LIFETIME OF GFRP IN A SHEAR WEB AND IN THE GIRDER OF A SAILPLANE WING SPAR

By Christoph W. Kensche

Presented at the XXVI OSTIV Congress 1999, Bayreuth, Germany

SUMMARY

Comparative lifetime predictions are presented for GFRP materials representing the girder, also known as flange or cap, and shear web of a sailplne wing spar. They were accomplished on the basis of the specific s-n curves and the sailplane standard of KoSMOS by applying the linear Palmgren-Miner rule. For this purpose, a lifetime prediction program was developed. For the spar caps, s-n curves or a constant amplitude life diagram of unidirectional glass epoxy (UD GI-Ep) respectively, established for wind turbine rotor blades were used. For the shear webs, fatigue data of torsion-loaded ±45° orientated GI-Ep-fabric tubes were created at R=0.1 and R=-1 for the design of a constant amplitude life diagram.

1. INTRODUCTION

The fatigue considerations on highly loaded structures made of glass fibre reinforced plastic (GFRP) composites are limited in the most cases on s-n curves, where stress or strain is plotted over load cycles to failure, of unidirectional (UD) reinforced materials which represent e.g. the girder of a spar beam. Especially in the wind energy field, a satisfactory amount of fatigue data is now available from UD-specimens of GI-Ep (glass epoxy) and GI-UP (glass polyester) (1-5). However, for a reliable lifetime prediction for a spar beam, the knowledge about the fatigue behavior of the shear web is also of major importance. Shear webs usually are designed from ±45° laminates using fabrics or UD layers. Very few fatigue data are known for such material up to now.

Therefore, s-n curves were established at DLR for shear-loaded fabrics as a basis for a lifetime assessment of a web. It was of special interest to learn whether in a lifetime comparison of a well balanced design of girder and shear web, the fatigue lives would be more similar or differ significantly. In the latter case, an advantageous result could be to concentrate future efforts on the weaker component of a spar beam.

2. MATERIAL AND TESTS

For this investigation, GI-Ep materials are considered since they are used in many sailplanes. For the girders, the same s-n curves or constant amplitude life (Haigh-) diagram, respectively, are used as described in (6) and (7).

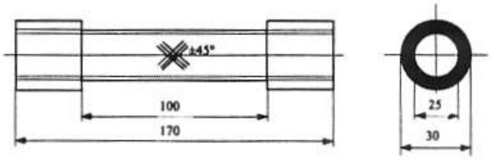

Figure 1: Geometry of GI-Ep torsion tube.

For simulating the in-plane shear in the web, torsion tubes with ±45° lay-up, as shown in Figure 1, are ideal specimens.

The specimens were manufactured by hand lay-up technology with plain fabric (Interglass 992115, 4 layers, 10 mm overlap) and the resin system GE162/C260. This has been the standard epoxy resin used for making GFRP sailplanes for more than 30 yeaars. Its application seems to lead to a lower lifetime than that with L20/SL resin, which was reported e.g. in (6,7). However, Figure 2 shows a minor difference between the constant amplitude fatigue life of torsion tubes made using the same fabric but the two different resin systems. Different camber of the fibers results in a more significant difference in the fatigue life. It is due to whether or not one specimen is woven in twill fabric with 2 over 2 fibers (less camber), or in plain fabric with 1:1 ratio.

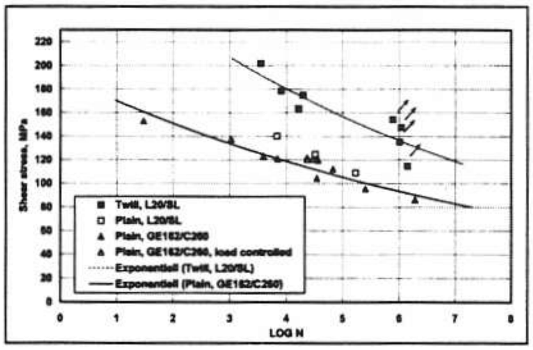

Figure 2: Shear s-n curves for torsion tubes made from plain and twill fabric as well as different epoxy systems.

The higher camber in the latter leads to higher bending stresses of the fibers and matrix nearby and thus to an earlier fatigue (8). For the purpose of achieving more conservative fatigue results, the tubes for the described investigation were therefore manufactured using plain fabric.

In contrast to the s-n curves for UD-material for the girder, where we need three R-ratios to describe a well defined Haigh-diagram, for torsionally loaded tubes we only need two R=01 and R=0.1. When τ_1 and τ_2 are the lower and upper shear stresses, then τ_1/τ_2=R=0.1 stands for biased torsion and is anticipated to be identical with R=10 for the constant amplitude life diagram because of symmetry in load application. The specimens were loaded with the displacement controlled using an electro-dyanamic machine of Schenck (PWS 16), with eccentric load application, see Figure 3.

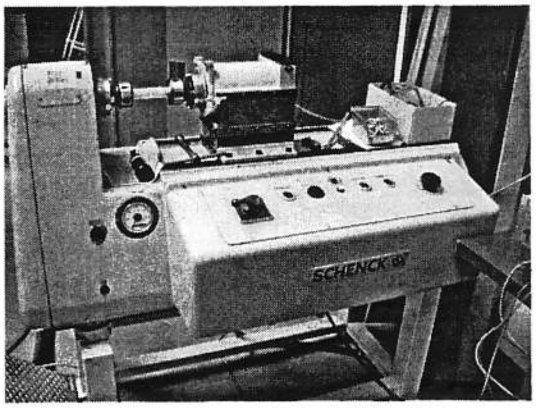

Figure 3: Torsion loading machine with GFRP specimen.

3. EVALUATION OF THE RESULTS

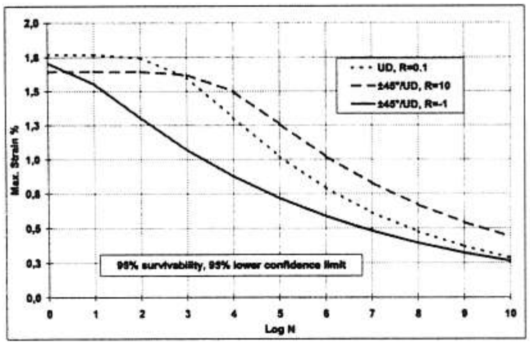

Figure 4: s-n curves for GI-Ep in the girder at R = 0.1, -1 and 10 (95%/95%).

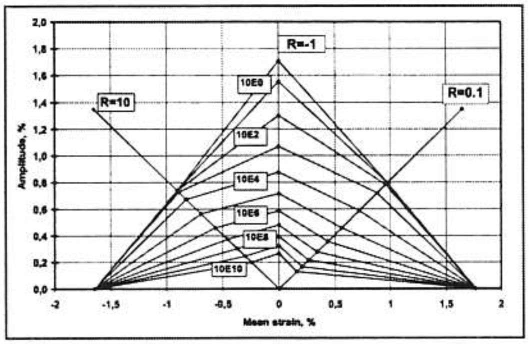

Figure 5: Haigh-diagram for GI-Ep in the girder (95%/95%).

The s-n curves for the UD-material of the girders and the relevant Haigh-diagram are extensively described in (6) and (7) and presented as curves of 95% survivability and 95% lower confidence limit in Figures 4 and 5.

The results of the R=0.1 and R=-1 s-n curves for the shear loaded GI-Ep tubes are related to a fiber volume content of 42%. They are presented in shear stress versus log n in

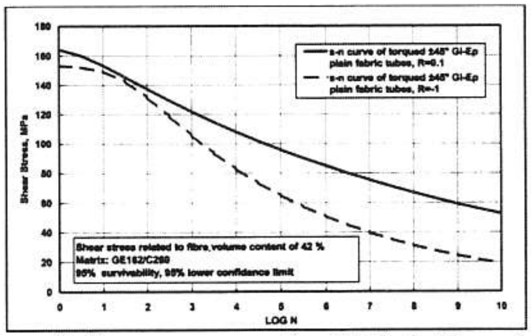

Figure 6: Shear s-n curves for GI-Ep in the web at R = 0.1 and -1 (95%/95%).

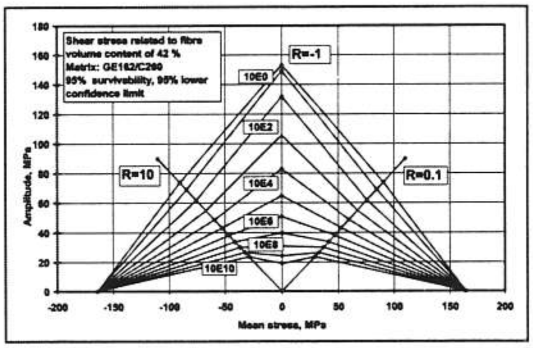

Figure 7: Haigh-diagram for GI-Ep in the shear web (95%/95%).

Figure 6 and as constant amplitude life diagram in Figure 7. The statistical evaluation was performed according to a method proposed by Sendeckyj (9), which is also described in (7).

4. LIFETIME PREDICTION

The method of the lifetime prediction is based on the assumption of a linear damage accumulation according to Palmgren-Miner in the GFRP structure and its components. The relevant load spectra must be rainflow-counted and stored in a Markov-matrix in a manner that mean stress and amplitude can be considered, see (7). Thus, the Haigh-diagram, with its presentation of amplitude versus mean stress (or strain) is an excellent means for the lifetime estimation because of the possibility of logarithmic/linear interpolation between the lines of constant lifetime or the static values respectively and the radials of the stress ratios. The method is described extensively in (7). For the lifetime calculation a program was developed which allows the following options:

- Calculation of 2-parameter Weibull-distributed s-n curves on the basis of a set of test data accordingly to (9).
- for any survivability and different confidence limits.
- Design of a constant amplitude life diagram from a set of s-n curves and
- a rainflow-counted Markov matrix from a load sequence.
- Prediction of the lifetime on the basis of the damage sum accumulated according to the linear Palmgren-Miner rule.

The load spectrum used is KoSMOS (10-12), the approved standard for sailplanes. One life cycle of this standard corresponds to 6000 flight-hours lifetime. In the case reported here, the short version KoSMOS 2 with an omission of ±7,14% and a load cycle number of 556660 was applied. With this load spectrum, torsion fatigue tests have been carried out to enable a comparison between lifetime prediction and experiment. For the D-specimens representing the girder, no tests are available with KoSMOS. However in (7), a relative good correlation between lifetime prediction and experiment was found by the application of the wind-energy standard WISPERX for GI-UP and GI-Ep as well. Thus, also for KoSMOS a reliable prediction is expected.

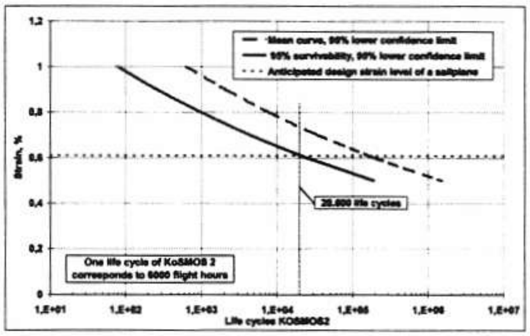

Figure 8: Lifetime prediction for GI-Ep girder.

The results of the lifetime prediction for the girder material is shown in Figure 8. They are presented as mean (50%) and 95% survivability curves with 95% lower confidence limit for design strains between 0.5 and 1.0%. For a design level of 0.61% as common for sailplanes, the 95% curve would predict a service life of 20600 life passes, i.e. $123*10^6$ flight hours which is an unimaginably high and rather academic lifetime of several thousand years. This indicates that possibly the material of the spar cap is not critical in fatigue under this low design strain.

The lifetime prediction of the shear web material is plotted in Figure 9 also for 50% and 95% probability. Some experimental data are available which support the validity

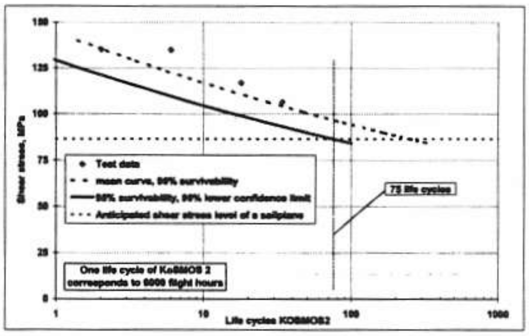

Figure 9: Lifetime prediction for GI-Ep shear web.

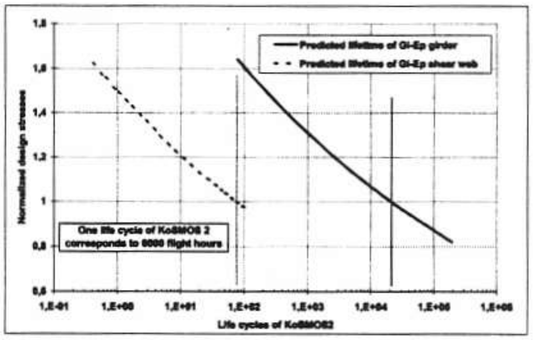

Figure 10: Comparison of lifetime prediction curves for girder and shear web related to common design levels.

of the mean curve, which shows slightly conservative fatigue behavior since it is based on the 95% lower confidence limit. The mean curve without consideration of a confidence limit would be slightly higher and meet the experimental results better.

At an anticipated design shear stress level of about 86 MPa, the lifetime with the 95%/95% curve would be about 75 life cycles of KoSMOS. Although this curve yields a lifetime which is some orders of magnitude lower than that of the girder, it nevertheless offers a pretty high possible flight time of $0.45*10^6$ hours, which is still in excess of 50 years of continuous operation.

The reported design values for the girder and the web were chosen, since they are in the experience of the author, in a balanced relation. An optical comparison can be demonstrated by normalizing the strain in the girder and the shear stress in the web. This is accomplished in Figure 10, which shows on one view that in a spar beam a shear web made of plain fabric will fail much erlier than the spar cap material. This shows that in future the shear web should be given more attention on fatigue than was done up to now.

5. DISCUSSION

The knowledge reported here is based primarily on the type of glass fabric and epoxy resin systems used for fabricating the specimens. It is common that for simplified lifetime calculations, it must be differentiated between glass epoxy (GI-Ep) and glass polyester (GI-UP). There exist, however, also epoxy resin systems with different qualities leading to laminates of different properties. In the reported comparison between girder and shear web fatigue life, it should therefore be pointed out that the high quality resin system L20/SL, which is applicable to 72° C as required for JAR 23 aircraft, was used in the girder whereas the GE162/C260 with a lower T_G was investigated with the web material. It must also be kept in mind that the calculation presented was based on the s-n curves and experimental service life data of plain fabric tubes.

As reported before, Figure 2 shows only a slightly higher fatigue life of the tubes loaded by torsion using plain glass fabric and L20/SL in comparison with the same fabric but with GE162/C260 matrix. However, twill fabric with L20/SL yields a much higher life than plain fabric with this resin system. Thus, the influence of different resin systems does not seem to have as significant an influence on the lifetime as the investigated fabric types.

The future aim is to provie that a complex structure like a spar beam will have much higher possible lifetime than the certified 12000 flight hours which gliders are limited to currently. This aim is expected to be demonstrated using plain fabric as material for the shear web of a spar beam leading to relatively short testing times which nevertheless will achieve satisfactory high certified flight hours. This will be a matter of a report to follow.

6. CONCLUSIONS AND OUTLOOK

Fatigue tests on torsionally loaded ±45° GI-Ep tubes fabricated using plain fabric were carried out. Lifetime calculations n the basis of an in-house developed fatigue life prediction code, the reported fatigue tests on the torsion tubes representing the web of a spar beam, as well as UD-material of a spar girder described in earlier reports were accomplished together with the sailplane-specific load spectrum KoSMOS. They indicate a significantly lower fatigue life for the web than for the girder of a spar beam, especially when in the web a plain fabric is used instead of twill. Nevertheless, a satisfying high lifetime of a sailplane with primary structures made of the materials investigated is predicted.

This forwards the idea to concentrate in future fatigue investigations of primary structures like spar beams on the shear web. Little attention has been given to the fatigue behavior of the applied bonding systems. This also plays a big role when a complex structure like a spar beam will be investigated. Since fatigue life tests for the certification of a certain lifetime are very time consuming it is (under the assumption of the validity of the linear Palmgren-Miner rule) proposed to investigate the possibility of a one step-fatigue loading of a structure instead of spectra loading. S-n curves for the materials used are however necessary.

7. REFERENCES

(1) Ch. W. Kensche, GFRP Fatigue Data for Certification, Proceedings of the EWEC Conference and Exhibition, Thessaloniki, Macedonia, Greece, October 10-14 (1994).

(2) r.M. Mayer (ed.), Design of Composite Structure against Fatigue, Mechanical Engineering Publications Ltd., Suffolk, UK (1996). ISBN 0 85298 957 1.

(3) B.J. de Smet, P.W. Bach, DATABASE FACT, Fatigue of Composites for Wind Turbines, 3d IEA-Symposium on Wind Turbine Fatigue, 21-22 April 1994, ECN Petten, The Netherlands.

(4) Ch. W. Kensche (ed.) Fatigue of Materials and Components for Wind Turbine Rotor Blades, European Commission, Directorate-General XII, Science, Research and Development (1996), ISGN 92-827-4361-6.

(5) J.F. Mandell, D.D. Samborsky, DOE/MSU Composite Materials Fatigue Data Base: Test Methods, Materials and Analysis, SAND97-3002, Sandia National Laboratories, Albuquerque, NM (1997).

(6) Ch. W. Kensche, Influence of Composite Fatigue Properties on Lifetime Predictions of Sailplanes, XXIV OSTIV Congress, Imarama, New Zealand (1995).

(7) Ch. W. Kensche, Method of Lifetime Prediction for Sailplane Fibre Structures, XXV, OSTIV Congress 1997, Saint Auban sur Durance, France, 3 to 11 July 1997.

(8) Ch. W. Kensche, Fatigue Behavior of Torsionally Loaded Tubes, International Conference on Fatigue of Composites, Paris, 3-5 June 1997.

(9) G.P. Sendeckyj, Fitting Models to Composite Materials Fatigue Data, in: Test Methods and Design Allowables for Fibrous Composites, ASTM STP 734, c. C. Chamis, Ed. 1981, pp. 245-260.

(10) H. Kossira, W. Reinke, Die Ermittlung von Lastkollektiven für die Bemessung von Segelflugzeugen, OSTIV-Vortrag 1981, ero-Revue 6/1983, Seite 42-46.

(11) H. Korrisa, H. Pohl, Die Erzeugung von zufallsartigen Lastfolgen für Betriebsfestigkeitsversuche aus Meßwerten, die in Markov-Übergangsmatrizen gespeichert sind, Materialprüfung 25 1983) Nr. 6, Seite 187-193.

(12) H. Krrisa, Determination of load spectra and their application for keeping the operational life proof of sporting airplanes, ICAS-Proc. 8/1982, ICAS-82-2.8.2, page 1330-1338.