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DESIGN AND TEST OF ADVANCED FIBRE-REINFORCED TRANSMISSION SHAFTS

The high specific stiffness and strength of composite materials with ultra-high modulus (UHM) carbon fibers as well as the possibility of creating a load-adapted property profile are ideally suited for the design of advanced transmission shafts for mobile applications. For a reliable development of such safety relevant components, material properties under static and dynamic loading conditions as well as adapted manufacture processes, which ensure a reproduceable quality, are required. Therefore, extensive fracture tests were carried out under multi-axial loading in order to determine the static and dynamic strength behaviour of UHM-carbon fiber reinforced polymers. Additionally, an advanced construction concept for fibre--reinforced transmission shafts in combination with an adapted winding process was developed, which enables the integral manufacture of advanced lightweight transmission shafts.

Key words: **transmission shaft, ultra-high modulus, dynamical loading, Woehler-line, integral construction**

KONSTRUOWANIE I BADANIE ZAAWANSOWANYCH WAŁÓW TRANSMISYJNYCH WZMOCNIONYCH WŁÓKNAMI

Wysoka sztywność i wytrzymałość materiałów kompozytowych z włókien węglowych UHM umożliwia konstruowanie bardzo lekkich wałów napędowych np. dla przemysłu lotniczego. Zaawansowana konstrukcja takich anizotropowych elementów wymaga znajomości właściwości materiałowych przy obciążeniach statycznych i dynamicznych, a także wybrania procesu produkcyjnego, zapewniającego odpowiednią jakość. W celu określenia wytrzymałości polimerów wzmocnionych włóknami węglowymi UHM przeprowadzono w ILK weryfikację przy złożonym stanie obciążeń. Dodatkowo opracowano zaawansowaną koncepcję konstrukcji wałów transmisyjnych wzmocnionych włóknami węglowymi przy uwzględnieniu procesu nawijania, umożliwiającego produkcję nowoczesnych lekkich wałów transmisyjnych ze zintegrowanymi częściami wprowadzającymi moment skręcający.

Słowa kluczowe: **wały transmisyjne, UHM-moduł, obciążenia dynamiczne, zintegrowane konstruowanie, linia Woehlera**

INTRODUCTION

The development of complexly stressed composites structures - especially with ultra high modulus (UHM) reinforcement - requires reliable dimensioning concepts in order to take best advantage of the high degree of the material's lightweight potential. Moreover, adapted cons- truction concepts in combination with adapted manufacture processes have to be developed in order to efficiently manufacture safety relevant lightweight components with a reproduceable quality. As an example the overall design, manufacture and test process of advanced transmissions shafts with ultra high modulus (UHM) reinforcement for mobile applications is presented here.

Nowadays, transmission shafts for mobile applications, e.g. for aircraft applications, are mainly made of metallic materials. These conventional materials have densities, which are up to five times as high as the density of fibre-reinforced polymers with the effect of a higher component mass and increased fuel consumption of the system. Additionally, these conventional shafts consist of several single components, as for example cost-intensive and weight-intensive hinges and supports, which require an immense assembling effort. First fibre-reinforced transmission shafts are characterized by a differential construction concept with several single components especially for the transmission of forces, which require additional assembling and joining steps. In contrast to the conventional transmission shafts here an integral construction concept for an advanced fibre-reinforced shaft was aimed at. This integral construction concepts is shown in Figure 1. The transmission shaft consists of three main areas: a middle cylindrical shaft and the two integrated force transmission areas flange and polygonal connection end.

For the overall design process the necessary static and dynamic material properties - especially the strength properties dependent on the fibre orientation - have been determined in adapted material tests, numerical simulations of the structural behaviour have been carried out, adapted manufacture processes have been developed and component test have been performed.

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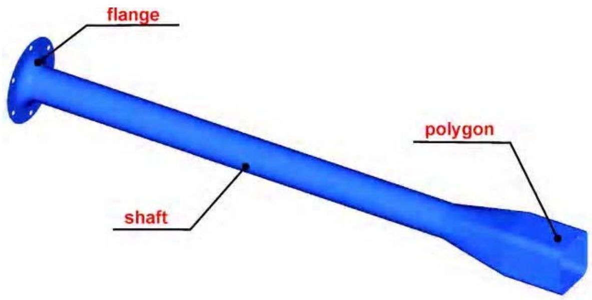


Fig. 1. Concept of an integral fibre-reinforced transmission shaft

STATIC AND DYNAMIC MATERIAL CHARACTERISATION

The tensile/compression-torsion experiment on tangentially and crosswise wound standard tube specimens was used to determine the static and dynamic strengths [1, 2]. The tube wall thickness was 1.0 mm, the inner diameter 40 mm and the tube length 162 mm. The investigated tube specimens were produced from pitch-based carbon fiber rovings (K63712 DIALED, Mitsubishi, Japan) with the winding angles of 90°, ±30° and ±45° respectively. Epoxy resin Araldit LY564 was used for the matrix material.

In order to characterize the static strength behaviour of UHM carbon composites, extensive quasi-static fracturing experiments were first carried out under single axis tensile, compression and torsion loading as well as multi-axial tensile/compression-torsion loading [2]. On the one hand, the fracturing experiments enabled the determination of the relevant failure stresses. On the other hand the tests on the parallel wound tube specimens made it possible to identify the corresponding fracture angles.

The short-term tests were used to determine the strength directional dependency. These experiments served as the starting point for the dynamic experiments on tube specimens. In the pulsating tensile stress range (load path 1) and the oscillating compressive stress range (load path 5), the stress ratios of minimum stress limit to maximum stress limit, $R = \sigma_{min}/\sigma_{max}$ (constant amplitude) were chosen as $R = 0.1$ and $R = 10$, respectively as shown in Figure 2 for tangentially wound specimen [3, 4]. The amplitude adjustments were made in such a way that the maximum and minimum stresses were 0.9 to 0.5 times that of the determined static tensile strengths σ_{ts} and compressive strengths σ_{cs} respectively.

The fatigue experiments were carried out on a PSB 100 hydrodynamic testing instrument (INSTRON, UK) which was load controlled. During the fatigue experiment, a test frequency of 3÷5 Hz was chosen in order to avoid extreme heating of the test specimens, which would lead to inaccurate results [5, 6]. To ensure that the test specimen temperature did not exceed 30°C, temperature was continually monitored.

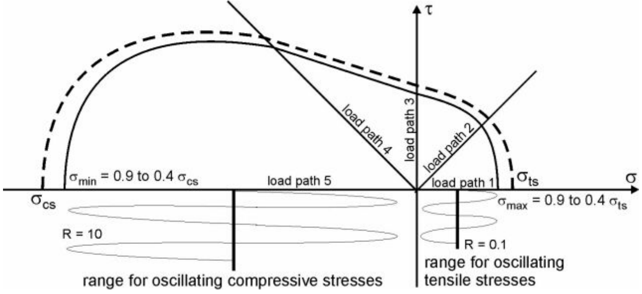


Fig. 2. Schematic correlation of the dynamic experiments with a fracture curve in the (σ_2, τ_{21})-stress plane for tangentially wound specimen (σ_2, τ_{21} in fibre adapted coordinate system)

The experimental results from the pulsating tensile stress and oscillating compressive stress investigations of 90°, ±30° and ±45° tube specimens with ultrahigh C-fiber reinforcement are shown as normalized Woehler- -lines in Figures 3-8. These figures include trend-lines and the mean values for strength. Furthermore, the data of specimen, which did not fail are displayed.

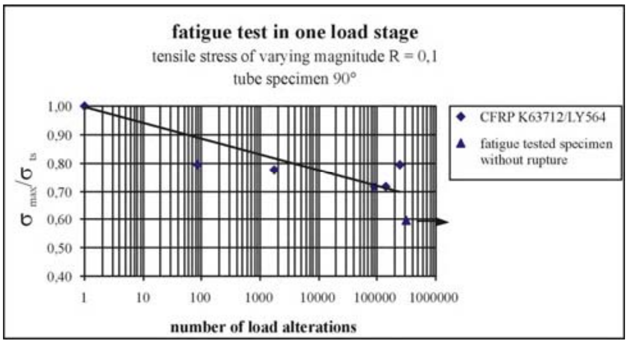


Fig. 3. Fatigue behaviour of 90° wound specimens in the range for pulsating tensile stresses

In the pulsating tensile stress range, a comparison of the normalized Woehler-lines and the corresponding trend-lines as a function of the wind angles reveals a large reduction in strength for the ±45° specimens. The strength degradation was significantly lower for the tangentially wound specimens.

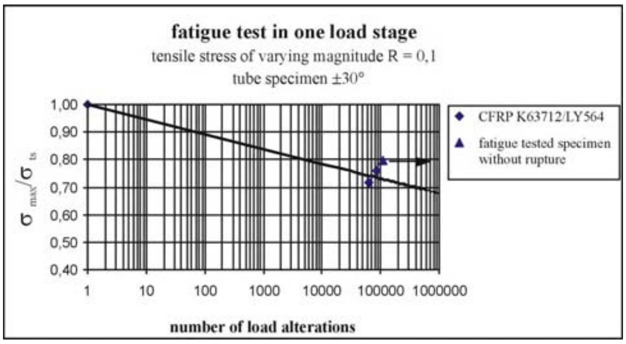


Fig. 4. Fatigue behaviour of ±30° wound specimens in the range for pulsating tensile stresses

A similar fatigue behaviour was observed in the oscillating compressive stress range (Figures 6-8). Although lower than in the pulsating tensile stress range, the greatest reduction in strength was also found on the ±45° specimens. On the other hand, the degradation of the 90° specimens decreased slightly while the reduction in fatigue strength of the ±30° specimens increased for *R* = 10 compared to *R* = 0.1.

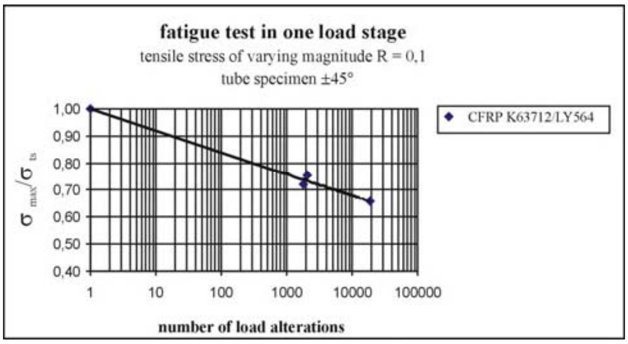


Fig. 5. Fatigue behaviour of ±45° wound specimens in the range for pulsating tensile stresses

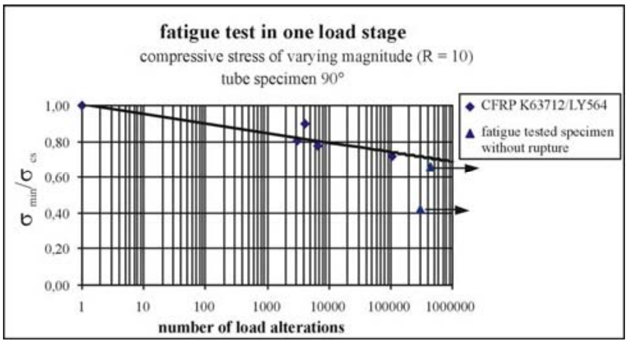


Fig. 6. Fatigue behaviour of 90° wound specimens in the range for oscillating compressive stresses

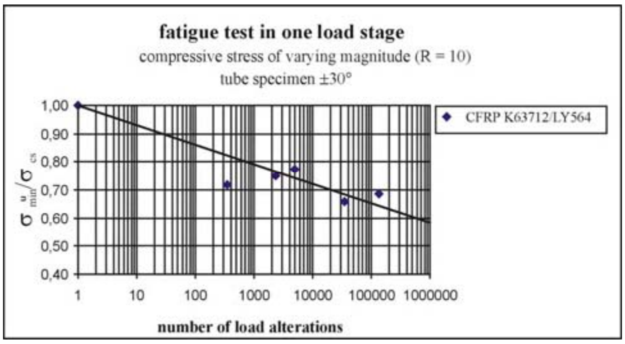


Fig. 7. Fatigue behaviour of ±30° wound specimens in the range for oscillating compressive stresses

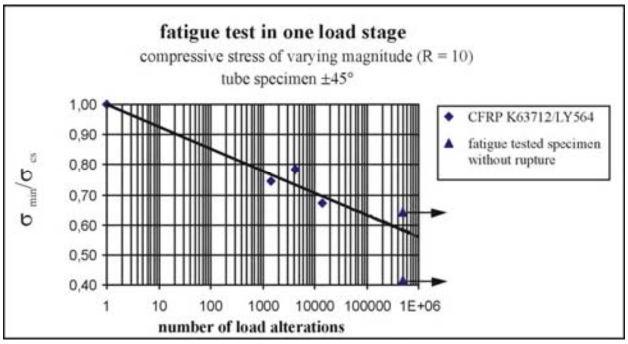


Fig. 8. Fatigue behaviour of ±45° wound specimens in the range for oscillating compressive stresses

In further investigations, quasi-static and dynamic torsion experiments as well as superimposed tensile/compression-torsion experiments on tangentially and crosswise wound tube specimens were carried out. To a large extent, these fundamental strengths permit the verification of the physically proven failure criteria for multi-axial quasi-static loading and on the other hand, the applicability of new failure criteria in dynamic loading cases [7].

NUMERICAL ANALYSIS OF STRUCTURAL BEHAVIOUR

Based on the mechanical properties, the structural behaviour of the transmission shafts was analysed using the Finite Element Method (FEM) based on the program system I-DEAS Master Series 9.0. One main focus was the optimisation of the fibre orientation and the failure analysis especially of the force transmission areas, which contain notches and high surface pressures conditional on constructive causes. Figures 9 and 10 show the models and selected boundary conditions of the flange and the polygonal area. The model has been meshed using 4-nodes thin shell elements. In a first step the a blurred continuum has been assumed and the corresponding material properties have been calculated using the classical lamination theory (CLT). In the following, multi-layered elements with a symmetric lay-up, using the I-DEAS laminate module, have been defined in order to perform a layer-wise failure analysis according to the Tsai/Wu failure criterion. The torsional moment applied to the flange and the polygon is 300 Nm. The flange is clamped at the border of the holes.

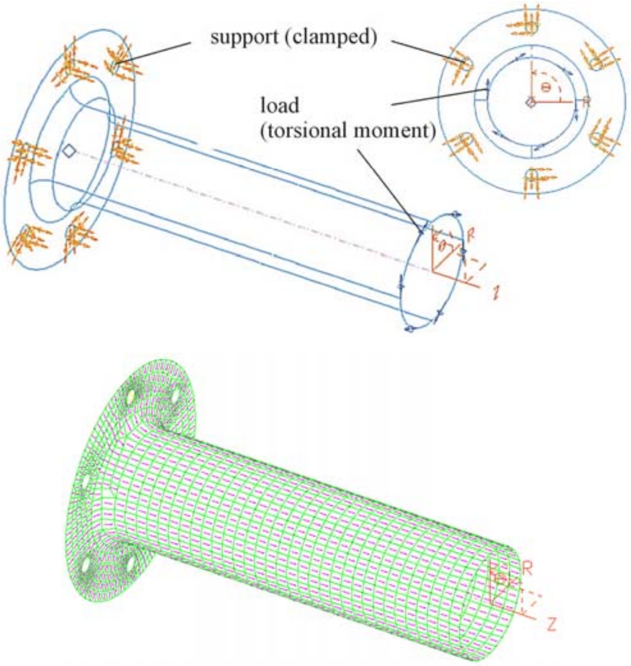


Fig. 9. Geometry, boundary conditions and FE-model of flange

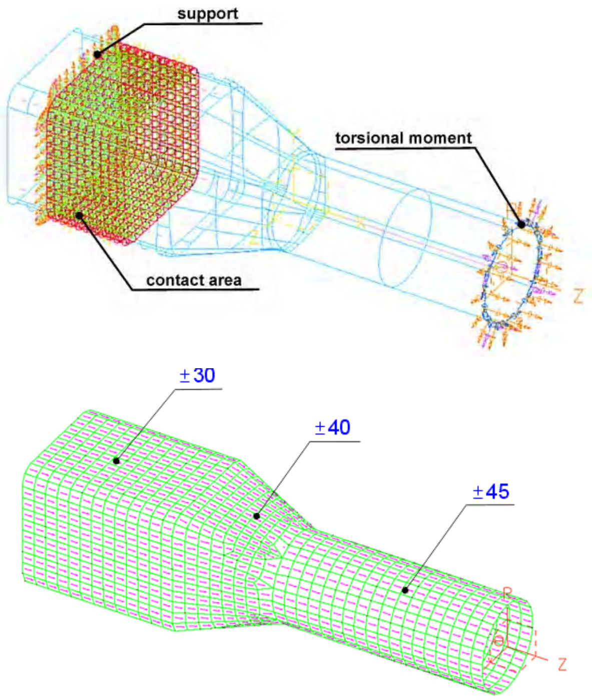
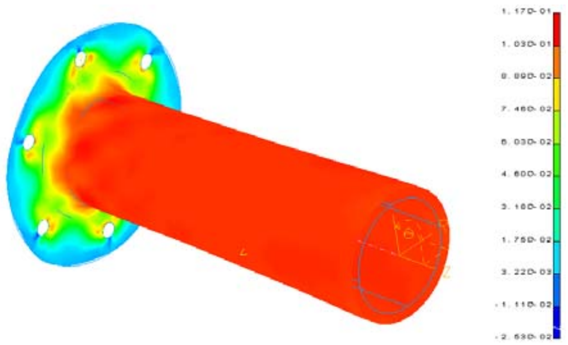


Fig. 10. Geometry, boundary conditions and FE-model of polygonal area



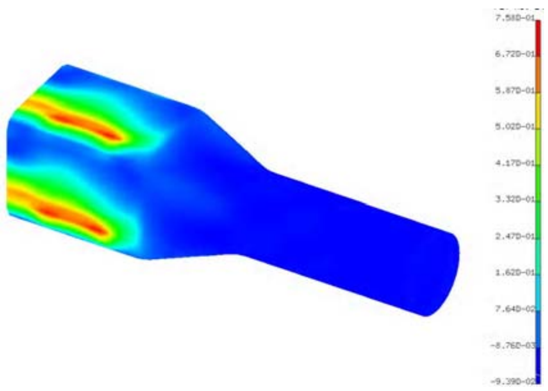


Fig. 11. Failure Indizes of optimized force transmission areas

In order to gain realistic results in the polygonal area contact elements had to be used, which enable the simulation of the interaction of polygon and a metallic connection element. The metallic connection element, meshed with 8-nodes solid elements, is fixed in all directions at the face surface. Furthermore, the influence of technically feasible fibre orientation due to manufacture restrictions and variable shaft diameters had to be considered, which leads to a winding angle of ±45° in the cylindrical area, ±40° in the transition area and ±30° in the polygon.

The numerically calculated stress peaks due to the notches in the flange and high surface pressures in the polygon could be eliminated by an adaptation of the winding pattern. Finally, an optimised geometry and lay-up was found, which resulted in a reduced Failure Index (FI) according to the failure criterion of Tsai/Wu as shown in Figure 11. The necessary condition (FI < 1) for a safe construction is fulfilled in all critical areas.

COMPONENT MANUFACTURE AND TEST

Based on the results of the design process the manufacture of first prototypes was carried out using the winding technology at the ILK. Therefore, an adapted mandrel was designed, which enables the integral manufacture of the transmission shaft including flange and polygonal connection (total shaft length 790 mm, inner shaft diameter 32 mm, shaft diameter 70 mm. In various winding simulations and manufacture tests the optimal parameters for the winding process on a 5-axis winding machine were determined and adapted to the complexly shaped mandrel (Fig. 12).

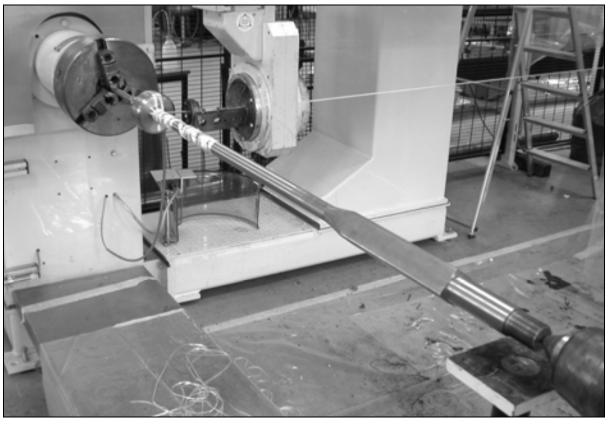


Fig. 12. Winding of transmission shaft on an 5-axis winding machine at ILK

For the following component tests under static and dynamic loading the tension/compression-torsion test unit was modified and adapted supports were developed. Subsequently, the prototypes of the advanced transmission shaft were successfully tested (Fig. 13). The theoretical results from the design process could be verified excellently by the experimentally determined shaft stiffnesses and failure loads.

CONCLUSIONS

Due to their high specific strength and stiffness, carbon fiber reinforced polymers, especially those with ultra-high modulus carbon reinforcement, are particularly suitable for use in fast-moving and accelerating components in mobile applications such as transmission shafts. For the overall design process of advanced fibre-reinforced transmission shafts reliable material properties were determined in static and dynamic material tests.

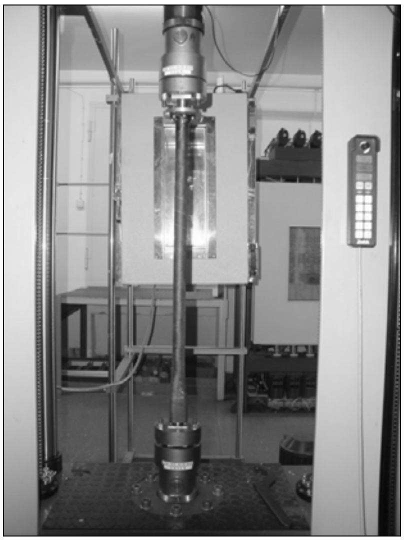


Fig. 13. Test-setup for torsion tests on prototypic transmission shafts

Oscillating strength experiments on carbon fiber reinforced polymers using pulsating tensile and compression loading were carried out in order to determine the fatigue behaviour and corresponding Woehler-lines. Moreover, composite compatible construction concepts for an integral transmission shaft and adapted manufacture technologies were developed. First prototypes of the novel lightweight transmission shafts, which were manufactured and successfully tested, demonstrate their excellent lightweight potential.

* For the sake of secrecy of patents and official secret, details are not publish.

Acknowledgement

The author would like to extend his gratitude to the Bundesministerium für Wirtschaft und Technologie (BMWi) for the financial support required to conduct the study.

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Recenzent
Marian Klasztorny