LIGHTWEIGHT DESIGN OF HYBRID, CIRCUMFERENTIAL REINFORCED HIGH-PRESSURE HYDRAULIC CYLINDERS

M. Birke[1]*, R. Gottwald[1], J. Meyer[2], B. Grueber[1], S. Spitzer[1] and M.Gude[1]

[1] Institute of Lightweight Engineering and Polymer Technology (ILK),
TUD Dresden University of Technology, D-01062 Dresden, Germany,
* Corresponding author, Email: michael.birke@tu-dresden.de,
web page: https://tu-dresden.de/ing/maschinenwesen/ilk

[2] Liebherr-Aerospace Lindenberg GmbH (LLI), Pfänderstraße 50-52, D-88161 Lindenberg im Allgäu,
Email: joerg.meyer@liebherr.com, web page: www.liebherr.com

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ABSTRACT

In the undisturbed area of conventional metallic hydraulic cylinder tubes under inner pressure, the mechanical stress distribution is homogeneous but different in longitudinal and tangential direction for physical reasons. Here, the use of carbon fiber reinforced plastics (CFRP) offers the potential to improve the utilization as well as the power-to-mass ratio in such structures. In the case of multi-axial mechanical stresses in loaded structures, the exploitation of their high orientation dependent specific stiffness and strength is associated with challenges in design and dimensioning. Selective hybridization offers numerous advantages for hydraulic cylinder requirements, especially in high-performance applications such as aviation. Hybrid hydraulic cylinder tubes can already be found in technical applications and are also the subject of research. However, there is little literature on the methods used to design them. For this reason, the authors present a basic method for the development of a lightweight hydraulic cylinder tube in metal-fiber composite hybrid design using selected insights from an aviation research example.

The hybrid design concept is developed in a virtual-physical combined procedure. For this, the hydraulic-functional regions of established metallic hydraulic cylinder tubes can be partially kept as an inner substructure. Externally, CFRP reinforcement is designed and dimensioned in such a way that a high utilization of the overall structure is given. Well-known analytical calculation approaches are useful for pre-dimensioning. Simulation studies on simplified models are used to specify the choice of materials and the geometries of the inner substructures. Depending on the requirements, these investigations are supported by physical experiments on the necessary material data, on the feasibility of manufacture and on mechanics on substructures or scaled models. To validate this engineering process, simulations and tests are performed on a full-scale specimen. The presented method offers a rapid approach for design and dimensioning of CFRP-metal hydraulic cylinder tubes.

1 INTRODUCTION

Hydraulic cylinders consist of a cylinder housing, which often has a tubular shape in the form of a cylinder tube, and a piston rod with a piston (cf. Figure 1).

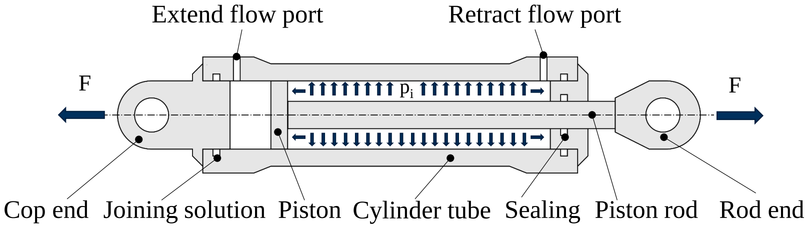

Figure 1: Schematic representation of a conventional metallic hydraulic cylinder design

The purpose of hydraulic cylinders is the transformation between hydraulic and mechanical power, whereby a cylinder-axial, translatory movement takes place between the load introduction regions of cylinder body and piston or piston rod. Depending on the configuration of the adjacent components and the boundary conditions in the overall system, complex spatial retraction and extension movements can be realized in mechanisms. According to the piston cross-sectional area, the working speed is influenced by the volume flow and the force by the working pressure in the hydraulic system. The design of the hydraulic cylinder largely follows the desired function. The dimensioning is on the one hand governed by stiffness, e.g. to ensure tightness or to prevent instability behavior such as buckling, and on the other hand by the required strength at the expected application or operating loads. [1]

In high-performance applications, such as aviation, hydraulic cylinders are usually made of high-strength steel alloys allowing high system forces at low weight and small installation space. These are essential lightweight requirements that enable a high transport mass or operating range.

In the course of time, various methods and lightweight design methods have been developed and researched to increase the performance of hydraulic cylinder structures [2, 3]. The cylinder tube usually accounts for the highest proportion of the total mass of a hydraulic cylinder [3]. Furthermore, within thin-walled cylindrical housing under isostatic internal pressure loading, the stress in axial direction is only 50% of the stress in the circumferential direction [4]. Changing this utilization ratio is not possible with conventional metallic hydraulic cylinder tubes due to their isotropic material properties.

Compared to steel alloys, CFRP have significantly higher specific stiffnesses and strengths in fiber direction [5] and promise a further increase of the lightweight potential, especially for hydraulic cylinders in high-performance applications.

In [6] the realization of a high proportion of fiber composite materials in a hydraulic cylinder tube is described. This tube, including the load introduction regions, is realized in a hybrid lightweight design. Here, a metallic liner is used inside the tube to guarantee the function and tightness of the hydraulic cylinder. Considering the given multi-axial loads, this development approach ensures the desired media protection and the required tribological wear resistance against the CFRP material. In the engineering process of such high-performance hydraulic cylinders, an iterative approach is often used to develop the concept as well as the detailed design.

The use of CFRP in hydraulic cylinders [7-8] has not yet been established in aviation. To support the use of fiber composites in aeronautical structures and thus increase performance, solutions for a modular methodology for hybrid lightweight designs were developed and presented [9] for 3 example structures within the FAWIBO research project. At present, hardly any thematic literature on such methodical approaches can be found. Therefore, in addition to the development of a graded CFRP/titanium aircraft suspension strut in [10], the authors demonstrate a further procedure in the context of this article using the example of a hydraulic cylinder relevant to practice.

2 METHODICAL APPROACH FOR THE ENGINEERING DESIGN PROCEDURE

For the fast, efficient design and dimensioning of a hydraulic cylinder tube in hybrid lightweight construction, an adapted procedure consisting of analysis of the requirements, engineering and validation is proposed. An initial presentation of such a method using the example of the development of a hybrid high-performance tension-compression strut is given in [11]. Adapting this methodology, an analogous procedure follows for the development of the hybrid cylinder tube (cf. Figure 2).

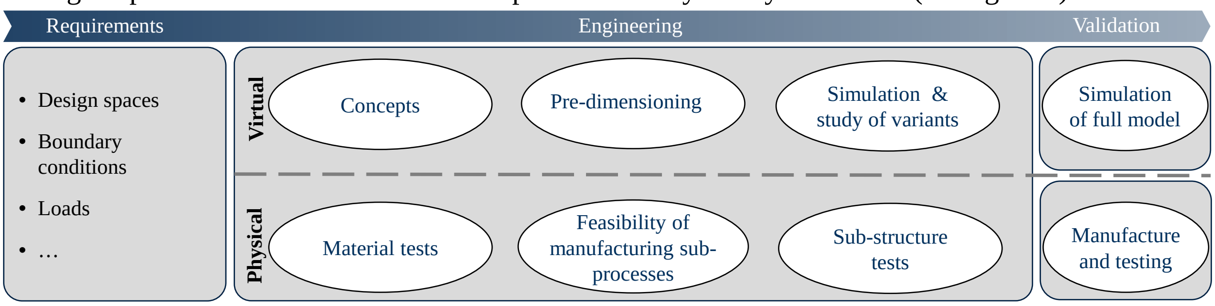

Figure 2: Scheme on suggested combined virtual-physical method for the fast development of design approaches for lightweight hybrid cylinder tube structures (modified according to [11])

2.1 Specification of requirements

For the definition of the requirements, the boundary conditions regarding geometry, loads and functions are determined and specified (cf. Table 1).

Specifications and Requirements		
Geometric	**Identification of critical loads**	**Functional**
• **Available design space or max. permitted dimensions** • **Minimum and maximum distance between load application points** • **Minimum inner piston cross section due to working pressure and required actuator force**	• Mechanical - Maximum isostatic internal pressure - Stability failure (column, cylinder buckling) • Chemo-mechanical - No unacceptable corrosion behavior and material degradation due to exposure to hydraulic fluid, humidity and other chemicals • Thermo-mechanical - Thermal based changes of material properties - Residual stresses due to different coefficient of thermal expansion (Δα) • Dynamic and cyclic load cases • Load case combinations	• Permitted maximum weight • Required cylinder stiffness to ensure function - Load capacity - Sealing • Friction pairing

Table 1: Selected boundary conditions, criteria and loads that can be part of the requirements analysis for the development of hydraulic cylinder tubes in hybrid design

2.2 Engineering

The engineering design process is characterized by an efficient combined virtual-physical approach to develop a concept for a hydraulic cylinder tube in hybrid CFRP-metal design that meets the mechanical requirements. Within this procedure, simulations and tests are carried out mainly at substructure level. The aim is to reach rapidly a stage where an overall model can be created, simulated, manufactured and tested in order to validate the design.

2.2.1 Pre-dimensioning for conventional hydraulic cylinder tube

For the pre-design and pre-dimensioning of a thin-walled cylinder tube under internal pressure load p_i, the Barlow's formula can be applied. The stresses of the cylinder tube with the inner diameter d_i and the wall thickness s can be calculated in the axial (σ_z) and tangential (σ_t) direction of the cylinder as follows:

$$\sigma_t = \frac{p_i * d_i}{2 * s} \tag{1}$$

$$\sigma_z = \frac{p_i * d_i}{4 * s} \tag{2}$$

These show that the cylinder tangential stress σ_t is two times higher than the axial stress σ_z and must therefore be considered in the calculation of isotropic metallic cylinders as a failure and dimensioning-relevant variable (cf. Figure 3). Depending on the required tensile or compressive force F of the hydraulic cylinder, the required wall thickness s can be roughly dimensioned after converting equation (1), specifying the internal pressure p_i and the internal diameter d_i.

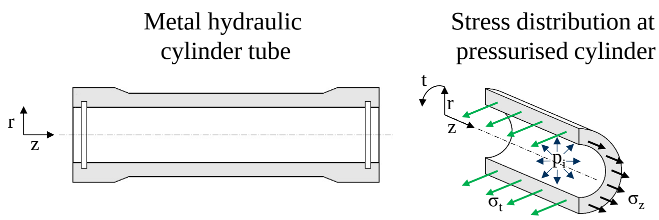

Figure 3: In conventional metallic thin-walled hydraulic cylinder tubes (scheme left) the stress in axial orientation is half of the stress in tangential orientation for physical reasons (σ_z/R_z = 0,5 and σ_t/R_t = 1 at maximum load; scheme right)

2.2.2 Concept and pre-dimensioning for hybrid design of hydraulic cylinder tube

The above-mentioned limited utilization potential in the axial direction of metallic hydraulic cylinders can hardly be improved in homogeneous isotropic design. In contrast, a hybrid design, consisting of one metallic and one fiber composite-based substructure in a suitable material combination, offers significantly improved utilization of the material strengths R at a lower mass m. For this purpose, the wall thickness s of the inner metallic tube component is reduced and then the tube is reinforced by a fiber composite component arranged on the outside (cf. Figure 4). The procedure proposed here makes use of the anisotropic property of a unidirectionally (UD) reinforced composite material, in which the highest stiffness and strength is oriented primarily in the longitudinal fiber direction. In the transverse direction, such materials have comparatively low stiffness and strength.

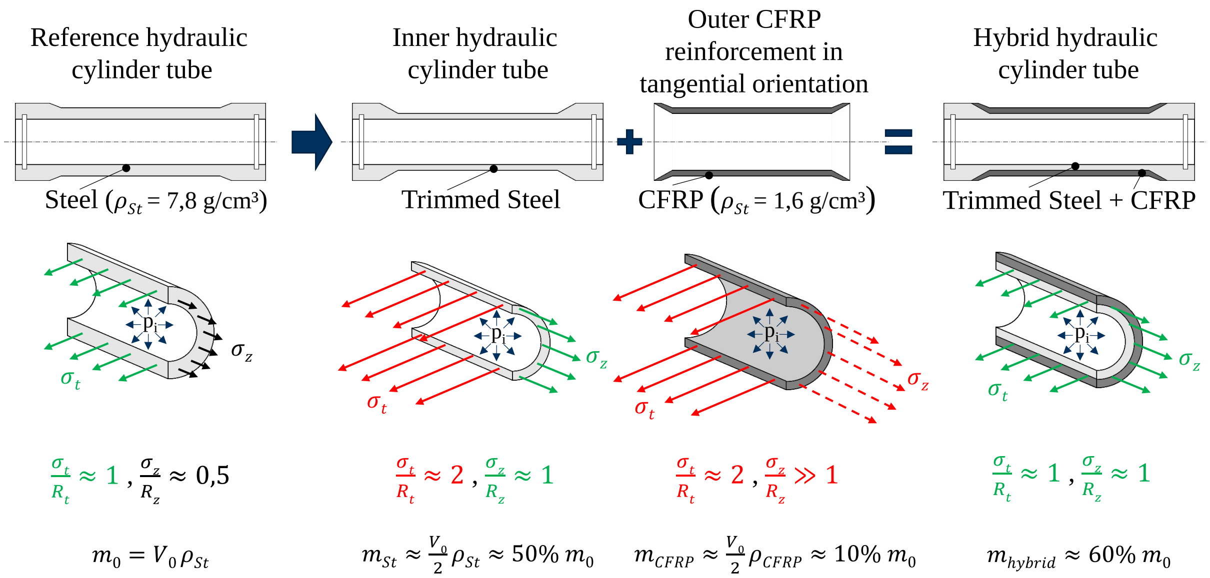

Figure 4: Schematic representation of reference hydraulic cylinder made of steel (left) which provides basis for the derivation of concept (middle) for hybrid lightweight hydraulic cylinder tube (right),

To improve the utilization of the material strength in the cylinder-axial direction of the inner metallic substructure (σ_z/R_z = 0.5 in Figure 4 left), the wall thickness s is reduced until in axial direction a theoretical utilization of σ_z/R_z = 1 is reached (cf. Figure 4, 2nd image from left). To simultaneously ensure load bearing capability in the tangential direction, a circumferential reinforcement with UD-CFRP is added (cf. Figure 4, 3rd image from left), so that a tangential utilization σ_t/R_t = 1 is achieved for the entire system (cf. Figure 4, right). The result of the proposed hybridization concept is a cylindrical tube (cf. Figure 5), which consists of functionally and load-bearing complementary substructures[1]. This makes it possible to improve the material load-bearing capacity of the undisturbed part of the cylinder tube compared to a purely metallic design, while at the same time reducing the mass m up to 40 %.

[1] Note: This approach of hybridization is also known for type II pressure vessels [12].

If required, analogous considerations can be carried out for the stiffness, in order to take into account a circumferential stiffness-dependent expansion or a possible instability under pressure load in the pre-calculation.

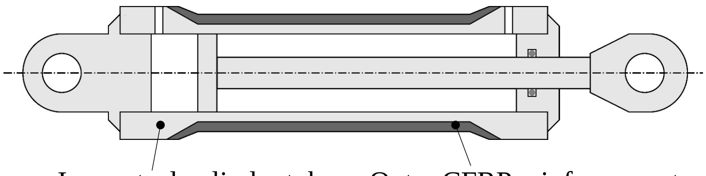

Figure 5: Scheme of a hydraulic cylinder with cylinder tube in proposed hybrid design

2.2.3 References and tests for determination of material data

Component developments often take place as a further evolution of an already existing system. In such a case, rough analytical pre-dimensioning or numerical simulation calculations based on existing material data can be performed for the hybrid cylinder tube. Missing characteristic values are to be determined using suitable material tests.

For the metal to be investigated, tensile tests are carried out to obtain the stiffness, strength and plastic behavior in the form of stress-strain-curve. Alternatively, these can also be approximated using curve fitting methods, e.g. from literature data on yield and tensile strength. For metals that undergo strain hardening during plastic deformation and exhibit a smooth elastic-plastic transition, this can be done, for example, according to the Ramberg-Osgood relationship.

In the case of fiber composites, the material properties (c typical results on tested specimens in Figure 6) are largely determined by the actual manufacturing conditions. Aspects such as fiber volume content or yarn pretension may have to be considered in the evaluation. In addition, depending on the application requirements, the specimens may be exposed to defined medial loads, such as temperature, hydraulic fluid or humidity, prior to mechanical testing in order to take into account degrading influences in the material properties. Depending on the stress profile in the real application, dynamic mechanical or thermomechanical tests (DMA) can also be useful for specifying the material data in more detail.

Figure 6: Tensile test stress-strain-curves of 0°-UD-CFRP-specimens made of HTS40 fiber and L20 resin system (modified according to [9], left) and their typical failure mode (right)

2.2.4 Feasibility of manufacturing sub-processes

In line with the approach of the hybrid cylinder, circumferential reinforcement is required for the tangential direction. A suitable and efficient manufacturing process for such tube structures is winding [13]. Depending on the manufacturing process, the fiber composite is built up by predefined computer-aided deposition of the fiber thread. In the end areas of the cylinder, the winding direction is reversed and a layer-by-layer structure is formed in the radial direction. The dimensions and placement of the fiber, the resulting thicknesses of the fiber composite layers and the design of the end sections require extensive investigations to find suitable parameters for manufacturing. If applicable, the wall thickness of the fiber composite reinforcement may be brought into the final contour by machining. Various relevant software tools are available for the virtual investigation and derivation of a winding strategy as well as the creation of the program sequence for the winding machine (e.g. CADWIND, cf. Figure 7, left). For easy physical verification of the manufacturing process, the winding can be tested, for example, with dry rovings on a model mold of the inner substructure (cf. Figure 7, right).

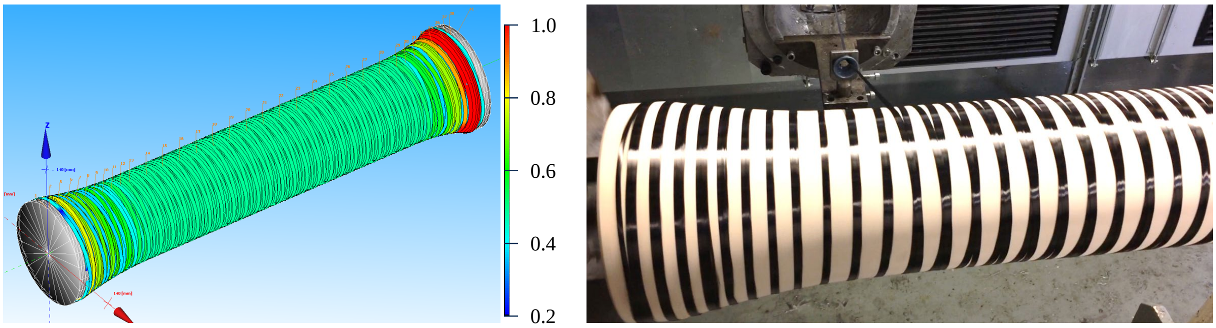

Figure 7: Example of the resulting angle ply thickness for the first layer for a CFRP reinforcement on the inner steel cylinder tube based on a pre-calculated set of winding parameters (left) and preliminary experimental investigations on CF-fiber deposition at winding process on the physical model cylinder (right)

2.2.5 Numerical investigations on substructures

For an efficient approach, the design process is supported by numerical simulation studies. The first step is to analyze how the stresses are fundamentally distributed among the substructures in the hybrid concept. For the creation of an initial model, the definition of the geometry and material properties, analytical calculations can be used (cf. section 2.2.1-2.2.2). Simplified investigations can also be carried out on a cylinder ring model to obtain initial findings for the straight, undisturbed cylinder region in sense of a pre-screening. With these approaches, the influence of different material properties and wall thicknesses can be investigated in variant studies. During the investigations, it is observed that a circumferential reinforcement with low stiffness in fiber direction (e.g. glass fiber reinforced plastic - GFRP) does not carry a sufficient part of the load and thus the inner metallic substructure is stressed excessively (cf. Figure 8, top).

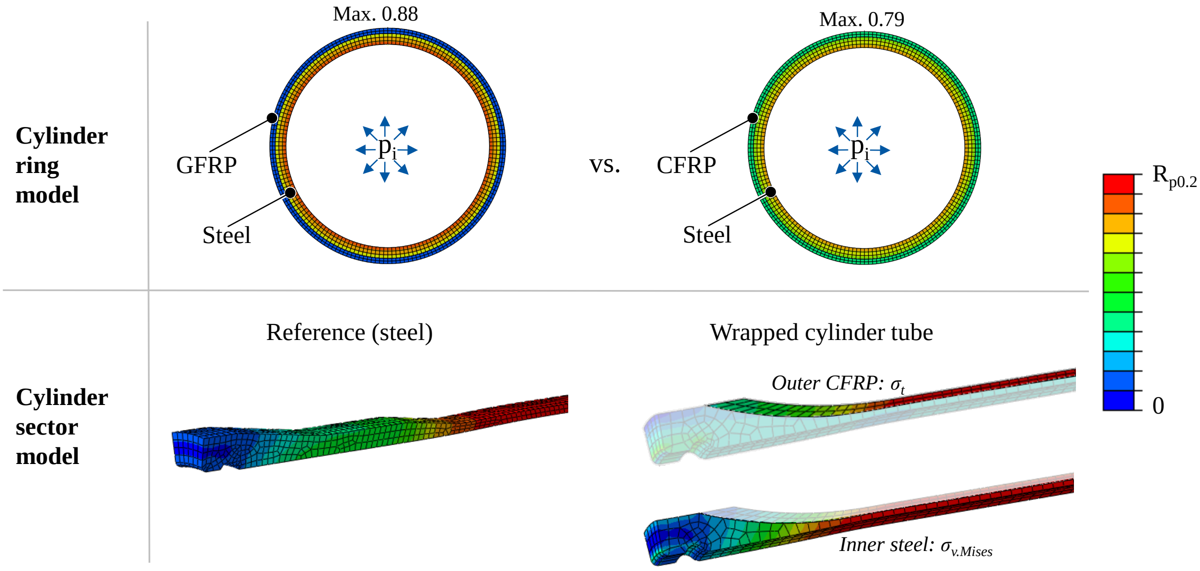

Figure 8: Numerical preliminary studies for the estimation of the hybrid design on simplified models under internal pressure loading (modified according to [9]): Exemplary representation for the influence of the reinforcement stiffness on the stress distribution (top) and of stress analyses along substructure contours (bottom)

Given rotational symmetry for geometry, material properties, boundary conditions and loads, it is possible to create a cylinder sector model to investigate the stresses over the entire longitudinal direction of the cylinder (cf. Figure 8, bottom). In the case of bending loads induced by bearing moments, considerations must be made in a half or full model due to the asymmetry. For the interface between the two substructures, the definition of a tied contact is assumed for simplicity in the present stage of concept development. For a rough assessment, the contact stresses can be evaluated and compared to known or to be determined interface strengths.

The aim is to adjust the material stiffnesses and wall thicknesses to achieve a uniform utilization in accordance with the hybridization concept (cylinder ring model). On the basis of the cylinder sector model, the design of the surface profile between the two subcomponents in the cylinder axial direction can be determined and developed.

For hydraulic cylinders, different safety factors against failure are taken into account depending on the area of application. In terms of lightweight design, it is therefore advisable to develop the cylinder tubes in such a way that they can withstand the highest expected load without damage (e.g. in general aviation: Limit Load (LL)). Here, the material used and the load cycles that occur can be dimension-relevant variables for the beginning of plastic deformation or fatigue damage. In order to ensure safety for unplanned overloads (e.g. in general aviation: Ultimate Load (UL, equals 1.5-times LL)), considerations up to the failure strength and yield behavior may be necessary.

Investigations show that in the case of reinforcements with low stiffness in relation to the metal, the composite is subjected to low stress in load cases below the plasticity limit (corresponds to LL), unless it is designed with unreasonably thick walls (structurally stiff). At higher loads, however, there is a significant load transfer to the composite reinforcement as a result of the yielding of the metallic base material (cf. Figure 9).

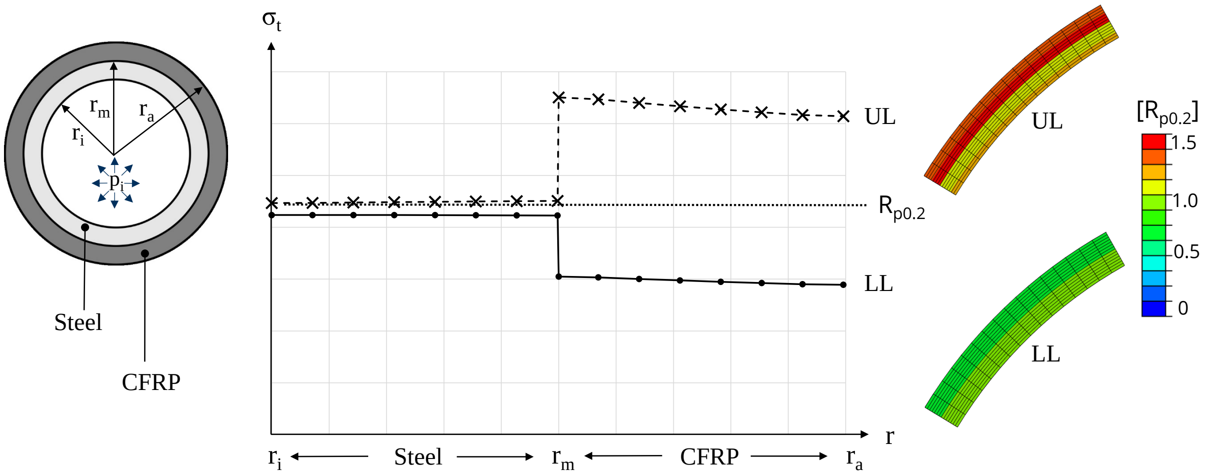

Figure 9: Scheme of hybrid cylinder ring segment (left) and compared tangential stress distribution within inner steel cylinder and the outer CFRP reinforcement (middle and right), stresses normalized with respect to the yield strength ($R_{p0,2}$ = 900 MPa) of the reference steel 15-5PH

The challenge in dimensioning is therefore to realize a sufficiently stiff composite reinforcement that adequately supports the steel under normal operating loads (e.g. at LL), but has sufficient reserve for the load redistribution in the case of overload (e.g. UL). In summary, the hybrid tube can thus be designed up to burst pressure beyond the yield strength, taking into account the safety factor (e.g. UL). Furthermore, the total stiffness and therefore also the maximum permitted elongations relevant for the piston seal can be determined.

2.2.6 Experimental preliminary tests on substructures

In order to reduce effort and costs in research and development, simplified preliminary tests may be performed, e.g. on scaled substructures. These tests and measurements provide experimental support for the results obtained so far, for example on aspects relating to hybrid design, materials and dimensioning. If relevant, the scalability of the selected approach must be checked and taken into account to ensure the transferability of the results from the reduced model to the component to be developed.

2.3 Validation based on numerical simulations and experimental tests

The combined virtual-physical design process is characterized by a series of simulations and tests, the results of which are combined and detailed. In order to validate the concept for the hybrid cylinder tube, numerical simulations on the full model, manufacturing of the real test specimen as well as its experimental investigation are carried out.

2.3.1 Numerical simulation of full model

For virtual validation, the findings are combined to form an overall model and the stresses under selected mechanical loads are studied in detail. The focus is on the specific effects that result from the metal-CFRP material combination. For example, at a high spread of the application temperature range, significantly high residual stresses can be induced due to the differing coefficients of thermal expansion of metal, composite parallel and transverse to the fiber direction (matrix-dominated behavior). Systematic simulation studies of relevant combinations of thermal and mechanical load cases (cf. Figure 10) allow to identify, analyze and evaluate critical stressed areas.

Item of interest	**Analysis of**
Steel + CFRP	Tangential stress
Steel	v. Mises
Steel	Plastic strain
CFRP	Cuntze
Interface	Shear stress
Inner surface	Deformation
…	…

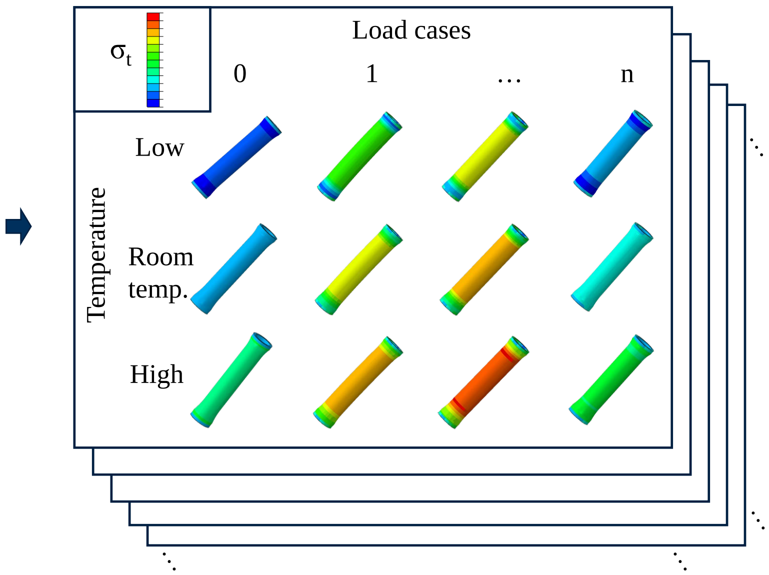

Figure 10: Systematic Analysis of items of interest at selected load case and temperature combinations

In addition to the investigations in the circumferential direction, analyses are required, for example, for the interface and the transverse fiber stress of the composite in the cylinder-axial direction. For the selected example of an aircraft hydraulic cylinder, inter-fiber failure up to LL are defined as not acceptable. This means that the reinforcement bears part of the load in the cylinder-axial direction despite its much lower stiffness. However, if intermediate fiber breaks occur in the overload case (e.g. UL), this support is reduced and a load transfer into the inner metal cylinder takes place. This can be represented in the simulation either by adjustments to the contact formulations or by further substantial reduction of the reinforcement stiffness in the cylinder-axial direction.

The shown considerations and FE studies promise an efficient analysis for the identification of critical states and provide an important basis for the following experimental validation.

2.3.2 Experimental testing of the hybrid cylinder tube specimen

The final step in the development of the hybrid lightweight cylinder tube concept is the experimental validation. In the selected example, the test is specified as internal pressure test on the cylinder tube. Next, the tube of the hybrid hydraulic cylinder is manufactured, the ends of the tube are closed and provided with appropriate connections for testing. For the analysis and subsequent evaluation of the resulting stresses, a suitable measuring system must be set up.

Here, the displacements over the entire structure are measured using a tactile displacement transducer. To measure the strain on the outer cylinder surface, strain gauges are attached in the axial and tangential directions.

To ensure safety in the event of a possible burst, the compression test takes place in a containment. After the test and the measurement equipment has been set up, the hybrid cylinder tube is subjected to internal pressure at defined load levels. A comparison of the recorded values with those of the simulations during or after the test run allows the quality of the results to be assessed and evaluated. (cf. Figure 11).

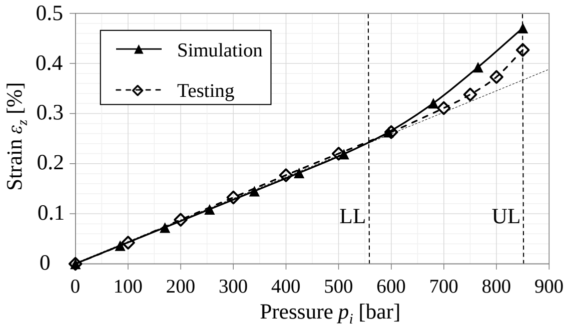

Figure 11: Result of the measured and pre-calculated strain on the outside of the CFRP-reinforcement in the undisturbed area in cylinder axial direction (modified according to [9])

3 RESULTS AND DISCUSSION

In the frame of the work carried out, a design methodology for the development of highly stressable hybrid lightweight structures was presented using the example of a hydraulic cylinder tube. The combined virtual-physical approach of requirements analysis, engineering and validation enables an efficient procedure. It is characterized by an illustrative representation of mechanical-physical relationships. Figure 12 shows the schematic of the adapted design approach method.

This was validated using a selected aircraft cylinder structure as an example. In the process, essential design considerations for hybrid designs were developed. It is shown that the combination or sequence of the individual engineering steps depends on the given conditions and already available data. According to the requirements of function, geometry and loads in combination with the physical-mechanical relations for internally pressure-loaded cylinder tubes, a hybrid design consisting of internal metallic and external composite reinforcement substructures is concluded.

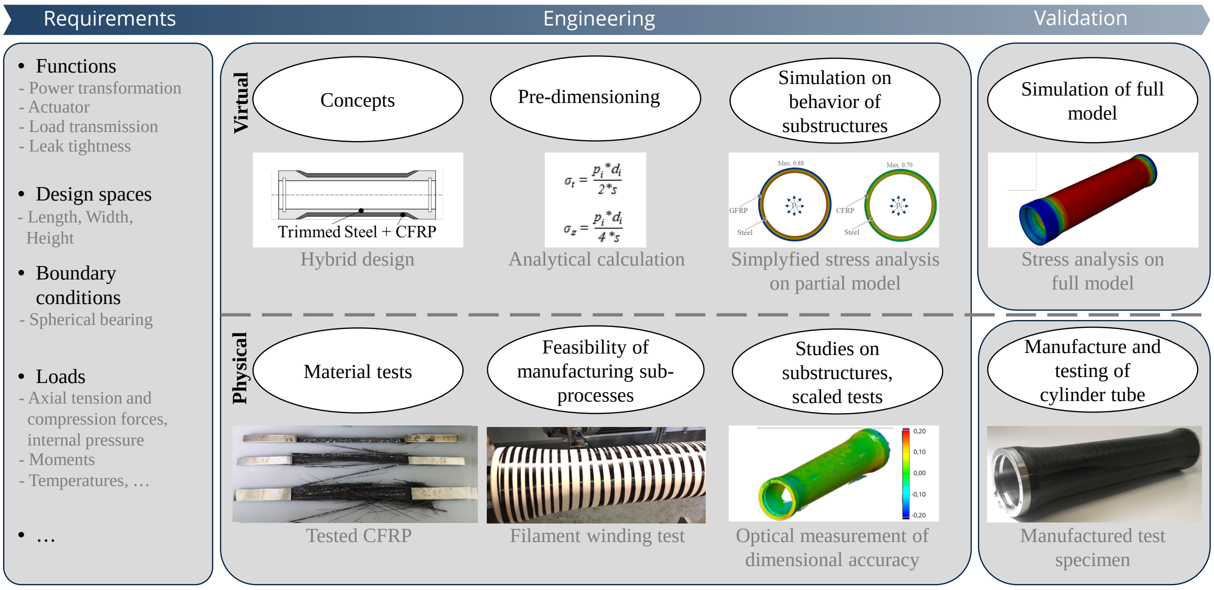

Figure 12: Schematic of the design approach method for the development of hydraulic cylinder tubes in hybrid lightweight design

The methodical approach enables the successful design, layout and dimensioning of the concept. The functional and load-bearing capacity of the substructures was extensively validated. Furthermore, application- and material-specific processes for manufacturing have been derived. The substructure can be efficiently realized by machining the inner metal tube, winding the outer composite material in combination with turning to the final contour. Overall, a weight reduction of 25 % was achieved for the entire cylinder tube structure. In conclusion, such hybrid designs promise competitive solutions in terms of cost and performance.

Further experimental tests on the fatigue strength and interface durability of the presented concept as well as tests under superimposed loads such as bending, tension or compression are still pending in order to achieve an increased TRL level. Since the selected example takes aviation-relevant aspects into account, it represents an important contribution to increasing the lightweight design of hydraulic cylinders and the use of fiber-reinforced composites for lightweight solutions in the aircraft industry. Therefore, essential foundations for environmentally friendly mobility can be created, e.g. in aviation, in the form of fuel reduction or an increase in range and/or load-bearing capacity.

ACKNOWLEDGEMENTS

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