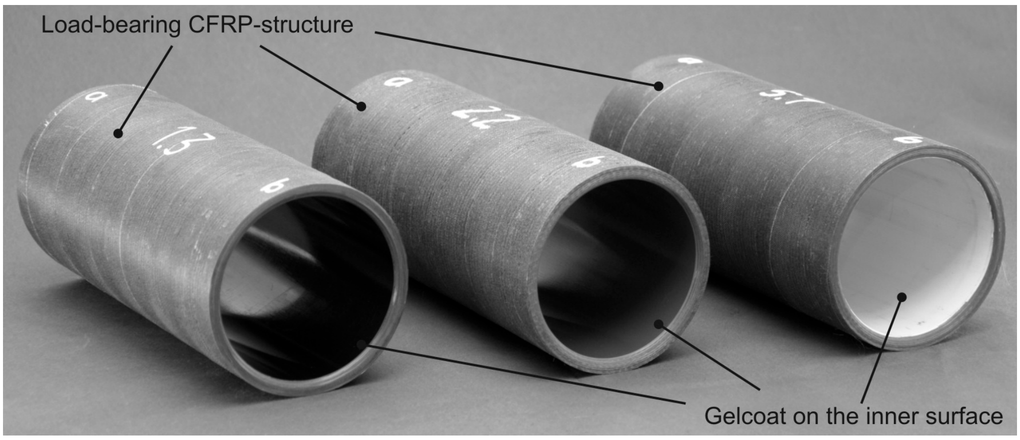

Figure 10: CFRP-cylinder tubes with different gelcoats on the inner surface

A unique test rig has been developed by the ILK for testing the tubular CFRP-specimens under a combination of mechanical and tribological loading (**Figure 11**). The tubular CFRP-specimen is axially moved on a fixed piston with an annular groove, which can be pressurized up to 310 bar. During the tests the operating force in axial direction, the pressure as well as the temperature are measured. The surface roughness of the inner surface of the CFRP-specimen is determined by a laser profilometer before and after testing to compare the wear resistance of different gelcoats.

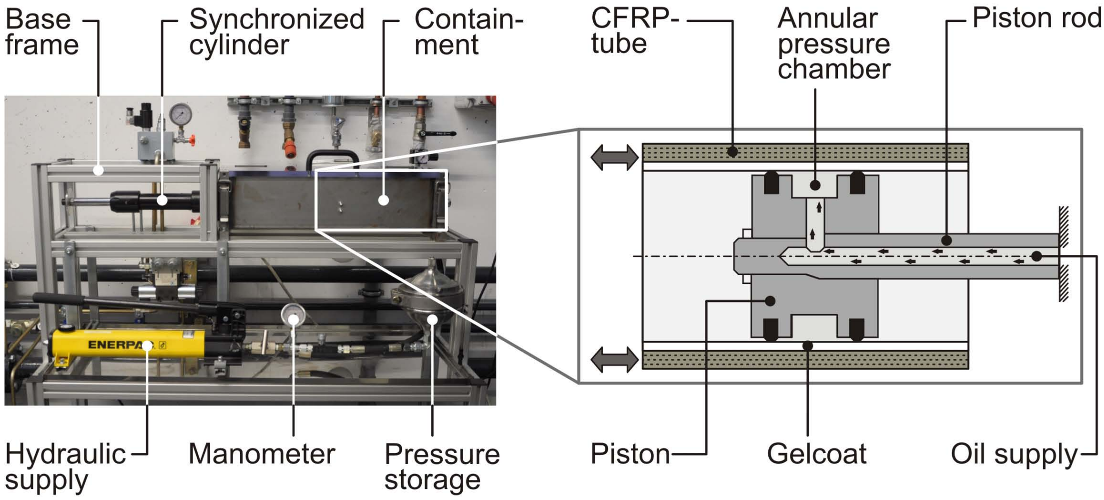

Figure 11: Test rig for mechanical and tribological testing of tubular CFRP-specimens

5. Conclusion

The realisation of innovative and cost-efficient lightweight hydraulic components in multi-material-design requires the development of new load introduction systems. Thus, the load introduction systems shown in this paper make an important contribution to the successful application of FRP in hydraulic components. The extensive studies on thermal induced residual stresses in hybrid structures allow the precise determination of the material efforts and deflections under thermal loading for hydraulic components in multi-materials-design. The developed test rig for testing of surface coatings as well as liners on the inner surface of tubular CFRP-specimen under mechanical and tribological loading allows the determination of the wear resistance under realistic test conditions.

6. Acknowledgement

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