Fatigue of composites for wind turbines

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Abstract

The size of wind turbine rotors has increased in the past decade from 40 m to more than 120 m diameter. The resulting mass of about 18 tons per rotor blade causes high bending moments at the inner part of a blade due to the gravitational loads. More than 10^8 load cycles will happen in the prospected lifetime of 20 years of a turbine. During this time the rotor blades are exposed to various hostile conditions such as extreme temperatures, humidity, rain, hail impact, snow, ice, solar radiation, lightning and salinity. In order to withstand these external conditions without diminishing the safety a sound knowledge of the fatigue behaviour of the material and structural properties is needed. To meet the upcoming requirements the paper will highlight some fatigue and lifetime aspects on wind turbine rotor blades made of composite materials. This includes an historical part in connection with glider technology, the presentation of relevant S-N curves not only for the 0°-orientated fibres representing the spar cap but also for ±45°-lay-ups in shear web and shell, the influence of fibre content and architecture, of environmental effects, a view on lifetime prediction on structural elements as well as on present and future work.

Key Words: Fatigue, composites, rotor blades, wind turbines, lifetime prediction

Introduction

Wind energy is a fast growing market worldwide. For higher efficiency, the size of the today's commercially erected wind turbines increased rapidly [1]. An installed power of 5 MW featuring a 126.5 m rotor diameter is realized. Figure 1 gives an impression of the size of a modern rotor blade. Additionally, future wind turbines will be installed offshore implying that the inspection of the blades, which in most cases are made of GFRP (Glass Fiber Reinforced Plastics), will be more difficult. Thus, they should be designed as safe as possible to withstand the fatigue loads and hostile environment over the whole time.

The fatigue design of a rotor blade has to be in agreement with the design requirements as described in the IEC-61400-1 ed 3 [2] or in the widely accepted national recommendations from e.g. the GL (Germanischer Lloyd). Although much information exists about the micro- and macro-damage mechanisms of the fibre reinforced materials applied in rotor blades at the very moment, it is not easy to transfer this valuable knowledge onto a full scale structure for the certification process. Thus, the paper will rather focus on the information which is achieved on the basis of constant and variable amplitude loading of specimens with the relevant material and the possible impact on the lifetime.

Historical aspects

Composite materials such as GFRP were applied in highly loaded structures like sailplanes and wind turbine rotor blades already in the middle of the fifties. The first aeronautical application of GFRP was realised interestingly 1955 in the fuselage of the LBS 2-glider a design of Professor Tsuyoshi Hayashi who was the first president of the Japan Society of Reinforced Plastics [3]. This work was followed two years later by two other pioneer constructions in Germany. Dr. Ulrich Huetter at Allgaier in Germany designed the first rotor blade in GFRP for the two-bladed 100 kW W 34 turbine (34 m diameter) [4]. For many years, these two blades were the largest primary structures made of GFRP. In the same year also the first full GFRP-glider “Phoenix” designed and built by Dr. Richard Eppler and Hermann Naegele had its maiden flight [5]. U. Huetter and R. Eppler were later appointed professors at the Stuttgart University for aircraft construction and engineering mechanics, respectively.

Rotor blades and sailplane wings show various similarities and joining aspects which make them comparable and allow to take advantage of synergetic effects. In both cases the composite material is normally laminated in similar technologies with room temperature (RT) curing matrix systems. The structures are slender, the aspect ratio varies between 15 and 30. Both structures feature spar beams against out-of-plane bending loads and a torsion shell also forming the aerodynamic shape as depicted in the examples in Figure 2. The spar beam illustrated in the glider wing is optimised against out-of-plane bending. This design is often used also for rotor blades. The “C-“spar shown of the rotor blade in Figure 3 is another possibility of spar design which offers the possibility of a larger moment of inertia against lead lag bending compared to the box-beam in the glider wing.

The historical view shows that certification requirements related to fatigue design were not developed before series production of the composite structures was started. That took place for sailplanes in the middle of the sixties with the establishment of specific service life programs. For the rotor blades similar requirements appeared much later. Thus, in the beginning of rotor blade production in composite technology in Germany, many engineers were recruited from the “Akafliegs” (acronym for Akademische Fliegergruppe or academic flying group) where the former students had learnt the composite technology during their own design and building of sailplanes. This was also the case in the development of the 100 kW wind turbine of 25 m diameter, the DEBRA 25 which started in 1981 at DLR in Stuttgart. This may serve as an example that glider technology was the basis for the development of an ambitious rotor blade design.

Fatigue design of the DEBRA 25 rotor blade

An 11.6 m GFRP rotor blade was developed which was divided into two parts of equal length. For the load introduction at the blade root and the connection of the two halves, the so called T-bolt connection principle was applied (for the first time at GFRP). The resin system L20/SL from Bakelite was used for laminating the glass fabric, since for this material combination, the static and also some fatigue properties at R=-1 were known from the various sailplane designs and from other sources and tests [6]. Because of the lack of experience about the possible fatigue behaviour of the resulting light weight design a service life program was developed on the basis of U. Huetter’s load assumptions [7], see Figure 4. By means of the linear Palmgren-Miner rule and the Goodman diagram derived from the fatigue data, additionally a reduction of the prospected $4*10^8$ to about $4*10^4$ load cycles was performed by increasing the load ranges, accordingly. The service life test was then successfully carried out in the DLR-laboratory via a 1000 kN hydraulic jack and a wiffle tree, see also Figure 5. The maximum strain measured in the area close to the load introduction of the middle section at design load was about 0.65 %. This high strain corresponds very well to the design allowables in sailplanes is, however, about twice as large as admitted later by the authority for rotor blades. The test blade survived the static test load of 1.75 times of the ultimate design load without any detectable damages. The DEBRA 25 wind turbine itself was then erected and commissioned at the former DLR test site at Schnittlingen in South Germany near Stuttgart and in operation from 1984 until 2003. An impression is shown in Figure 6. The rotor blades are still in good order. The operation was stopped merely because the owner has installed a commercial MW-turbine, and the building authority did not permit the operation of both machines at the close distance. It is now planned to dismantle the DEBRA 25 and to perform an extensive investigation program on the blades which includes not only a residual strength test but also the establishment of S-N curves of the conditioned material (including the possible influence of the gained humidity) cut out from selected parts of one blade in comparison to specimens from the original test blade which was stored over the years in dry conditions.

These results will be of special interest as in the meantime many fatigue tests with laminates of the same combination of resin and glass fabric but with coupons of laboratory quality have been carried out. Furthermore, the design strain, the material, and even the T-bolt connection used in the rotor blades of today's Multimegawatt turbines are comparable and thus, the results will be extremely valuable for the improvement of the commercial turbines.

Establishment of fatigue data bases for 0°-orientated laminates

Fatigue investigations of numerous composite combinations were started within European Commission research programs in the middle of the eighties [8, 9] and also in national programs which resulted e.g. in the FACT data base of de Smet and Bach [10] and the DOE/MSU data base of Mandell and Samborsky [11]. These were especially tests on glass fibres with epoxy matrix (Gl-Ep) and with unsaturated polyester (Gl-UP). The fibre orientation was dominated by 0°-fibres representing the load carrying spar caps. An example for the S-N curves of Gl-Ep at stress ratios of R = 10, -1 and 0.1 is shown in Figure 7. The results are presented as curves of 95 % survivability and 95 % lower confidence limit following the common certification rules for wind turbines. The slopes are between k = 9 and 11 for Gl-Ep and for Gl-UP as well. Thus, in the case that the fibre content is not too high a slope of 10 can be applied for both material combinations. This is proposed e.g. in the GL-recommendations.

In the beginning of the series production of rotor blades, Gl-UP material was favoured by the manufacturers due to its relatively low price. In the mean time and with the growth of the rotor blades, Ep becomes more interesting. The main reason is the lower shrinkage (3 %) of Ep compared to UP (6 %) and the slightly higher thermomechanical properties. Disadvantages such as allergic reactions of staff members can be avoided by changing formulations, new production technologies such as RIM (Resin Infusion Moulding) and/or other protection means [12].

The influence of fibre content also in combination with the architecture of the fabric was investigated in detail by Mandell, Samborsky and Sutherland [13]. The example in Figure 8 for various laminates shows clearly an increase of the slope (reciprocal value of coefficient b) in the range of 39 and 60 Vol% whereas unstitched laminates can have higher fibre contents. Manufacturers applying technologies such as RIM producing relatively high fibre contents should keep this in mind for their fatigue evaluation.

Fatigue of ±45°-orientated GFRP-laminate in the shear web

The web of a spar beam has the function to transmit the loads between the spar caps via shear. Necessarily the fibre direction of this highly loaded spar component must be oriented ±45° and it is important to have an eye on its fatigue properties. For simulation, torsion fatigue tests were accomplished with tubes having a ±45° lay-up, see also Figure 9 for the dimensions.

Figure 10 shows the difference in the fatigue behaviour between plain fabric and twill which has less undulation than plain. The diagram demonstrates distinctly the advantage of twill having a lifetime which is orders of magnitude higher compared to the results with plain fabric tubes [14].

The shear investigations with the tubes were originally carried out for the purpose of lifetime prediction of sailplanes [15]. In Figure 11, S-N curves are presented in fibre strain versus log N for Gl-Ep torsion tubes with plain fabric at R = -1 and R = 0.1. The fibre volume content of the hand-laminated tubes was about 38%. New studies at tubes are being carried out within the current EU project OPTIMAT BLADES (OB) [16] with a stitch-bonded fabric from Saertex Company. The cloth is wound several times under ±45° on a mandrel with an overlap of about 10 mm. The lamination process is carried out by RIM technology. Thus, the resulting fibre content is relatively high (about 61 %). First results at R = -1 are plotted in Figure 11 compared with plain fabric. Surprisingly, the results are relatively close to the R = -1 curve. An explanation may be that the high fibre content, which according to [13] is disadvantageous, is compensated by the fact that the laminate has no or only a few undulation. The presentation in strains along the 45° fibres was chosen because the shear stresses are not comparable due to the different fibre contents. Also the shear-moduli deviate significantly one from another with 10 GPa for the plain fabric and 14 GPa for the OB-material. A reason for this fact is beside the different fibre content also the less stiff behaviour of the plain fabric laminate due to the undulation of the strands.

Unfortunately, all OB specimens failed by delamination of the whole overlap, visible e.g. in Figure 12. This could be referred to the relatively steep drop at the end of the overlap. An improvement was achieved by tapering the overlap, see the marked test result in Figure 11. The delamination zone at the tapered overlap was reduced significantly, see Figure 13.

Fatigue of ±45°-orientated GFRP-laminates in the shell of a rotor blade

The shell of a rotor blade in general obtains a ±45° dominated GFRP lay-up for torsion stiffness. This is not fatigue-critical for loads in flapwise direction, because the bending spar is designed to bear these loads without loosing stiffness significantly. Thus, the loads onto the ±45° laminate of the shell are deflection-controlled and due to the low strains applied, a possible stiffness degradation will be without consequences on fatigue. But for lead lag loading, a spar like it is shown in Figure 2 has only a relatively low stiffness and the shell must bear the main part of the loads which here are load controlled. Figure 14 shows S-N curves for tensile loaded ±45° Gl-Ep and Gl-UP material in comparison. The Gl-Ep material was investigated by the German research institutes DLR, BAM and IFB with respect to requirements in sailplanes to have an indication whether a certified resin can be exchanged against a new one. The lowest curve was achieved with a resin system which is very similar to the L 135 from MGS which is applied frequently in modern rotor blades. Although with a lower slope the curve is at a comparable level to the Gl-UP curve derived from [17]. The stiffness degradation measured for the load controlled Gl-Ep tests was up to 40%. It could be worthwhile for manufacturers to have this behaviour in mind when designing the shell structure of a rotor blade, since the leading and the trailing edge have to endure a large repeated strain amplitude during there service life.

Lifetime prediction for a cap and a shear web of a spar beam

The existence of S-N curves for the cap and the shear web of a spar beam shown in the Figures 6 and 11 allows to compare their possible lifetime [15]. A common prediction method described e.g. by Echtermeyer et al. [18] is used. It is based on the linear Palmgren-Miner rule, the wind energy specific load sequence WISPER [19] and constant amplitude life diagrams derived from the relevant S-N curves. To be able to compare the lifetimes of the shear web and the cap materials against another, the lifetime prediction was accomplished for various maximum design levels which are normalised with respect to a maximum strain of 0.4 % in the UD-material representing the cap and a maximum shear stress of 85 MPa in the ±45° material in the web. It is obvious that for this case, the shear web is much more fatigue-critical than the spar cap. For gliders, this result is conservative, since they have normally twill instead of plain fabric in the web. However, in rotor blades nowadays often a resin infusion technique is applied producing a higher fibre volume content than in gliders. Then with correspondence to Figure 11 the lifetime prediction in comparison to the cap is not conservative.

Lifetime prediction models

For a more realistic lifetime prediction on the basis of wind speed distributions which are specific for wind turbine sites it is worth wile to apply also other models than the linear Palmgren-Miner rule. Amongst many publications, 2 interesting references are mentioned here because they report about tests with wind turbine materials. Nijssen et al. proposed to design a constant amplitude life diagram in the way that the lines of constant life are parallel to the N=1-line which connects the stress ratio radial closest to the abscissa with the static value [20]. Mandell reports about measurements which seem to confirm this assumption [21]. A benchmark activity within the above mentioned OB-project revealed that by application of the same model, the most severe influence is given by the Rainflow counting algorithm and the constant-life diagram. These process-steps can increase or reduce the predicted lifetime decisively and can affect the results more than the application of a different physical model [22]. For the lifetime prediction under multiaxial stress which is also a main feature of the OB-project, an interesting model is proposed by Philippidis and Vassilopoulos [23].

Environmental effects

Environmental effects such as humidity and impact by hailstone have been investigated at the same Gl-Ep as shown in Figure 7 [24]. The laminate was exposed at 90 % relative humidity up to saturation. The weight gain was 0.4 to 0.5 %. Some laminate plates supported on the rear side with PVC-foam were also impacted with ice balls of 20 mm diameter with a velocity of about 100 m/s. The cut-out specimens were then subjected to fatigue tests at R=-1. The results are presented in Figure 16. In contrast to the hailstone impact, the humidity has a significant influence on the fatigue behaviour of the material. At strain levels of 0.8 % and more, the load cycle number is reduced by more than order of magnitude. However, at 0.6 % the fatigue life is still higher than that of the dry specimens. This may be explained with the less brittle behaviour of the humid matrix compared to the dry one whilst at higher loads microbuckling is responsible for the earlier failure.

Fatigue of CFRP (Carbon fibre reinforced plastics)

For the application in large commercial rotor blades CFRP could be an alternative to GFRP, since it is much stiffer and lighter. However, the introduction is hampered by several reasons. On the one side the manufacturers hesitate due to the high price, although industrial fibres are in the meantime significantly cheaper than those certified for aerospace application. But on the other side, the manufacturing technology makes high demands on the production grade, especially thick laminates need high-tech quality. However with respect to future possibilities, the CFRP-application was investigated within an

EU project also with respect to the cost effectiveness [25]. Figure 17 shows the S-N curve for the industrial fibre Panex 33 with an epoxy matrix at R=-1 demonstrating that it can compete with the fatigue properties found for an NF12-epoxy material described in [6]. The slope of these two curves is about 25 showing that CFRP is much less fatigue-critical than GFRP.

Fatigue of load introductions

It was already mentioned that in the DEBRA 25 the T-bolt (or IKEA-) connection principle was realised for the first time at GFRP [7, 26]. Figure 18 shows how the two halves of the divided blade were reconnected. Numerous blade designs meantime have applied this connection system successfully, see e.g. [24]. Another connection system is the stud connection principle. A cross section is presented in Figure 19 [25]. For both systems, the steel studs have to be pre-stressed in a manner that no loose state can happen at the maximum compression load. At all tests known it were nevertheless the steel studs which failed when the design and manufacturing technology were sound. In these tests multiple of the expected 20 years lifetime were simulated.

Conclusions

A review was given on fatigue aspects of fibre reinforced plastics used in wind turbine rotor blades, exemplary on the DLR DEBRA 25. This material may serve as information for a safe fatigue design. Special attention should be given, however, in the design and production process of rotor blades to the experience that

- high fibre contents may lead to a steeper slope of the fatigue curves,
- a shear web may be more fatigue-critical than a spar cap and
- stiffness reduction in the leading and the trailing edge may occur when the lay-up is ±45°.

CFRP shows highly interesting properties with respect to stiffness, specific weight and fatigue properties. However, technological problems and the price of the carbon fibres are still hampering reasons for a wider application. The T-bolt and the stud connections are two widely used load introduction principles in modern rotor blade designs. Here it is more the steel itself which is fatigue-endangered than the composite parts. In the area of lifetime prediction development it was shown that it is essential for a sound comparison of different models to apply the same Rainflow counting algorithm for each model.

Outlook

Many items still have to be solved. Currently the EU program OPTIMAT BLADES intends to increase the knowledge on fatigue on composites by investigations in the following areas:

- Variable amplitude loading including the establishment of a NEW-WISPER standard,
- Complex stress state,
- Extreme climate,
- Thick laminates and repair,
- Condition monitoring.

The results of the findings will be the basis for a revision of the present certification requirements.

But also other aspects still must be solved such as more information about the fatigue of

- Adhesives,
- Structural Components,
- repeated incoming inspection of semi-finished products (resin, fibres),
- new products etc.

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Figure 1: Size of the E 112 rotor blade in comparison to an Airbus 340 (photo courtesy A&R Rotec)

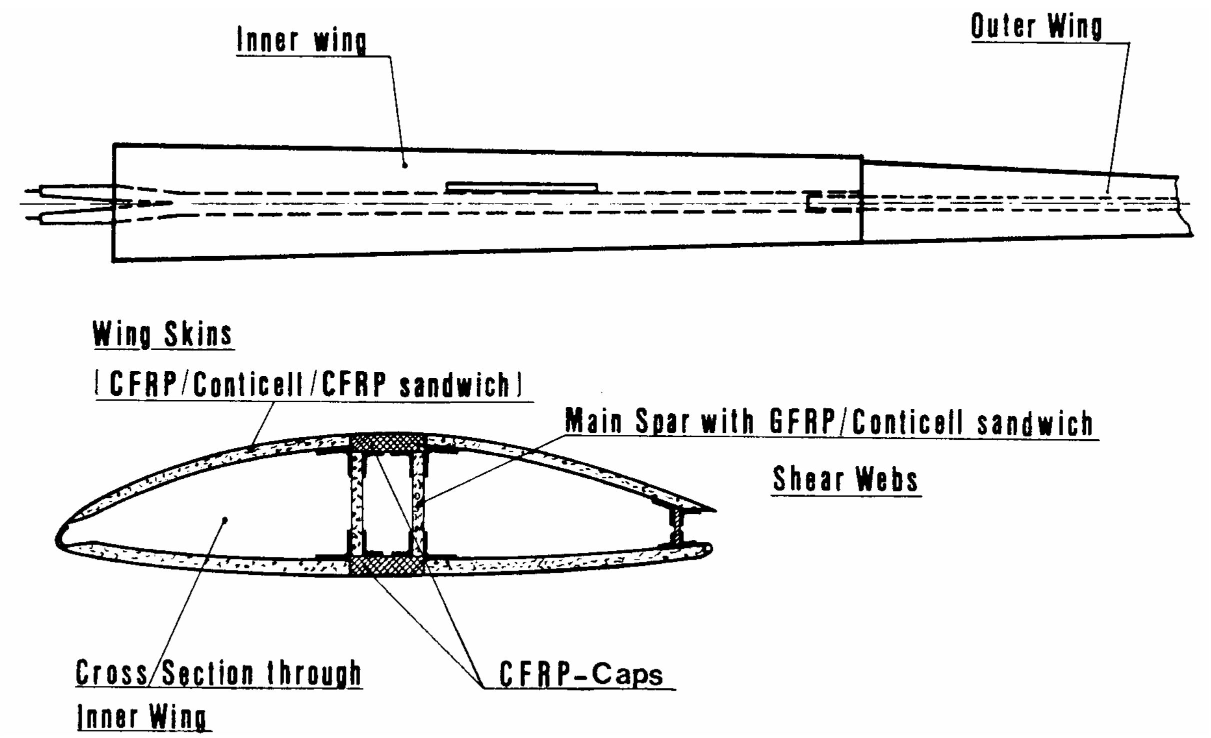

Figure 2: Structural details of a typical sailplane wing

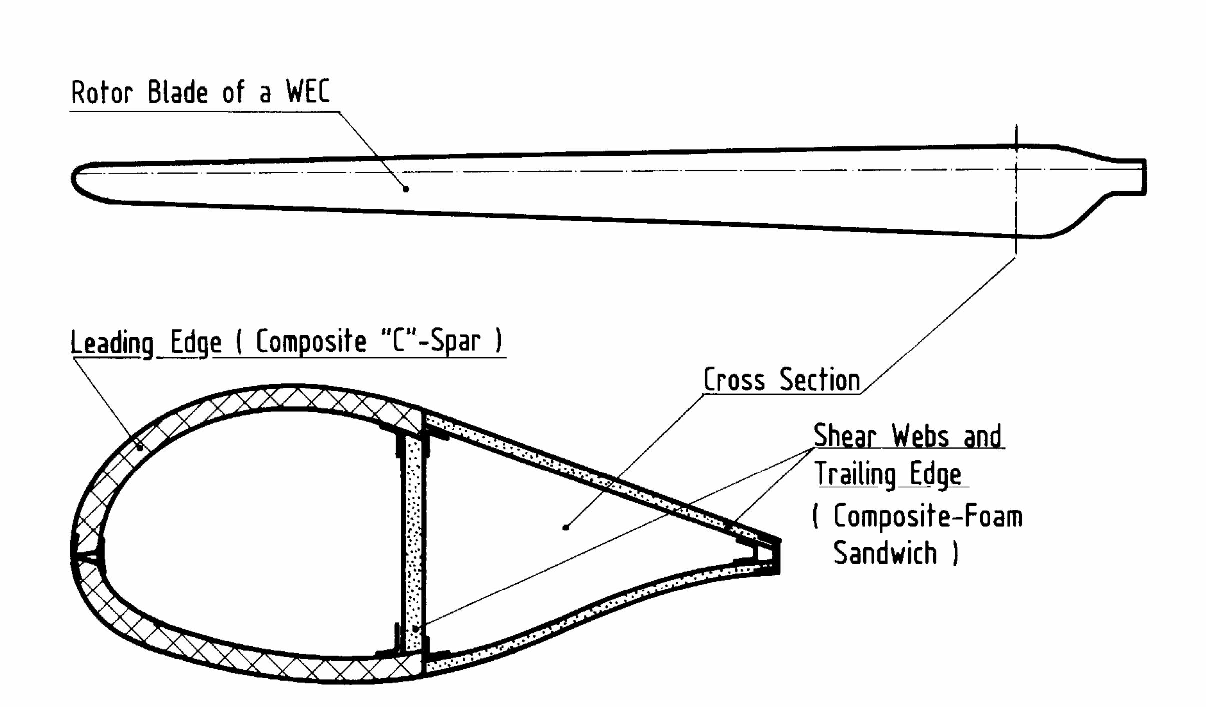

Figure 3: Structural details of a typical rotor blade

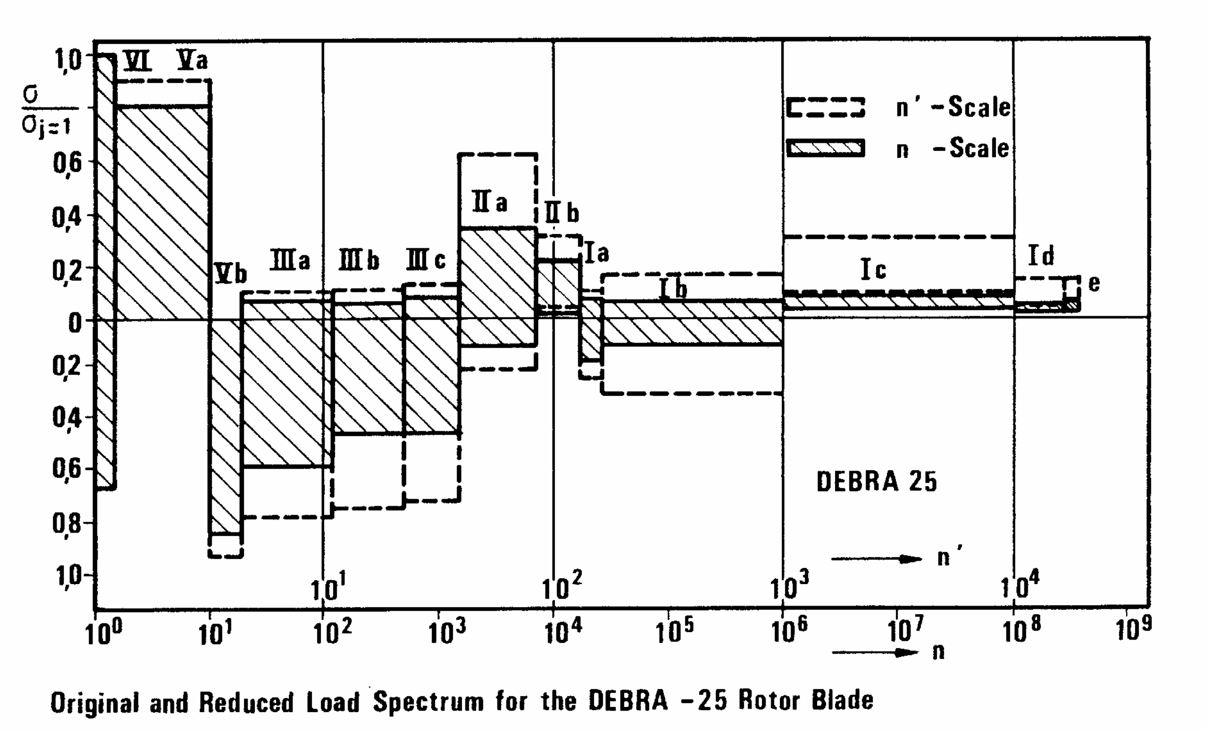

Figure 4: Service life program developed for the DEBRA 25-rotor blade [7]

Figure 5: DEBRA 25 blade in test bed for service life investigation

Figure 6: Debra 25 at the former DLR test site at Schnittlingen near Stuttgart

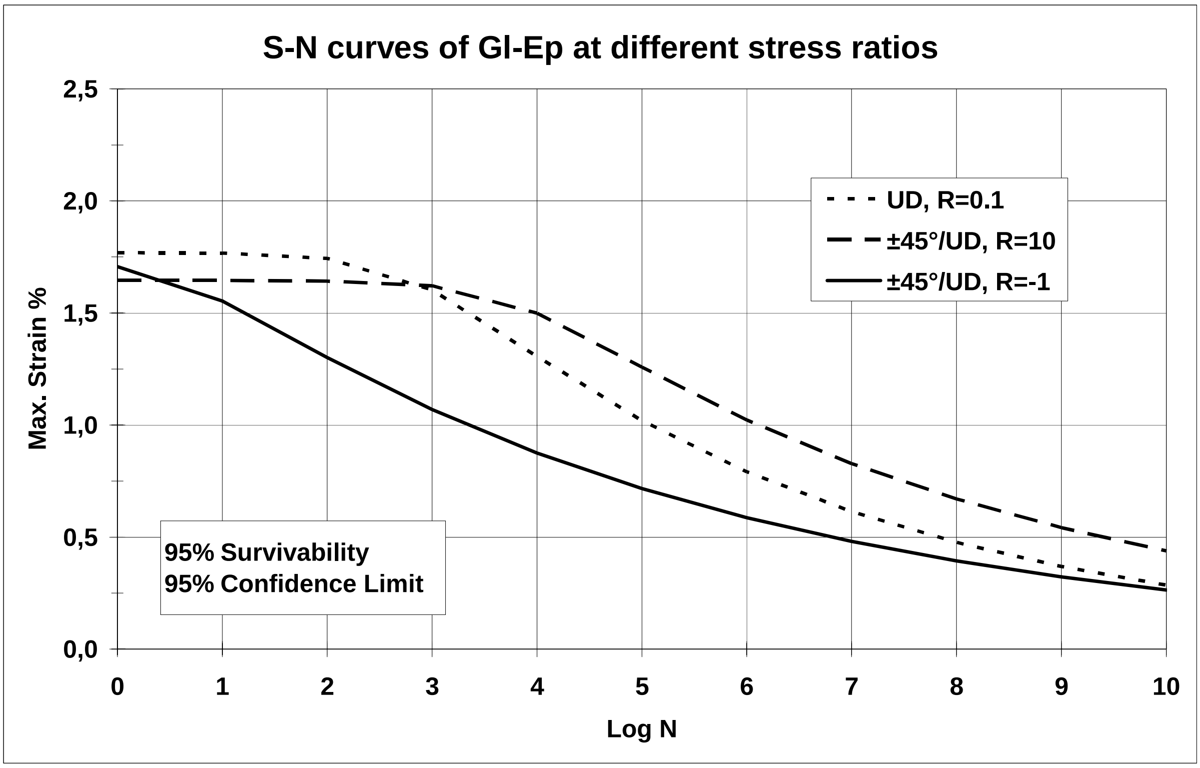

Figure 7: Example of S-N curves for Gl-Ep at different stress ratios [8]

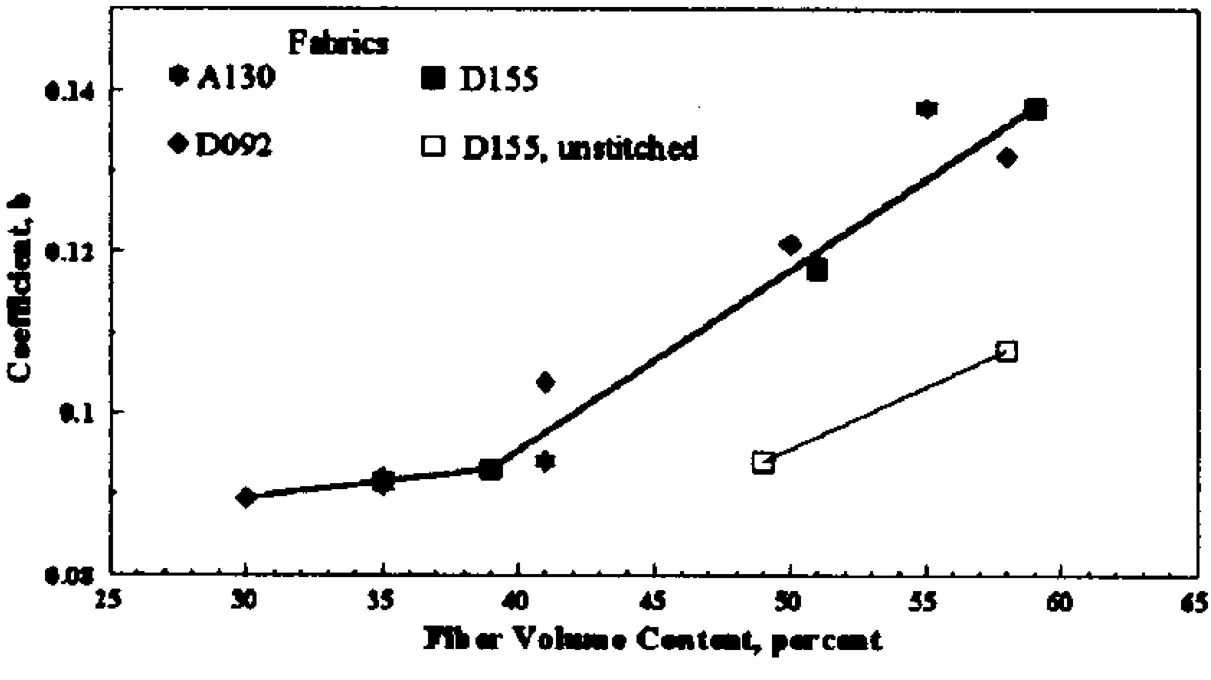

Figure 8: Influence of fibre content and fabric architecture on the slope of S-N curves [13]

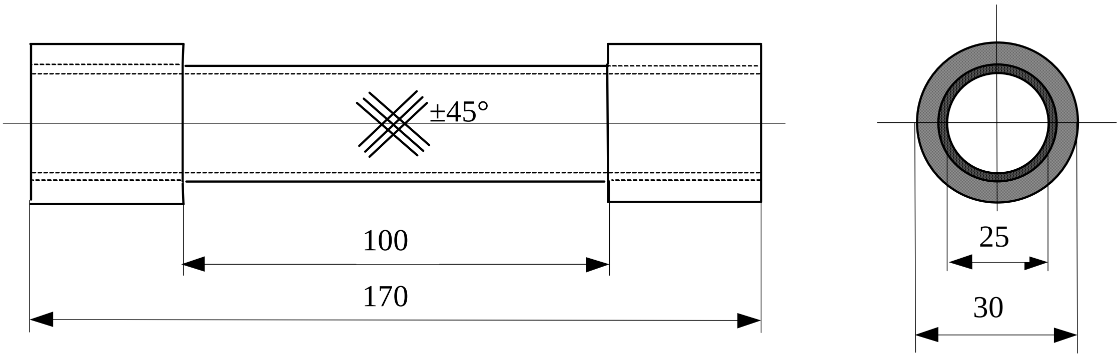

Figure 9: Geometry of ±45° torsion tubes

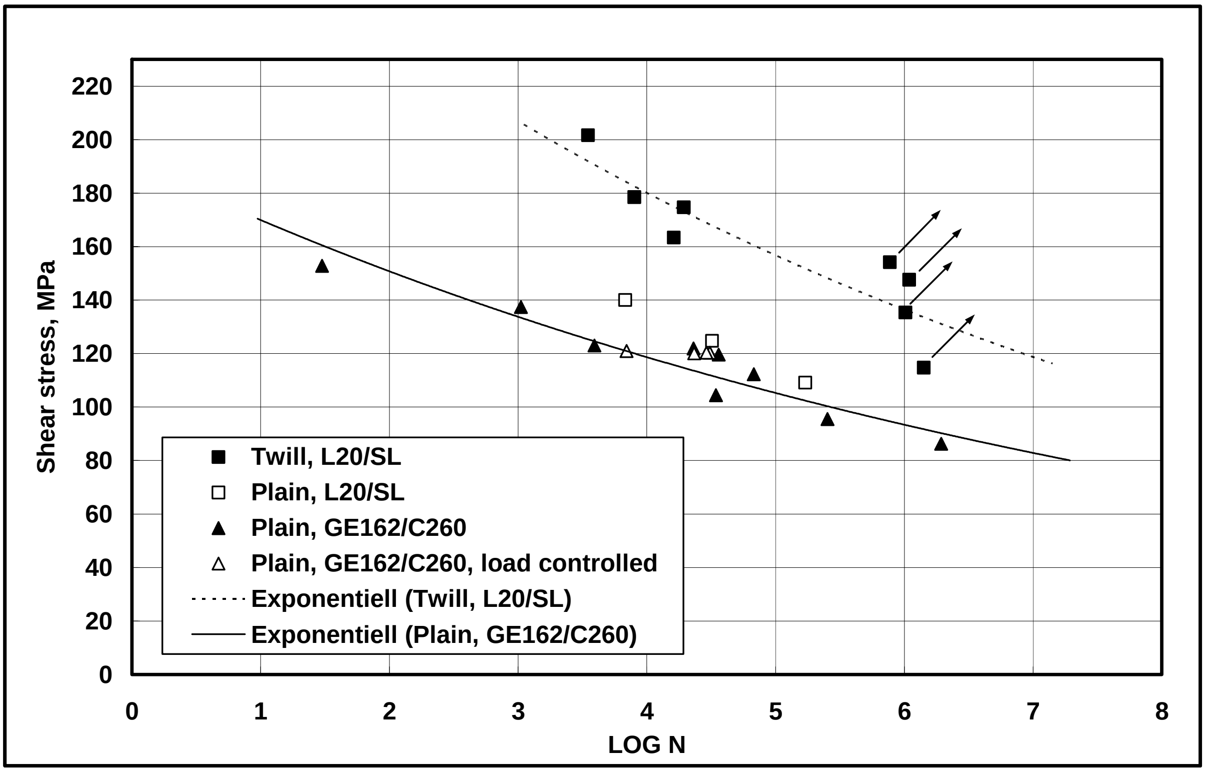

Figure 10: Fatigue behaviour of torsion loaded Gl-Ep tubes with different undulation, R=0.1 [14]

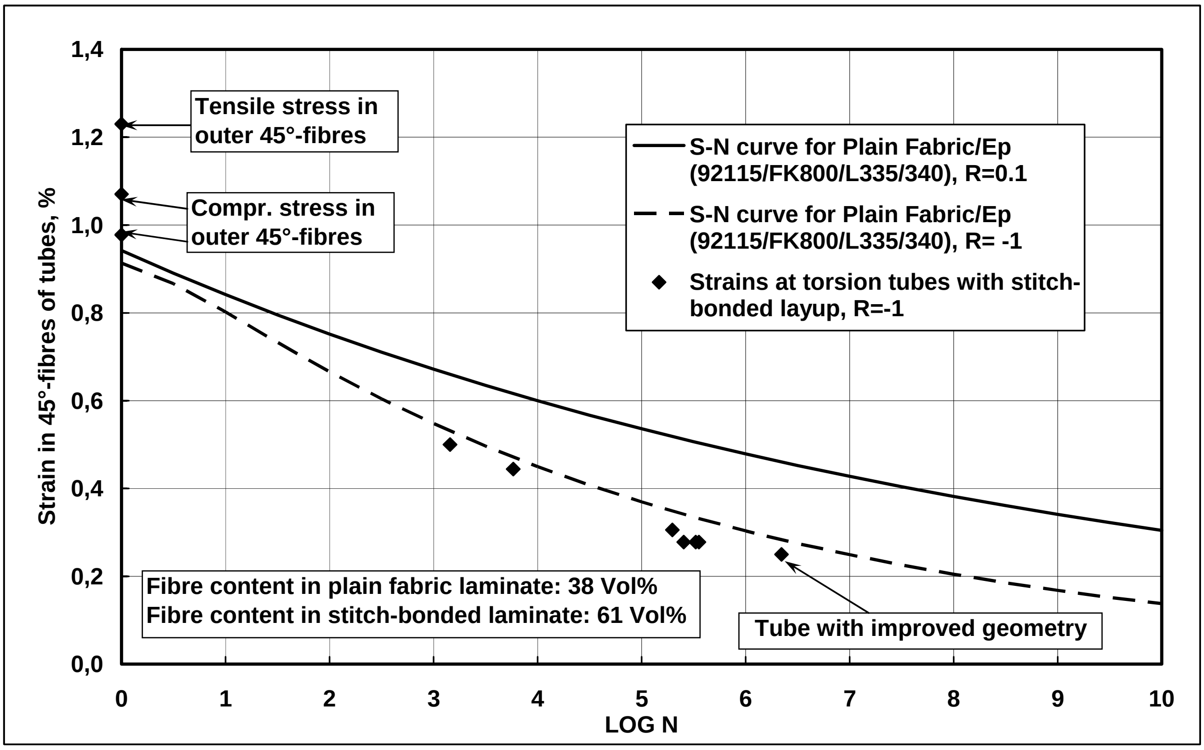

Figure 11: Fibre strain versus log N for torsion tubes with ±45° lay-up

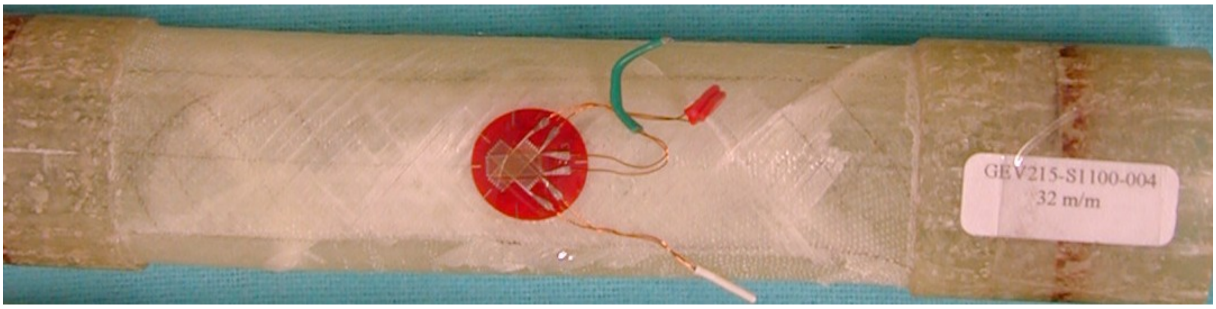

Figure 12: Delamination failure of overlap due to steep drop

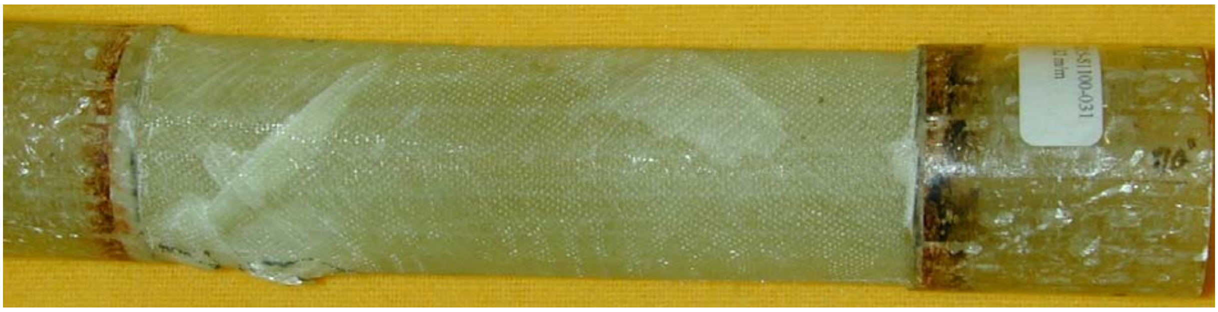

Figure 13: Improvement of failure mode with tapered overlap

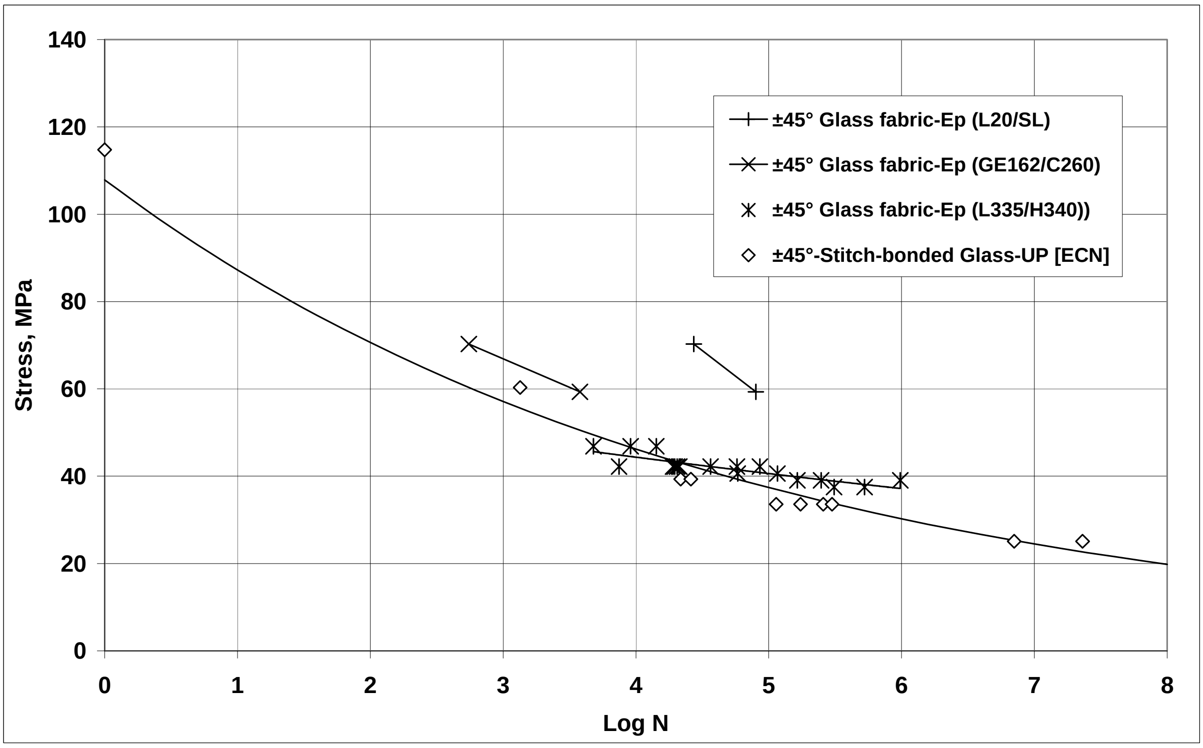

Figure 14: S-N curves for shear loaded ±45° GFRP at R=-1

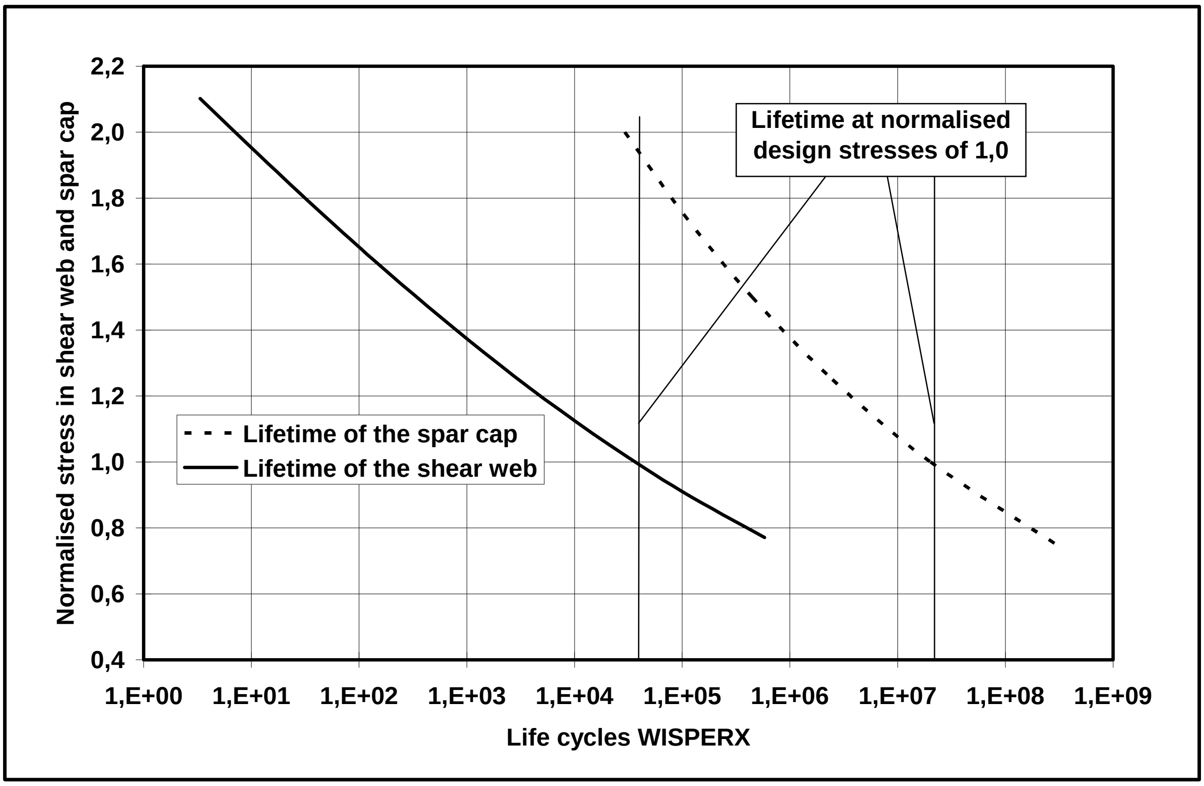

Figure 15: Lifetime comparison of a shear web and a cap of a GFRP-spar beam [15]

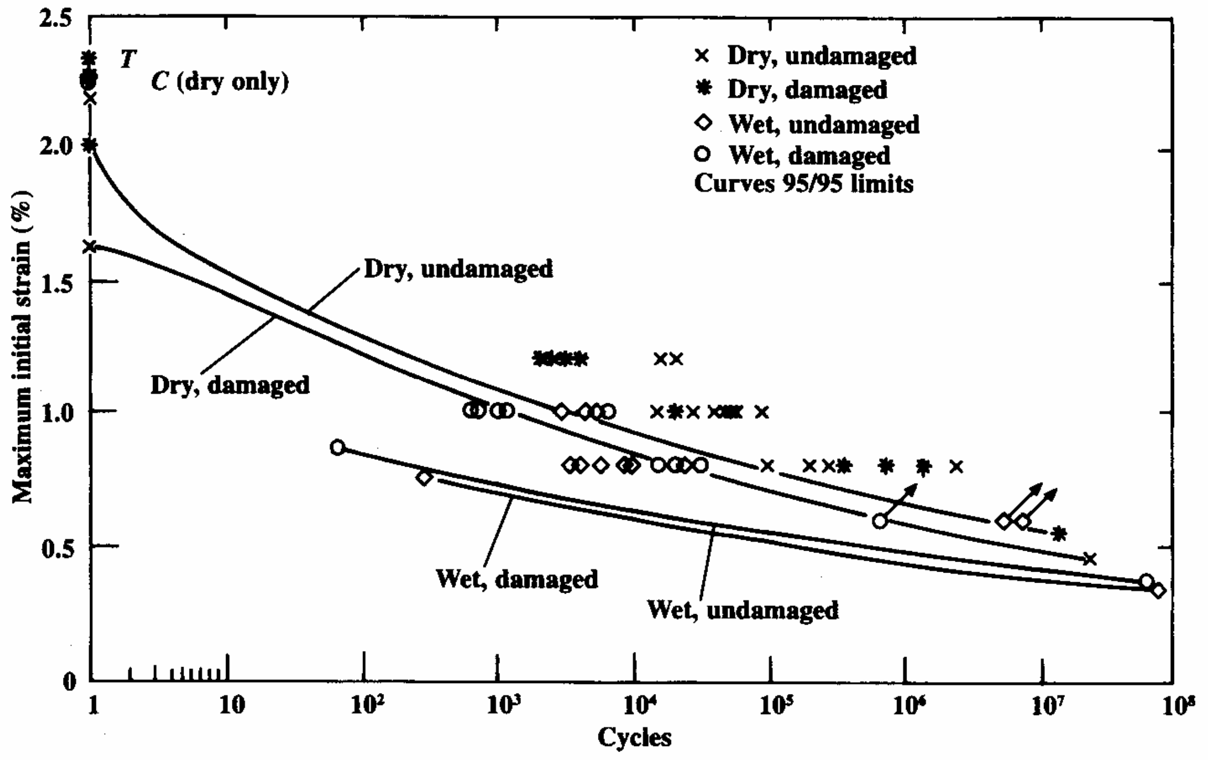

Figure 16: Environmental effects on the S-N curves of Gl-Ep at R=-1 [23]

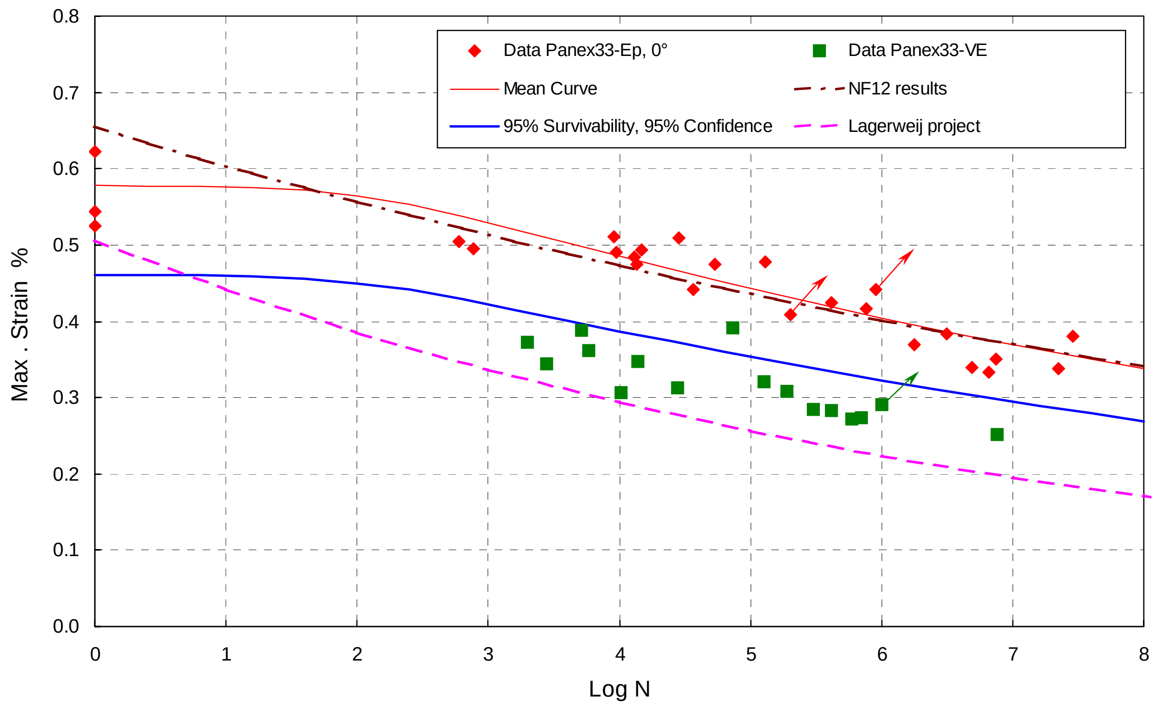

Figure 17: S-N curves of CFRP at R = -1 [24]

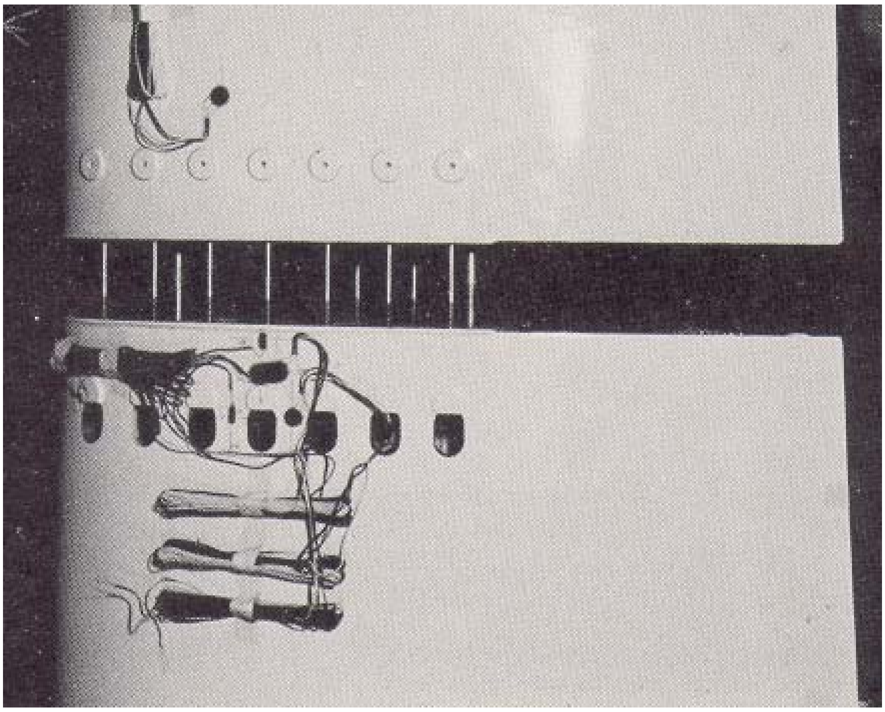

Figure 18: Picture of a T-bolt connection at the DEBRA 25 rotor blade [25]

Figure 19: Picture of hybrid laminate in a stud joint [24]