PROPOSAL FOR A CERTIFICATION PROCEDURE OF EXTENDED SAILPLANE LIFETIME

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SUMMARY

A method is presented to predict the lifetime of sailplanes by the experimental and analytical investigation of spars as their highest loaded primary structure. In this approach, the knowledge about the fatigue behavior of the spar cap or flange and the shear web material is used, since these are the main load carrying fiber components of a spar beam. In an FE (Finite Element) –analysis, the strains of a spar beam are calculated and compared with measurements. On this basis, a lifetime calculation is accomplished for the shear web which is more fatigue-sensitive than the flange. It shows that at those maximum strains, the lifetime would achieve the very high and rather academic figure of more than 10 million flight hours. Under application of the linear Palmgren-Miner rule, this lifetime corresponds to a load cycle number in a proof test of about 10^6 when the spar beam is loaded in a monotonic (one-step) fatigue test up to the design load. First results achieved by testing two spars correspondingly, confirm that this method may be a new and beneficial possibility for lifetime approval of sailplanes.

NOMENCLATURE

_a, %	strain amplitude
_m, %	mean strain
_o, %	upper strain
_u, %	lower strain
FE–analysis	Finite Element–analysis
FRP	fiber reinforced plastic
G, MPa, GPa	shear modulus
Gl–Ep	glass–epoxy
Gr–Ep	graphite–epoxy
HT	high tensile
j	safety factor
k	fatigue slope
ksd#, km	term for a mass related loading in fiber direction of a ±45° shear web
Mt, Nm	torsion moment
n	number of fabric layers
q, g/m_	fabric mass per area unit
rm, mm	mean radius
R = _u/_o	stress ratio
RT	room temperature
s–n curve	strain–load cycle curve

1. INTRODUCTION

The state of certified lifetime for the most modern sailplanes made of composite materials is 12,000 flight hours. Some gliders have, however, already reached this limit. An example is an ASK- 21 that has flown in a club in the U.K. and passed the set limit in 2001 (1). Owners of other sailplanes may not document the complete flight time, fearing the extension of the official service life. In the past, several times intensive service life tests were accomplished in Germany to increase the certified time of flight hours of fiber reinforced plastic (FRP) gliders, raising it first from 3,000 h in the sixties to 6,000 h in the early eighties and then to 12,000 h in the late eighties (2-5).

In the meantime, the knowledge about the excellent fatigue behavior of FRP has grown. Experience gained from test programmes with materials used in sailplanes, light aircraft and wind energy turbines, as well as combined with approaches in lifetime prediction strongly suggest that the possible service life of FRP gliders may still be much longer than allowed at the moment (6-8). Load spectra tests would merely prolong the certified lifetime for a certain amount, however would not be able to prove the FRP-inherent advantageous fatigue properties.

Instead, new tests were made to get more profound information about the possible lifetime by means of a one-step i.e. constant amplitude fatigue test on a spar beam representing a sailplane wing. For this purpose, lifetime information is needed about the materials that transfer the loads in such a structure, i.e. relevant s-n (strain-load cycle) curves especially of the cap and the shear web material. The procedure will end up in a better knowledge on the possible fatigue of a glider in a significantly shorter time than by means of the commonly used multi-load level service life tests.

2. SPAR BEAM STRUCTURE

Six spars were designed and produced by a German glider manufacturer. The box beams had a length of 1.90 m as shown in Fig. 1. A two-point fixture held each beam at two bearings that were located at one end and 0.39 m apart. A single load was applied to the other end of the beam.

The spar caps that were laminated with HT-carbon fiber rovings and had cured separately were bonded to the sandwich core of Rohacell 51. The shear webs were wet-laminated on each side of the core with two layers ±45° oriented plain glass fabric 92115 (finish FK800) from Interglas with the epoxy resin system L335/H340 from MGS.

They overlapped with the caps in order to increase the bonding surface. The spars were strengthened in the area

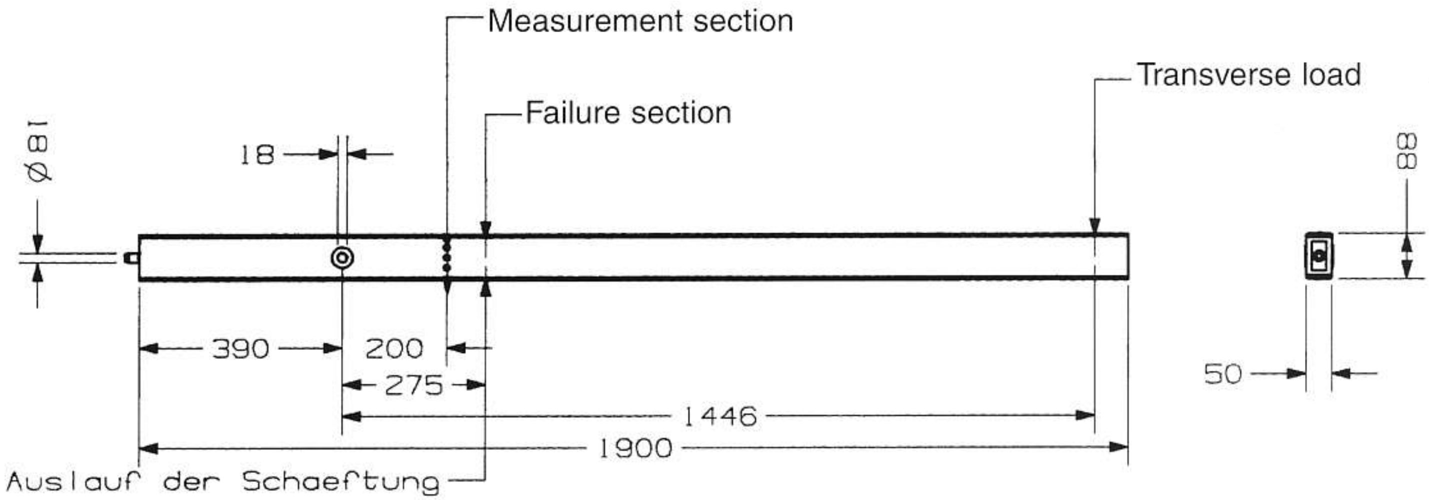


Figure 1: Geometry of spars.

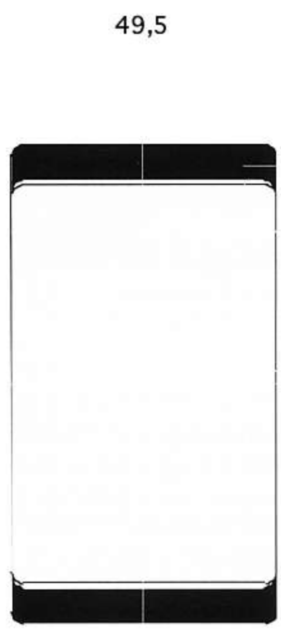


Figure 2: Test section.

The spars were designed for a single transverse load of 6.33 kN corresponding to a safety factor of j = 1 and should fail at more than j = 1.725. The design philosophy was, that in a static test the shear web should fail before the cap, i.e. the maximum design stress of the cap should stay a certain amount below the design allowable. As to the fatigue aspect, it was already demonstrated in (8) that the fatigue evaluation of the spars can be focused on the web material, since a glass–epoxy (Gl–Ep) plain fabric shear web is much more sensitive than a common Gl–Ep spar cap material. This is especially valid for the applied graphite–epoxy (Gr–Ep) material used in the spar caps, since its fatigue slope (k≈30) is considerably less steep than that of Gl–Ep (k≈10) (6).

The design procedure of the web was carried out according to the requirements of the VDI article 2013 (10). In this document the loading term

$$k_{\sigma_{d\#}}[km] = \frac{\frac{kN}{cm}\ \text{shear}\ load}{100\frac{N}{m^2}\ \#\ fabric}$$

where the load was applied and then tapered to 275 mm from the inner transverse bearing. From this position on, the spar had constant dimensions. Thus, it had a defined critical test section where failure was expected and where it was fitted with strain gauges. For the geometry and dimensions of the spars see Fig. 2.

is defined acting in the direction of the ±45° oriented fibers which is related to the load bearing fiber volume. It is anticipated in this approach that the resin matrix does not contribute to the strength.

In case of the spar webs, the term $k_{\sigma d\#}$ is composed mainly by two parts that result from shear loads and spar flange elongation induced by the bending moment. A third

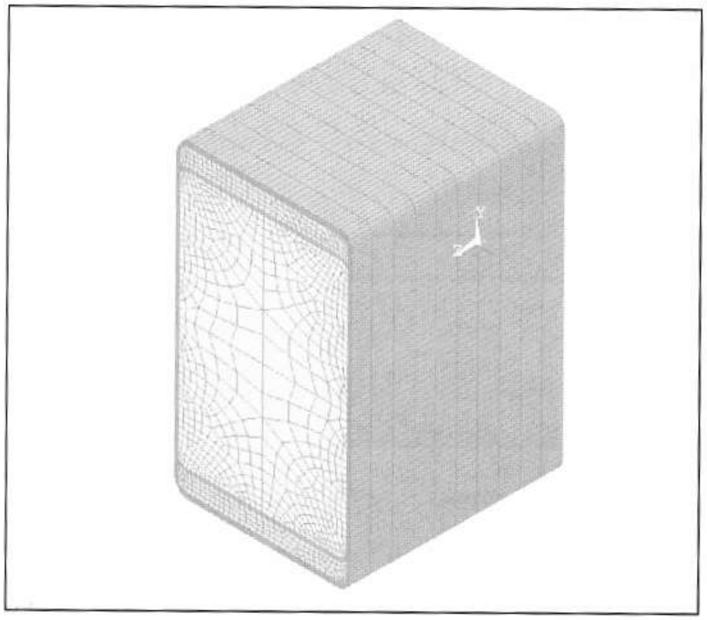


Figure 3: Disk model of FE-analysis simulating the test section of the spar beam.

part caused by the compression load between the cambered upper and lower spar caps which normally plays a minor role, is, however, also regarded. A failure of the web occurs when the sum of the three parts exceeds a critical value (19 km at limit load) and, thus, a fiber is overloaded. In this theory it is of no importance which part contributes more to the failure. Therefore, it was used in a first step for the torsion fatigue investigation on Gl-Ep tubes with ±45° lay-up as described in 4. where the $k_{\sigma d\#}$ value is represented by pure shear loads.

For a sound fatigue evaluation it was decided to install a number of strain gauges at the spars and the statically tested tubes. A comparison of the strain measurements on the spars and the tubes at the defined limit load case ($k_{\sigma d\#}$=19 km) have shown significantly different values. This can be explained by the applied VDI 2013 procedure which does not consider the influence of the foam core stiffness (G ≈ 30 MPa) which in our case is very high filling the whole area of the box beam. Thus, the new reference value of $k_{\sigma d\#}$ in the spars is 13.12 km that results from the ratio of the measured strains in the tubes to the corresponding strains in the spars.

The strain gauges on the spars were distributed over the height of the cross section of spars 1 to 4 in order to get information about the strains close to the spar cap. This was also useful to compare the results with those of an FE-analysis (9) which was done parallel. The geometry of the beams as well as the material properties were considered in the FE-analysis. The test section was modeled as a disk, see Fig. 3.

The strains and stresses were calculated at the limit load (j=1). There was good agreement between the calculated strains and the measured ones described in Chapter 3. Figure 4 presents the calculated distribution of the com-

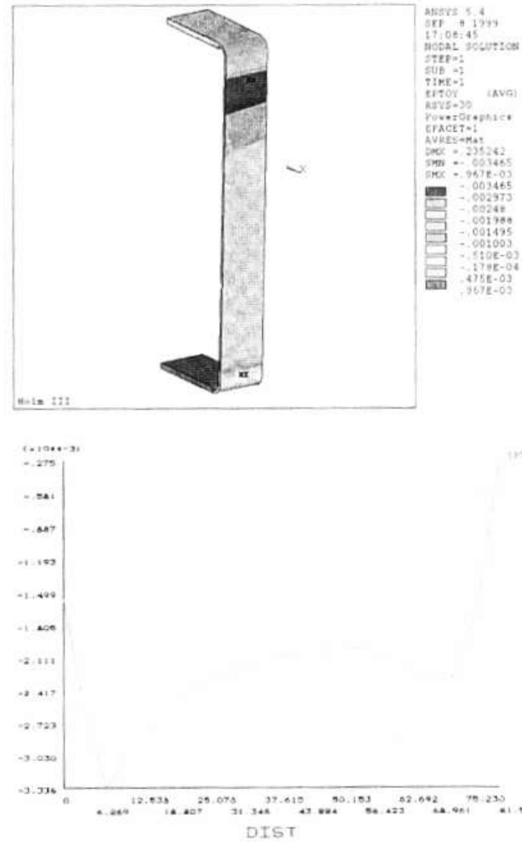


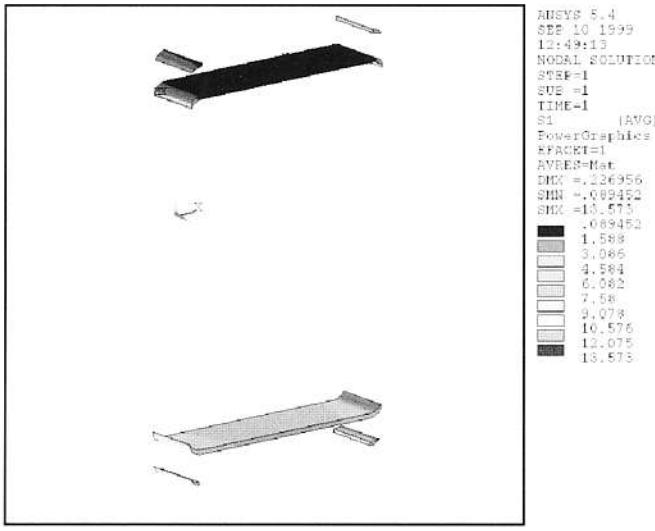
Fig.: 4: Compression straings in the web fabric, 45° to spar parallel axis (illustration 90° twisted.

pression strains versus the height of the beam of the web fabric at an angle of 45° to the spar-parallel axis, i.e. in fiber direction of the ±45° web lay-up. While the loading capacity of the perpendicularly oriented fibers in the middle of the shear web is well balanced, it is biased in the area close to the spar cap due to the bending induced strains in the outer phase of the spar beam.

Although the shear web is highly endangered to fail earlier due to fatigue than the spar cap the FE-analysis also shows other critical design areas. On the upper cambered surface, large radial tensile stresses exist along the longitudinal edges of the glass-epoxy lay-up of the test section. Additionally, the principal stresses between foam, caps, and shear web are so large that premature cracks can occur in the matrix due to fatigue, see also Fig. 5.

3. SPAR BEAM TESTS

The 6 spars were investigated in an assembly, which has been well proven in other static and fatigue investigations on similar structures. It is suitable for testing individual spar components or two simultaneously in a twin test bed (e.g. for time consuming load spectra tests), see Fig. 6.



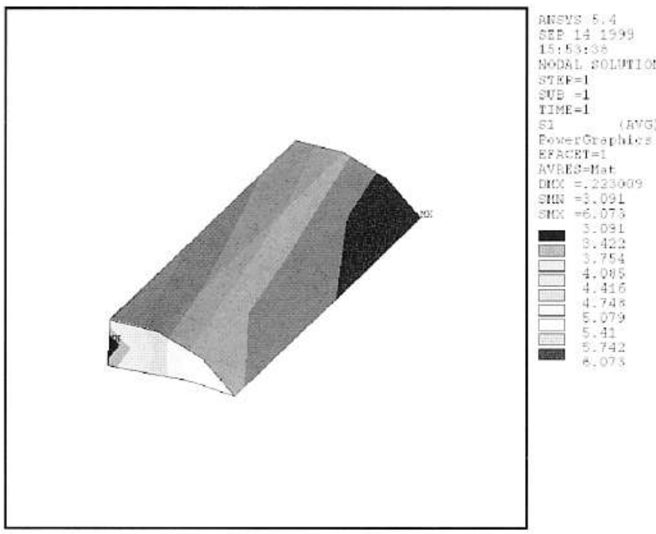


Figure 5: Principal stresses in the adhesive.

At first, two spars were tested statically at 54°C in order to show that design and manufacturing had been done properly. Then the spars No. 3 and 4 were fatigued with the load spectra standard KoSMOS2 (11-13) and tested individually for residual strength at 54°C.

Finally, one-step fatigue tests were carried out on spars No. 5 and 6 until the first failure occurred.

The static fracture tests were carried out at the first spar components according to the normal procedure: j=1 at room temperature (RT), then j=1 at 54°C and finally the fracture test at 54°C. Both spars showed a sufficiently high safety factor of about 1.725 with respect to the design allowable of the shear web. Fig. 7 shows the failure of spar beam 2 close to the critical test section.

The second pair of spars was tested with KoSMOS2 (11-13). This version of the load spectrum standard has an omission of all loads below ±7.14%. One life cycle corresponds to 6,000 flight hours. Before, during and after the fatigue investigation, static tests at room temperature (RT) to the design load were carried out. After a simulation of 36,000 flight hours no stiffness change could be detected and the tests were continued to 72,000 flight hours again without any stiffness change. In the static residual strength tests at 54°C a safety factor of 2.0 was reached for both components, more than the uncycled ones.

The strain measurements at these 4 spars showed that the spar caps had the intended low strains. The absolute averaged design reference strain in the shear web evaluated by the 45° strain gauges that was closest to the spar caps, was about -0.35%. This is in good agreement with the results of the FE-simulation. For lifetime calculation, this value must be compared with the corresponding strain in the torsion tube tests, see Figure 4.

The one-step fatigue tests were accomplished on the spars No. 5 and 6. The maximum positive load was the design load (6.33 kN), whereas the negative load corresponded to that from the v-n diagram (utility category) and KoSMOS2. For spar No. 5 an R-value of –0.55 was chosen, for No. 6 R = –0.5. In contrast to the other 4 spars, these spars were supplied with strain gauges only on the flanges and at the center of the webs. The lack of information was admitted, since the structural behavior was expected to be quite similar to the other spars.

The fatigue tests were carried out with a frequency of 1.5 Hz. Static inspection tests gave the information about first signs of stiffness degradation. The loads, deflections, and strains at the caps and the web were documented. Additionally, the spars were inspected continuously by eye, especially near the edges of the test section.

Spar beam No. 5 was loaded until 486,200 load cycles at R = -0.55. After that the test was stopped due to a failure of a steel fitting at the end fixture whose repair was difficult. After about 10,000 load cycles some small cracks started to occur at the edges of the tensile spar cap in the area of the adhesive (filler-thickened resin) between foam, cap and shear web. The number of cracks increased linearly with lifetime. At 34,700 load cycles, a delamination flaw occurred in the edge between compression cap and the web laminate, which did not propagate later on. These events can be explained with the high stresses in that area shown in the FE-calculation. Spar beam No. 6 was loaded in a similar procedure at R = -0.5. After about 68,000 load cycles, the test had to be stopped, because the relative brittle foam started to fail (friction noises). This could have eventually led to a buckling failure of the shear web.

The crack formation of the adhesive was similar at both spars. As an example, Fig. 8 gives a view at the described area of spar No. 6 after about 10,000 load cycles, where very few cracks were merely visible (see dashes at lower edge).

The Figures 9, 10 and 11 show plots of the deflection, the strains in the shear webs, and in the caps of spar beam No. 5 versus the number of load cycles.

The static tests of the spars were a good means to detect the starting point and the possible cause of stiffness

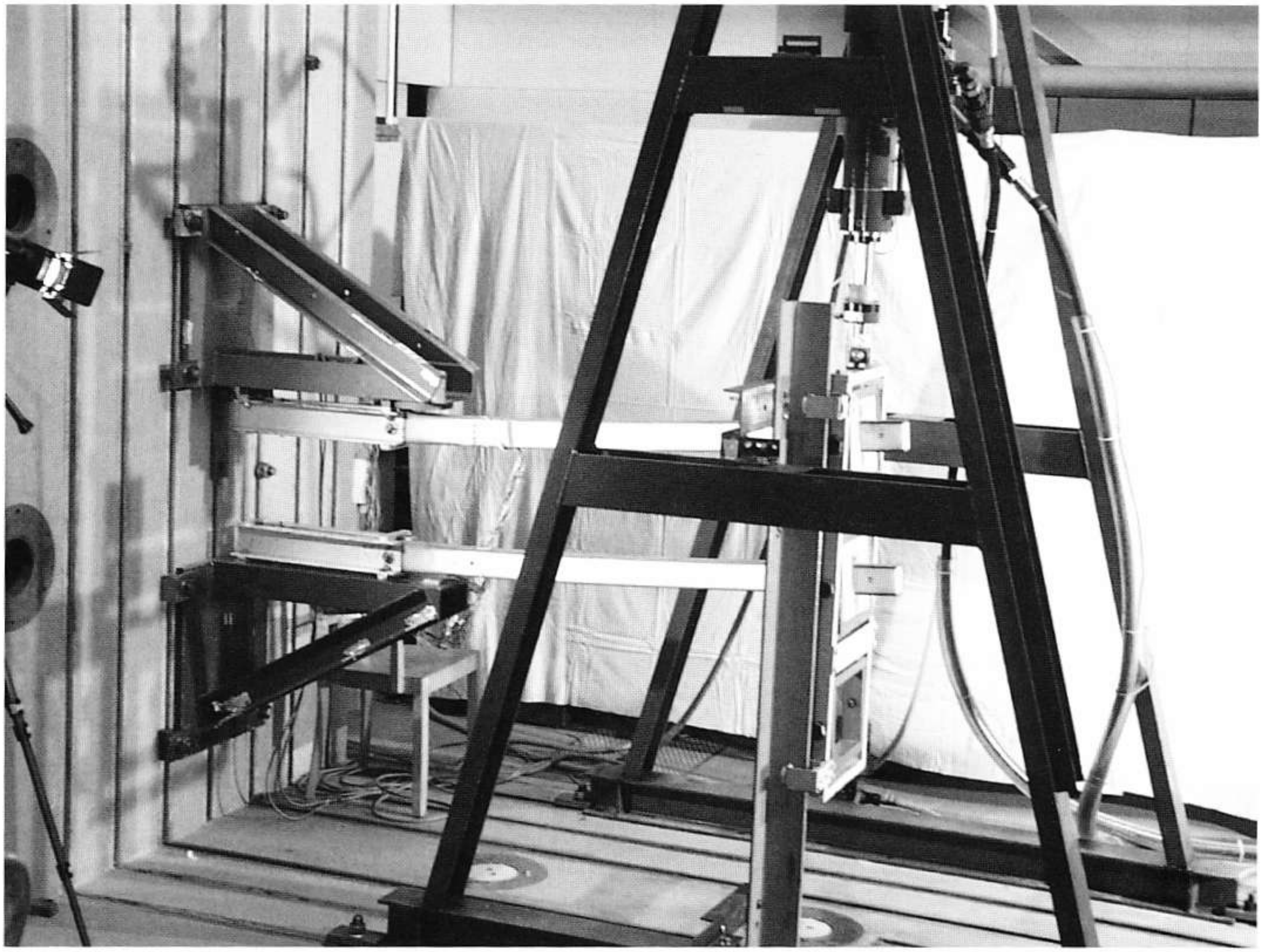
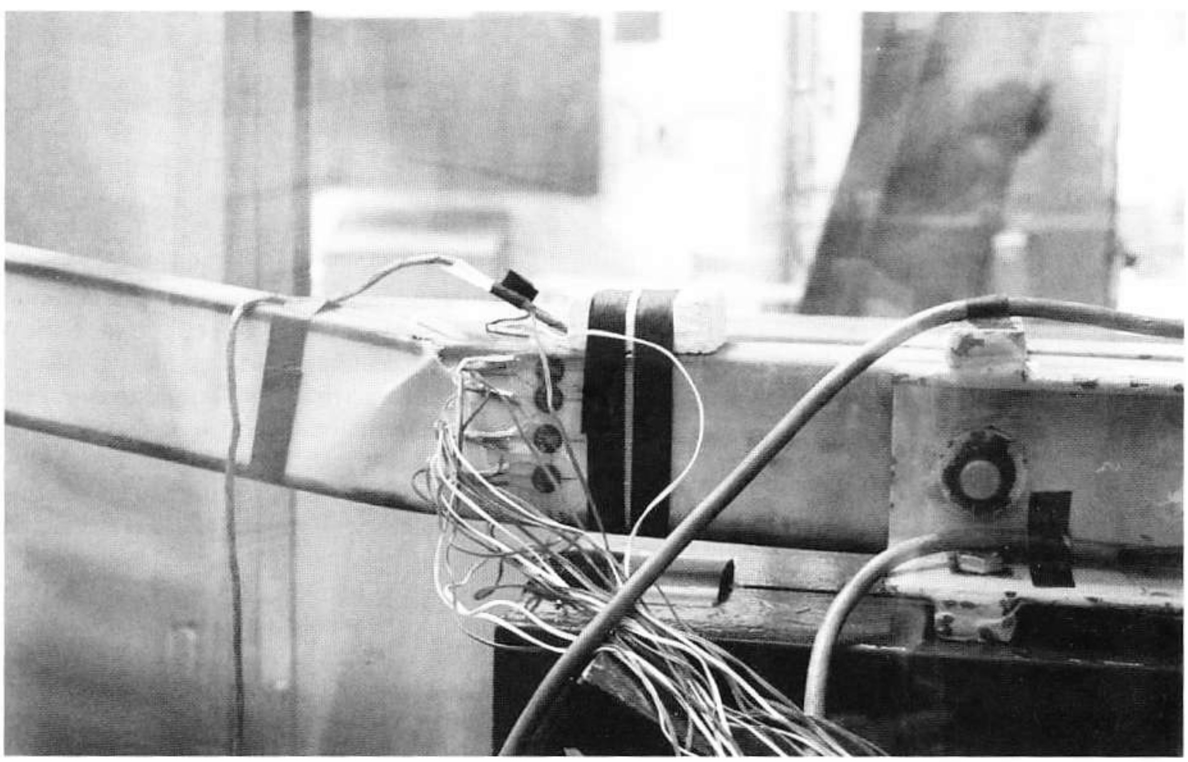


Figure 6: Test bed with two simultaneously tested spars.

Figure 7: Fracture of spar beam 2



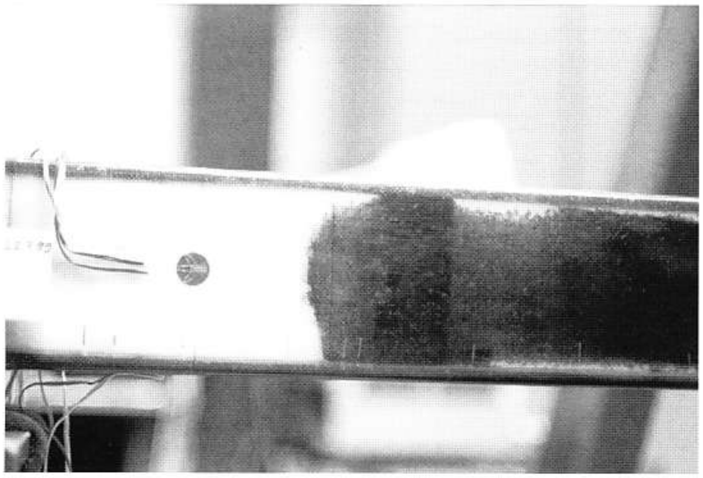


Figure 8: Cracks in the adhesive of the (lower) tensile cap area of spar beam 6 after 10,000 load cycles marked by dashes at the lower edge.

change. It is obvious that the beginning is relatively early compared to the total lifetime. The deflection does not change significantly before 30,000 to 50,000 load cycles are reached, see Fig 9. After 20,000 load cycles, the strain-measurement results of the shear web and the caps that are shown in Fig. 10 and 11 reveal a fatigue behavior that is more likely due to strain gauges failing than due to the spars themselves. Because the gauges were not replaced early enough with new ones, the last static test provides the only prove for this, since the signals of the new gauges present the true behavior of the spar. While the signals in Fig. 10 indicate a weakening of the shear web, those of the spar caps in Fig. 11 do not show any change of stiffness.

The different changes in stiffness of the various spar components can be explained with the fact that the graphite-epoxy spar caps are not as critical to fatigue as the glass-epoxy web-material. The apparent decrease of the shear web stiffness may be influenced by the described crack formation in the adhesive. The combination of both effects leads to the increase in spar deflection. In summary, no significant rise in stiffness was observed for either test spar up to 30,000 load cycles.

4. LIFETIME EVALUATION

It was demonstrated in (8) that the lifetime of the web material is some orders of magnitude lower than that of the spar caps. The experience from the spar beam tests shows that the shear web (including its connection to the spar cap) seems to be the weak point of the structure. (8) also lists curves of the fatigue behavior of glass-epoxy tubes that have the same lay-up as the web material of the test spars. The tubes were subjected to cyclic torsion loads. Whereas, however, (8) presents the test results in terms of shear

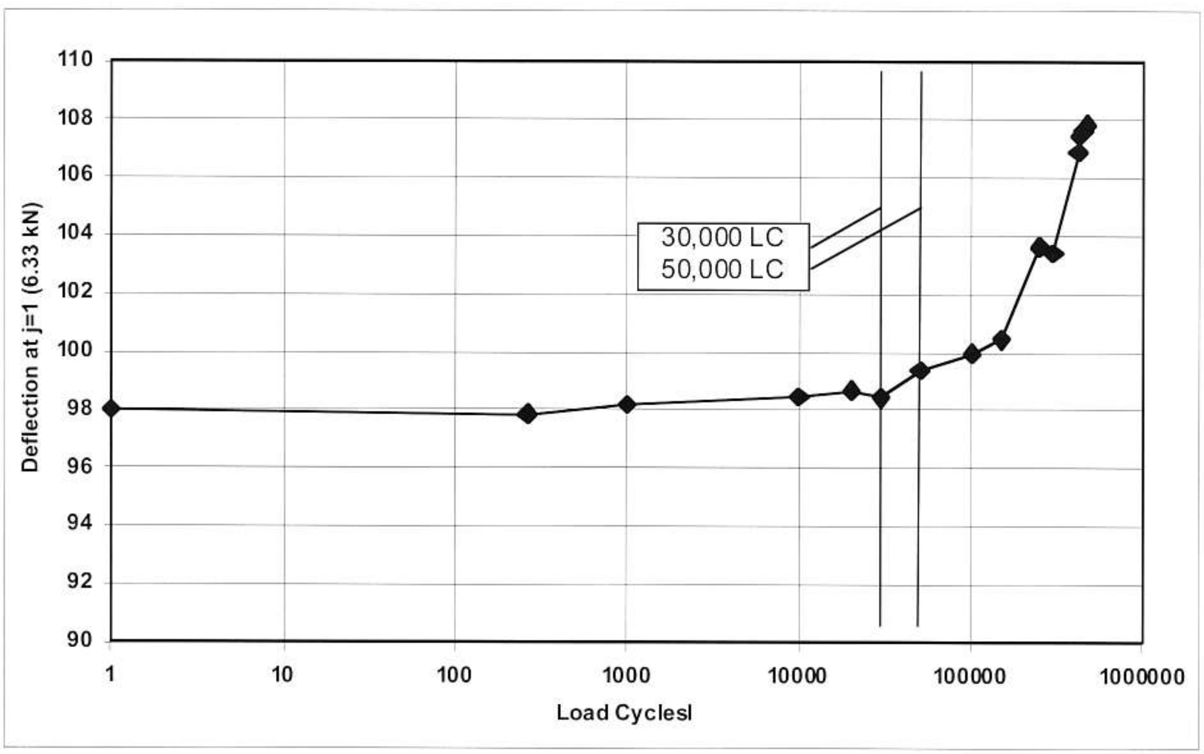


Figure 9: Spar beam 5, deflection versus load cycles.

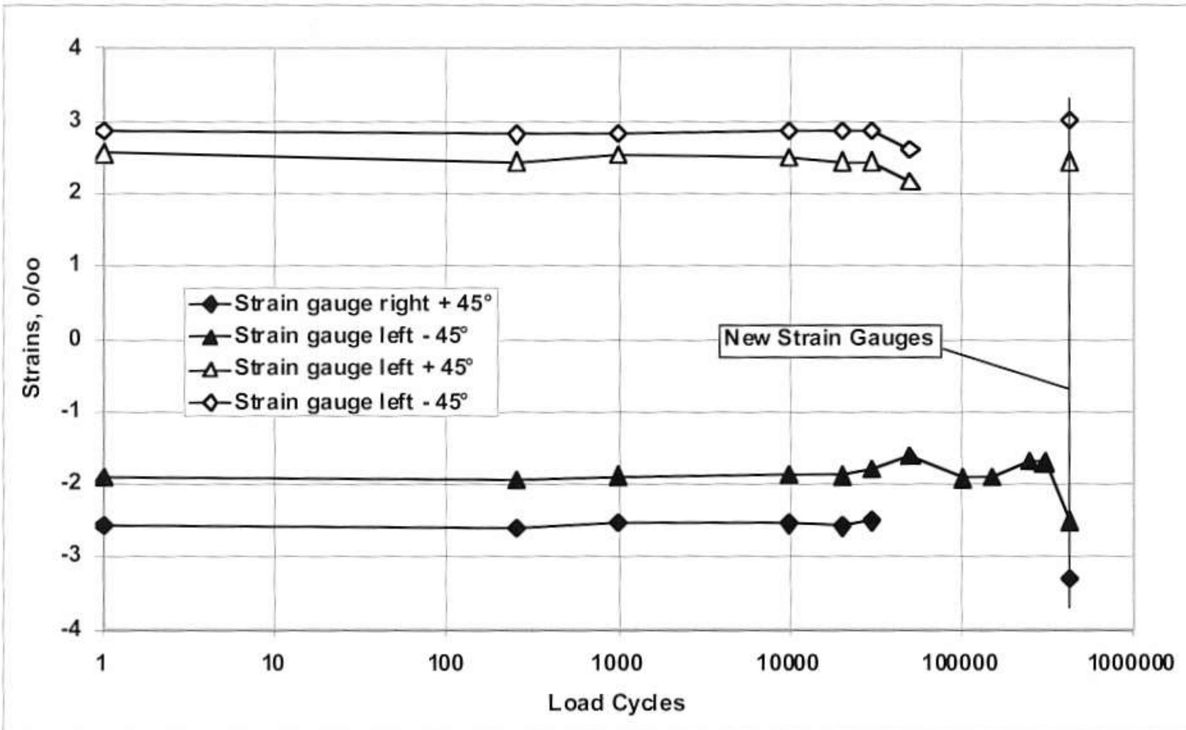


Figure 10: Spar beam 5, strain in shear webs versus load cycles.

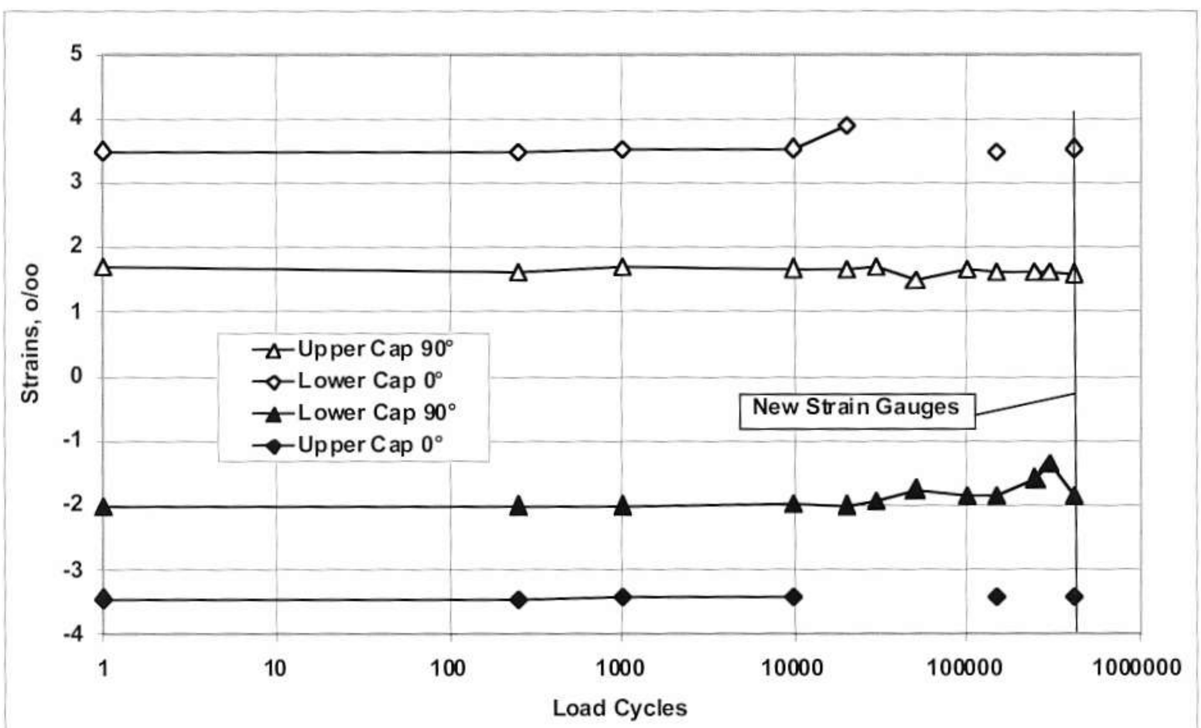


Figure 11: Spar beam 5, strain in spar caps versus load cycles.

stresses (MPa), the presented values herein are in terms of strain (%) in order to rule out a dependency on fiber content, which influences the stress levels. Additionally it allows a cross reference with the strains that were observed in the shear webs of the spars.

As described in 2., the $k_{\sigma d\#}$-value of the tubes is produced by pure shear loads:

$$k_{\sigma d\#} = M_t / nq\pi rm^2$$

with torsion moment M_t, n number of fabric layers, a fabric mass per m^2 q and a mean radius r_m.

The strain that was measured in the ±45°-fibers of the statically tested torsion tubes at $k_{\sigma d\#}$ = 19 km (design limit value) was slightly more than 0.5%. However the reference strain in the spars was about 0.35%, thus yielding a maximum $k_{\sigma d\#}$ = 13.12 km (see also 2.). This value will be the basis for the lifetime consideration of the spar web.

Fig. 12 shows the s-n curves for ±45° fiber-glass epoxy tubes that were subjected to torsion loads with stress ratios of R=0.1 and R=-1. The fabric as well as the epoxy resin L335/H340 are identical to the material that was used in the test spars. The stress or strain ratio, R, is the ratio of the minimum strain, εu, over the maximum strain,εo, that the test specimens were tested with for the load-cycle diagrams.

Fig. 13 represents the corresponding constant-amplitude-life (Haigh-) diagram, which is used for the lifetime calculation.

On the basis of the theory described in (7), a lifetime prediction was carried out for the tubes. The results of the maximum strains in the ±45°-lay-up versus the cycles according to KoSMOS (1 cycle = 6,000 flight hours) are shown in Fig. 14.

The lifetime at a maximum strain of about 0.35% can be obtained from this chart assuming that this kind of lifetime prediction also applies to the fatigue behavior of the web material near the caps. It is about 6,500 cycles of KoSMOS, which corresponds to 39,000,000 flight hours.

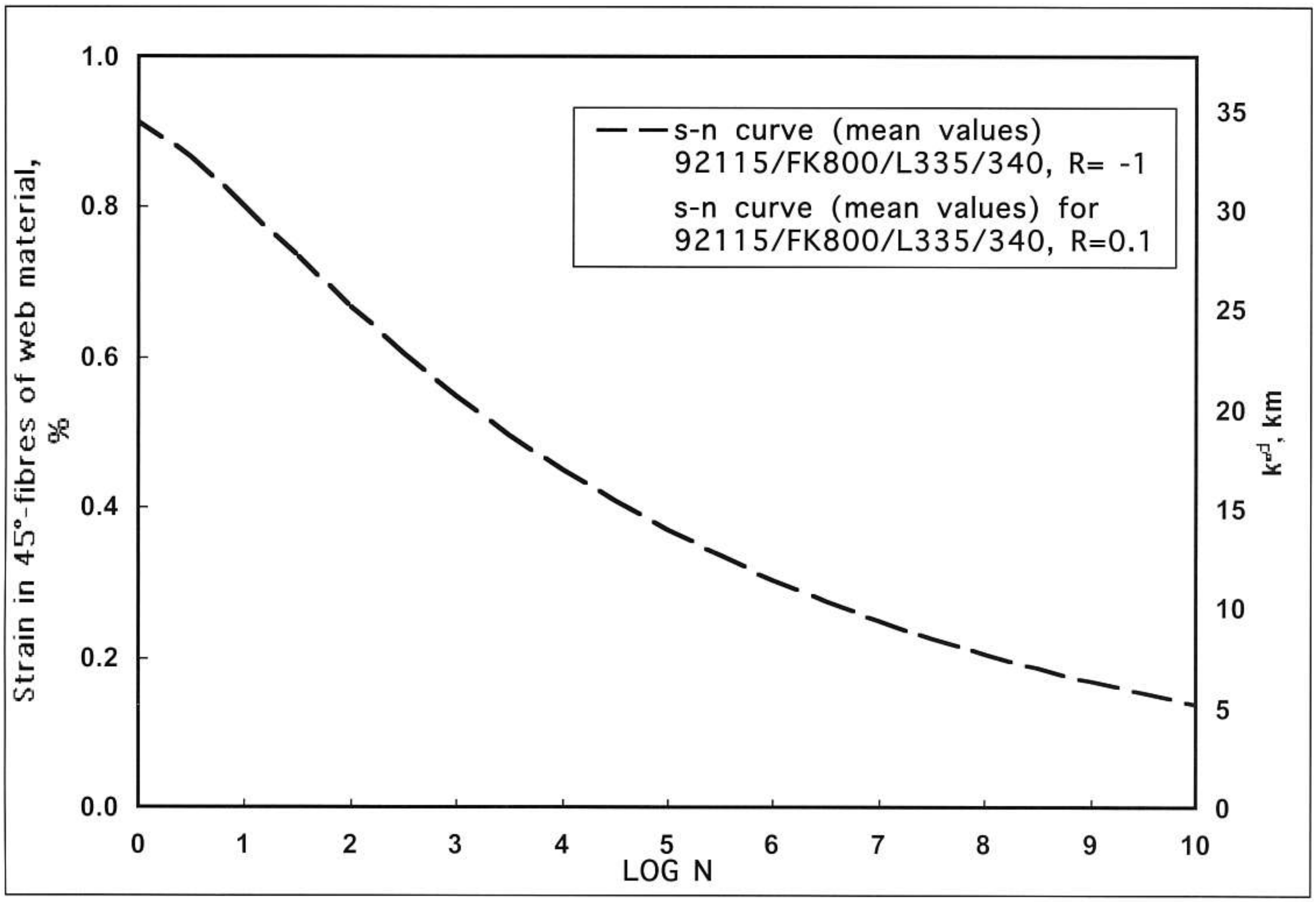


Figure 12: s-n curves of torsion tubes (92115/FK800, L335/H340) with ±45° lay-up for R=0.1 and -1, mean values.

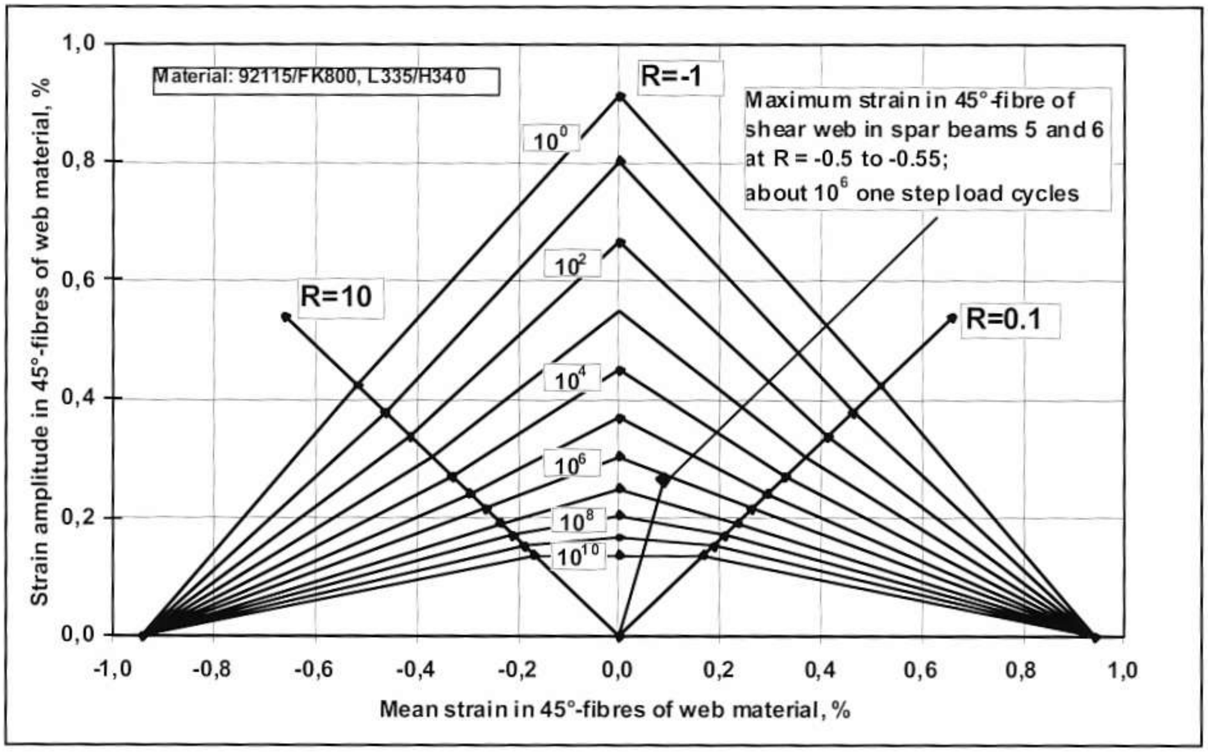


Figure 13: Constant amplitude life (Haigh-) diagram of torsion tubes (92115/FK800, L335/H340) with ±45° lay-up, mean values.

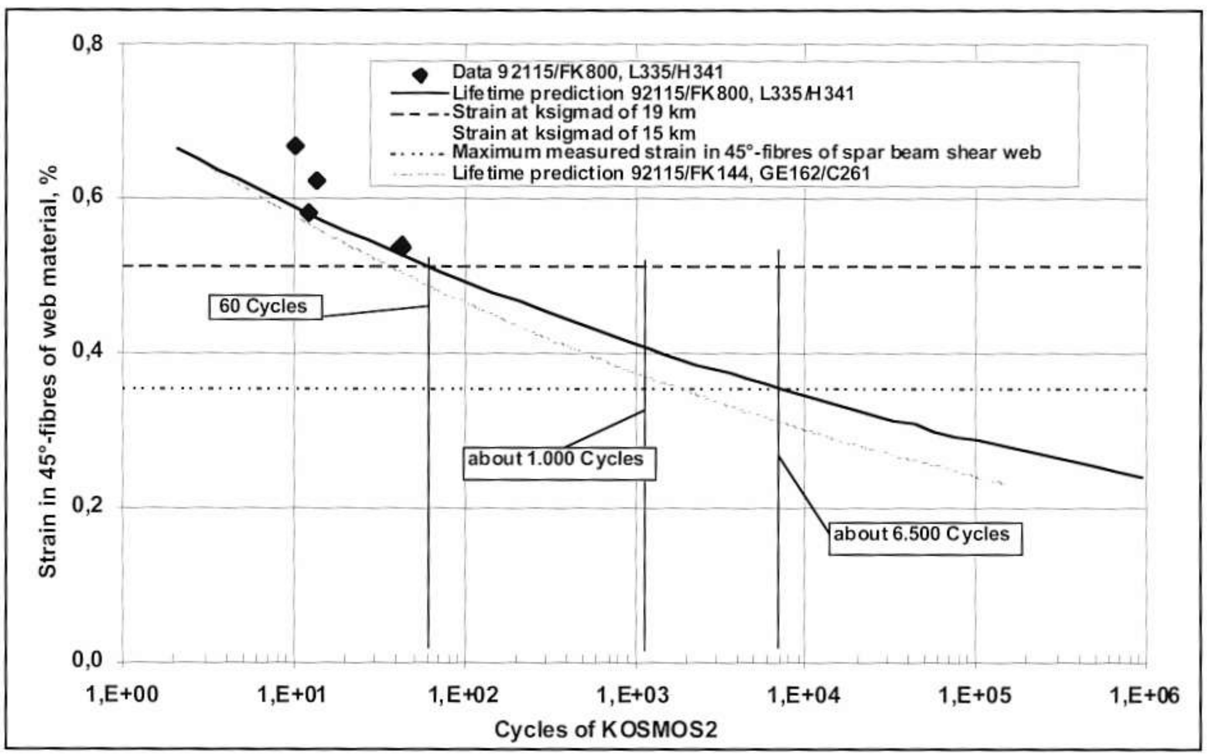


Figure 14: Lifetime prediction and test results of Gl-Ep torsion tubes with ±45° fabric lay-up, mean values.

The equivalent number of one-step load cycles can be found by plotting the mean and amplitude strain with the maximum applied strain of__o=0.35% and a stress ratio of R=-0.5 or –0.55 into the Haigh-diagram. The resulting figures are

_m = (_o+_u)/2 = (_o+R*_o)/2 ª 0,088%

and

_a = (_o-_u)/2 = (_o-R*_o)/2 ª 0,265%

They intersect with the R = –0.5 or –0.55-radials at about 1.000.000 load cycles, see Fig. 13.

The lifetime prediction was performed using the mean values (50% probability of survival) of the measured data. It can be assumed that the investigated spars possibly have achieved lifetimes close to the theory, because no composite related failures were observed when the tests were terminated for other reasons. Thus, it can be concluded that the experiment and the theoretical prediction are in agreement.

The results with the test spars can only be related to the s-n curves of torsion tubes that are of the same composite material. Many sailplanes are manufactured with Interglas fabric with FK144 sizing and the resin system GE 162/C260 from Shell. In order to be able to compare the fatigue life predictions of the two different composite materials, the relative fatigue-load-cycle curve of the composite with the FK144/GE162/C260 version is also plotted in Fig. 14. This data is based on experimental results with torsion tubes, which are shown in Fig. 15. It shows a slightly lower fatigue life than the tubes with the other sizing and resin system. The curves would be closer and intersect at a lower strain when the properties are related to ksd# and not to the strains. The reason seems to be in the stiffness of the matrix which is not considered in the VDI 2013 approach.

For comparison, Tab. 1 shows the correlation of the strain and the shear modulus for the two materials at ksd# = 19 km.

Fabric	Matrix	Strain, %	G, GPa
92115/FK800	L335/H340	-5.045	9.76
92115/FK144	GE162/C260	-4.851	10.59

Tab. 1: Strains in fiber direction and G-Modulus of ±45° plain fabric Gl-Ep tubes at ksd# = 19 km

The slightly smaller modulus of L335/H340 causing a higher ductility could be a reason for the better fatigue behavior of this laminate.

5. CONCLUSIONS AND OUTLOOK

The question was investigated whether one-step fatigue tests on the spar structures can be used to get useful information about the possible lifetime of a sailplane. Additional to the experiments on six spars, fatigue tests on torsion tubes were carried out. They simulate the Gl-Ep shear webs, which are the weakest component of a spar beam. The lifetime prediction that is based on the fatigue curves and the sailplane load spectra standard KoSMOS, suggests $39*10^6$ possible flight hours with a maximum reference strain of about 0.35% in the 45°-fiber direction. This is the average strain from the measurements with the four

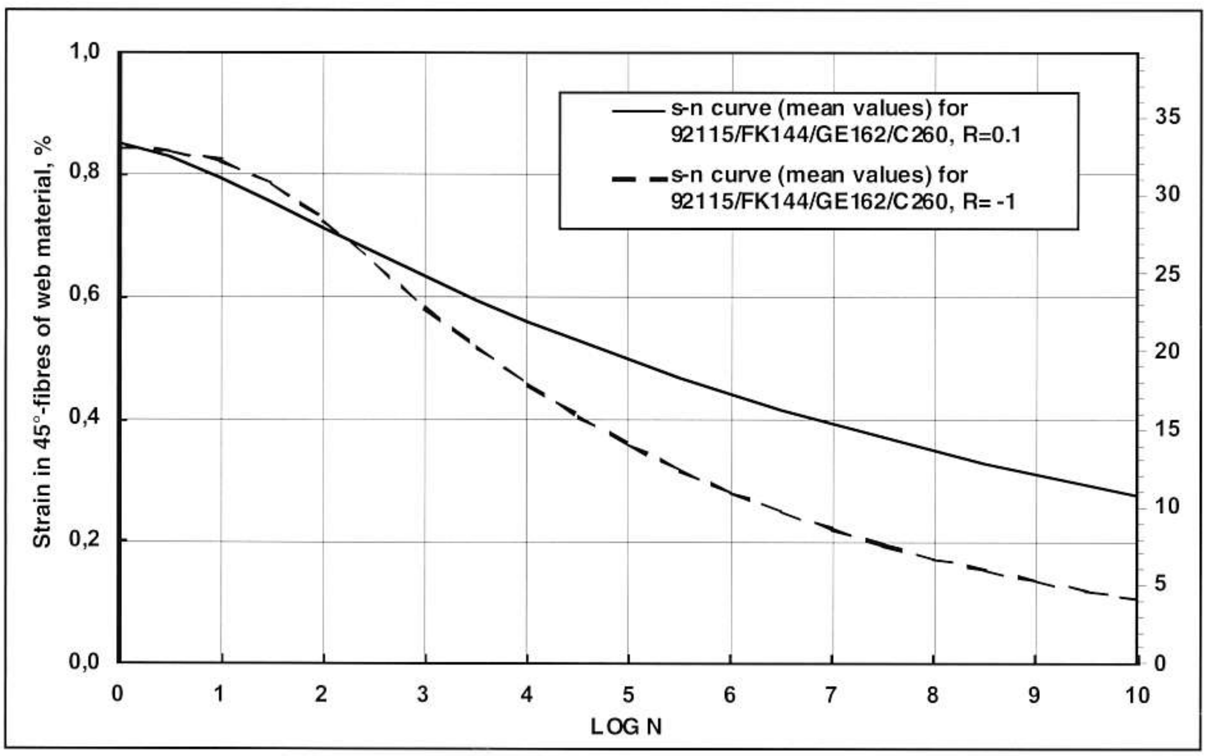


Figure 15: s-n curves of torsion tubes (92115/FK144, GE162/C260) with ±45° lay-up for R=0.1 and -1, mean values.

test spars. The theoretical lifetime equivalent was found to be about 106 load cycles in a one-step test.

Two spars were loaded in a static fracture test at 54°C up to the required safety factor of 1.725. Two other spars were fatigue tested with the standard KoSMOS to 72,000 flight hours without any stiffness change. Both demonstrated in a residual strength test at 54°C a high factor of safety of 2.0.

Next two spars were fatigued in a one-step test at the reference strain of 0.35%. These tests had to be stopped because of the failure of a steel fitting at one structure with about 0.5*106 load cycles and about 0.07*106 load cycles at the other where the sandwich core foam failed too early. Nevertheless it was demonstrated that at least about half of the predicted lifetime can be achieved if premature failure other than in the primary composite structure could be avoided. Thus, the used approach of lifetime prediction seems to be a future possibility for the approval of a higher service life for sailplanes and light aircraft. It should be accompanied by data on crack formation and possible stiffness degradation.

For structures with the imposed strains, the most important results of the investigation can be summarized in the following:

- In the one-step tests to the limit load at R ª -0.5 no significant stiffness change was observed until 30,000 load cycles.

- At 10,000 load cycles, first delaminations or crack formations started in the adhesive material, i.e. no visible signs of fatigue before that.

- Following the theory, 10,000 load cycles correspond to about 390,000 flight hours.

- No fatigue could be detected at the spars tested by the KoSMOS standard load spectrum to 72,000 flight hours.

- Those spars showed a safety factor of 2.0 in a residual static strength test at 54°C.

- Hence, a lifetime of 50,000 h can be recommended with a high safety factor on life.

However, in sailplanes, the limit design ksd# is normally higher than in the tested spars since less foam core material is used than in this program. As an example, the ASK 21 mentioned in (1), has a maximum ksd# of about 15 km corresponding to a reference strain of slightly more than 0.4%. According to Fig. 14, this would lead to 1,000 cycles of KoSMOS. Furthermore, this glider is manufactured with the resin GE162/C260 from Shell and Interglas fabric with FK144 sizing. Using the corresponding curve in Fig. 14, 400 cycles of KoSMOS are equivalent to 2,400,000 flight hours.

The use of plain fabric in the shear webs of a glider could be critical, however, when the spar would be designed to the allowable of ksd# = 19 km. As shown in Fig. 14, this would result in 60 cycles of the KoSMOS spectrum or 360,000 flight hours, but this will not be a problem, since in most cases sailplane wing spars have twill fabric in the highest loaded parts of the shear webs. As shown in (8), twill is much less fatigue sensitive than the plain fabric that was used in the herein introduced investigation.

There were several conservative design aspects in the tested spars. Besides the use of plain instead of twill fabric, the box beam design is also suboptimal. The sandwich foam was brittle and failed too early. The high amount of stiff core material hampered the desired high loading of the shear webs. Additionally, the load introduction points should be strengthened such as the steel fittings which are liable to fail earlier than the investigated composite.

More experience is therefore desirable, for example:

- The testing of more structures to get a better statistical evaluation of data.

- The testing of more realistic or optimized designs of spar beam structures.

- The investigation of complex stress situation in the shear web.

6. ACKNOWLEGMENT

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