ANALYSES ON FORMED BOLTED JOINTS FOR THICK-WALLED CFRP IN WIND POWER INDUSTRY

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ABSTRACT

For the design of highly loaded assemblies, load introduction areas of separate components need special attention. Different joining technologies for fiber-reinforced plastics are available. For thick-walled fiber-reinforced plastics, bolted joints are suitable, requiring drilled holes which generate three effects: Firstly, reduced cross sections for the load transmission causing higher mean stresses in the structure. Secondly, the single presence of a hole provokes a notch effect with stress concentrations at the hole circumference. Thirdly, the drilling process can induce fiber and matrix damage. These detrimental effects result in high stresses which often limit the usability of the whole assembly.

With respect to a cost effective manufacturing of a bolted load introduction for a thick-walled, mainly torque loaded carbon fiber-reinforced plastic drive shaft, the forming of a hole and thereby redirecting of fibers around the hole seems to be a promising option compared to conventionally drilled bolted joints. In order to investigate such a formed bolted joint in detail, experimental investigations on representative test specimens were realized using conventionally drilled bolted joints as a reference.

Results show a benign damage mechanism due to the combination of bearing failure and plastic pin deformation of formed and drilled bolted joints. Apart from an improved manufacturing process, reduced load introduction stiffness can be found for formed bolted joints. An additional adhesive bonding between the two joining partners increases the joint stiffness significantly. An expected improved fatigue behavior will be investigated on representative test specimens within the near future.

1 INTRODUCTION

High loads have to be transferred from the rotor hub of a wind power plant to the generator. Therefore, thick-walled metal drive shafts are usually installed for load transmission. As a result of installation tolerances and changing wind conditions, offsets have to be compensated by using couplings. Rough weather conditions as well as mechanical wear limit the durability of these metal parts, resulting in high maintenance costs during the whole product life cycle, impacting especially off-shore installations. In order to reduce wear and increase the fatigue behavior, an integral design approach of the drive shaft was chosen by eliminating the mechanically critical components. In consequence, radial and angular offsets, which had been corrected by these additional couplings, have to be compensated by the drive shaft itself. For this purpose, carbon fiber-reinforced plastic (CFRP) drive shafts are suitable, since they simultaneously provide a moderate bending stiffness and a high torque stiffness when a suitable laminate lay-up is chosen. Allowing better damping and fatigue properties, a CFRP drive shaft with an innovative, formed load introduction was designed using analytical and finite element (FE) methods, manufactured and experimentally tested. A prototype of this drive shaft, which is called *FlexShaft* to reflect its properties, has been operating in a wind power plant since 2013, cf. figure 1. Formed bolted joints were preferred to conventional drilled bolted joints, since a better fatigue behavior is ascertained due to the uncut, redirected fibers within the laminate [1].

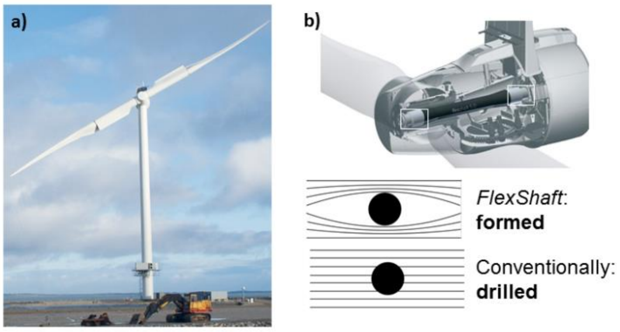

Figure 1: **a)** Picture of the experimental wind power plant. **b)** Schematic section view of the nacelle including the CFRP drive shaft. The *FlexShaft*'s formed load introduction is characterized by a fiber redirection around the pin which is assumed to provide enhanced fatigue properties (fibers: lines; pin: black circle; resin not shown).

In most cases, load introductions are the most critical parts of an assembly. In case of bolted joints, dimensioning stress concentrations occur around the hole circumference [2,3]. Since no transferable experimental data of formed bolted hybrid joints for thick-walled parts are known to the authors, static tests of the *FlexShaft* load introduction were performed. Therefore, an appropriate experimental set-up had to be derived.

2 SET-UP DERIVATION AND MANUFACTURING

The *FlexShaft* load introduction between the thick-walled CFRP laminate and the metal steel flanges on both sides of the drive shaft consists of more than 200 pins per side, cf. figure 2. With respect to the sizeable material and manufacturing effort for a single non-scaled drive shaft, a specimen with a representative and less costly load introduction had to be developed. For this issue, a step-wise numerical approach was chosen.

Figure 2: Schematic section view and general requirements of the *FlexShaft* assembly consisting of the CFRP drive shaft with mostly ±45° orientated fibers along the shaft axis, two steel flanges and pins within the load introduction area. A high torsional stiffness in combination with a moderate bending stiffness allows torsional load transfer as well as radial and angular offsets between the rotor and the generator with no use of additional couplings.

In a first step, a parametric, global FE model of the assembly was generated. This global FE model represents a thick-walled endless carbon fiber-reinforced drive shaft as well as metal flanges and bolts within the load introduction areas. The purpose of this simulation was to understand the general mechanical behavior of the assembly. The fiber redirection within the laminate caused by the forming of the bolt holes was not modeled since a detailed representation of the load introduction area would lead to exhaustive computation times. Instead, the mechanism of load transmission was investigated by using the submodeling technique for the load introduction area. Within this detailed FE submodel, the fiber orientation around the formed bolted joint, determined using the deply technique of a manufactured specimen, was included. [4]

The global FE model of the assembly confirmed that the load transfer strongly acts inhomogeneous along the different pin rows, cf. figure 3. This effect is already well understood for isotropic materials [5]. Comparing the results from literature to the orthotropic drive shaft material, the nonuniformity of load transmission along the pin rows seems to be more pronounced for fiber-reinforced plastics (FRP). Thus, following a conservative design approach, the experimental set-up should correspond to the stress state of the highest loaded pin row of the *FlexShaft*. In order to fulfil this requirement, various numerical simulations of a possible experimental set-up have shown that the mechanical behavior of a single pin can be represented by a uniaxial single lap shear test of the two components, FRP shaft and steel flange. The reasons for good accordance of a single lap shear test and the highest loaded pin row of the global FE model are the following:

- The local load introduction via a pin acts in circumferential direction of the drive shaft caused by the torque M_t.
- The dimensions of the drive shaft are large (diameter d = 760 mm). Consequently, the curvature radius of shaft plays a minor role for the load introduction, as multiple numerical analyses have confirmed

Thus, a uniaxial tensile force can be applied, which simplifies the design and test realization.

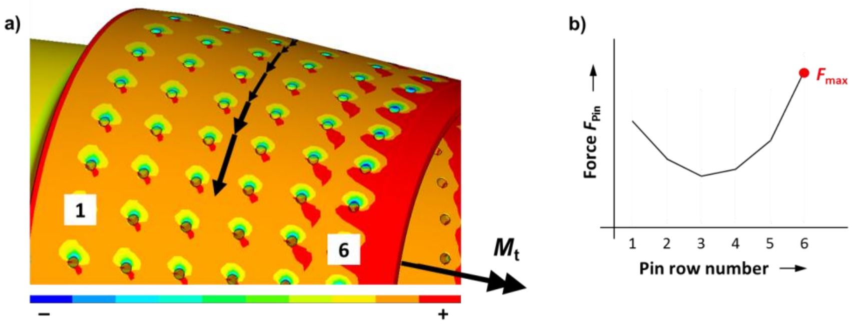

Figure 3: a) Finite element analysis of the bearing stress σ_{III} of the steel flange within the load introduction area caused by the applied torque M_t , bolt rows 1 and 6 are highlighted, and **b)** qualitative distribution of the load transfer of the pin rows. The load introduction mainly acts in circumferential direction of the shaft, whereas the highest forces are transferred in pin row number 6, towards the CFRP shaft.

In order to keep the manufacturing parameters constant compared to the *FlexShaft* manufacturing, a wet filament winding process was applied. Thereby, a winding mandrel was used for the representation of the steel flange, cf. figure 4 a). The test specimens were cut out in longitudinal direction of the shaft, see schematically in figure 4 b). As noted above, the load acts in circumferential direction of the *FlexShaft*, thus requiring a rotation of the laminate lay-up of the test specimen shaft by 90°. The single specimens were produced from the test specimen shaft by water jet cutting.

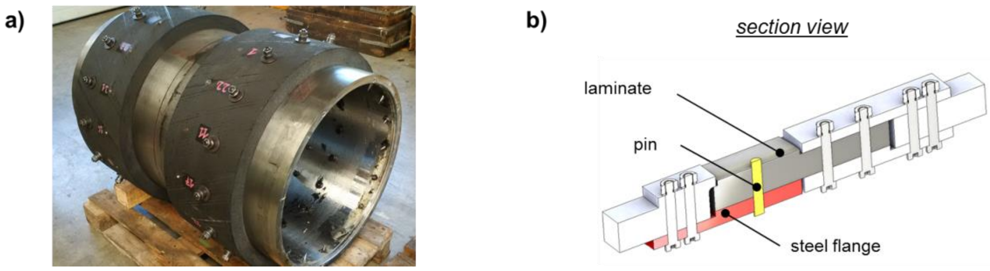

Figure 4: a) Picture of the test specimen shaft before cutting into single specimens and **b)** single specimen: schematic cross-sectional view of the developed pin test set-up of the *FlexShaft* load introduction. The steel parts at both ends (colored in white) are used for attachment to the existing test rig.

3 EXPERIMENTAL SET-UP

Four different variants of the load introduction were investigated. In order to compare the innovative formed bolted joint to a reference specimen, conventionally drilled bolted joints were tested as well. Furthermore, a second load path within the load introduction area was investigated by realizing an additional adhesive bonding between the two joining partners. An overview of the different variants of load introduction is given in table 1.

Table 1: Variants of manufactured and tested *FlexShaft* load introduction specimens.

pin insertion	interface	specimen description
into the cured laminate *preparation: drilling, deburring*	release agent	drilled bolted joint
into the cured laminate *preparation: drilling, deburring*	coupling agent	drilled bolted joint with additional bonding
into the uncured laminate *no preparation*	release agent	formed bolted joint
into the uncured laminate *no preparation*	coupling agent	formed bolted joint with additional bonding

For the quasi-static single lap shear tests, a servo-hydraulic actuated testing machine with a maximum force of 250 kN, three-dimensional digital image correlation (DIC) methods for strain measurements and acoustic emission (AE) methods for the measurement of damage events were used, cf. figure 5. In order to reduce settling, a preload of 1 kN was applied before starting the displacement controlled single lap shear test. The joint stiffness K_j was defined as the gradient of the force displacement curve between two load levels in the linear-elastic region, namely given in following formula:

$$K_j = \frac{F_{60kN} - F_{20kN}}{s_{60kN} - s_{20kN}} \tag{1}$$

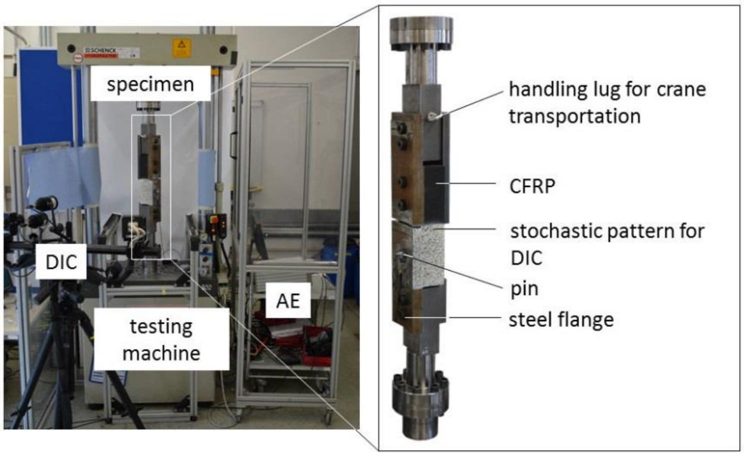

Figure 5: Experimental set-up of the single lap shear tests.

4 RESULTS

In the light of an expensive manufacturing and testing procedure only two specimens of each variant were tested. This procedure is valid since low scatter of maximum 5 % of the joint stiffness was observed. Just the peak force of bonding failure shows some scatter which is attributed to the difficulty of quality control during bonding application as well as possible induced minor damages during water jet cutting of the test specimen shaft. In the following, only one tested specimen for each variant of load introduction is presented. For reasons of clarity, specimens with lower mechanical properties (peak force at bonding failure, joint stiffness, etc.) are shown, following a consistent and conservative design approach. The specimens were not tested until total specimen failure, as occurring transverse forces would exceed the allowable safety limits of the test rig. For this reason, all tests were previously aborted at a maximum force of $F_{abort} \approx 150$ kN. However, all relevant mechanical information except from the maximum failure force was identified.

All specimens show a pronounced linear-elastic behavior until at least $F_{lin\text{-}el} \approx 85$ kN, cf. figure 6. The additionally bonded specimens retain their linear-elastic behavior up to higher peak forces until bonding failure (+ 20 %). However, the specimens which were not additionally bonded already show some non-linear material behavior caused by bearing stress and plastic pin deformation at lower load levels. The effect of an additional bonding between the two joining partners contributes significantly to the joint stiffness, cf. table in figure 6. Thanks to the large bonding surface of the specimens, the load transfer is mainly provided by the bonding itself. Until its failure, it is assumed that the pin mostly remains unloaded. This effect is observed independently from the variant of load introduction. While a conventionally drilled bolted joint with an additional bonding increases the joint stiffness by 51 % compared to a non-additionally bonded specimen, the joint stiffness is increased by 70 % for a formed bolted joint with an additional bonding. In comparison, the difference in joint stiffness between a formed and a drilled bolted joint is moderate. Independently from the interface pretreatment, the joint stiffness of a formed bolted joint is slightly lower: - 6 % with an additional bonding and -13 % without an additional bonding. This tendency was expected, since different load introduction mechanisms take effect. Drilled bolted joints have fibers aligned perpendicularly to the pin hole around the whole perimeter, whereas formed bolted joints provide a local load introduction transverse to the fibers. In addition, resin rich regions are present along the perimeter for formed bolted joints [4]. This leads to a more pronounced laminate deformation and a successive inter-fiber and fiber failure around the hole circumference when applying pin loads. Hence, the bearing strength and the joint stiffness of a formed bolted joint are reduced.

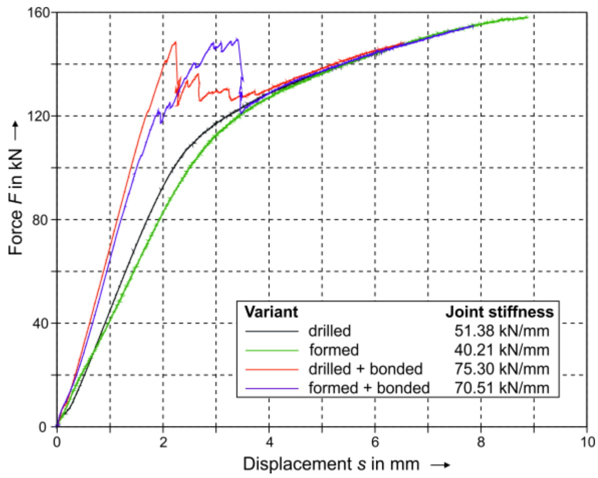

Figure 6: Exemplary force displacement curves of the investigated variants of load introduction. The additionally bonded specimens show a higher joint stiffness and a slight scatter at peak force at bonding failure. After bonding failure, the damage mechanism remains comparable resulting in a nearly identical material behavior.

However, the damage mechanism of both variants of pin insertion remains similar. The benign bearing failure of the laminate results in a borehole expansion, which allows a distinct bending deformation of the slender pin. Due to the higher bearing strength of the drilled bolted joint, the effect is less pronounced there. In both cases a plastic pin deformation is observed, cf. figure 7. Furthermore, the tests showed excellent bonding properties since neither adhesive nor cohesive failure of the bonding could be stated. By contrast, an inter-laminar failure of the laminate within the first three plies neighboring the steel flange occurred (delamination). Thus, the shear strength of the bonding exceeds the shear strength of the matrix resin. The delamination was also observed for a specimen which was tested without an inserted pin in order to investigate the pure bonding properties.

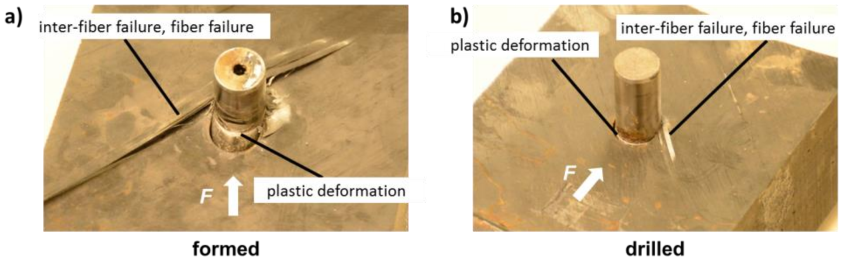

Figure 7: Damage progress of laminate and pin depending on the pin introduction: **a)** Formed and **b)** conventionally drilled bolted load introduction. A formed bolted joint shows a more pronounced laminate widening and thus plastic pin deformation for the given laminate lay-up.

The acoustic emission measurement showed a different behavior depending on the interface between the two joining partners. Regarding specimens without an additional bonding, first acoustic events were detected from the start on non-linear-elastic material behavior. These first signals are assigned to first inter-fiber failures within the laminate as well as a slight plastic pin deformation. In contrast, first acoustic events were already detected at the end of the linear-elastic region for the additionally bonded specimens. It is assumed that first inter-fiber failures within the first layers of the laminate were detected announcing the delamination ("bonding failure").

The described experimental results were used to validate the numerical analyses of the different load introduction variants. Regarding the joint stiffness, good agreement was found since formed bolted joints also showed a lower stiffness compared to conventional drilled bolted joints.

5 CONCLUSION

Experimental investigations on formed and conventionally drilled bolted joints for a thick-walled CFRP laminate have shown different mechanical properties. The results for a given laminate lay-up are:

- Formed bolted joints show a about 10 % lower joint stiffness compared to drilled bolted joints.
- If a high load introduction stiffness is desired, an additional bonding between the joining partners should be preferred. Regardless of the pin introduction mechanism an increase of the mean joint stiffness of about + 60 % is achieved.
- The damage mechanism of both formed and drilled bolted joints is similar. It can be stated that the combination of laminate bearing and pin plasticity generates a benign material behavior of the load introduction. These fail-safe properties can be improved using an additional bonding, since a second load path is created.

The slightly lower mechanical properties of formed bolted joints are expected to be compensated by its fatigue properties compared to the conventionally drilled bolted joints. Consequently, the next steps include cyclic experimental investigations.

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