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Mechanical fastening of carbon composite tubes, numerical calculation of axial loading capacity and experimental verification

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ABSTRACT

This contribution improves the mechanical fastening technology for a CFRP-tube with a rough surface texture (knurled surface [11]) in the contact area. Numerical analysis (extended by Puck's fracture condition) and experimental analysis are used in this paper to investigate which knurled geometry has the best rate of fiber failure, and also the inter fiber failure in relation to the increased friction force of the mechanical joint. In contrast to the position generally held in the literature it is possible to achieve high loading capacity, even if the laminate is damaged partly and locally by the joining technology, as shown by the following analysis with conclusions. Furthermore, it gives the opportunity to integrate a ductile behavior in the material structure. Overall, this leads to new ways of designing components with CFRP.

1. Introduction

With the desire for advanced energy efficiency and optimized lightweight components, the use of carbon fiber reinforced plastics has grown in the last few years. Specifically, the use of semi-finished products has been increased significantly. The challenge in practice is to use a joining technology that does not diminish the beneficial properties of the CFRP tube (high stiffness, high limit load and low weight) [1,2]. In addition, the joining technology has to be rather simple, reliable and inexpensive. With the appropriate joining technology it should be possible to transmit forces safely into CFRP-lamina. This can be achieved with a suitable mechanical fastening device. Most of the connections for a CFRP tube to metal are realized by adhesive joining techniques, e.g. [3]. These are characterized by low weight and low forces (in relation to the limit load of the CFRP tube) which can be transmitted. In contrast, adhesives have a complicated joining process and cannot be disassembled without destroying the lamina (maintenance and repair).

Force transmission in thick-walled applications is mostly solved by positive connections. These are characterized by high transmittable loads, but also by high weight as well by the damage caused to laminates by machining, e.g. drilling [4].

In addition to the established positive [5–8] and adhesive [3] joining technologies for CFRP tubes, the frictional connection has not yet been efficient enough. The relationship between transmittable force and weight cannot compete with the other technologies at present because it is not possible to transmit the required forces through a small area only by friction.

One way to improve this situation is to increase the roughness of a hard surface in contact. It is known that this has a positive effect on the friction coefficient in the joint. [9] conducted investigations of shaft-hub connections with material combinations of steel (shaft) and plastics (hub). It was found that higher loads can be transmitted by knurled surfaces.

Also, [10] notes significantly increased loads which can be transmitted in connection with cross-loaded bolted joints. In this case, a fiber-plastic composite was used. The use of knurled surfaces causes an approximate fourfold increase in the maximum load transmitted, which allows for small and light weight connections.

By the use of a proprietary mechanical fastening device for CFRP tubes with a defined knurled surface texture, the performance of the frictional connection will be examined and improved. The influence of the sharpness of the surface texture on the friction coefficient and the damage of the laminate is of special interest, and will hence be analyzed numerically and experimentally. The surface is not fully characterized and tested for the influence of the geometry.

2. Mechanical fastening device for CFRP tube

In general, the fastening device should not decrease significantly the very good strength to weight ratio of the CFRP tube,

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Nomenclature

F_P	Tightening preload in fastening device for CFRP tubes (N)	s	Displacement (mm)
T_{tot}	Tightening torque in fastening device for CFRP-tubes (N m)	r_{CA}	Contact area ratio
F_{Rad}	Radial clamping force of the fastening device (N)	A_1	Cut tip area (mm^2)
F_Y	Axial pullout-force of the fastening device (N)	A_0	Ground tip area (mm^2)
μ_b	Friction coefficient in screw head	f_{E1}	Stress exposure for inter fiber failure
μ_{KK}	Friction coefficient between taper keys	$f_{E,FF}$	Stress exposure for fiber failure
μ_{St_CFRP}	Friction coefficient between steel and CFRP	r_{FF}	Relative damage ratio for fiber failure
μ_{th}	Friction coefficient in screw thread	r_{IFF}	Relative damage ratio for inter fiber failure
μ_1	Friction coefficient between screw and sleeve	t_p	Penetration depth (FEA calculation) (mm)
d_2	Pitch diameter of bolt thread (mm)	r_{Fy}	Relative increase of pullout force
P	Pitch of the thread (mm)	F_R	Friction force (N)
D_b	Effective diameter for the friction moment in bolt head area (mm)	F_N	Normal force (N)
α	Taper key angle (°)	TR_{FF}	Transmission ratio for fiber failure
		TR_{IFF}	Transmission ratio for inter fiber failure
		t_{PM}	Measured penetration depth (experiment)

and should also provide nearly the same limit load as the CFRP tube. By using a double taper key, it is possible to fasten a CFRP tube with a normal screw joint, as shown in Fig. 1.

The analytical relation between the axial preload, F_P, and the tightening torque, T_{tot}, is shown in Eq. (1), according to [12].

$$F_P = \frac{2}{d_2 \cdot \left[\frac{P}{\pi \cdot d_2} + 1155 \cdot \mu_{th} + \frac{\mu_b \cdot D_b}{d_2}\right]} \cdot T_{tot} \qquad (1)$$

For the fastening device, it is possible to specify the relationship between radial force, F_{Rad}, and tightening torque, T_{tot}, according to Eq. (2).

$$F_{Rad} = \frac{(\cos\alpha - \mu_{KK} \cdot \sin\alpha)}{-\mu_1(\mu_{KK} \cdot \sin\alpha - \cos\alpha) + (\mu_{KK} \cdot \cos\alpha + \sin\alpha)} \cdot \frac{2}{d_2 \cdot \left[\frac{P}{\pi \cdot d_2} + 1155 \cdot \mu_{th} + \frac{\mu_b \cdot D_b}{d_2}\right]} \cdot T_{tot} \qquad (2)$$

The values for the friction coefficients (thread, μ_{th}, nut head area, μ_b, taper key, μ_{KK}, and between taper key and screw, μ_1) are identified by means of measurements on a fastener test bench. To this end, a complete fastening device has been mounted five times (to ensure repeat accuracy) while the friction coefficients (thread, μ_{th}, and nut head area, μ_b) were recorded. The friction coefficients for the taper key (μ_{KK}) and between screw and sleeve (μ_1) are the same as the friction coefficient of the head area, because of the identical surface condition.

The relationship between F_{Rad} and T_{tot} is of great importance and was additionally verified with an experiment. To examine this, the screw of the fastening device and a cylindrical sleeve are fitted with strain gauges. By this means it is possible to measure the preload, F_P, (quarter bridge) and the resulting radial force, F_{Rad},(half bridge) while tightening the device.

To strengthen the CFRP tube against the large radial stresses produced after tightening, a ring winding is used (same fiber and matrix material as tube).

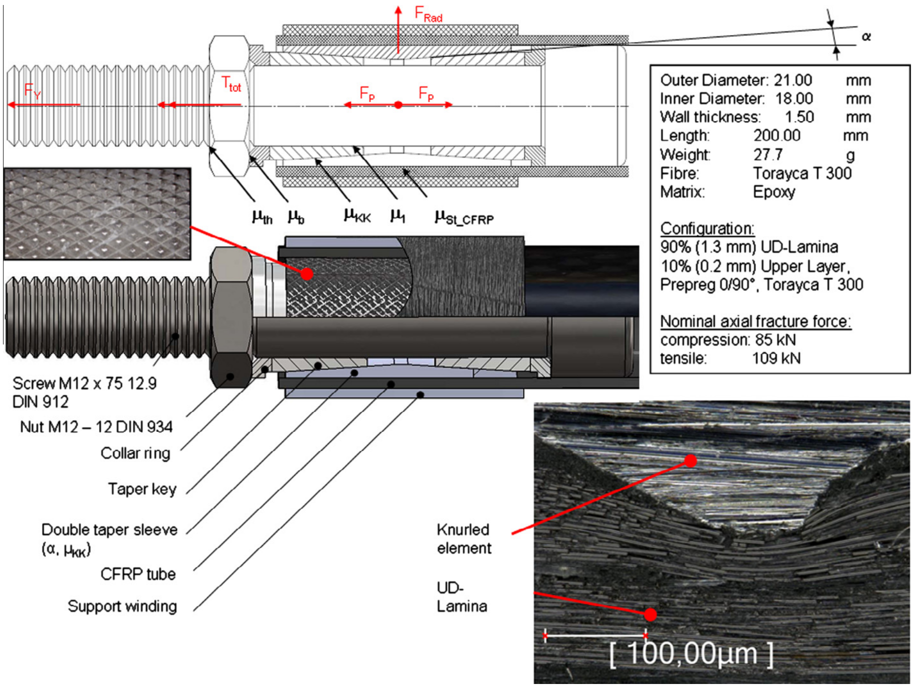

Fig. 1. Fastening device for CFRP tubes.