SAFE LIFE SUBSTANTIATION FOR A FRP-SAILPLANE

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SUMMARY

This report is initiated by the LBA, the German Federal Office for Civil Aviation, in order to summarize the state of the art in fatigue substantiation for sailplanes. Special regard to the safety of life-time-calculation methods is given. The author has decided to use time as the guideline of this report. To its major part it is based on literature published by OSTIV and uses some other contributions, which are available from Airworthiness Authorities or libraries. Thus, the background literature referred to may be available for many sailplane designers.

This report is not yet an accepted means of compliance, however it may be a procedure to be followed for future tests, which may result in shorter but harder fatigue tests and better life time predictions by concurrent damage accumulation calculations.

History of fatigue substantiation of FRP-sailplanes in Germany

Since the early 1960's FRP (Fibre Reinforced Plastics) sailplane wings were tested for fatigue by applying simulated air loads according to a load spectrum agreed by the authorities represented by DVL-PfL or LBA.

First full scale tests were performed by Eugen Hänle for the Libelle H-302 originally in his small factory and Akaflieg Darmstadt e.V. for the D 34d glass-FRP wing.

Whereas Hänle used a load spectrum of different load amplitudes, Akaflieg Darmstadt demonstrated 10000 load cycles at maximum and minimum limit load, based on damage accumulation calculations of Dr. Gassner and a final static load test to destruction.

In the 1970's Prof. W. Thielemann did several full scale fatigue tests on FRP sailplane wings using Mr. F. K. Franzmeyer's load spectrum at increasing load levels. The Libelle 302 was tested again during this research work.

Beginning in the late 1970's, but mainly in the 1980's, Professors W. Thielemann and H. Kossira increased the stress and strain test levels of glass and carbon fibre reinforced plastic spar specimen, which were representative for sailplane design.

In 1980 and 1981 H. Kossira (outer wing) and Chr. Kensche (inner wing) tested a full scale Nimbus 2c wing. German sailplane designers had to prove that their new design was covered by the previous fatigue tests in design and stress and strain level.

The disadvantage of the procedure described above is, that the real fatigue lifetime of the wings or the test specimen is unknown, as they were more or less destroyed in final static tests in order to demonstrate sufficient residual strength.

Is there a reserve in the life factor of FRP sailplane structures?

It is the author's belief that a potential in FRP sailplane fatigue resistance exists, which has not been tested yet. Some fatigue failures of metal parts during the full scale tests demonstrated that the reserves in lifetime were higher for the FRP-structure than for the metal parts, even though designers were hoping to achieve a well balanced structure with similar fatigue resistance of both metal and FRP.

Ample research on fatigue of FRP wind turbine blades showed that the service life of such rotor blades may exceed 25 years at stress levels similar as used for sailplane wings. So it is wise to look to areas close to aviation for possible transfer of material database and calculation methods for mutually used materials.

History of analytical lifetime substantiation for sailplanes made from several materials

In 1963 K. R. Obee published a paper, see [Ref. 1], about the fatigue of wooden gliders using the "Palmgren - Miner cumulative damage theory." He predicted 15200 hours of service life with a life factor of 3.6 for a fictive "training glider" designed to n = 4 - 1,5 = 6 ultimate load, and 100500 hours of service life with the same life factor of 3.6 for a fictive "cloud flying glider" designed to n = 5 -1,5 = 7,5 ultimate load. The spar beam material used was spruce.

In the light of load spectra applied today, both examples are quite highly stressed sailplanes. Assuming that "Kiefer 4002" as used for the Ka 6 B/C, BR/CR or E model variants, has the same fatigue resistance as the (less dense) spruce, as calculated by Obee, the Ka6 - series being designed to n = 4 .2 = 8 ultimate load have an expected service life of about 150000 hours, also with a life factor of 3,6 and assuming the load spectrum of the "cloud flying glider."

As it is our common experience, that wooden gliders have "no fatigue problem" when well maintained, the analytic substantiation method gets quite attractive, as about 150000 hours life time is - by practical operation experience - the "eternal life" of a sailplane.

In May 1973 US DOT published a "Final Report" issued by the FAA, [Ref. 2], "Fatigue Evaluation of Wing and

Associated Structure on Small Airplanes," which was at that time not a standard, specification or regulation but a possible means of compliance.

This report contains three important subjects:

- The use of the "Palmgren - Miner hypothesis" as cumulative damage fatigue theory or "Miner's Linear Cumulative Damage Theory,"
- loading spectra for various types of aircraft and usage, scatter factors (life factors) for

1 full scale fatigue test 3 to 4,

1 component fatigue test 5 to 7, with lower factors for multiple component tests and scatter factors 7 to 8 for analytical substantiation according to the report.

As can be learned from [Ref. 2, 3, 7 and 9], the analytic method was used in comparison to a full scale test [Ref. 7] and another cumulative damage hypothesis H1 by Heywood, [Ref. 3], not quoted here. Life factors varied from 3 for high confidence specimen data to 4 or 5 for conservative calculations.

It is important to know, that [Ref. 3] quotes a re-calculation of the life time of the "Blanik" aluminium alloy sailplane using a different flight usage load spectrum which was accepted by the Australian authority and allowed to extend the service life from 3750 hours to a higher number.

[Ref. 7] reports about full scale fatigue tests of "composite material" sailplane components (two wing panels and a stabilizer half) including intended damage together with a calculated failure probability 1 / 1000 to 1 / 10000 for 1000 hours of service life.

[Ref. 9] is a similar study as quoted in [Ref. 3]. A safe fatigue life of an aluminium alloy sailplane could be extended from 10000 hours and 30000 landings, calculated by using a most severe load spectrum, to more than 15000 hours, depending from the area regarded. It is important to know, that the full scale fatigue test was conducted at two load levels by the manufacturer and that the lifetime was evaluated by calculation "on a duly conservative basis" and accepted by the airworthiness authority.

The author has not heard from fatigue failures of these aircraft which have now been in service for quite a time, exceeding 15000 hours and possibly approaching the calculated service time.

Comparison of different load spectra

In June 1983 H. Kossira and W. Reinke published the KoSMOS cycle, [Ref. 4], simulating 6000 hours operation time. KoSMOS was revised later, [Ref. 22] published March 1986, and is quite a strict envelope of all sailplane and small airplane usage compared to other spectra used earlier. The author feels that KoSMOS2 as used today is very much to the conservative side despite an omission of low amplitude cycles. This is confirmed by Christoph Kensche, who has checked the KoSMOS2 for applicability for sailplanes, as well as by Prof. Dr.-Ing. Wilhelm Reinke in a private letter to the author, dated 05 June 2001. It was also confirmed, that for 12,5% of the total flight time aerobatics were included in KoSMOS [Ref. 22]. This was still an open subject in the status of KoSMOS as given in [Ref. 4].

There was also a discussion whether the loads measured with the Janus and its specific response to gust inputs is representative for other sailplanes. Prof. Reinke reported, that comparison measurements on other aircraft in the same air mass did not show significantly other spectra despite different pilot feel. It was learned that the pilots do not feel the highest g-loads but more the acceleration increase with time, which is more rapid in alpine soaring compared to flat country soaring. The resulting peak loads, however, are the same.

In 1986 and 1989 [Refs 5 and 6], Payne, Sue-Yek and Coates evaluated load spectra for glider operation in Australia (the so called "Dorning spectrum") and made first calculations about fatigue sensitivity of FRP gliders using a "Linear Cumulative Damage Hypothesis."

In [Ref. 9], load spectra for different locations inside Australia are given, demonstrating the influence of strong thermal flying (at Tocumval) and 8% of the total flight time aerobatics which cause almost similar load spectra and therefore the shortest life time.

In [Ref. 15] Chr. Kensche has shown by calculation that the low load amplitude omission between KoSMOS1 and KoSMOS2 is almost uncritical for glass FRP compared to the high life factors applied to the calculations.

Life-time calculations as an accepted means of compliance

In 1991 LBA [Ref. 8] published standards for structural substantiation of sailplane and power sailplane components made from glass and carbon FRP, in which an analytic calculation was not yet considered. However in 1995 the JAR-22 Study Group [Ref. 10] started to update the fatigue requirements of JAR 22.627, having a close look on equivalent OSTIV- Standards.

The July 1992 Issue of OSTIV AS defined Safe Life, Life Factor, Fail Safe Structure and Inspections Interval, which are used in this article and further allows a fatigue life estimation by analysis alone, when it is conservative.

An important step forward in analytic methods was achieved by Chr. Kensche, [Refs. 11 and 12], in which the wide data base on FRP gathered by EC sponsored research for wind turbines [Ref. 13] was used as additional information to the FRP research done for sailplanes. It was shown that the damage accumulation using the "Linear Palmgren-Miner Rule" coincides very well with specimens which were tested under the calculated conditions.

The calculated lifetime prediction using 95% reliability values resulted in 1.03 and 1.14 time longer tested life of two specimens. This is an unusual high accuracy of calculation result versus test when compared to corresponding efforts in metal structures.

As a very preliminary result Chr. Kensche calculated the service life of a fictive sailplane under quite high design strains, but below 0.4% to 1.5% strain of the coupon tests, using the same database and calculation methods. He predicted almost an unbelievable 5.900.000 to 27400000 service hours for a spar cap (flange) design with a strain of 0.7% (limit load) for glass-epoxy based on the "Franzmeyer Load Spectrum" and using 50% reliability coupon test data. He also proposed a fatigue test of 10.000 load cycles at design stress level to cover fatigue of a FRP structure. That is exactly what Dr. Gassner had asked for in 1963 for the D34d of Akaflieg Darmstadt.

Dr. J. Gedeon published a paper on load spectra [Ref. 14] which is based on measured atmospheric gusts and develops a connection between structural load spectra and measured applied meteorological data.

In July 1997 C. Alan Patching reported about a full scale fatigue test of a Janus wing at R.M.I.T. in Australia [Ref. 7]. Nearly 36000 service hours were simulated at a high strain level of 1000 microstrain per g, which is about 25% more than a Janus will experience in flight.

As an important result of this test at elevated load level it was found that the rate of growth of cracks was slow such that they would have been detected in operation and all progressive damage in FRP was found using simple non-destructive inspection techniques.

In July 1997 and August 1999 Chr. Kensche presented papers at the OSTIV Congresses, [Refs. 23 and 24], which demonstrate the reliability of damage accumulation calculations versus test results.

In October and November 1998, Chr. Kensche delivered a first report about calculated service life of an existing sailplane [Refs. 16 and 17].

In an important meeting of Alexander Schleicher Segelflugzeugbau, Mr. Kensche and the LBA it was stated, that the calculation is acceptable in principle, however it must be demonstrated that the calculated damage accumulation proves correct not only in small specimen but also in components.

In [Ref. 18] published in November 1998 J. F. Mandell, D. D. Samborsky, D. D. Combs, M. E. Scott and D. S. Cairns showed that spars of wind turbine blades - very similar to I-spars of sailplane wings - withstood slightly more load cycles than small coupons under the same strain. This is important as there needs not to be an extra life-factor for calculation versus component test. A similar result was shown by tests on a carbon/glass spar beam produced by A. Schleicher Segelflugzeugbau for the LuFol -program where V. Trappe could show that the spar withstood higher cyclic loads then test coupons taken from the same material. A report is not published yet.

H. J. Sutherland reports 1999 in [Ref. 19] about "best practices" for fatigue analysis of a wind turbine component. He quotes the "Palmgren-Miner Linear Damage Rule" commonly called "Miner's Rule": "This damage rule is currently used throughout the industry."

In a summary Sutherland states that three sets of information are required to estimate the service lifetime of a wind turbine:

- The fatigue load cycles on the turbine as a function of the inflow conditions
- The S-N behaviour (or the linear crack growth of the material(s) being analysed and
- The annual wind speed distribution

According to Sutherland, with the database known today, a factor of 2 between damage predictions and measured lifetimes should be expected.

Also in 1999 [Ref. 20], J. F. Mandell, D. D. Samborsky and H. J. Sutherland published experience on fatigue of FRP wind turbine blades based on material parameters and design details which are similar to sailplane spars. In that paper the authors state, that the U.S. (many materials tested not as much in depth) and the EC data (few materials tested in great depth) are in general agreement in fibreglass fatigue, more in tension than in compression. It is important, that the author of this report adds that the European database includes materials used for sailplane construction. The fatigue performance however in compression varies less than in tension, which is important for sailplane application, where compression loads of the spar flanges are generally assumed to be the critical ones.

It is important, that the fibre volume content of glass FRP must not be higher than 35% to 45% to get good fatigue performance. The fibre volume contents of glass FRP UD strands is about 57,5% in weight for German designed sailplanes, corresponding to 39% in volume. For hand lay up laminates of woven fabric, the fibre content is less than 40% in weight corresponding to 27% in fibre volume only.

Thus, conventional sailplane manufacturing methods produce fatigue resistant structures. The authors of [Ref. 20] call similar results on wind turbine structures the "most significant and surprising findings" of the test program. This fact however is not so new and corresponds to the knowledge gathered with sailplane fatigue where the same conclusions have been determined. The difference in matrix content compared to an ambitious high temperature pre-preg autoclav process may explain possible differences in fatigue resistance.

Another important result of report [Ref. 20] is, "that the materials in the structure [I-beam] performed much as reported in the data base using coupon tests". A similar experience was reported by V. Trappe, G. Arnst, P. Horst, as well as by M. Heide, with a carbon FRP flange and glass FRP shear web where the flange structure performed better than test coupons of suitable size from the same material [unpublished LuFo 1 Program report, July 2000].

It is also interesting that at a maximum strain of 0,61 %, which is about the limit strain of a sailplane spar, about 800.000 load cycles are shown for a "poor" triax laminate spar flange and about 8.000.000 cycles for a +/- 450 web. In the first, case the coupons are slightly better, in the latter case the components are better.

[Ref. 21] is an abstract of Mr. Kensche's unpublished LuFo 1-Prograrn report "Einstufige Ermüdungsversuche an Holmbauteilen zur Vereinfachung der Lebensdauer - Zulassungsverfahren" of July 2000. In this abstract, presented at the OSTIV-SDP- Meeting October 2000 in Prague and as a paper presented at the first OSTIV-Seminar at Mafikeng South Africa, 2001, Christoph W. Kensche discusses the possibility that expensive and time consuming fatigue tests of full scale wings or (multiple) representative spar components could be replaced by one step load cycle tests at about limit load and R=-0,55 to cover negative loads also. He also presented specimen data of the oldest materials used for glass FRP sailplane production and predicted that the lifetime of UD glass spar ("girder") flanges and shear web and bonding made of +/- 450 glass in plain weave. As the prediction for the UD-flange is 3.5 decades higher than for shear web and bonding, he continues his research on the latter subject.

S-N curves and a constant amplitude life diagram (Haigh diagram) are given, which show that one million load cycles to failure can be expected at limit shear web stress. Also the lifetime prediction of the GE162/C260 epoxy resin system, also known as Epikote 162/Epikure 113, which is no longer in production, is shown in comparison with Scheufler L335/H340 resin as its replacement. These two resin systems are very comparable especially at high shear loads. This may be important for future tests, where Epikote/Epikure structures must be "simulated".

A spar beam geometry is presented which has the design goal to test high shear web and glue bonding loads. Two static tests at 540C showed j = 1,725 related to the shear web allowable of K_{sdx} = 13,12 km.

Two more spar beams were produced in a slightly different way of resin impregnation. They were fatigue cycled with 12 KoSMOS2 cycles corresponding to 72000 flying hours. The residual static strength test at 540C resulted in j = 2 related to the shear web allowable.

This unexpected result demonstrates a "training effect" as known from some metals as well as an influence of the production method. Nevertheless the test shows that the potential in fatigue of the FRP is by far not yet used.

Consequently two more spar beams were tested with 486.200 and 68000 load cycles at j = 1 and R = -0.55 and R = -0.5 respectively. Both components did not fail due to FRIP failure. After 486.200 load cycles the steel pin in the end of the specimen failed in an irreparable way. Before that two metal main pins had to be replaced after they failed during the tests. After 68.000 load cycles the other probe was stopped as noises in the sandwich foam core were experienced.

It should be noted that in both cases, 10.000 load cycles did not show any fatigue signs and that at 30000 load cycles first cracks near the highly loaded flange to shear web bonding were detected, as well as a first de-lamination bubble between flange and shear web at that place which did very slowly grow but did not cause the end of the tests, 2 respectively 15 times later.

In the summary, Chr. Kensche makes the important point, that 1.000.000 one step cycles at limit load simulate the equivalent of 39.000.000 flying hours when "Miner's Rule" is applied for damage accumulation. Only 10000 load cycles are equivalent to 390000 flying hours, which is more than needed for a sailplane, even when high life factors are applied. No significant stiffness changes were found up to 30.000 load cycles (equivalent to 1.17 million flying hours). This makes it easier to understand why 72.000 simulated flight hours were just "training" the component specimen, so that they carried higher static loads than new ones. Also the spar beams were of conservative design.

Note: Some metal parts of the test specimen failed during the test, as did the strain gauges which are also from metal. This latter case is an important hint that FRIP is more fatigue resistant than metal at the same strain.

Kensche puts the admission of 50000 flight hours into discussion for glass sailplane wings for which the tested spar design is representative. He proposes to invite a working group consisting of sailplane manufacturers, scientists, and the airworthiness authority to establish the one step fatigue test as an acceptable means of compliance to demonstrate safe fatigue life of FRIP sailplane structures.

Conclusions

All literature quoted herein uses what is termed, in short, "Miner's Rule" for damage accumulation. The method was called "Palmgren-Miner Hypothesis" and "Miners Linear Cumulative Damage Theory" [Ref. 2] and "Palmgren-Miner Cumulative Damage Theory" [Ref. 1] in the early years. It is called "Palmgren-Miner Linear Damage Rule" today (see also [Ref. 19]). Today "Miner's Rule" is state of the art in metal aircraft and metal design and also accepted in wind turbine blades made from FRP- Chr. Kensche has proved this for 7 coupon tests with very low scatter factors. The similarities are such that the calculation methods are applicable for sailplane spars. This was also demonstrated by Kensche using mean value material data for calculation compared to component tests [Ref. 21] and 95% survivability / 95% lower confidence limit fatigue curves for predicting coupon fatigue tests correctly.

All quoted literature agrees in that test components have the same or better fatigue resistance than coupons.

From all the load spectra found in the literature given here, the KoSIVIOS2 cycle [Ref. 22] is a very "hard" spectrum, covering all missions in an enveloping way including 12,5% flying time of "simple aerobatics."

For the special case of an existing sailplane the UID-glass spar flange lifetime is well covered by multiple full scale (Janus) [Ref. 15] and spar beam tests at higher strain/stress levels. The +/- 450 glass shear web and bonding to the spar flange is covered by [Ref. 21] in an impressive life time calculation, backed up by 72-000 hours CoSMOS 2 cycles and an equivalent of almost 20.000.000 hours (more than 2000 years of continuous operation !) in the limit load cycle tests. This corresponds to a life factor of 380 for a life time of 50000 hours. In all tests it has been shown that fatigue related damage occurred in such a way that it would have been detected in service by inspections. In case of the spar beam tests quite massive de- laminations of the spar cap to shear web glue joint at 37.000 cycles did not grow so fast that they led to FRP failure at 486.200 load cycles. The glue joint load in the spar beam test specimen was about 20% higher than calculated with the same method at limit load for an actual sailplane design.

As for the existing sailplane in question the spar stubs, root rib and the first 0.5m behind the root rib are the highest stress/strain areas of the structure and easily accessible for inspection, an extension of the service life beyond 12.000 flight hours is proposed by the author. Some highly loaded metal parts must be exchanged.

Apart from the special problem of life time extension of this existing sailplane with its low stress/strain and glue load level, it must be stated, that fatigue substantiation by calculation alone is not yet state of the art. However, fatigue tests at one or two high load levels together with concurrent damage accumulation calculation, as well as comparative calculations of life time due to different load spectra, have already been successfully done with metal sailplanes and were agreed by the authorities.

In wind turbine blade design life time calculations have already become state of the art for FRP structures. For FRP sailplane structures a suitably representative test specimen should still be tested at elevated stress/strain level, may be in a simple one step fatigue test only, and then compared with the damage accumulation calculation caused by an applicable load spectrum.

A very important finding of Dipl.-Ing. C. Alan Patching should be regarded, when damage accumulation calculations are compared with one-step fatigue tests: " The simple test should be at a load level (inside the load spectrum), where the material in question has the lowest fatigue resistance" in order to be on the conservative side with the fatigue test.

The author must admit that lucky circumstances let him get deep insight into the fatigue problem generally and to FRP-fatigue in particular. He feels, that a sailplane designer as well as the certification authority should accept an expertise of a recommended fatigue specialist in a similar way as usually agreed for the flutter investigation for a sailplane.

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