PAPER • **OPEN ACCESS**

Potential of fibre metal laminates in root joints of wind energy turbine rotor blades

To cite this article: E. Petersen *et al* 2022 *J. Phys.: Conf. Ser.* **2265** 032039

Potential of fibre metal laminates in root joints of wind energy turbine rotor blades

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Abstract. The length of rotor blades is showing continuous growth for future wind energy turbines leading to high bending moments, which must be transferred to the hub by the root section. As the growth of the root diameter is limited by factors such as transportability, motivation to improve the load carrying capacity without changing the geometry is high. Hybridisation with metals shows a possibility to intrinsically increase the bearing strength of fibre-reinforced plastics. This publication presents experimental investigations into hybrid laminates to be used in so-called T-joints for connecting rotor blades to the hub of the nacelle of a wind energy turbine. An overview is given about the bearing strength of several material combinations hybridising glass- and carbon fibre-reinforced plastics (GFRP, CFRP) with aluminium, titanium and steel alloys. A GFRP-steel-hybrid can be identified as a material with a high reinforcing effect even for low amounts of steel. A hybrid T-joint demonstrator is manufactured by resin infusion and tested under static tension. In comparison with a GFRP reference, a joining strength increase of about 33% is achieved for a steel content of 3%. Further coupon level tests reveal a weak spot in the transition zone between the monolithic GFRP region and full hybrid region as the static and fatigue resistance clearly decreases in comparison with monolithic GFRP and full hybrid references.

1. Introduction

The continuous growth of rotor blades for wind energy turbines brings about the challenge of how to transfer the enormous bending moments between the blade root section and the hub of the nacelle. Compensating by increasing the root diameter, which is accompanied by a higher moment of inertia and an increased number of fasteners, is not easily possible. For onshore turbines, transportability limits the root diameter very strictly and the blade design would also become inefficient for offshore turbines. Therefore, motivation to increase the load carrying capacity in the root region without changing the geometry is high.

Today two joining technologies are established in the wind industry to connect the rotor blades with the hub: these are laminated inserts in the root section of a rotor blade or so-called T-Joints. The latter method has existed for longer and is still employed today as 2 in 4 onshore and 1 in 3 offshore turbine developers use them in their blades. In T-joints longitudinal bolts are connected with threaded bolts, to which tension is applied pre-stressing in order to prevent gaping during alternating loading.

Every material exhibits unique mechanical properties that can be positive or negative in terms of foreseeable application. Metals are a stalwart of engineering materials as they possess high strength and stiffness and exhibit low notch sensitivity thanks to their ductility. On the other hand, their high density limits their load carrying capacity through weight coefficient and leads to high gravity loads in dynamic applications. Fairly poor fatigue strength is a further weakness. Fibre-reinforced plastics (FRP) are often the first choice for lightweight structures. They provide excellent stiffness and a high strength-to-weight ratio. Furthermore, complex curved contours can be manufactured and their fatigue resistance is higher than that of metals. However, a weak point is their low resistance to shear or bearing stress caused by their brittle fracture behaviour; this means that careful engineering is required to meet the design requirements of bearing joints.

The engineer's choice of material is driven by many requirements, which may lead them to make use of different material properties together in multi-material and hybrid systems. The best-known hybrid material in aerospace is GLARE - Glass Laminate Aluminium Reinforced Epoxy [1]. Hybridisation is also applied in mechanical joints in order to overcome the low bearing strength of FRP laminates [2]. This technique, known as local metal hybridisation, can allow compensation methods such as laminate thickening to be avoided and also enables the number of fasteners in a cross section to be increased [9].

A local metal hybridisation could be used to increase the possible number of T-joints in the root section without changing the root diameter. Combining GFRP with steel could result in a material that is relatively cost-effective, easy to machine and provides a strong reinforcing effect. Fig. 1 shows a demonstrator part that was built by the DLR, without identifying its mechanical strength. Recently, Gerendt et al. carried out a number of investigations into joint strength prediction [5]. Furthermore, Beyland et al. presented static test results on the increasing effect of GFRP-steel hybrids [6]. Both studies indicate great potential for the use of GFRP-steel in rotor blade T-joints. Several challenges such as high cycle fatigue or the need for low-cost production are yet to be resolved.

Figure 1. Possible candidate for GFRP-steel hybridisation: T-Joint root connection of rotor blades; source DLR

The aim of this publication is to identify the potential as well as possible showstoppers for steel hybridisation in T-joint root connections for rotor blades. The bearing strength of several materials such as typical metals, FRPs and hybrid materials is compared in order to highlight the major strength increasing effect of GFRP-steel. Furthermore, a manufacturing concept is developed for a hybrid T-joint demonstrator. This demonstrator, in both the hybrid variant mentioned and a GFRP reference, is tested under static loads to determine the increase in load carrying capacity achieved thanks to hybridisation. Furthermore, experimental investigations are conducted on the transition zone (TZ) between the hybridised region and monolithic GFRP via coupon testing as this could be a weak spot of the joining technique.

2. The local metal hybridisation technique

A method to intrinsically increase the bearing strength of FRP laminates is local metal hybridisation. Thin metal foils are added or used to substitute FRP plies locally in the joining area, but the laminate in the overall structure is not affected. In the event of substitution, layers with the lowest contribution to the strength and stiffness of the structure are substituted first as ±45°- and 90°-layers. Replacing 0°-layers should be avoided. Local hybridisation leads to a full hybrid region, the monolithic FRP structure and a transition zone between these regions, in which the metal foils end. The technique was already used to reduce the weight of structures in aerospace, where reducing weight is also reducing fuel consumption and therefore operating expenses [12].

Because of this application region, mainly structures made of carbon fibre-reinforced plastics (CFRP) were investigated in the past. If weight restrictions are very important and high temperature differences are expected as is the case with space application, the use of titanium alloys is preferred [11, 12]. They provide relatively comparable thermal expansion coefficients and low densities. However, they are very expensive due to the cost of the material itself and also the fact that machining is very difficult. Where weight requirements are less strict than for space application, the combination of CFRP and steel showed a high potential in aircraft [3]. If the amount of fasteners can be reduced, even a cost reduction could be possible [4]. Experimental investigations on the TZ with CFRP-steel hybrids already revealed a high sensitivity to delamination and a limited load carrying capacity if its design is not carried out properly [13]. Aluminium is rarely considered for hybridising CFRP, due to galvanic corrosion occurring under moisture and the huge difference in the thermal expansion coefficients. However, there are a few known applications for satellites [14].

Focussing on wind energy rotor blades, any possible candidate must fulfil the requirements in this specialised industry. In contrast to aerospace, reducing weight is not leading directly to lower operational costs, for example a reduced fuel consumption. However, a reduced mass reduces the gravity loads leading to durable and material saving designs. Cost requirements are very strict and stringent fatigue life conditions must be fulfilled. The basic shells of a rotor blade are made from GFRP, which is the basis for hybridisation. Titanium alloys seem to be too expensive, but aluminium and steel could be possible candidates.

3. Materials and methods

This section contains a comparative prestudy on the choice of material and experimental investigations with two aspects:

- A T-joint demonstrator part is manufactured to ascertain the feasibility of common manufacturing techniques for thick hybrid laminates and to investigate the joining strength by static testing.
- As the transition between the hybridised region and the GFRP shells of the rotor blade could be a weak spot under fatigue loading, it is investigated using representative coupon specimens.

3.1. Bearing strength of conventional and fibre metal laminates

Figure 2 presents the bolt bearing strength σ_{LB} of different metallic, FRPs and hybrid materials. The tests are related to the AITM 1-0009 standard [7]. The data is partly taken from self-conducted static tests and partly from the literature. As bolt bearing tests are very sensitive to test conditions, such as lateral pre-stress for example, and different approaches for bearing

Journal of Physics: Conference Series **2265** (2022) 032039 doi:10.1088/1742-6596/2265/3/032039

strength calculation are possible, it is clear that full comparability cannot be guaranteed, as not all of these test parameters were publicly available.

Depicted is the comparison of three metal alloys: aluminium 2024-T3 (Al), steel 1.4310 (St) and titanium Ti-15-3-3-3 (Ti) with basic GFRP and CFRP laminates as well as hybrid laminates. These basic FRP laminates are composed of pure unidirectional (UD) 0°- and 90°-layups, quasi-isotropic (QI) (0°/90°/ ± 45°), cross-ply (0°/90°) and 60% 0°, 20% 90○, 20% ±45° (UD-dom) laminates. These layups are typically for their application-related use and therefore not completely identical base layups for hybridisation are considered.The basic laminates are combined with the metal alloys mentioned to create the hybrid materials. Combined are aluminium with GFRP, titanium with CFRP as well as steel with GFRP and CFRP. In doing so different metal volume fractions (MVF) are possible depending on the number of GFRP layers substituted for metal foils. All CFRP hybrids exhibit 20% MVF whereby the MVF varies for different GFRP hybrids, as denoted by the last number in the column label, e.g. 0° − 76 means 76% MVF.

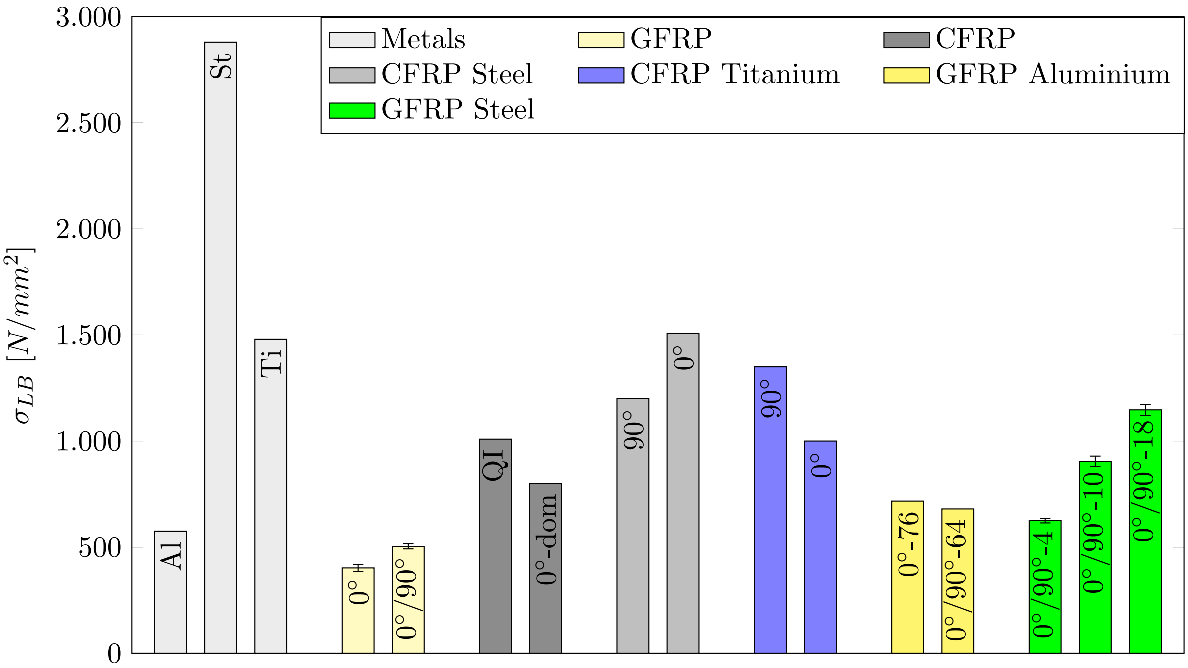


Figure 2. Bearing strength determined by AITM-1.00009 test procedure; Data metals: [4], data CFRP and CFRP-steel: [9, 4], data GFRP and GFRP-aluminium: [8], data GFRP-steel: [5]. MVF 20% for CFRP-steel and CFRP-titanium hybrids. MVF of GFRP-aluminium and GFRP-steel in series description; sample size N=3 for series with error bars

The test results show that the steel alloy considered is the metal with the highest absolute bearing strength, which logically leads to the highest σ_{LB} increase by steel hybridisation. Compared to CFRP, GFRP laminates show significantly lower values. A more balanced layup, including 90°- and ±45° plies, leads to higher bearing strengths than unidirectional 0° layups for GFRP and CFRP. At all, the scatter is in an acceptable range (maximum 3% for GFRP-St-0/90-10).

If GFRP base laminates are considered, the hybridisation by aluminium leads to an increase in σ_{LB} about 25-30%. However, relatively high MVFs are necessary (64% and 76%). Steel hybridisation of GFRP laminates requires smaller MFVs to achieve high bearing strength increases. For instance, an MFV of 3% increases σ_{LB} by 20% for the 0/90 GFRP basic laminate. Furthermore, if 10% of the original thickness are substituted, the static bearing strength of a 0/90 laminate increases by about 80%, while the weight only increases by 25%. This means an identical strength could be achieved by a fibre metal laminate that has only 12.5% thickness. In comparison, the hybridisation of the CFRP QI-layup shows an increase of 33% for steel and for hybridisation by titanium an increase of 25%, both for 20% MVF.

Considering the material costs and an increased manufacturing effort with more metallic layers, GFRP hybridisation by steel is assumed to be more feasible and leads to lower costs than hybridisation with aluminium, as the required metal content is clearly lower.

3.2. T-joint subcomponent demonstrator

A test set-up is developed for static and fatigue tests on subcomponent level as shown in Fig.3. It is composed of the specimen (either GFRP or hybrid), a metallic frame representing the joining partner and the T-bolt consisting of bolt and barrel nut. A connection between the test machine and the metallic part or specimen is established by hydraulic clamping. The specimen dimensions are w = 250 mm and l = 600 mm with a threaded bolt or barrel nut of D = 50 mm and a longitudinal bolt of D = 33 mm in a drilled hole of 40 mm diameter. The frame is necessary to allow tightening the length bolts with a preload of 338 kN or 395 N/mm2.

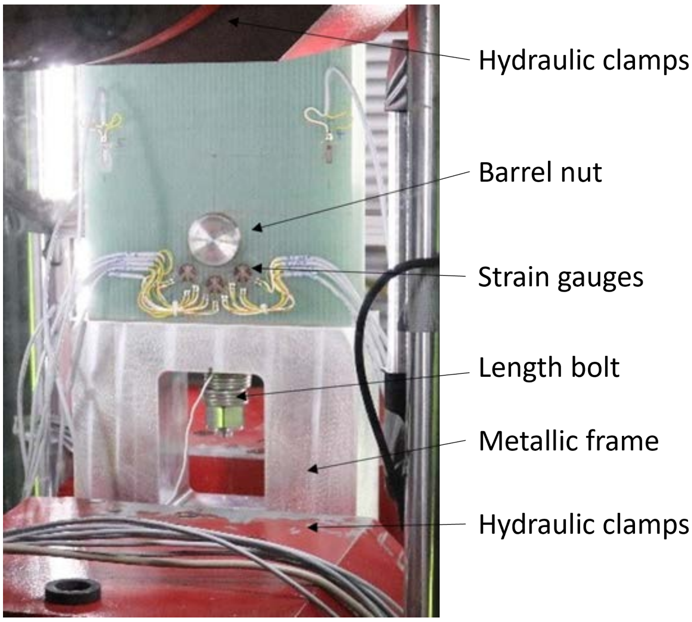
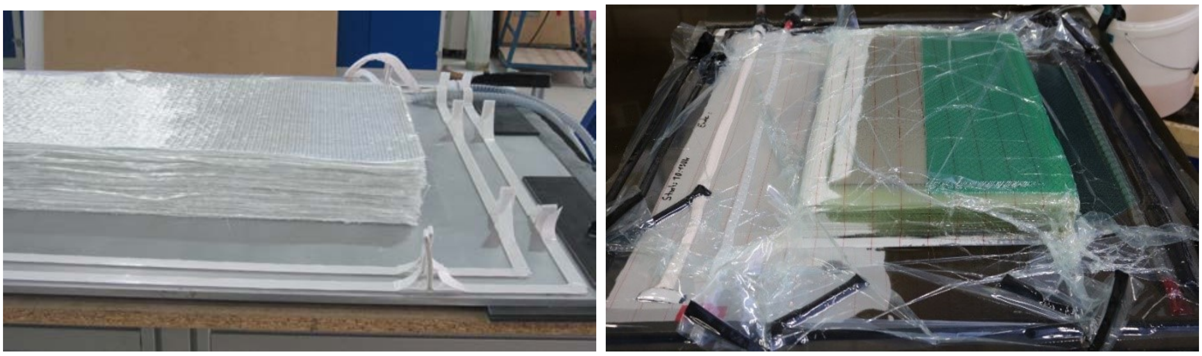


Figure 3. T-joint demonstrator test set-up

For both GFRP and hybrid specimens, vacuum resin infusion, the common manufacturing technique for rotor blades, is considered. The layup of the monolithic GFRP specimen consists of a total of 80 layers, 25 of which are biaxial, and 54 Saertex triaxial fabrics (areal density 812 g/m^2 / 1217 g/m^2). In Fig.4(a)(a) a stack of dry plies is depicted. Layup is carried out by hand and an overall laminate thickness of t = 60 mm is achieved. Figure 4(b)(b) shows the vacuum assembly.

Firstly, curing takes place at a temperature T=45° for 12 hours using Airstone epoxy resin 880E and hardener 886H. Then tempering is performed for 5 hours at 80° in an oven. After curing, holes are drilled for the bolt and the barrel nut, the latter with a diameter of D = 50.1

mm leading to 0.1 mm clearance. Then the distances from the bolt to the edge are w/D = 5 and e/D = 1.5, whereby e is the distance to the front edge.



(a) Stack of dry fabric (b) Resin infusion process

Figure 4. T-Joint laminate manufacturing by resin infusion

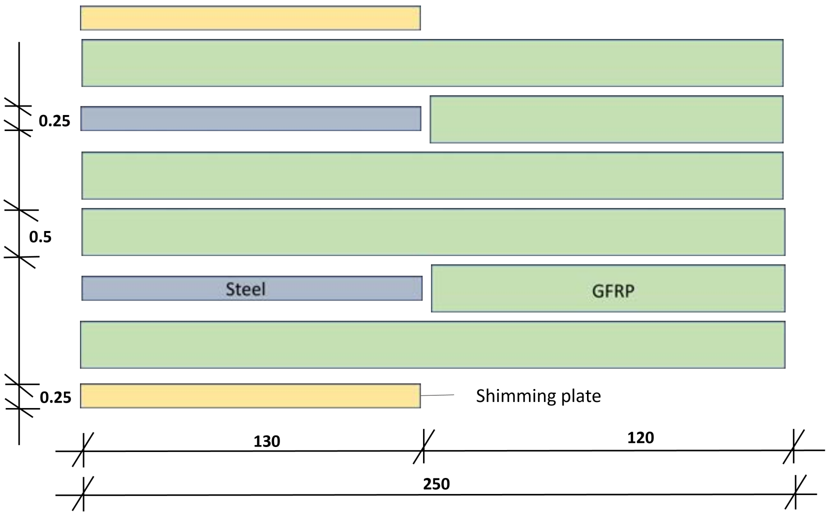
One hybrid specimen for testing with MVF = 3.3% is manufactured. This MVF is achieved by adding 8 metal foils made of austenitic cold rolled spring steel 1.4310, each with a thickness t = 0.25 mm. Pretreating the steel foil is necessary for adequate adhesion. Firstly, vacuum grit blasting is carried out in order to remove the contaminated oxide layer followed by a sol-gel process to build a new reactive surface as described by Stefaniak [15]. As the hybrid specimen should be of the same thickness as the GFRP specimens, two biaxial GFRP layers were removed. The specimen edges are cut by water jet and the holes are added by milling. The steel foils are positioned only in the outer regions of the laminate, where the barrel nuts are supported. Therefore, milling through metal layers lengthwise is not required as depicted in Fig.1. However, the barrel nut hole must be milled through the full thickness of the laminate.

The infusability of the full stack containing steel foils and dry GFRP plies must be guaranteed. Preliminary investigations showed that the resin was distributed inadequately between the steel layers. Because of this, the biaxial GFRP layers underneath the steel foils were replaced by an internal flow aid based on biaxial GFRP with a lower areal weight (533 g/m^2), which supports the resin flow. Thanks to this small layup adjustment, full infusability of the hybrid specimens for small (3%) to medium metal contents (18%) was achieved.

The tests are conducted displacement-driven at 1 mm/min. At a distance of 3 mm around the hole, the strain in specimen length direction is measured by a strain gauge. This is required to identify the local stress-strain relationship in the vicinity of the hole, as identifying local failure behaviour solely via the global force-displacement curve may be inconclusive.

3.3. Transition zone fatigue tests

The fatigue tests are conducted force-driven in accordance with ASTMD 3479D/3479M-12 Procedure-A [16] with a frequency of 1 to 2 HZ and a load ratio of R = 0.1 in a tension-tension regime. Tested are monolithic GFRP and hybrid specimens with and without TZ and a length of l = 250 mm and width w = 25 mm. Load introduction elements of length 50 mm made from GFRP are applied leading to a free length of l = 150 mm. The GFRP reference layup consists of six biaxial layers $[\pm 45°]_{3S}$. A hybrid reference is made by completely substituting two ±45° plies with steel foil leading to $[\pm 45°, St, 45°, \pm 45°]_S$. In doing so, the requirement on symmetrical specimens leads to a minimum of two substituted layers, which is an MVF of 25% in the hybrid area. By partly substituting the hybrid, TZ specimens are created with an internal steel drop-off as sketched in Fig.5(a). A sudden change of stiffness between the materials occurs here, which leads to a stress inhomogeneity. In the GFRP region specimens have a thickness of t = 3.1 mm and the hybrid region t = 2.65 mm, which would lead to an eccentricity in the TZ specimens. To avoid this eccentricity, shimming under the hybrid area during vacuum infusion is necessary as depicted in Fig.5(a). This thinning of the cross section leads to an increase of the stress concentration in the TZ area



(a) Sketch of TZ layup in mm

(b) Photographed specimens in top view

Figure 5. Manufacturing and finished hybrid TZ specimens

Fig.5(b) shows three TZ specimens after manufacturing. The areas with brighter colours show the monolithic GFRP and the darker areas the hybrid. An initial deformation in the TZ specimens can be identified, which was induced from the difference in the thermal expansion of the monolithic and hybrid regions during the curing process. This curvature is balanced during testing by application of the tension preload (R=0.1).

4. Results and discussion

4.1. T-joint demonstrator

The stress-strain relationship of all specimens is highly nonlinear from the beginning. A first load drop (onset) occurs from which the load can be increased again until the point of total failure (max). Table 4.1 shows the failure loads of the static tests with the demonstrator part and two GFRP reference specimens. The stress is calculated by the force and the supporting net cross section, which is supporting the barrel nut. The determination of the stress in the contact area σ might be accompanied with uncertainties in measuring the correct net cross section in the range of 1-2%.

Considering the reference specimens, the average stress at onset of damage behaviour is σ_{onset}=260 N/mm^2 with about 5% difference between both specimens. Ref. 1 reaches a value 25% lower than Ref. 2 at maximum stress σ_{max}. The hybrid specimen exceeds the average σ_{onset} by about 33% and σ_{max} by about 15% compared to specimen Ref.2. As the beginning of irreversible deformation limits the permissible loading of a wind turbine, the onset value is assumed to be more relevant. Of course, the sample size is too small here to identify a reliable

Table 1. Static tension test results of T-joint demonstrator

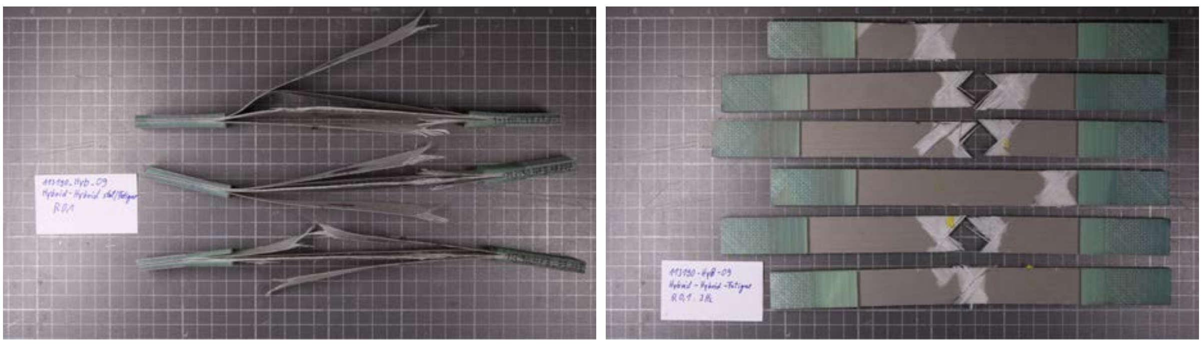
	Ref.1	Ref.2	Hybrid
σ_{onset} in N/mm^2	273	247	387
σ_{max} in N/mm^2	273	264	421

joint strength or coefficient of variation, but the investigation gives an indicative value of the increasing effect of steel layers in T-Joints.

Looking at the root joint as a whole, the longitudinal bolts tend to show failure first and are limiting the load carrying capacity. Assuming the 33% higher load carrying capacity of the hybrid laminate can be used to increase the number of barrel nuts and length bolts by a third as well, this could help to create longer and more slender blade designs. However, failure types for reduced distances must be investigated and net section failure must be avoided, as this will immediately lead to catastrophic failure. Another aspect is the impact of the root section stiffness on the loading on the bearing rings inside the hub. Higher stiffness tends to lead to decreased deformation and loads, which could extend the lifetime of the bearing rings. Further manufacturing issues have to be considered when deciding how hybridisation could be incorporated into today's blade manufacturing processes.

4.2. Transition zone fatigue tests

The monolithic specimens fail for the free length in the static and the fatigue load case with an identical intralaminar failure type. In the TZ specimens the steel drop-off can clearly be identified as the failure position, as the specimens are separated here for both static and fatigue loading. The full hybrid fatigue specimens (Fig.6(b)) show a similar failure type to the monolithic GFRP specimens: intralaminar failure occurs in the GFRP plies and the steel layers show separation at the same position. After the static full hybrid tests, the specimens show delaminations between steel foil and GFRP (Fig.6(a)), whereby the GFRP layers themselves show a failure type similar to the monolithic specimens. Although plasticity can be observed in the steel foil, it is fully intact. Without further investigations to identify the failure process, it is not absolutely clear whether the failure type of hybrid static and fatigue tests is identical and can be used for evaluating an S-N curve. In this case, validity is assumed and all specimens are considered for evaluation.



(a) Static test (b) Fatigue test

Figure 6. Failure types of full hybrid specimens

The S-N plot in Fig.7 presents all monolithic GFRP static and fatigue test results, full hybrid and partly substituted (TZ) laminates. Engineering stresses are calculated by measured cross sections and maximum forces. The smallest cross section for TZ specimens is considered. A double logarithmic Basquin fitting is used to achieve linear trend curves. In all the fatigue tests, a reduction in the stiffness of the specimen was observed with fatigue cycles. The full hybrid laminate shows the highest values leading to a curve with an inverse exponent of m = 16.6, considering all values. After $N = 10^5$ a change in the test data can be observed and the data points show a much steeper decrease. This means the linear approach might not be applicable for evaluation However, no change in the failure behaviour can be observed in the related specimens (Fig.6(b)) . The damage growth seems to accelerate from load cycles after $N = 10^5$.

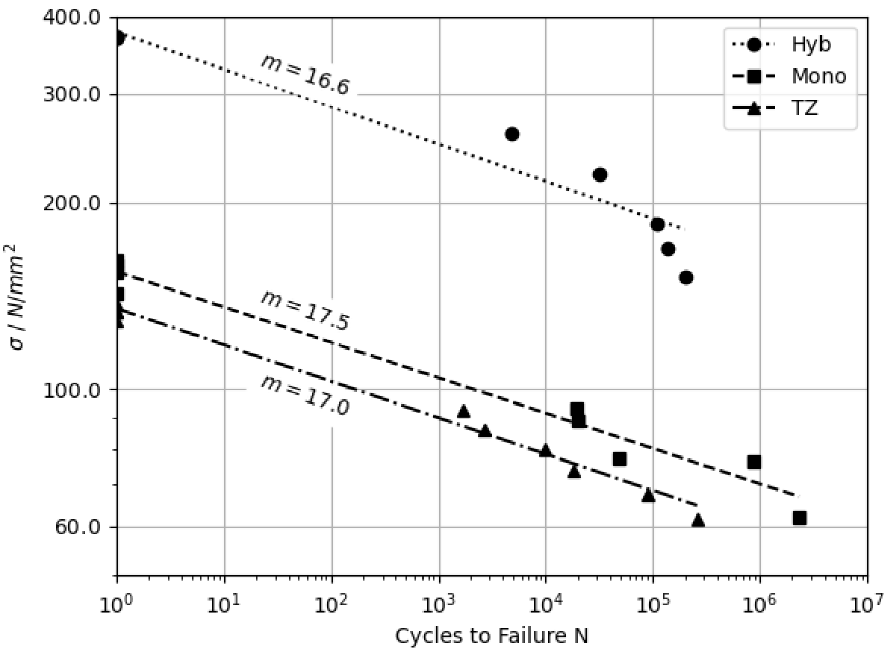


Figure 7. S-N-curves of monolithic GFRP, full Hybrid and partly substituted hybrid laminates with transition zone TZ

The exponent m = 17.5 for monolithic GFRP seems to be relatively high in comparison with literature values. It must be considered that the layup is composed of ±45° plies only, which makes the specimens very compliant. The part-substitution with TZ produces the curve with the lowest achieved stresses, whereby the decrease from GFRP varies from 15% in the static case to about 18% at $N = 5 * 10^5$. Therefore, m = 17 is close to the slope of the monolithic GFRP. Unlike with the full hybrid, a change at $N = 10^5$ cannot be observed.

The tests reveal the strength decrease by the discontinuity of the steel foil drop-off for TZ specimens. Although absolute values lie clearly below the references, fatigue loading does not lead to an earlier total failure than specimens without a TZ. Extending test data in the very high cycle regime at $N = 10^5$ would be useful to consolidate this assumption. It must be noted that the coupon samples only reflect the real structure in a very simplified way. Thicker laminates with lower MFVs, which are less affected by the geometry, should be investigated.

5. Conclusion

Presented were investigations on the joining strength of a T-joint demonstrator, which showed a clear strength increase (+33%) if 3% of GFRP is replaced by steel foil. For such low metal contents (3-18%) an adequate infusability quality for thick laminates was achieved with negligible changes made to the layup. The hypothesis is made that the higher strength of the laminate can be used to increase the number of fasteners in the root section by decreasing distances between the fasteners. This would lead to a higher load carrying capacity, while the roots diameter can be kept constant. Hence, higher bending moments could be transferred, and blades be increased in length. To validate this hypothesis, additional investigations are necessary to focus on the transferability of the results to a structural level and especially, to guarantee a bearing type failure under static as well as fatigue.

A drawback was identified during the experiments on the TZ. The steel foil run-outs lead to a clear decrease of the static and fatigue resistance. The conclusion can be made that this area could be a weak spot under fatigue. However, it must be borne in mind that testing with standard related coupon specimens allowed only a relatively high MVF (25%) and that the stress decrease could be much lower with moderate MVFs. More detailed investigations are necessary with more representative specimens for a better understanding of the failure causes and to identify compensatory methods.

Acknowledgments

The work presented in this paper was funded by the Federal Ministry of Education and Research of the Federal Republic of Germany under the project "HANNAH - Challenges of the industrial application of nanomodified and hybrid material systems in rotor blade lightweight construction" (Grant No. 0324345C).

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