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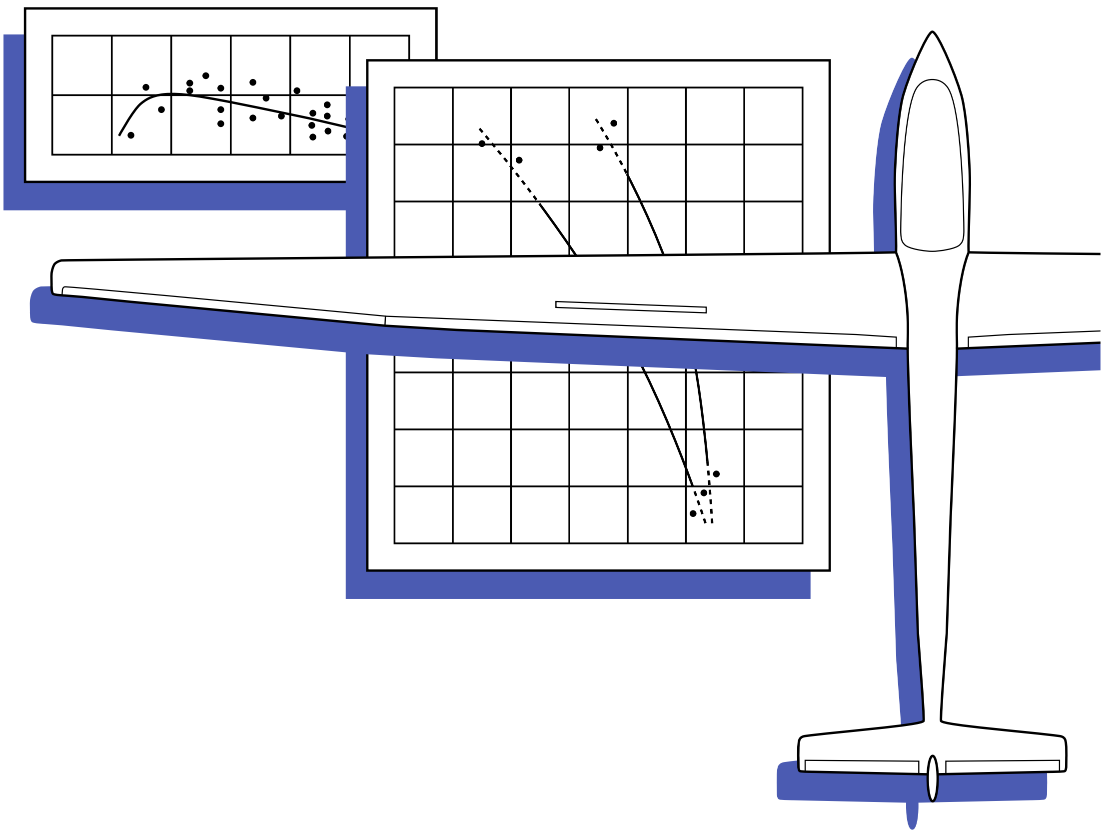

• **Numerical Comparison of Glider Load Spectra**

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From the Editor

Publication Date

This issue is the fourth of Volume 43 of *TS*, corresponding to October-September 2019. For the record, the issue was published in October, 2020.

About this issue

Aerodynamics is often seen as the main driver for performance improvements of gliders since it determines the most important parameter, the glide ratio. But without progress in other engineering disciplines, such as lightweight construction, further enhancement of L/D, for example by increasing the wing aspect ratio, is not possible. Within this context, the following article by Christoph Kensche deals with the lifetime calculation of fiber reinforced glider structures. A highly important issue for future sailplane designs. Enjoy reading "Numerical Comparison of Glider Load Spectra".

Very Respectfully,

Arne Seitz
Editor-in-Chief, *Technical Soaring*
ts-editor@ostiv.org

Numerical Comparison of Glider Load Spectra

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Abstract

Eight glider load spectra which were developed in Germany, Australia and Poland were investigated numerically. The original data commonly used for the presentation of a cumulative frequency distribution were ordered in the scheme of a 29x29-Markov transition-matrix. For the individual lifetime assessments, fatigue data of glass and carbon fibre composites representing the girders and shear webs of wings have been considered. The damage accumulation was performed according to the linear Palmgren-Miner rule. The lifetime was calculated for different maximum design values of the composite materials used. It became obvious that, at equal design levels of the materials, the lifetimes can differ between 2 to 5 orders of magnitude in relation to the load spectrum and the material. It was also shown that the KoSMOS-spectrum is among those yielding the most conservative results and, thus, rightly the recognized OSTIV-standard.

Introduction

[1] Typical life load spectra for sailplanes have been developed over the past 50 years in Germany, Poland and Australia for the purpose of proof testing the composite life of the highly loaded structures. Since the illustration of the pure data at a glance is not very informative, the spectra commonly are presented as a cumulative frequency distribution like shown in Fig. 1.

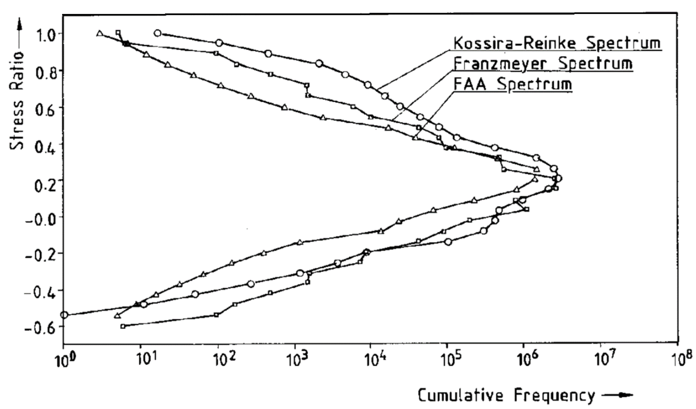

Fig. 1: Typical presentation of a cumulative frequency distribution for light aircraft.

This is a very descriptive and well proven method to compare different load spectra qualitatively. But when asking for the difference in their damaging character this type of presentation does not seem to be very helpful. It even can result in a misleading prediction of the respective damaging influence. Those plots just show the envelope of the upper and lower loads in the life history of a spectrum, irrespective of the actual amplitudes and their mean. Additionally, the influence of the fatigue data of the materials used in the gliders' load carrying structure is not reflected.

Fatigue data of GFRP and CFRP (Glass- and Carbon Fibre Reinforced Plastics) have not been available in the beginning of the application of composite materials and their development and investigation started only slowly. Over the years, however, a profound data base has formed and can be found in literature, and some of it can be referred to the composite material used in gliders, see e.g. [1, 2]

Some attempts have been accomplished in the meantime to predict a theoretical lifetime on the basis of the data of some individual spectra and material fatigue data, [3–5]. However, an objective comparison of the different available spectra was not performed.

For this investigation, the method described in [3] is applied. The computer code was developed at the German Aerospace Center DLR and proof-tested in a benchmarking task for the European Union funded wind energy project OPTIMAT Blades, [6, 7]. In practice it was also used in the vein of prolongation of the life of the ASK21 described by Gerhard Waibel in his paper "Safe Life Substantiation for a FRP-Sailplane", [8].

Service life spectra

Franzmeyer block program

The first service life spectrum used by the German aviation authority (Luftfahrtbundesamt, LBA) for certification of composite gliders is generally a multi-step program which was developed in the sixties by Franzmeyer, based mainly on theoretical assumptions about the loads and their frequency during 1.000 hours of flight time, [9]. The mission profile considered

[1]This article has been reviewed according to the *TS* Fast Track Scheme.

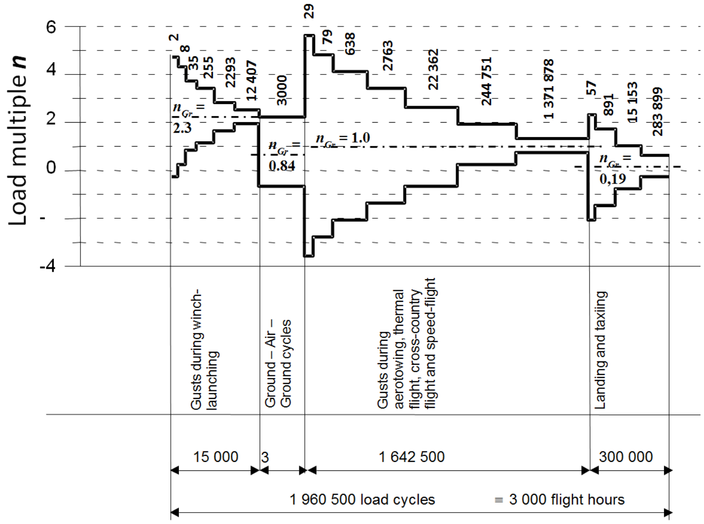

Fig. 2: Franzmeyer-block program.

cyclic loads by gusts in winch launching, take-off and landing, aero-towing and cross-country flight as well as landing impacts and taxiing, see Fig. 2. For a certification by test, a scatter factor of 3 has to be applied upon lifetime. Thus, to allow for a certified flight time of 12.000 h (what is nowadays the limit), the block-program has to be repeated 3x12, i.e. 36 times. The Franzmeyer-program (in the following diagrams referenced as "A") is still recognized by the LBA for the certification of gliders. It can be considered as the "grandfather" of a row of other sailplane spectra.

KoSMOS spectrum by Reinke and Kossira

A new way of establishing a spectrum was followed in 1980/81 by Reinke and Kossira from the Technische Universität Braunschweig in Germany, [10–13]. Scientifically guided by W. Reinke, flight measurements with a Janus were carried out. The data of the individual flight phases were extrapolated to a defined flight time and, by combining all of them, the envelope of all flight phases was developed representing 6000 h of simulated flight time. Thus, all different types of operation for the aircraft during its life time were covered. In difference to Franzmeyer, the various flight missions were classified especially by adding e.g. school- and training flights, cross-country flights in the high-mountain area as well as lee-wave flights. When plotted together, the Franzmeyer-collective – extrapolated to 6000 h – and the envelope of the measured flights showed a "rather good approximation", [10].

The data of the flight measurements were stored in a 32x32-Markov transition-counted matrix with the class 1 (bottom line) for the maximum possible load. In a first step the matrix was established for flights without aerobatics. Then it was rearranged by implementing 750 hours (12.5%) of aerobatic flight. And finally, the service life matrix "KoSMOS" was designed which considered also motor flight of FAR 23-aircraft. For time saving purposes during testing, two different configurations were created by a 5.36% load omission for KoSMOS 1 and 7.14% for KoSMOS 2. From these spectra, a time history was configured by means of a random number generator establishing the service

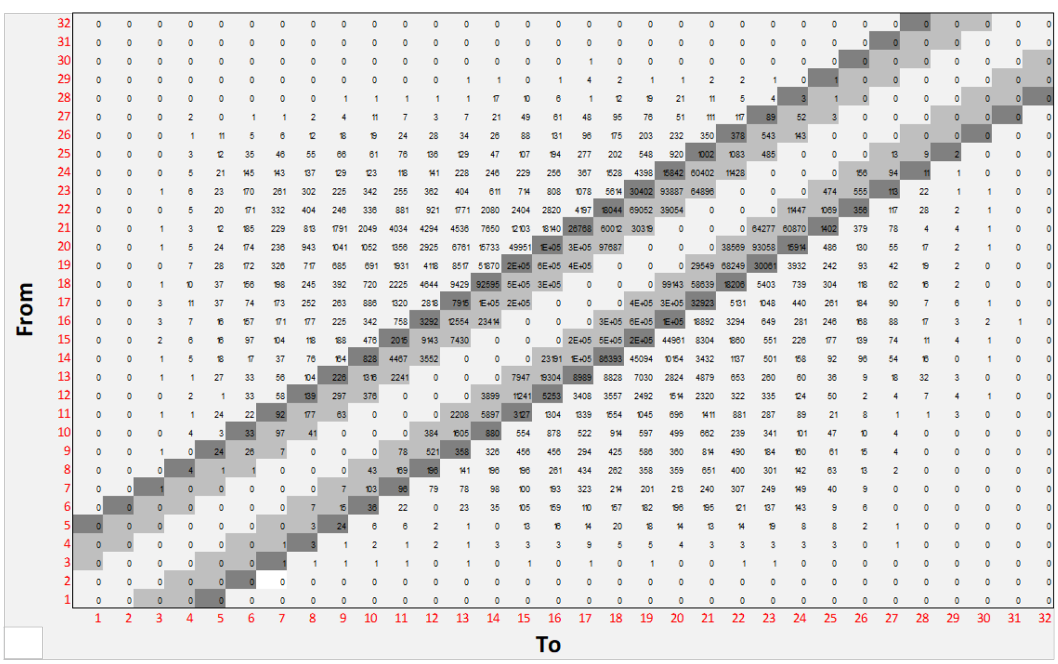

Fig. 3: Markov-transition matrix for KoSMOS, the differently shadowed cells represent when set to 0 the omission of 5.36% for KoSMOS 1 and 7.14% for KoSMOS 2.

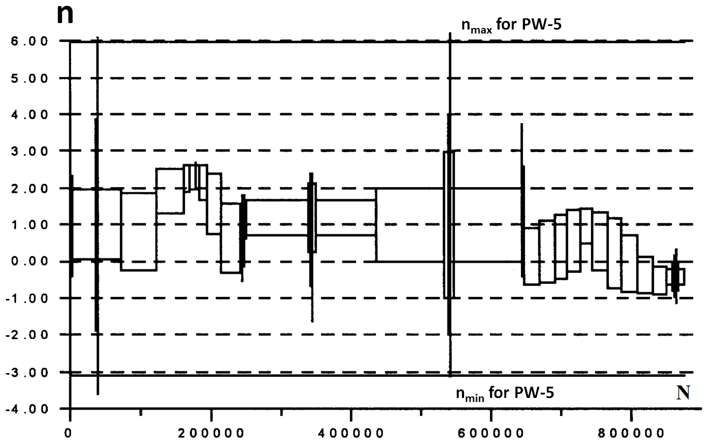

Fig. 4: Block program for the SZD-51-1 "Junior" and the PW5 "Smyk", [16].

life spectra "KoSMOS 1" and "KoSMOS 2" which were recognized as standard by the LBA and as such later by the OSTIV. In the following, the pure glider spectra without aerobatics and with 12.5% aerobatics will be considered, as well as KoSMOS 2, referenced as "B", "C" and "D".

Figure 3 shows the original 32x32 Markov-matrix for KoSMOS. The lighter and darker shaded diagonal cells are set to zero for the omission involved in KoSMOS 1 respectively 2. Intentionally, the classes were defined such that classes 1 and 2 (maximum loads) and 32 (minimum load) were not occupied for the case that a requirement for even higher classes should arise. Thus, with a load-ratio of -0.55, class 3 was to represent the positive design load (safety factor j=1) and class 31 the maximum negative load (j=-0.55). The zero-load was defined to be at class 21.

Spectra by Stafiej and Rodzewicz, Poland

In Poland similar mission structures have been used in the eighties by Stafiej and later also by Rodzewicz. Under their leadership, extensive measurements were carried out by flights with the SZD-48-1 "Standard-Jantar-2", SZD-51-1 "Junior", see [14] and [15], and lastly with the PW5 "Smyk", [16] . Stafiej's evaluations of the Jantar- and Junior-flights led to the establishments of block programs for experimentally investigating the fatigue behaviour of the respective glider or glider parts ("E", "F"). Later, Rodzewicz evaluated the flight data of the PW5 in combination with Stafiej's data and created similarly to Reinke/Kossira also a 32x32 transition-matrix ("G") based on his flight measurements, see [4]. So, he could test the PW5 with a tailored program. Figure 4 shows as an example the block spectrum for the SZD-51-1 "Junior" and the "PW5" for 1000 flight hours.

Dorning-spectrum, Australia

The Dorning-spectrum was developed in the early eighties in Australia, [17, 18]. It was intended to create a load collective based on flight measurements in the meteorological conditions of Australia eventually containing a more severe damaging character than anticipated for the Central Europe regions. In contradiction to the other transition-counted spectra, the measurement data of the Dorning-spectrum have been collected in a rainflow-counted Markov-matrix, but then – for testing purposes – have also been rearranged in a block-program scheme. This spectrum was used e.g. to perform a well-described full-scale fatigue test with a GFRP-Janus wing, [18]. The plot of the block program ("H") is shown in Fig. 5.

In total the following spectra as shown in Table 1 are investigated numerically. With the exception of the Franzmeyer-program, which was developed on theoretical assumptions about the level and number of the loads, the other spectra are based on measurements during flights of several hundred flight hours each. The flight time for all of them is extrapolated to a 6.000 h life cycle. In Fig. 6 the eight investigated spectra are presented as plots of the normal acceleration versus the number of load cycles. With regard to KoSMOS the version with 7.14% omission was chosen (KoSMOS 2). Lifetime calculations have shown that the influence of the omission only plays an inferior role.

Material data

For the experimental certification of a sailplane it is generally accepted to investigate the wing as a primary structure of which the bending spar is the highest loaded component. It is designed from 0°-oriented GFRP or CFRP in the spar cap and ±45°-GFRP in the shear web.

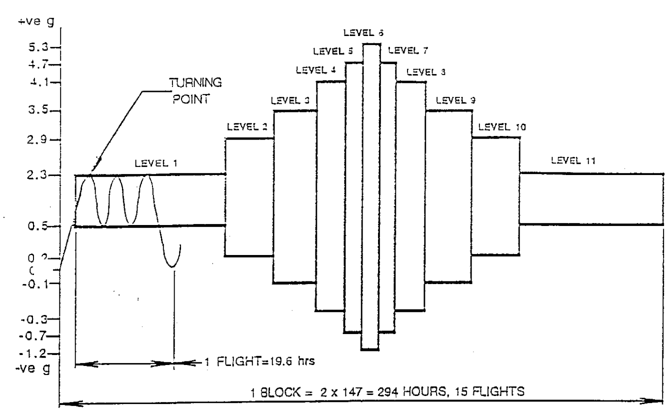

Fig. 5: Dorning-block program for 6000 flight hours [17, 18].

	Spectrum	Reference
1	Franzmeyer block-program	[9]
2	Kossira-Reinke spectrum without aerobatic flights	[10-13]
3	Kossira-Reinke spectrum with 12.5 % aerobatic flights	[10-13]
4	KoSMOS-spectrum (including loads from GA-flights)	[10-13]
5	SZD-48-1 "Standard Jantar"	[14]
6	SZD-51-1 "Junior"	[14, 15]
7	PW5-spectrum	[4, 16]
8	Dorning-spectrum	[17, 18]

Table 1: Survey upon the investigated service life spectra.

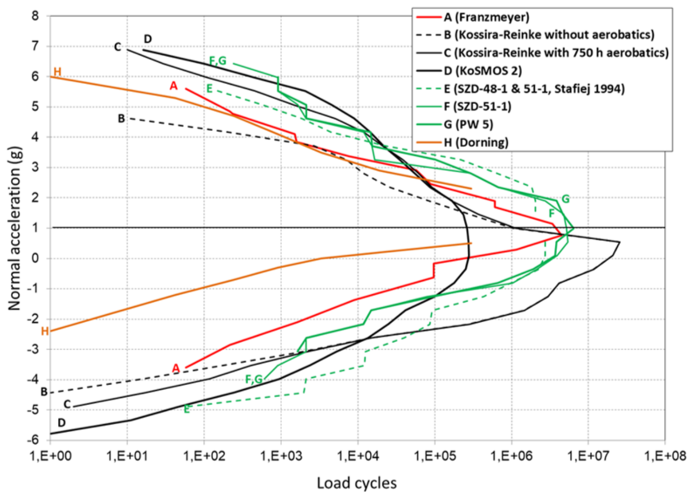

Fig. 6: Cumulative frequency distribution of the eight different glider load spectra for a lifetime of 6.000 flight hours.

	0°-CFRP			0°-GFRP			±45°-GFRP**		
R	0.1*	-1	10*	0.1	-1	10	0.1	-1	10
n	17	17	17	37	57	14	21	15	21
α	28,09	28,09	28,09	16,48	13,99	17,43	29,40	21,75	29,40
β	0,66	0,66	0,66	2,25	2,23	2,19	0,89	0,88	0,89
C	1,0000	1	1	0,0015	0,22	0,0002	0,3000	0,031	0,3
S	0,0354	0,0354	0,0354	0,1105	0,0868	0,092	0,0523	0,1068	0,0523

* anticipated values (conservative)

** values conservative because of the use of plain instead of twill fabric

Table 2: Weibull-parameters of s-n curves for 0°-CFRP, 0°-GFRP and ±45°-GFRP.

The fatigue data for such material are available and have been reported for example in [1–3]. Their values are statistically evaluated according to the Sendeckyj-approach, [19]. For complete information, the respective Weibull-parameters are shown in Table 2. Please note that the scale-parameter b represents the strain in fibre direction.

The constant amplitude diagrams derived from the mean values of those data are presented in the Figs. 7–9. As reported in [2], the s-n curves of the ±45°-GFRP representing the shear webs are conservative since the fatigue tests have been carried out with tubular specimens made of plain fabric. Sample tests using specimens with twill fabric normally applied in the spar beams have shown a lifetime of around two orders of magnitude higher.

Design of the Markov matrices

For the lifetime calculation, the original data sets of the investigated spectra have been ordered in the same manner in a from-to transition-matrix as shown for KoSMOS in Fig. 3. In order not to change the relatively complex DLR-code, however, two structural reorganizations of the matrices have been necessary.

The first item is that in KoSMOS the highest load is contained in the bottom class. Yet the DLR-code was written for a matrix-

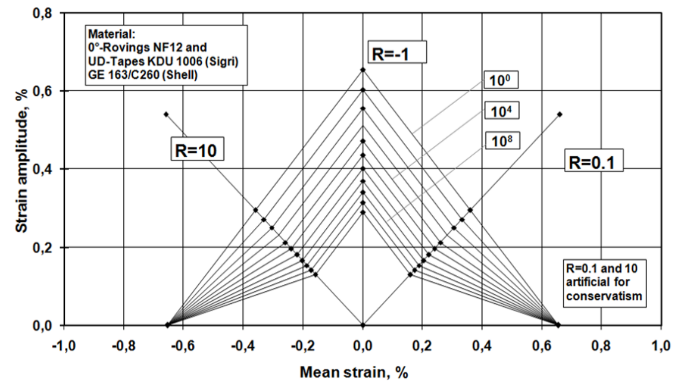

Fig. 7: Constant amplitude diagram (CLD) for 0°-CFRP UD-Lay-Up (mean values), missing data for R=10 and R=0.1 are held conservative.

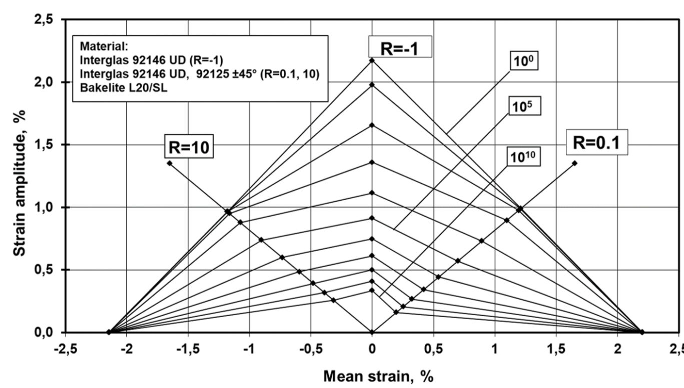

Fig. 8: Constant amplitude diagram (CLD) for 0°-GFRP UD-Lay-Up (mean values), see also [1]

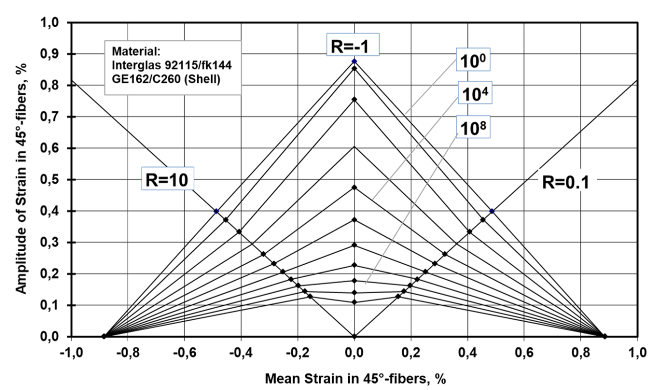

Fig. 9: Constant amplitude diagram (CLD) for ±45°-GFRP Torsion Tubes (mean values), see also [2].

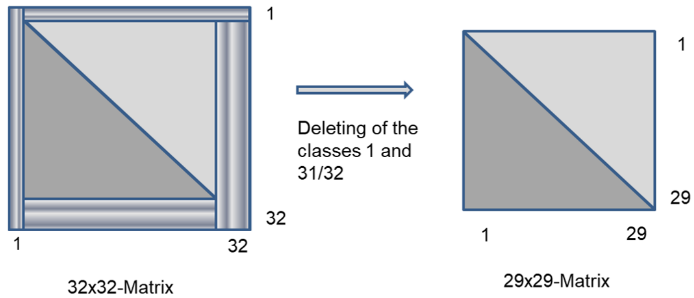

Fig. 10: Decreasing procedure of 32x32- to 29x29-matrices.

format which is used in wind energy for the WISPER-standard, which relates the highest class (top line) to the highest load, see [20]. Therefore, the matrices of the glider spectra had just to be reversed column-wise according to the WISPER-format. Then the highest load still corresponds with the bottom row, but now the matrix structure fits to the counting algorithm of the program.

The second item is, as mentioned above, that in the KoSMOS-matrix the classes 1, 31 and 32 are intentionally not occupied. Since the DLR-code, however, refers the maximum load to the highest class, an empty class would lead to a decrease of the accumulated damage compared to a calculation with a fully occupied matrix. To meet this problem accordingly the matrices were decreased to 29x29 classes. Fig. 10 shows this procedure in the format of reversed matrix.

For KoSMOS the 0-level is class 21. However, the envelopes of the other spectra suggest that class 18 would fit better as their 0-level. For a fair comparison of all spectra and based on the location of the highest counts in the Markov matrices, the classes of the KOSMOS 2 spectrum were shifted to lower loads, to make class 18 also the 0-level. This preserves the load amplitudes, but reduces the mean load. Lifetime calculations in another study on a GFRP shear web with the KoSMOS 2-spectrum including aerobatic flights have shown a lifetime prolongation of factor 2.6 to 3.7 when decreasing the 0-level from class 21 to 18. So when using KoSMOS in the standard fashion (class 21 as 0-level) it generates a lower lifetime, making this comparison conservative in respect of KoSMOS. Class 18 becomes class 14 for the new 29x29-matrix.

The data of all spectra were normalized in relation to the KoSMOS-spectrum which shows the highest positive and negative normal accelerations which are represented by the occurrences in the classes 29 and 1, see Fig. 6.

Numerical assessment and results

The lifetime calculations with the three material data sets shown in Table 2 and the data of the eight spectra have been carried out for 5 distinct maximum load levels anticipated for the GFRP- and CFRP-spar cap and the GFRP-shear web. The results are plotted separately for the three materials showing the influence of the chosen design levels (in % strain) upon the logarithm of lifetime (in life cycles of 6,000 flight hours). As mentioned above the resulting curves are based on the mean values of the material considering just the goal of the presentation, namely the comparison of the life lines. The results are presented in Figs. 11–13.

The spectrum-dependency of the individual lifetimes for 0°-GFRP representing the girders of a spar beam is shown in

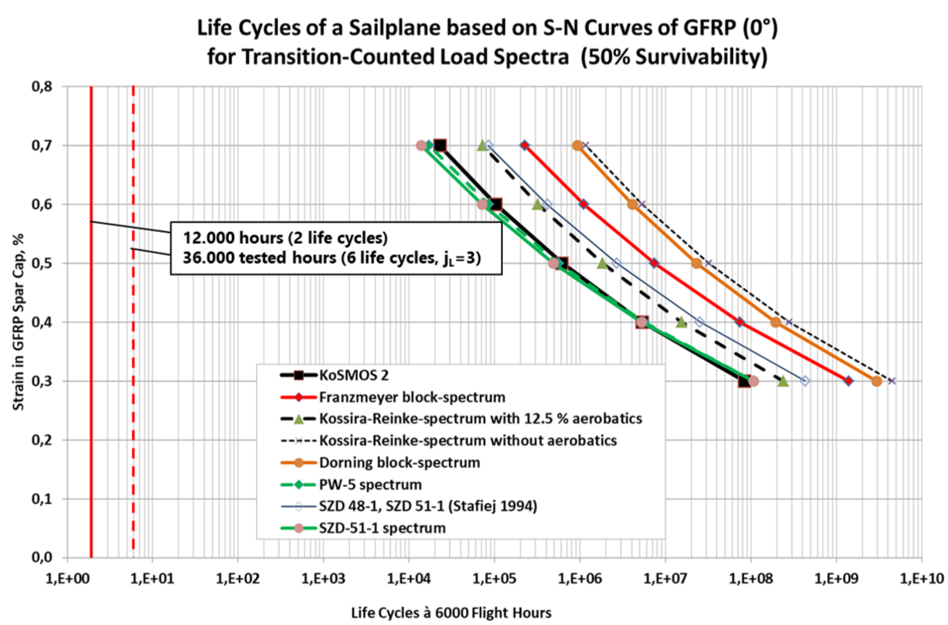

Fig. 11: Lifetime assessment for different service life spectra and GFRP

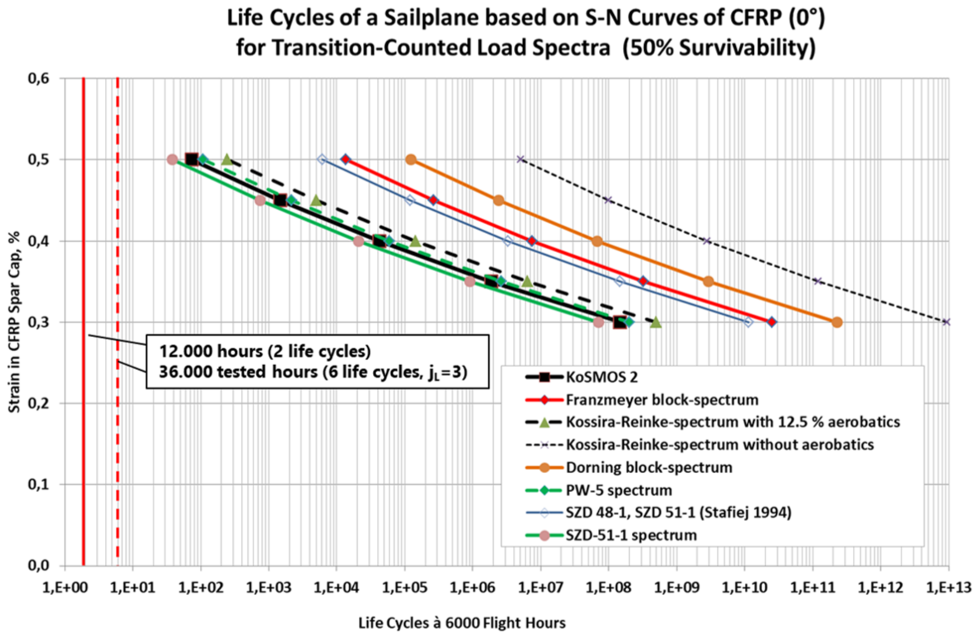

Fig. 12: Lifetime assessment for different service life spectra and CFRP.

Fig. 11. The calculations were carried out for limit strains between strains of 0.3% and 0.7%. The influence of the maximum strain upon the lifetime is clearly shown. When looking at the spectra there is a significant difference in the individual lifetimes. There are about two orders of magnitude between the KoSMOS-standard representing the conservative side of a service-collective and the Kossira-Reinke spectrum without aerobatics showing the lowest damaging character. With the exception of the Junior- and the PW5-spectra which are very similar to KoSMOS, the damaging effects of the other spectra are between the extreme ones. The calculated lifetime at the highest limit strain of 0.7% for the KoSMOS- standard is more than 3 orders of magnitude distance to the vertical lines of the certification limits indicating an extremely large safety margin.

For the CFRP shown in Fig. 12 the lifetime was calculated for maximum strains between 0.3% and 0.5%. Because of the very flat slope of the respective s-n curves also the slope for the fatigue life curves is correspondingly flat. This is in contrast to GFRP with a significantly steeper slope of the fatigue- and lifetime curves. Another difference to the GFRP results is the extremely high distance of around 5 orders of magnitude between the more conservative spectra (KoSMOS, Kossira-Reinke with aerobatics as well as the Polish spectra being very close one to the other) and the Kossira-Reinke spectrum without aerobatics. It becomes also clear that an increase of a design level from e.g. 0.4 to 0.5% leads to a reduction of lifetime of more than 2 orders of magnitude. However, at the 0.4%-level there is a comfortingly big distance of around 3 orders of magnitude to the certification margins. Since the calculations for CFRP were performed yet with a presumably quite conservative construction of the constant amplitude diagram with its artificial design of the R=10- and R=0.1-values one can act on the assumption that the safety distance is still higher.

Figure 13 shows the lifetime for ±45°-GFRP representing the shear web. The calculations were accomplished for design levels between a strain in fibre direction of around 0.3% and 0.5% representing (according to VDI 2013) ksd#-values of 11 km and 19 km, respectively. Compared with the KoSMOS-fatigue life curve the Polish spectra show still more conservative results whereas in this case the Dorning-spectrum yields the curve with the longest life with around 2 orders of magnitude distance to KoSMOS. Even at the high end of the strain scale, the KoSMOS-based calculated lifetime is still a hundred times longer than the 12,000 hour certification limit. However, the maximum stresses in a shear web in common designs may be lower. In [21] the design and fatigue test of spar beams with CFRP-girders and a respectively highly loaded GFRP shear web is described with a ksd#-value of 13.12 km which corresponds to a strain of around 0.35%. Such web design seems to be typical and the calculated fatigue life for KoSMOS exceeds the certification limit by more than 3 orders of magnitude. And additionally, as mentioned before, the common web design with twill fabric will lead to still higher safety of lifetime.

Discussion of the results

The lifetime calculations reveal a significant difference between the investigated spectra. And also a big influence of the material is obvious. So, a difference in lifetime is found of nearly 2 orders of magnitude for 0°-GFRP as the spar cap material and around 3 for the ±45°-GFRP representing the shear web.

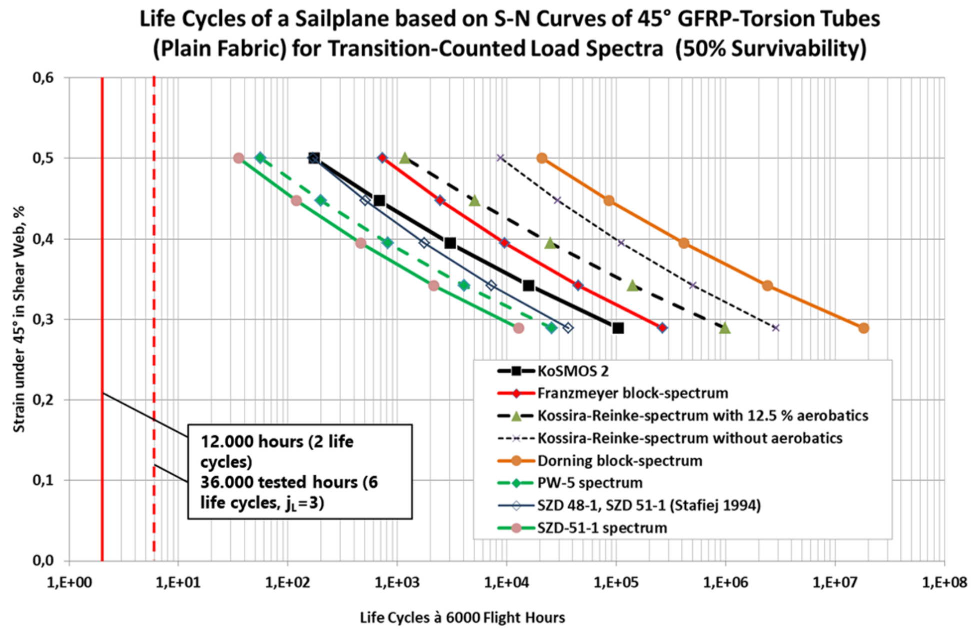

Fig. 13: Lifetime assessment for different service life spectra and GFRP torsion tubes.

For the 0°-CFRP more than 5 orders of magnitude difference exist due to the flat slope of the s-n curves of CFRP.

Primarily it can be stated that KoSMOS and the spectra developed for the Junior- and PW5-sailplanes result for all materials in the shortest or most conservative lifetimes. Nevertheless, they show, even at the high design levels, still a lifetime with good distance to the existing lifetime-allowable of 12,000 flight hours. This is also still valid in the case of using the original 0-level of class 21 for KoSMOS which can lead to a lifetime reduction of factor 2.6 to 3.7 as mentioned before.

The two spectra with the lowest damaging effect are the Kossira-Reinke spectrum without aerobatics and the Dorning-spectrum. The other collectives are in between changing their position depending on the material considered.

The relatively low damaging character of the Dorning-spectrum may be amazing, since the flight measurements for its establishment have been made in the thermal conditions of Australia which are thought to be more severe than those forming the basis of the European spectra. A reason is seen in the establishment of the basic Markov matrix by the rainflow-counting method in contrast to the transition-counted matrices of the other spectra.

For the ±45°-GFRP material, the three spectra developed for the Polish gliders "Standard-Jantar", "Junior" and "PW5" are close to or even more damaging than the KoSMOS-spectrum. But the difference is not significant enough to start a discussion on KoSMOS as the recognized standard-spectrum.

The influence of the material properties on the resulting lifetime curves is twofold. First there is the slope of the basic s-n curves which reappears in the slope of the lifetime curves, see e.g. the difference in the slopes of UD-CFRP and GFRP. Second, also the properties in the tensile and compression area of the different constant amplitude diagrams have a big influence on the lifetime calculations of the spectra comprising different extrema and mean-values.

The lifetime calculations upon the eight spectra have been carried out for design levels of the individual materials which ought to vary from some lower design levels to an anticipated design allowable. So, the resulting plots offer the possibility to the observer to recognize without problems the dependency between the maximum strain (or stress by considering e.g. the Youngs-modulus) and possible lifetime.

Conclusions

A survey has been given on eight glider load spectra which have been developed over the past fifty years in Germany, Poland and Australia. A comparative presentation has been given in a cumulative frequency distribution plot which gives a qualitative image of their damaging impact. Numerical investigations by means of a lifetime-code developed at DLR were carried out using the fatigue properties of composite-materials commonly applied in the highly loaded spar beams of sailplanes. The fatigue data of the 0°-GFRP and -CFRP as well as the ±45°-GFRP representing the spar cap and shear web material were taken from earlier publications, [1–3]. It is pointed out here that the fatigue results for the CFRP-spar cap and the GFRP shear web material are conservative and had to be applied by the lack of better data.

The loads of the data sets of the individual spectra were normalized, ordered and rearranged in 29x29-Markov-transition matrices to fit them to the applied code. Finally, the individual lifetime computations for the eight selected spectra, three materials and five design levels each were executed fulfilling the goal of the numerical comparison of the spectra.

The results were presented in diagrams which allow a graphical evaluation of the single lifetimes. Surprisingly, the resulting fatigue curves show – depending on the material – a difference in lifetime between around 2 and 5 orders of magnitude for the various spectra. Of course, it is of importance that the KoSMOS standard itself is amongst the most conservative spectra. Also the Polish spectra developed for the sailplanes Junior and PW5 show a very conservative behaviour, which for the ±45°-GFRP is even slightly more severe than KoSMOS. Interestingly, the Australian Dorning-spectrum showed for nearly each material the longest lifetimes and, thus, seems to be not as damaging as anticipated before.

The calculations have been accomplished mainly for comparison purposes and, as mentioned above, just the mean values of the material data have been used showing a significant distance of the lifetime curves to the generally certified flight time of 12,000 h. An exemplary calculation with the KoSMOS2-spectrum and the 0°-GFRP-data shows a decrease of lifetime of around a factor 6 for 90% survivability (B-values) and a factor 12 for 99% survivability (A-values) at the high load level end of the lifetime curve. In this case the distance to the certified lifetime is still more than a factor of 100.

This nourishes the idea to use the lifetime diagrams as nomograms for a fatigue design. For such a standard project the question of a possibly certified safety against lifetime should be spotlighted.

But there are also other tasks open. There is the point that the 0-level in the Markov-matrix should be fixed again on the class 21, when applying the KoSMOS-standard, just as it is prescribed for testing. Furthermore, it did not become clear why the SZD-51- ("Junior"-) and the "PW5"-spectra are resulting in so high damage rates, partially even higher than KoSMOS as described. This should be investigated in more detail. Also should be investigated the question whether transition-counted spectra may lead to a higher damage rate than rainflow-counted ones such as the Dorning-spectrum. On this point benchmarking lifetime assessments would be highly appreciated.

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