

INFLUENCE OF COMPOSITE FATIGUE PROPERTIES ON LIFETIME PREDICTIONS OF SAILPLANES

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Abstract

Results of fatigue investigations mainly on glass epoxy (GI-Ep, dry and wet) and glass polyester (GI-UP) are presented as e-N curves and constant amplitude life diagrams. Some minor fatigue data for graphite epoxy (Gr-Ep) are available, too. They are statistically evaluated for 95% survivability and 95% confidence limit. Service life estimations carried out with the wind energy specific standard WISPER on the basis of the linear Palmgren-Miner rule show good conformity with the corresponding load sequence tests. Thus, the same approach was used to assess the fatigue life of sailplanes with a glider mission program for GI-Ep and GI-UP for various design strain levels. At all levels, the calculated fatigue life of GI-Ep gliders exceeds that of GI-UP. These results are valid solely for the high-loaded fibers in a pure spar cap. They cannot be applied to the lifetime validation of e.g. a whole wing with its complex stress distribution. A proposal is made for future certification procedures of whole structures.

1. Introduction

The lifetime of the most sailplanes made of glass and graphite epoxy (GI-Ep and Gr-Ep), at present, is limited

to 12,000 flight hours. This is based on service life tests applied to wings or spar beams. Only few years ago, the limit was 6,000 hours. However, a prolongation of the certified lifetime had been shown to be necessary since, at some sites with excellent soaring conditions, gliders had reached this time much earlier than expected. In the meantime, there are some sailplanes which are exceeding even the 12,000 hours flight time. Following the established certification procedure, new expensive fatigue tests are again necessary if the gliders shall not be grounded by the authority or the manufacturer, respectively.

A proposal is made to avoid this long-lasting procedure. It is based firstly on the fact that in a sailplane the spar cap of a wing in general carries the highest stresses. Fatigue results obtained from investigations on wind turbine rotor blade materials can be applied also to assess the lifetime of sailplanes (1,2). Previously, those tests were carried out by research institutes of several countries in the EU (European Union) on glass polyester (GL-UP) and glass epoxy (GI-Ep) with the aim to obtain high-cycle fatigue data (3).

The influence of moisture was also tested (4). The

presentation of the fatigue lives, also called Wöhler curves, is done as strain ϵ versus load cycle numbers N . They are statistically evaluated for 95% survivability with 95% lower confidence limit.

For a lifetime estimation, the construction of a constant amplitude life diagram or Haigh diagram is possible and especially useful if ϵ - N curves are available for several stress ratios, i.e. not only $R = 0.1$ (tension-tension) but also $R = -1$ (tension-compression) and $R = 10$ (compression-compression). For this case, the mean and the alternating strain must be derived from, e.g., the upper strain and the stress ratio of the fatigue curve.

For supplementing the fatigue data available for sailplanes the results of some previous tests on Gr-Ep are also presented (1,5).

The second step of the proposal concerns the fact that for a lifetime estimation of a complete structural part like a sailplane wing or a spar the consideration of solely the spar cap material is not sufficient. In those structures, the stress distribution is much more complex than in simple specimens. A relatively cheap certification procedure is proposed which, however, needs the information obtained from the coupon tests carried out in the first step.

2. Fatigue tests

2.1 Fatigue tests on fiberglass reinforced plastics

The fatigue tests which are the basis for the statistical evaluation were carried out within two projects of the EU (3,4). The first project dealt with investigations on fiberglass reinforced plastics (GFRP) by six European research institutes, namely ECN and NLR/NL, Risø/DK and RUG/B on GI-UP, FFA/S and the DLR on GI-

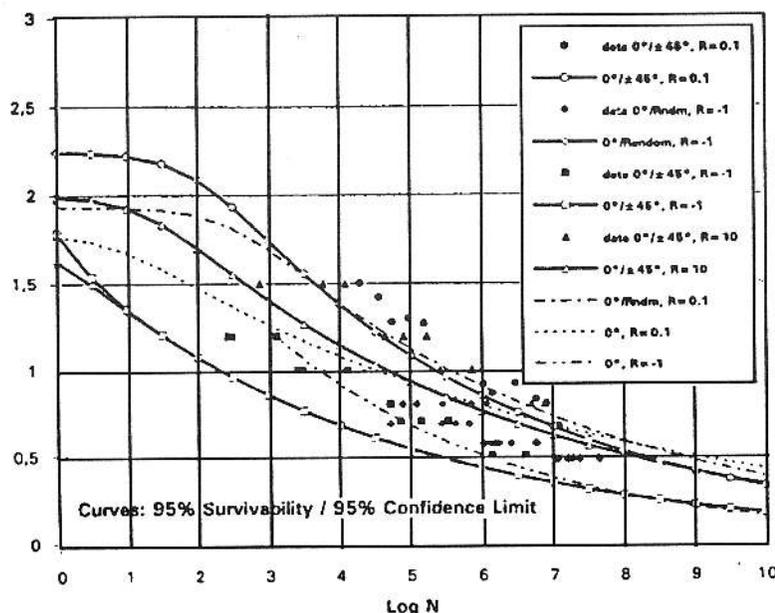


Figure 1. Fatigue Curves of GI-UP at Different R-Ratios.

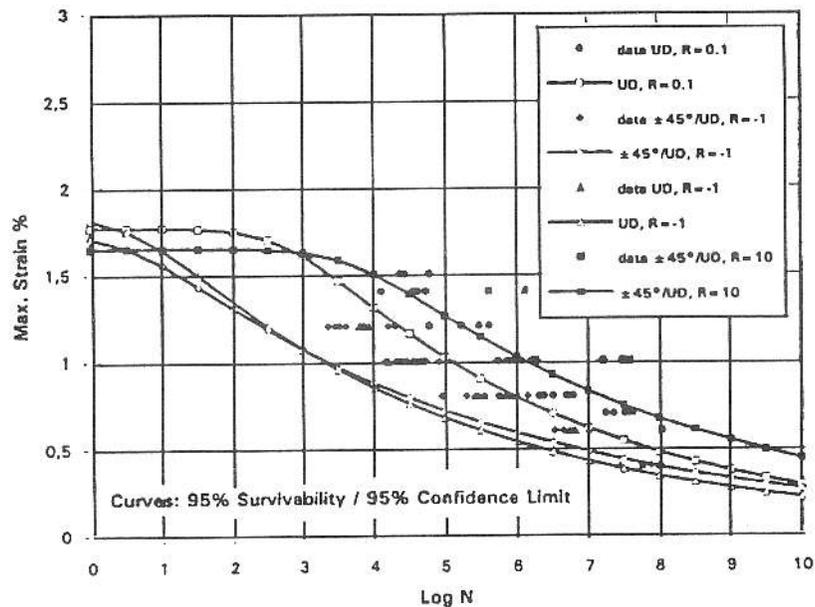


Figure 2. Fatigue Curves of GI-Ep at Different R-Ratios.

Ep. Ref. (4) contains DLR fatigue data for the same GI-Ep materials as tested in the previous program, however also including humidity.

For the fatigue evaluation, 23 data sets of GI-UP material, and 16 of GI-Ep are available. However, only those fiber lay-ups are selected for the extended fatigue life evaluation which are 0° -fiber dominated which corresponds more to the spar cap design. Thus, 7 curves are chosen for GI-UP and 4 for GI-Ep, see Figures 1 and 2. The diagrams show the ϵ - N curves of 95% survivability with a 95% lower confidence limit.

For a reliable life estimate of GI-UP material, those curves were favored which showed more conservative behavior in the high cycle area and which had similar or identical shapes, e.g. different lay-up but the same loading conditions. This is the case for the two corresponding curves with a 0° /random and a $0^\circ/\pm 45^\circ$ lay-up, respectively, at a stress ratio of $R = -1$. For $R = 0.1$ and 10, the fatigue lines with a $0^\circ/\pm 45^\circ$ lay-up were selected. These curves, plotted together with the corresponding data points, were used for the construction of a Haigh diagram.

In the case of GI-Ep material, there exist two curves for $R = -1$ which are very similar. Here, it was decided to omit the curve with the pure unidirectional (UD) fiber lay-up. The main reason was that the curve representing the $\pm 45^\circ$ /UD fiber compound is the result of a pooling of the fatigue data of the two projects described in (3) and (4). This curve contains more than 40 test points and is, thus, the statistically best established curve of the diagram.

A comparison of the fatigue curves shows that in the high cycle area, the GI-Ep material

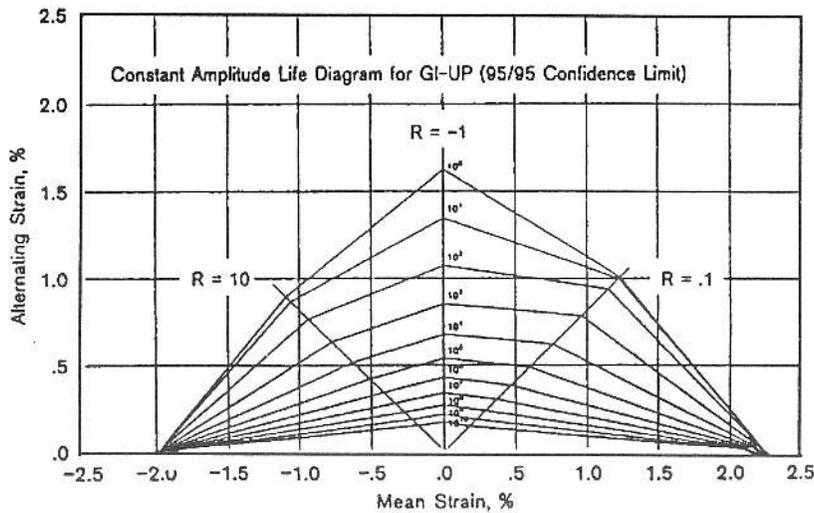


Figure 3. Constant Amplitude Life Diagram for GI-UP.

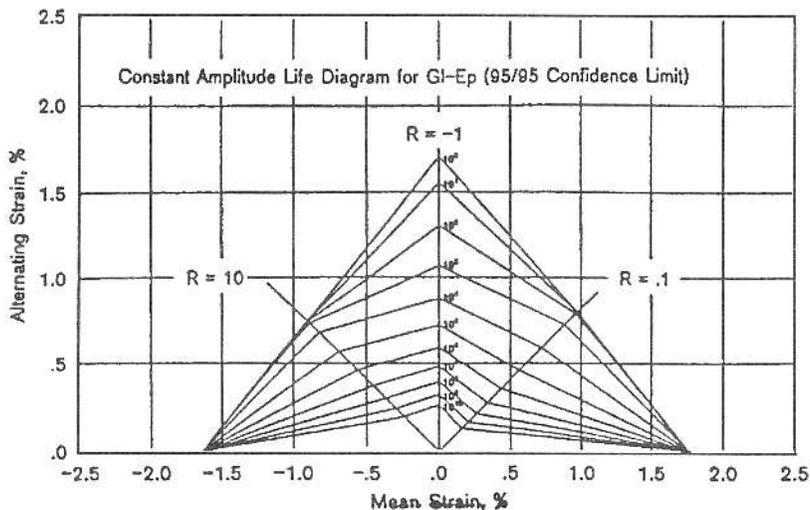


Figure 4. Constant Amplitude Life Diagram for GI-Ep.

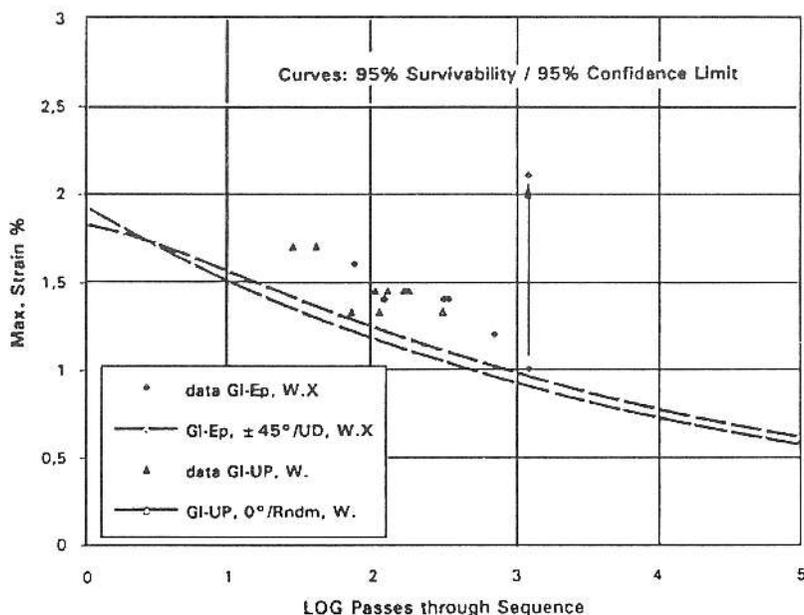


Figure 5. Fatigue Curves of GI-UP and GI-Ep with WISPER/WISPERX.

at $R = -1$ is superior to GI-UP, while GI-UP exceeds the fatigue properties of GI-Ep at $R = 0.1$.

Figures 3 and 4 show the constant amplitude life diagrams resulting from the ϵ -N curves in Figures 1 and 2. In these diagrams, which give a complete survey of the fatigue behavior of a material, the difference between the two resin types is more obvious, especially in the right side of the plot which represents the tensile area of the mean stresses.

A lifetime evaluation was carried out on the basis of the linear Palmgren-Miner rule together with the range-pair-range counted WISPER/WISPERX standard, which is described later. The fatigue curves of 95% survivability with a 95% lower confidence limit for these standards are shown in Figure 5. The WISPER tests were done on GI-UP at the ECN, the short version, WISPERX, on GI-Ep at the DLR. These curves allow a comparison with the theoretically based calculations.

Another result of the investigations described in (4) is the fatigue curve for wet GI-Ep at $R = -1$. Before (and partly during) fatigue testing, the material was exposed up to saturation to air of 45°C and 90% relative humidity. Figure 6 presents the fatigue life in comparison to dry material which is also shown in Figure 2. In the low-cycle area, a significant decrease of the fatigue properties of the wet GI-Ep can be noted, whereas in the extrapolated high-cycle space, the curve crosses even the curve of the dry material.

This is demonstrated quite well also in the Haigh diagram for wet GI-Ep (see Figure 7) where the alternating strains at the high load cycle numbers are as high as those of the dry GI-Ep and higher than those of GI-UP.

The construction of this constant amplitude life diagram and the lifetime estimation contain, however, some uncertainties. These are the definition of the point representing the static tension strain and the behavior of the material at stress ratios between tension-compression ($R = -1$) and high tensile mean strains, because no fatigue values are available at $R = 0.1$. To solve the first problem, we had recourse to the static tension values of the wet material which has the same strength as the dry one (3). Thus, the same point on the mean strain axis was used as in the Haigh diagram in Figure 4. The solution of the second problem is less certain. Disre-

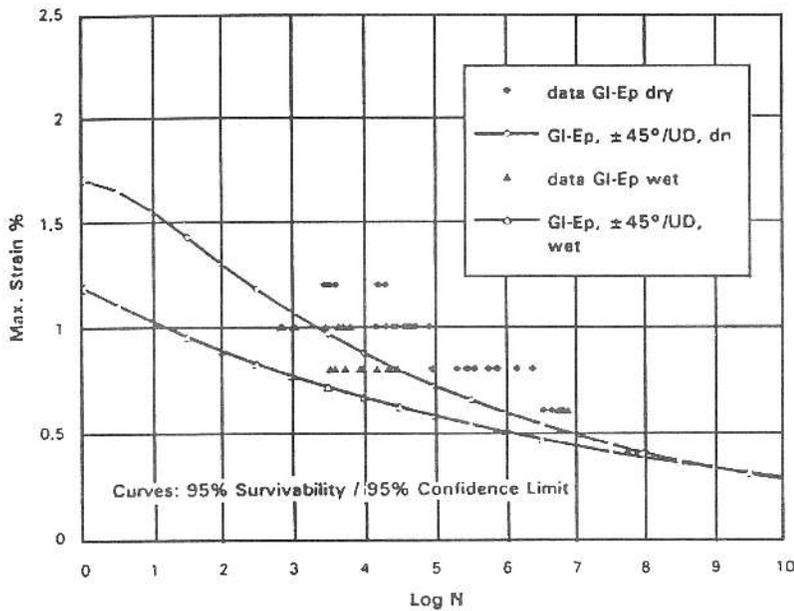


Figure 6. Fatigue Curves of GI-Ep and Dry and Wet Conditions at $R = -1$.

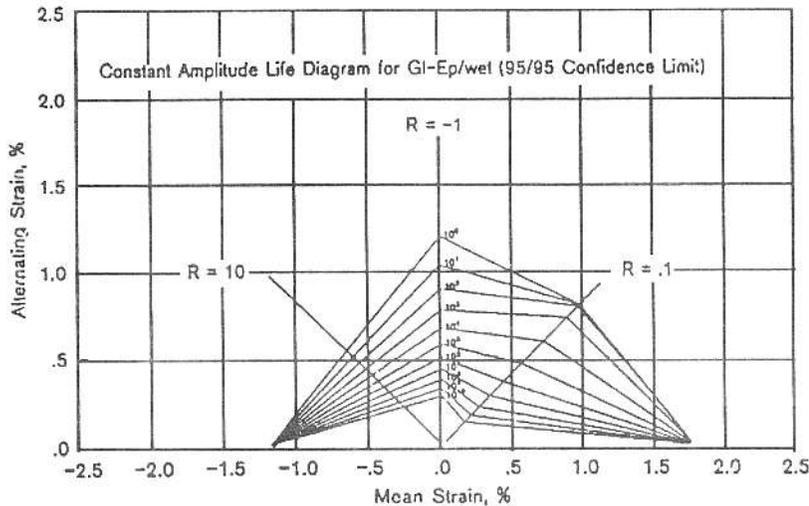


Figure 7. Constant Amplitude Life Diagram for GI-Ep/wet.

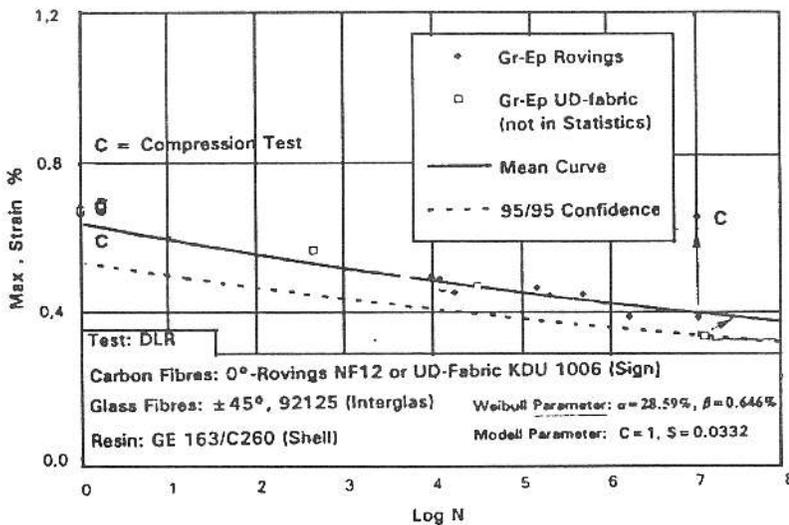


Figure 8. Fatigue Curve of Gr-Ep at $R = -1$.

garding $R = 0.1$ values means linear interpolation of load cycle lines for all stress ratios between the static value point and the alternating-strain axis. However, this would, obviously, lead to an unreasonably high lifetime for the wet material since, in the high-cycle area of the tensionally loaded dry GI-Ep ($R = 0.1$ -radial in Figure 4), the fatigue curve is too low (6). So, it was decided to assume that the wet material had the same curvature for this stress ratio as the dry one, being aware that this procedure may still lead to results which are too optimistic. The justification for this procedure is seen in the consideration that the tensile fatigue is strongly influenced by, the moisture-unaffected fibers and less influenced by the moisture-penetrated soft matrix or interface. On the compression (left) side of the Haigh diagram, no estimation of the behavior at compression-compression is possible. Therefore, it was linearly interpolated between the $R = -1$ axis and the static compression value derived from the point of 10^6 load cycles at the $R = -1$ axis.

2.2 Fatigue tests on Gr-Ep

For Gr-Ep, no other fatigue data are available than those reported in (1) and (5). The lay-up was a hybrid laminate with unidirectionally orientated Gr-Ep in the middle section and one layer $\pm 45^\circ$ GI-Ep fabric on each side. The carbon fibers of the Gr-Ep laminate were either HT (high tensile) rovings or HT UD-fabrics. The data points of the constant amplitude fatigue tests at $R = -1$ are presented in Figure 8 together with the statistically evaluated fatigue curves of 50% and 95% survivability.

3. Statistical evaluation

The statistical evaluation of the individual data sets was done by means of an approach described by Sendekyj (7). This method is well established when only small fatigue data samples are available. Beside the fatigue failure and the static strength data it considers also residual strength data, runouts (termination of cyclic testing prior to fatigue failure) and tab failures (failure mode suspect). The data fitting procedure is based on the following method.

The fatigue life is expressed by a two-parameter ϵ -N curve which is a particular form of the so-called wearout model by Halpin et al. (8). One parameter S determines at high cycles the slope of the ϵ -N curve in a log-log plot. It is equivalent to the

reciprocal value of k in (9). The other parameter C allows for flattening or steepening of the curve at low cycles. Due to the large scatter of the fatigue results, a probabilistic approach is needed. Each test result in a log-log ϵ - N plane is transformed into an equivalent static strength by using the S - and C -parameters of the ϵ - N curve. Hence, a complete data set of fatigue data yields a new set of equivalent static strength data. It is assumed that this new data set is two-parameter Weibull distributed. The ϵ - N curve takes the following form:

$$\epsilon_a = \beta \times \frac{(-\ln P(N))^{\frac{1}{\alpha}}}{((N-A) \times C)^S} \quad (1)$$

ϵ_a is the maximum applied strain, β the scale and α the shape parameter of the Weibull distribution. N is the number of cycles to failure and $P(N)$ the probability of survival. A stands for $-(1-C)/C$. Following the certification rules for wind turbine design (9), the presentation of the fatigue curves takes into account 95% survivability with 95% lower confidence limit.

Table I presents, beside the Weibull parameters, also the model parameters, including the slope k , for the curves selected for the lifetime evaluation. Beside the special case of the wet GI-Ep, the k -values are located between 9.4 and 11.5. This seems to be characteristic for the slopes of GFRP fatigue curves (9). Another objective parameter of the material properties is the strain at high load cycle numbers. Therefore, the strain of the GFRP curves at 10^8 load cycles is also shown in Table 1. It is obvious that at $R = -1$, GI-Ep shows better fatigue behavior than GI-UP while GI-UP has superior properties in the tension-tension mode, see also the fatigue curves plotted in Figures 1-4. Thus, for a more objective lifetime evaluation, the different stress ratios should be considered together with the expected life load spectra.

For Gr-Ep, the slope ($k = 30.1$) is relatively flat compared with that of GFRP. The strain at 10^8 load cycles is relatively high and agrees with the good fatigue behavior of carbon fibers. The five data points obtained with the UD-fabric specimens were not used for the calculation of the curves. However, they show that they are within the scatter of the roving specimens.

4 Fatigue life evaluation

4.1 General

Since for both sailplane wings and rotor blades the same material can be used, the knowledge obtained from investigations in the area of wind energy may be transferred to sailplanes. The results of lifetime investigations on materials of rotor blade, therefore, will be the basis for fatigue life considerations on glider wings. The calculation is made according to the linear Palmgren-Miner rule, which is

$$D = \sum_{i=1}^k \frac{n_i}{N_i} = 1 \quad (2)$$

where k is the sum of the load steps, n_i the number of sequence load cycles at strain ϵ_i and N_i the number of load cycles to failure at ϵ_i . D depends mainly on the load spectrum, the working stress level and the composite layup.

Experience has shown that the value of D can vary over a wide range, from 10^{-1} to 10^1 , for metals as well as for composites. If the experimentally obtained number of cycles or passes through the sequence, respectively, are higher than the calculated one, the lifetime estimation is conservative. The validation of the Palmgren-Miner rule by means of wind energy specific standards is anticipated to justify the application of the same rule also to sailplanes.

4.2 Fatigue life evaluation of rotor blades

For testing load sequence effects and to compare

Test Institute	Lay-Up	0°-Material	Stress ratio R	Fatigue Tests	Weibull Parameters		Model Parameters		k = 1/S	Strain at N = 10E8
					α	β	C	S		
Risø	0°/±45° (2 x 0°/±45°/0°)sym.	GI-UP	0.1	11	30,183	2,657	0,00968	0,106	9,4	0,520
ECN	0°/Random	GI-UP	-1	26	9,542	2,525	0,625	0,1	10,0	0,270
NLR	0°/±45° (from Risø)	GI-UP	-1	12	15,230	2,498	1,61	0,1	10,0	0,270
NLR	0°/±45° (from Risø)	GI-UP	10	11	21,501	2,539	0,046	0,09	11,1	0,500
DLR	UD	GI-Ep	0.1	32	16,482	2,250	0,00146	0,1105	9,0	0,476
DLR	±45°/UD (1 x ±45°/2 x 0°)sym	GI-Ep	-1	39	13,988	2,230	0,22	0,0868	11,5	0,394
DLR	±45°/UD (1 x ±45°/2 x 0°)sym	GI-Ep	10	7	17,429	2,190	0,000175	0,092	10,9	0,670
DLR	±45°/UD (1 x ±45°/2 x 0°)sym (wet)	GI-Ep	-1	21	15,066	1,600	1	0,0635	15,7	0,370
ECN	0°/Random	GI-UP	WISPER	12	22,095	2,450	2,45	0,107	9,3	---
DLR	±45°/UD (1 x ±45°/2 x 0°)sym	GI-Ep	WISPERX	7	25,653	2,264	0,387	0,105	9,5	---
DLR	±45°GI-Ep/UD Gr-Ep (1 x ±45°/2 x 0°)sym.	Gr-Ep	-1	11	28,590	0,646	1	0,0332	30,1	0,290

Table 1. Statistical Parameters of GFRP and CFRP Fatigue Curves.

Evaluation with Palmgren-Miner	GL-UP		GI-Ep. dry		GI-Ep. wet	
	WISPER	WISPX	WISPER	WISPX	WISPER	WISPX
Damage Sum for 1 Pass through Sequence at a Strain of 0.6%	$2.06 \cdot 10^{-5}$	$1.72 \cdot 10^{-5}$	$1.02 \cdot 10^{-5}$	$9.63 \cdot 10^{-6}$	$2.60 \cdot 10^{-3}$	$1.98 \cdot 10^{-5}$
Theoretical Passes through Sequence at a Strain of 0.6% (D=1)	48481	58257	98059	103824	38460	50612
Tested Passes through Sequence at a Strain of 0.6% (see Fig.7)	55349	—	—	106611	—	—
Damage Accumulation Factor	1.14	—	—	1.03	—	—

Table 2. Results of GFRP-Lifetime Evaluation for WISPER and WISPERX at 0.6% design strain level.

different materials, the wind energy-specific standard load sequences WISPER (10) and WISPERX are established. The WISPERX standard is shortened from the full WISPER spectrum by reduction in the number of cycles, see (3). Tests were carried out applying both versions within the projects described in (3). Figure 5 shows the fatigue curves of 95% survivability with 95% lower confidence limit for GI-UP tested with WISPER and for GI-Ep in combination with WISPERX. In these figures, the maximum working strain level is plotted versus the log of passes through the sequence. One pass corresponds to two months lifetime of a fictive wind turbine.

A lifetime calculation was carried out for the three materials GI-UP, GI-Ep/dry and GI-Ep/wet, the constant amplitude life diagrams of which are shown in the Figures 3, 4 and 7. The design strain level was anticipated to be 0.6%, which corresponds to possible allowables in GI-Ep sailplanes. In order to enable accurate lifetime prediction, the relevant fatigue data should be available for all R-ratios which exist in the load sequences used in WISPER and WISPERX. Since this is not the case, they must be found by an interpolation along the polygon life lines in the Haigh diagrams. For our ease, the R-values of the load sequence were taken from the range-pair, range counting results reported e.g. in (3).

Table 2 presents the results of the lifetime estimation. It contains the damage sum for one pass through the sequence and the possible passes for a theoretical damage accumulation sum $D = 1$. Considering primarily the GI-UP and the dry GI-Ep, the latter would

have about twice the lifetime of the glass-polyester, for WISPER as well as for WISPERX. Nevertheless, the number of passes of the GI-UP through the sequence corresponds to a lifetime of the fictive wind turbine of more than 9000 years. The theoretical fatigue lives are about 20% for GI-UP and 6% for GI-Ep greater for WISPERX than for WISPER, i.e. the omission carried out in WISPERX has less influence on the epoxy than on the polyester material.

The calculated wet GI-Ep lifetime is not much lower than that of the GI-UP, but, as explained above, there are some uncertainties in the construction of the Haigh diagram. Nevertheless, the high-cycle properties of the wet material at $R = -1$ are extremely good, see Figure 6 and Table 2, and can explain in part the relatively high lifetime.

Since experimental results with the load sequence were available, see Figure 5, it was very interesting to see how they correspond with the prediction. For this case, at a strain level of 0.6%, the passes through the sequence of the - extrapolated - WISPER/ WISPERX fatigue lives of 95% survivability with 95% confidence limit were defined. The results are presented in Table 2 and show that they are higher than but very close to the calculation. For GI-UP, the damage accumulation factor is $D = 1.14$, for GI-EP even 1.03, i.e. assuming the validity of the Palmgren-Miner rule, the applied estimation is relatively close to reality and - fortunately - on the conservative side. This justifies the application of the lifetime estimation model to sailplanes.

4.3. Fatigue life evaluation of sailplanes

Two glider specific service life load spectra are available for certification purposes in Germany, the Franzmeyer block program and KOSMOS (1), (2). The

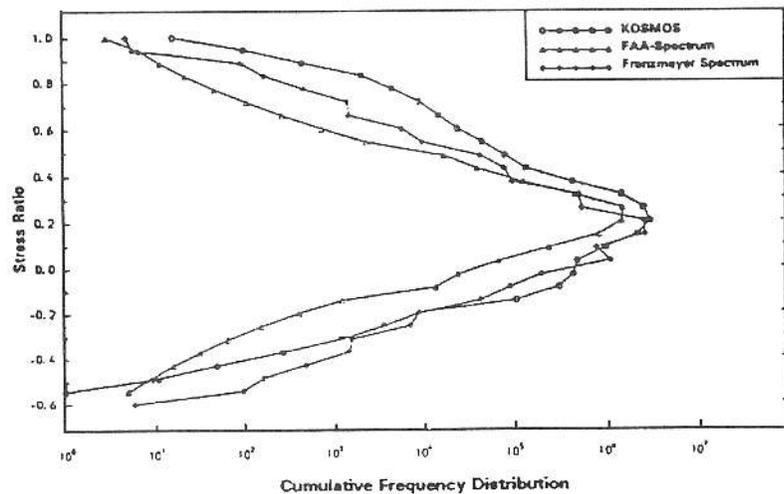


Figure 9. Cumulative Frequency Distribution of Different Service Life Load Spectra for Gliders (12).

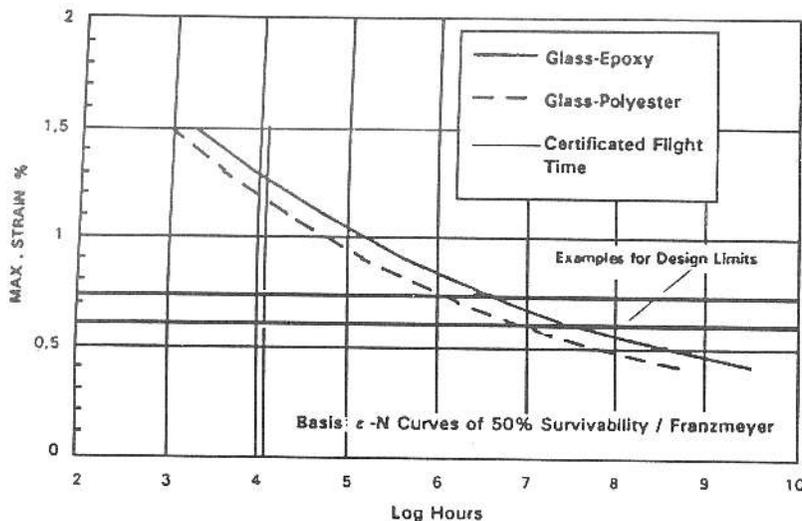


Figure 10. Lifetime of GI-Ep and GI-UP Spar Caps of Sailplanes.

difference in the shape of the cumulative frequency distribution is not very significant, see Figure 9. Due to the simple handling for a quick look, the block program was chosen for the fatigue life evaluation. The calculation was carried out for glass epoxy and glass polyester at design strains between 0.4% and 1.5%.

Figure 10 shows the resulting lifetime curves. As for the WISPER standard applied to rotor blades, also for the glider service life program GI-Ep is superior to GI-UP. However, the difference is larger, e.g. at a limit strain level of 0.6%, GI-Ep sailplanes would have a 3.5 times longer life than GI-UP gliders while for WISPER the factor is about 2. The reason for the difference is that there are more load cycles near the tension-compression area in the Franzmeyer program than in WISPER. Thus, in WISPER the good properties of GI-UP at $R = 0.1$ compared to GI-Ep improve the lifetime for the GI-UP rotor blades.

All calculations refer to the tension loaded spar caps. For the compression side, the difference will increase since the properties of GI-Ep at $R = 10$ are superior to those of GI-UP.

At strain levels of 0.6% to 0.7% in the GFRP-spar caps, which are applicable in sailplanes, the lifetime ranges from 27,400,000 to 5,900,000 flight hours. This figure would grant eternal life to sailplanes if only the spar cap material would be responsible for the lifetime and if the figure would reflect reality.

4.4. New proposal for certification procedure

However, the stress distribution in a spar beam or wing is more complex because of

- stresses in the shear web
- interlaminar shear stresses between the shear web and the spar cap
- stress concentrations in the load introduction zone
- areas of steep decrease or increase of stiffness
- local instabilities, etc.

All these effects diminish the possible lifetime of a structure and, obviously justify the present certification procedure. However, after the proof of a certain lifetime, the structure is usually destroyed in a residual static strength test. This has the disadvantage that it is not available for eventual further life-prolongation tests.

Another possibility of fatigue life certification is to carry out constant amplitude tests of structural parts at a relatively high strain level. These may exceed the design strain levels. If no damage growth is observed after a specified number of load cycles (e.g. 10,000) it can be assumed that in service flight missions no fatigue damage will occur. There may also exist the possibility, of recalculating the constant amplitude damage accumulation into that of a

service life program. However, the validity of the simple Palmgren-Miner rule has to be proved for that purpose.

5. Conclusions and Recommendations

A considerably large number of fatigue data for GI-UP and GI-Ep (dry and wet) was statistically evaluated by means of the Sendekyj method and, according to the wind turbine certification requirements, presented in the form of ϵ -N curves with 95% survivability and 95% lower confidence limit. Since static tension and compression test results and fatigue curves for stress ratios of $R = 0.1, -1$ and 10 were available, constant amplitude life diagrams could be designed.

Also some statistically evaluated fatigue data of Gr-Ep at $R = -1$ are presented. The slope of the fatigue curve is flatter than that of the GRFP. This indicates a very good fatigue behavior of the carbon fibers.

For a reliable service life evaluation, the use of Haigh diagrams is necessary. Lifetime predictions were made for the selected GFRP material combinations with the wind energy specific standards WISPER and WISPERX on the basis of the linear Palmgren-Miner rule. It was shown for the anticipated design strain level of 0.6% that the GI-Ep material has an expected life about twice as long as GI-UP. This was confirmed by corresponding load sequence tests. For GI-UP, the resulting damage accumulation factor was 1.14 in relation to WISPER, for GI-Ep and WISPERX it was 1.03. Both values are sufficiently close to the theory and, additionally, on the conservative side.

This justifies the application of the Palmgren-Miner model to sailplane structures since the fatigue properties of the load carrying material in the spar caps of both rotor blades and glider wings are similar. On the basis of the Franzmeyer service life load spectrum the expected lifetime of sailplanes with GI-Ep and GI-UP wings was estimated for design strains between 0.4% and 1.5%. The advantages of GI-Ep compared to GI-UP are still greater for this case than for WISPER. Lifetimes of more than

5,000,000 flight hours would be feasible at a design strain of 0.7% in a spar cap of GI-Ep UD material.

However, a structural part like a sailplane wing or spar beam has a more complex stress distribution. It must be fatigue tested itself to get information about the influence of stress concentrations, stiffness changes, instability effects etc. Life prolongation tests or investigation ad infinitum by means of a service life program are too expensive or even impossible. Therefore, the possibility of carrying out constant amplitude fatigue tests to e.g. 10,000 load cycles at strains of at least the design strain level should be used. Results like no-damage growth of the structure together with the knowledge about the fatigue curves of the pure UD-material should lead to more confidence in the design and, thus, longer certified fatigue life.

Future work should include:

- the establishment of a constant amplitude life diagram also for Gr-Ep, i.e. fatigue tests in the tension-tension and compression-compression domain,
- the application of a load spectrum (Franzmeyer or KOSMOS) to specimens in order to compare the results with the Palmgren-Miner rule, i.e. the validation of the applicability of the theory for Gr-Ep,
- structural fatigue investigations corresponding to the proposal.

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