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Fatigue of Composite Materials in Sailplanes and Rotor Blades

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The application of composite materials as primary structure in sailplanes as well as in rotor blades of wind energy converters (WEC) is state of the art since 1956. In that year R. Eppler and H. Nägele built the Phönix (fs 24), a sailplane made of glass fibre reinforced plastics (GFRP) with a balsa sandwich. At the same time U. Hütter, the designer of the H 17, and his team (e.g. E. Hänle and S. Armbrust) constructed and installed the W 34, a 100-kW WEC with two GFRP rotor blades of 16,5 m length each.

It is well known, that this new composite technology was taken over by the whole sailplane industry in the following years. After being familiar with the GFRP design and together with the development of new fibre materials efforts were made to introduce the so-called advanced composites carbon and aramid fibre reinforced plastic (CFRP, AFRP) in sailplanes.

The advantages especially of CFRP are, compared with GFRP, the higher strength and stiffness and the lower specific weight. Consequent upon that the performance of the gliders could be improved, longer flight distances, higher average speeds were possible. But this increase of the performance was accompanied by an increase of the costs, which is a factor perhaps not so important in the sporting industry. Wind turbines are producers of energy, however, and must be cheap. They have grown to a considerable economic factor in some European countries, e.g. Denmark. The rotor blades still have the same GFRP design as 30 years ago. Weight reduction is not so important as in sailplanes. It is argued that the uniformity of rotation– especially in stall controlled WEC–is favoured by a larger mass of the rotor, i.e. moment of inertia.

Though there are differences between sailplane wings and rotor blades in the fields of operational destination or structural details they show similarities and joining aspects which make them comparable.

Both are fatigue-critical structures, affected by gusts and control manoeuvres. And in the case of the same built-in material and similar structural design the same basic fatigue data as S-N curves can be used. Sailplanes have a certificated life time of 6000 flight hours. Some of them have reached already this limit. Wind turbines are designed for a 20–30 years time. An information about the possible service life of the rotor blades seems to enable an optimized design by achieving a weight reduction as a cost-saving factor. Additionally this would favour the operation of pitch-controlled WEC by decreasing the loads in the control and the break-down cases. To get more insight in the possible lifetime of sailplanes and rotor blades a fatigue investigation of the applied composites is necessary by means of a life time evaluation using the specific life load spectra and S-N curves.

Common characteristics

As a basis for the comparison of wings and rotor blades some joining aspects are demonstrated in the sequel. In both cases the composite material is laminated in the hand lay-up method with cold hardening resin systems. Both structures are slender. Their aspect ratio is between 15 and 30. They must be designed not only against strength but also against buckling failure. A sailplane wing is mainly stressed by cross-wind loadings which cause flapwise bending and torsion of the wing. Fig. 1 shows a typical cross section of a wing structure. The box spar beam with–in this case–CFRP caps and GFRP webs takes the bending load while the leading and the trailing edge, made of GFRP-foam sandwich, give the torsional stiffness and are forming the aerodynamic shape.

A rotor blade of a horizontal axis wind turbine must be designed additionally against lead lag bending due to the gravity loads. Fig. 2 shows a possibility for solving that problem. Here the leading edge is a complete GFRP design with a unidirectional (UD-) and +45°-lay-up of the glass fibres. The advantage is that the stiffness in plane and out of plane is suffi-

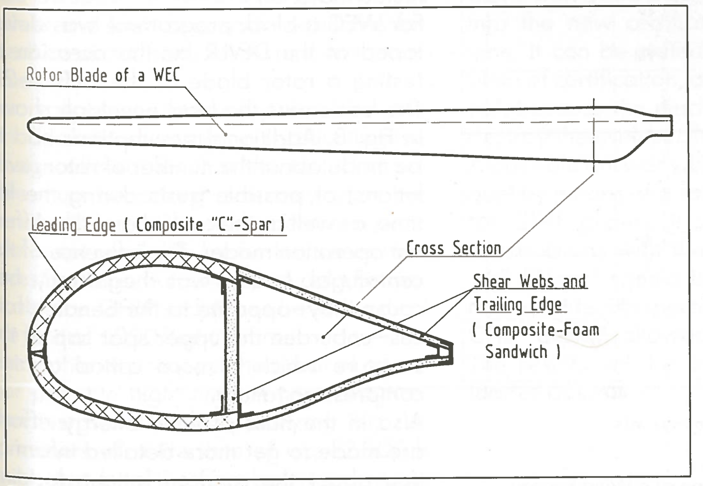

Fig. 1: Typical Structure of a Rotor Blade

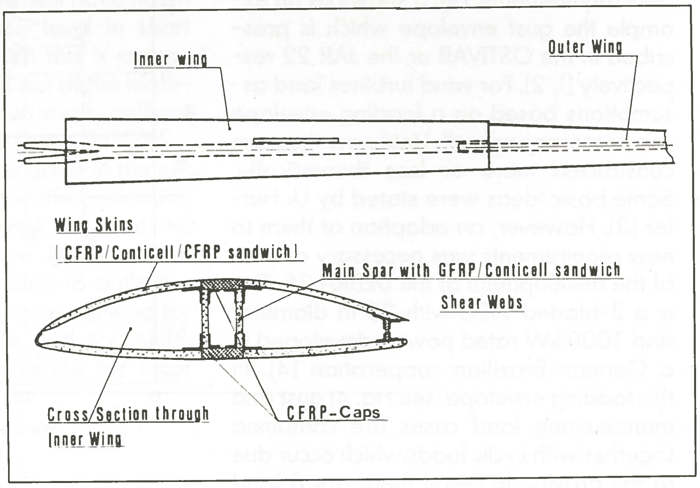

Fig. 2: Typical Structure of a Sailplane Wing

ciently high. Beside of that the centre of gravity is nearby the twist axis which, in a pitch-controlled machine, results in small control forces.

A general problem for both structures is that the transfer of the shear forces of the web into the normal forces of the spar caps induces interlaminar shear stresses (ILS) in the overlapping area. Their values are difficult to assess. This is combined with a necessary safe-life design, because the inspection possibilities are rather limited.

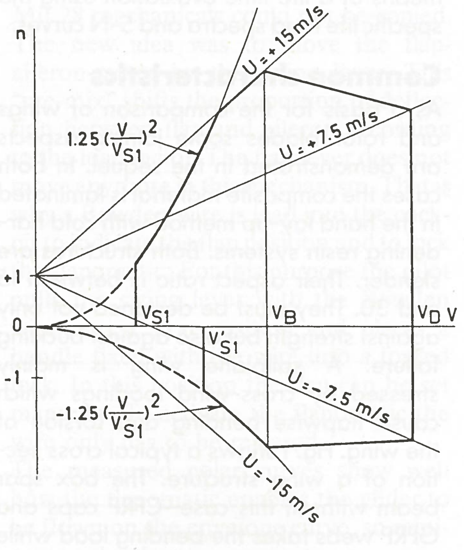

Fig. 3: Basic Gust Envelope of a Sailplane

S-N curves of coupon specimens therefore can only be a decision support in the evaluation of life time. Those results must finally be proved by tests on whole structures which overall include influences just as ILS or load introduction. The comparison of the loading envelopes leads to common characteristics too. The flight loads of an airplane are calculated on the basis of the manoeuvring and the gust envelope which are part of the airworthiness requirements. Fig. 3 shows as an example the gust envelope which is prescribed in the OSTIVAR or the JAR 22 respectively [1, 2]. For wind turbines load assumptions based on a loading envelope are necessary as well. Until now they are constructed more or less theoretically. Some basic ideas were stated by U. Hütter [3]. However, an adaption of them to new requirements was necessary as part of the development of the DEBRA 25. This is a 3-bladed WEC with 25 m diameter and 1000 kW rated power, developed in a German-Brazilian cooperation [4]. In this loading envelope (see Fig. 4) gust and manoeuvring load cases are combined together with cyclic loads which occur due to the gravity. In detail there are 8 load cases defined: I Normal operation, II Blade angle errors in gusts, III Over speed, IV Emergency stop, V Standstill cases, VI Extreme gust conditions, VII Icing of the blades, VIII Loss of one blade

The character of the design allowables

The allowables for the design of a composite sailplane are of highest interest for the constructor to make an optimum layout. The most important ones are surely the design stress level σ of the spar caps of a highly loaded wing structure in combination with the shear web loading K. Basic investigations were done at the TU Braunschweig for GFRP [5] and at the DFVLR Stuttgart for CFRP [6]. The results of these certification tests are shown in Fig. 5. A stress of 250 N/mm² is the limit level for GFRP caps in combination with a GFRP web loading of 19 km. The limit stress of CFRP is 400 N/mm², together with the same maximum web loading as for GFRP. However, for both materials only 6000 flight hours are certificated. This has been proved as not sufficiently long enough as mentioned above. The certification procedure of lifetime is including a safety factor of life of 3,0, i.e. that for the proof of 6000 possible flight hours 18 000 h must be run in a service life test. That is corresponding to c. $12 \cdot 10^6$ load cycles. The results of the investigations on GFRP, carried out at the TU Braunschweig, admit also the 6000-h certification for sailplanes with the old design stress level of 160 N/mm². Of course at first those gliders will have reached their time limit which are built with that low level, because they are built earlier and thus will have flown more hours. Rotor blades have to endure more than $0{,}4 \cdot 10^9$ load cycles in their expected life time of more than 20 years. The knowledge about th fatigue behaviour of GFRP at this hig number of load cycles is rather limite This fact may be a further reason why th composite rotor blades of the most WE are no lightweight constructions.

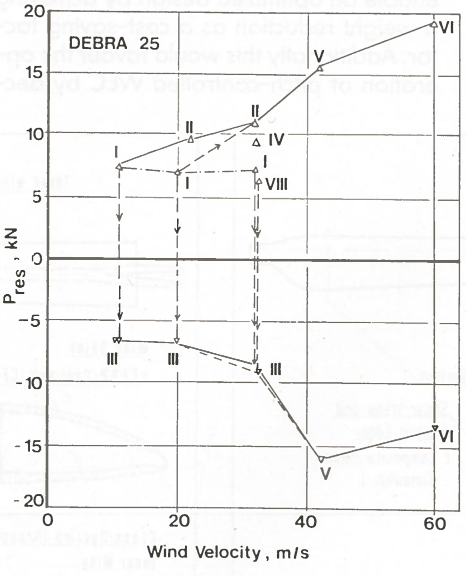

Fig. 4: Loading Envelope of a Wind Energy Converter

Therefore a large interest should be exis ing in an extensive information about longer life time certification of sailplane and well-defined design allowables fo rotor blades respectively.

In the case of using GFRP the same fa tigue investigations could be applicab for both parts. As a first step S-N curve must be available. To get insight in th possible life time of a wing or a weigh optimized rotor blade these data are t be observed in connection with the spe cific life load spectra.

Service life programme

For sailplanes in Germany a theoretical based service life programme was use in the last two decades for fatigue life cer tification tests [7]. It took into considera tion gust loadings during winch launching aerotowing, and cross-country fligh loadings during take off and landing a well as ground loads e.g. landing impa and taxiing (Fig. 6). However, meantime random fatigue programme is availabl which is established on the basis of flig measurements by Kossira and Reinke [8 The data of load cycle numbers and clas transitions are stored in a Markov matri For the fatigue investigation of a spec men or structural component they ar worked out again in a random sequenc In Fig. 7 the life load spectrum of Kossira Reinke [8] is compared with that of Thie lemann-Franzmeyer [7]. The similarity o the curves proves true that the considera tions for establishing the block pro gramme in [7] have been quite corre One main advantage of the new pro gramme is however the use of a realist load sequence. This might be of impor tance for the fatigue behaviour of th tested material.

For WEC a block programme was deve loped at the DFVLR by the occasion o testing a rotor blade of the DEBRA-2 The basis was the load envelope show in Fig. 8. Additional assumptions had t be made about the number of rotor revo lutions, of possible gusts during the lif time, as well as the control and the differ ent operation modes. The influence of th centrifugal forces was neglected, be cause they—opposite to the bending for ces—unburden the upper spar cap of th structure which is more critical again compression failure.

Also in the field of wind energy effor are made to get more detailed informa tion about the random fatigue loadin based on measurements during opera

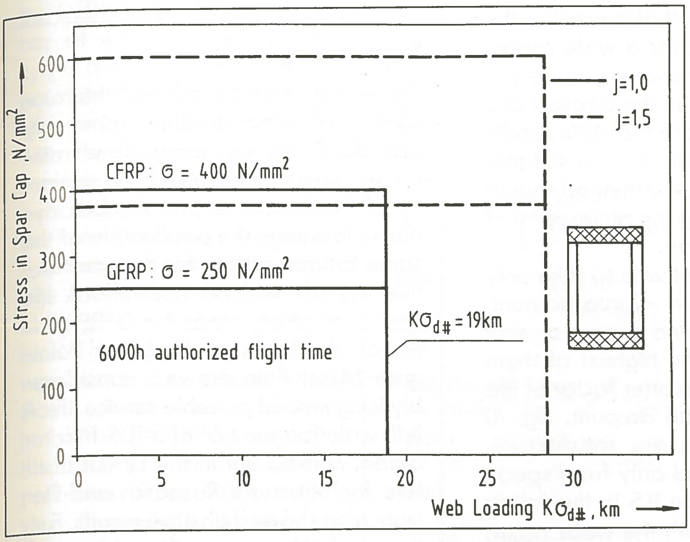

Fig. 5: Design Allowables for Box Spar Beams with GFRP/CFRP Caps and GFRP Shear Webs

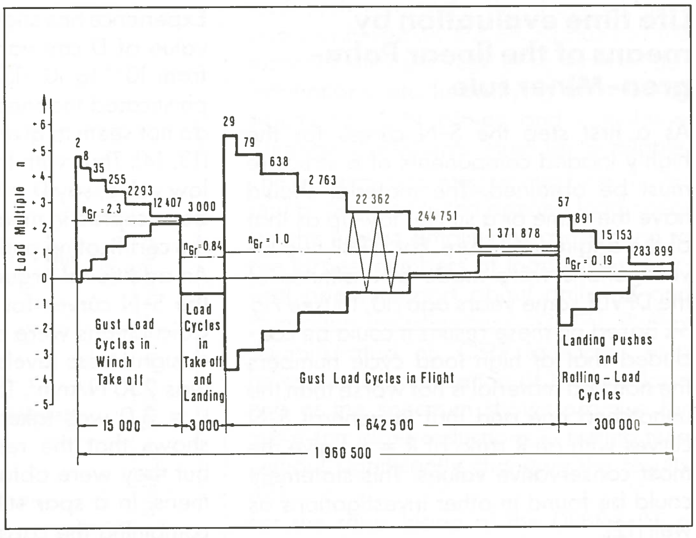

Fig. 6: Life Load Programme for Sailplanes [7]

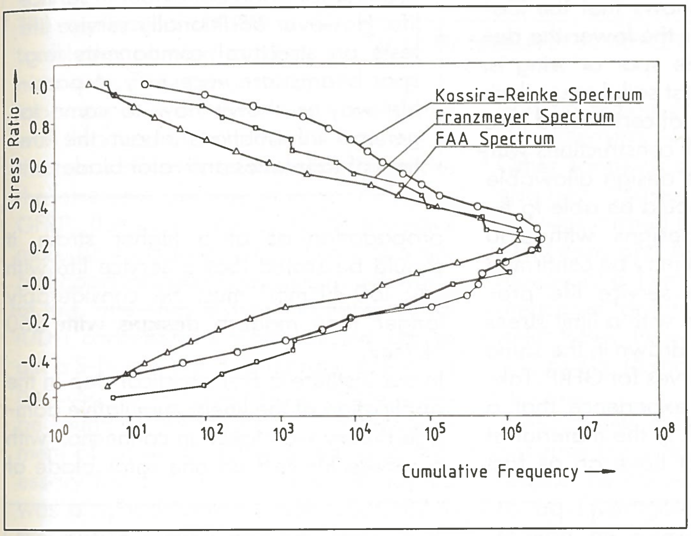

Fig. 7: Cumulative Frequency of Three Load Spectra for Sailplanes and Light Aircrafts

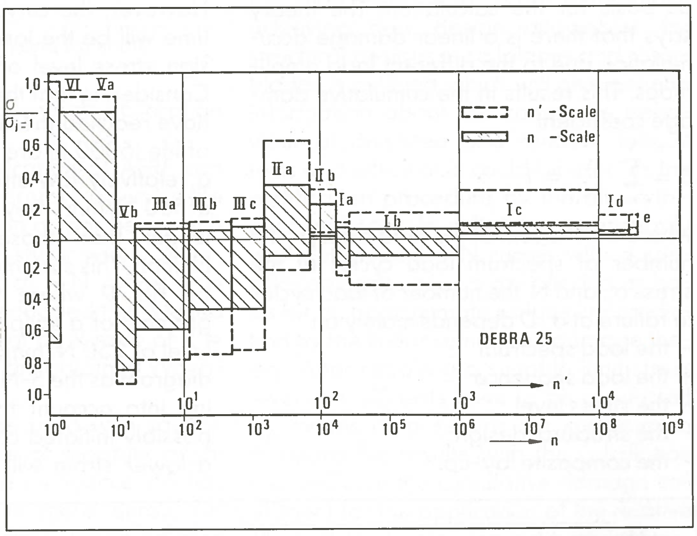

Fig. 8: Original and Reduced Life Load Programme for a Rotor Blade

tion. A group of the IEA (International Energy Agency) is discussing the possibilities of combining the load measurements of the participating countries into one service life spectrum which shall give realistic values und load sequences available for medium-sized horizontal axis wind turbines.

For sailplanes commonly remains the principal disadvantage in certificating the design allowables that the tested structure must be broken statically after the service life test [9], and therefore in general is not available for further service life investigations. But now this would be desirable as GFRP sailplanes have reached the limit of 6000 flight hours.

The authorities request the proof of a longer possible flight time. A new certification test however for satisfying this requirement of a life time of e.g. 12 000 h must start from the very beginning again and therefore takes much longer time and is more cost-intensive than necessary. In the meantime the concerned gliders must be grounded. The problem will come up again when the sailplanes in those regions with good thermals will have flown into the new certification level in short time. It can be stated that this is a problem of certification, and not of the material, because the machines surely will not destroy themselves after these 12 000 h.

A possible answer will be given in the sequel by means of a fatigue life evaluation for GFRP gliders. It shows e.g. that the constructions with the low stress limit of 160 N/mm² should be able to outlast a human's life. Perspectives are outlined for CFRP design allowables and for AFRP. The results will be applicable for rotor blades as well.

Life time evaluation by means of the linear Palmgren-Miner rule

As a first step the S-N curves for the highly loaded components of a structure must be obtained. The material should have the same or a similar lay-up as that of the original structure. For GFRP two investigations were made by institutes of the DFVLR some years ago [10, 11] *(see Fig. 9)*. Based on these results it could be concluded that at high load cycle numbers the notched material is not worse than the unnotched one and that in general S-N curves with an R ratio of R = −1 give the most conservative values. This statement could be found in other investigations as well [12].

As a next step a life time evaluation was made for GFRP gliders. Additionally to [7] the linear Palmgren-Miner rule was used as basis for the calculation. The theory says that there is a linear damage accumulation due to the different load amplitudes. This results in the cumulative damage coefficient

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} = 1$$

where k is the sum of the load steps, n_i the number of spectrum load cycles at the stress σ_i, and N_i the number of load cycles to failure at σ_i. D depends mainly on

- the load spectrum
- the load sequence
- the stress level
- the structural design
- the composite lay-up.

Experience has shown, that in practice the value of D can vary over a wide range, from 10^{-1} to 10^{1} [13]. However, more sophisticated theories than the applied one do not seem to give more realiable results [13, 14]. Thus with the choice of a suitable low value, say D = 0,1, the method should be accepted in meeting the philosophy of the certificating authority.

An additional argument was to take only the S-N curves for R = −1 into account. Calculations were carried out for several design stress levels, the highest of them was 250 N/mm². The scatter factor of life j_L = 3,0 was taken into account. *Fig. 10* shows that the results are satisfactory, but they were obtained only from specimens. In a spar still the ILS in the fabric combining the caps with the webs occur. Therefore structural tests have to confirm the positive impression obtained by this first evaluation of flight time.

However, the curve shows that the lifetime will be the longer the lower the design stress level of the spar or wing is. Considering that the first sailplanes which have reached the limit of certificated time of life (6000 h) are still constructions with a relatively low stress design allowable of 160 N/mm² they should be able to fly longer than those designs with 250 N/mm². This statement may be confirmed by Fig. 9 where the service life programme of a sailplane with a limit stress level of 250 N/mm² is drawn in the same diagram as the S-N curves for GFRP. Taking into account the experience that a possibly initiated crack in the material at a lower strain will not have an as fast propagation as at a higher strain, it should be stated that a service life with say 160 N/mm² must be considerably longer than modern designs with 250 N/mm².

In our institute a first practical step in the application of the linear cumulative damage theory was taken in connection with a service life test on one rotor blade of

Summary

The wings of sailplanes and the rotor blades of wind turbines commonly are designed by using fibre reinforced plastics. Because of the similarity of the structures and the aerodynamic loadings the application of the same fatigue criteria for the constructive lay-out will be possible. A life time evaluation, made for GFRP gliders on the basis of the linear Palmgren-Miner Rule shows a considerably long time of possible service life. A full-scale fatigue test of a 11,6-m rotor blade, carried out in the DFVLR Institute for Structural Research and Design, also showed positive results. Furtheron S-N curves of carbon and aramid fibre reinforced plastics (CFRP, AFRP) are presented and give promise for good behaviour in service life. However additionally service life tests on structural components (e.g. spar beams) are necessary. A possible way is shown how to come to general informations about the life time of sailplanes and rotor blades.

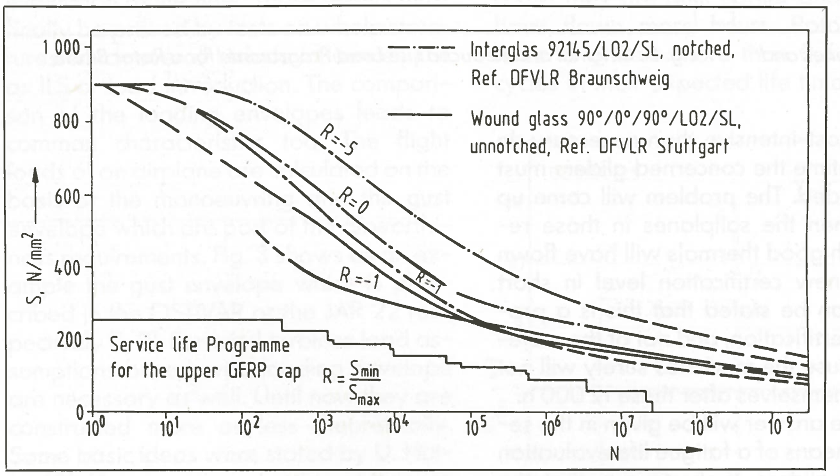

Fig. 9: S-N Curves for UD-GFRP Compared with a Fatigue Programme for a 12 000-Flight-Hour Certification

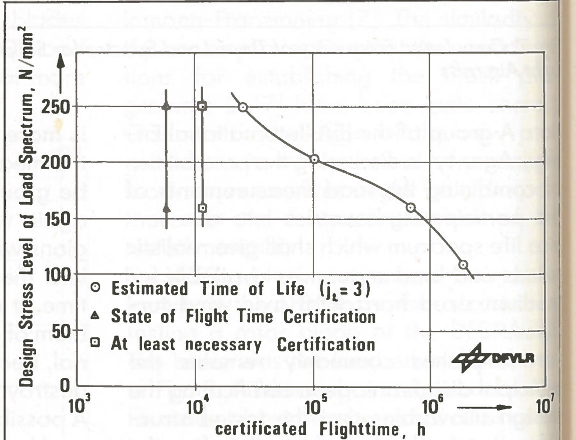

Fig. 10: Life Time Evaluation by means of the Linear Miner Rule for GFRP Sailplanes

the DEBRA 25. The high number of 4×10^8 expected load cycles during life time was impossible to be tested from the view of time and cost intensity with the test objectives. The number of cycles for one test was reduced in the way that the load level was increased assuming the cumulative damage coefficient to be constant (see Fig. 8). A final check of the blade during the fatigue test was made by means of a static load test up to j = 1,5*1,25 = 1,875 (related to the century gust) without any problems. From this point of view the service life test has shown that with respect to the necessary stiffness the rotor blade could be designed still lighter.

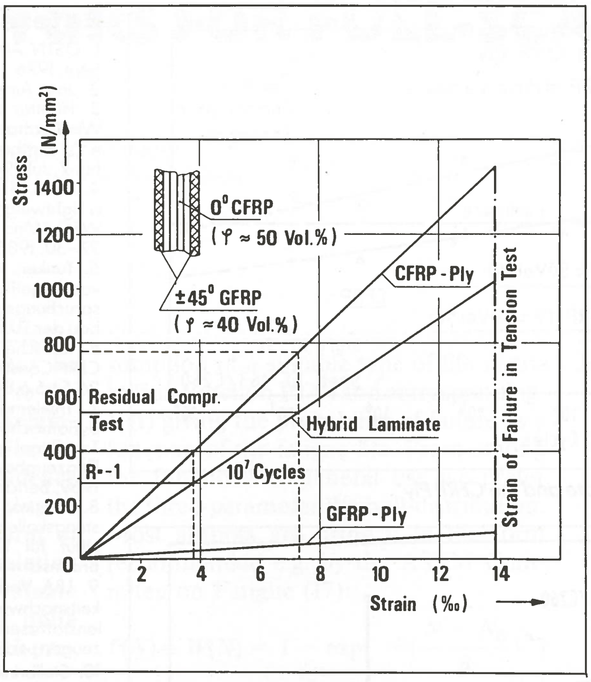

Fig. 13: Ply Stresses of a CFRP-GFRP-Hybrid Laminate

The application of CFRP in rotor blades of wind turbines is not usual. The carbon fiber is too expensive and—additionally—the wall thickness of the blades is high due to the a.m. stiffness requirements. Therefore the stresses are low enough for using GFRP. But in sailplanes CFRP promises more performance, and it has a proverbial good fatigue behaviour. To get inside of this, one-step tests with unidirectional (UD-) carbonfibres were carried out to get a S-N curve at a stress ratio of R = −1 because no relevant fatigue data could be found in the literature. The development of an antibuckling device was necessary for that investigation. The lay-up was a hybrid laminate with UD-CFRP in the middle section and one layer +45° GFRP fabric on each side. The results of the calculation of the single ply stresses versus the strain are shown in Fig. 13, the S-N curve of the hybrid laminate and the CFRP ply in Fig. 14. The calculated curve of this ply is compared in Fig. 15 with the service life programme Franzmayer for a 12 000-flight-hour certification. This crosscheck seems to indicate, that the inherent capabilities of the carbonfibre are not yet completely exploited.

For the introduction of new advanced composites certification tests are required too. Aramid fibre reinforced plastics (AFRP) promise to be qualified for application in sailplanes due to their low specific weight and good tensile strength. Because of the fact that their compressive strength is only a fraction of the tensile strength they are used almost only in secondary structures. However, in the fuselage of the fs-31, a two-seater construction of the Akaflieg Stuttgart, AFRP was combined with CFRP in a lightweight design promising good energy absorption characteristics [15].

Other forms of application of AFRP can also be imagined. Therefore a service life test was carried out on a spar beam with CFRP caps and AFRP shear webs. Simultaneously a number of S-N curves was measured for torsion-loaded thin-walled AFRP tubes, likewise at an R ratio of R = −1 [16]. Fig. 16 shows the obtained Woehlercurve.

These results must be used with caution because the influence of moisture might reduce the values. This influence still has to be investigated in more detail. Although an approximate life prediction was made and gave sufficient results, a better statistical confirmation is still necessary.

An application in rotor blades is imaginable in the case that the price of aramidfibres would be reduced again.

Relative Miner Rule

Investigations with variable amplitudes have shown that the cumulative damage coefficient D is similar for similar load spectra and structural forms of the test sample [11, 12]. Therefore for a life time evaluation the failure criterion

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} = \text{const}$$

is used with a value of D resulting from other tests with similar structural and load parameters. This is based on the assumption that when applying similar load spectra, equal differences with respect to the failure criterion D = 1 can be expected because of similar accumulative damage at different load amplitudes. The advantage of this method is that it overall takes into consideration the interactions in the material such as crack propagation, delaminations, etc. In applying this method results for S-N curves and cumulative damage coefficients must be available. The problem of a long testing time still remains, because in the applied load spectra the lowest amplitudes correspond to the largest numbers of load cycles. Several papers report about omission and truncation investigations [12, 17]. Phillips demonstrated on CFRP laminates with holes that the truncation of the low-load end of the spectrum shows promise for achieving large reductions in testing time without significantly changing the results [17].

For the rotor blade of the DEBRA-25 a kind of omission was made. However, in that case the reduction of the load cycles was accompanied still by an increasing of the load level. A possible method for achieving new design allowables for structural designs in sailplanes and rotorblades is outlined which will give general information about the composite behaviour at one-step and random fatigue tests and which also could be used as the certification procedure by the airworthiness authority. In a first step statistically well determined S-N curves with a specific composite lay-up are needed as basis for an approximate fatigue life prediction by the linear cumulative damage theory. After choosing a suitable limit stress level (j = 1,0) tests have to be conducted by means of a service life spectrum to compare the results with the calculation that will give the cumulative damage coefficient for the application of the relative Miner Rule. By carrying out further investigations with omission the stress level can be varied to correct the estimated curve of life time. After these tests with specimens the results must be confirmed by means of larger structures, such as spar beams of wings or rotor blades to be valid for the certification. In this way it should be possible to come close to the performance limits of the material and to take the best benefit of its inherent capabilities. For rotor blades additionally the influence of humidity is to be investigated.

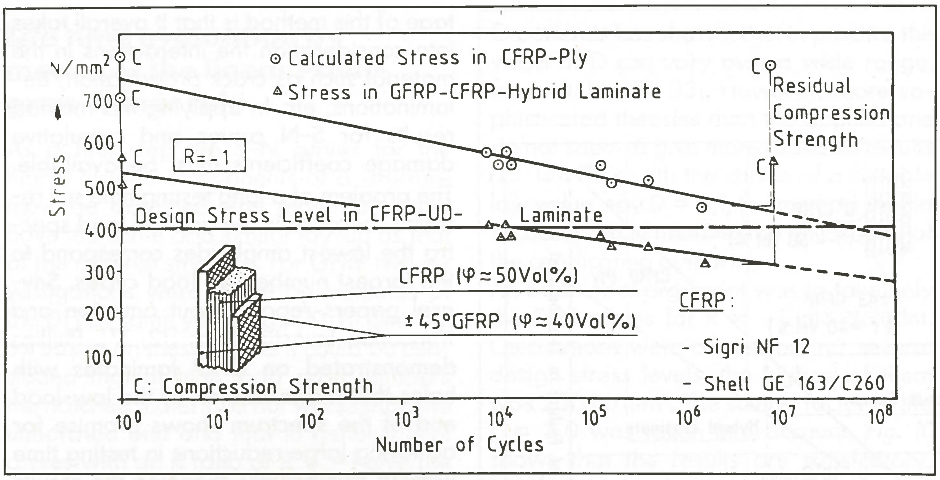

Fig. 14: S-N Curve of a CFRP-GFRP-Hybrid Laminate and the CFRP Ply

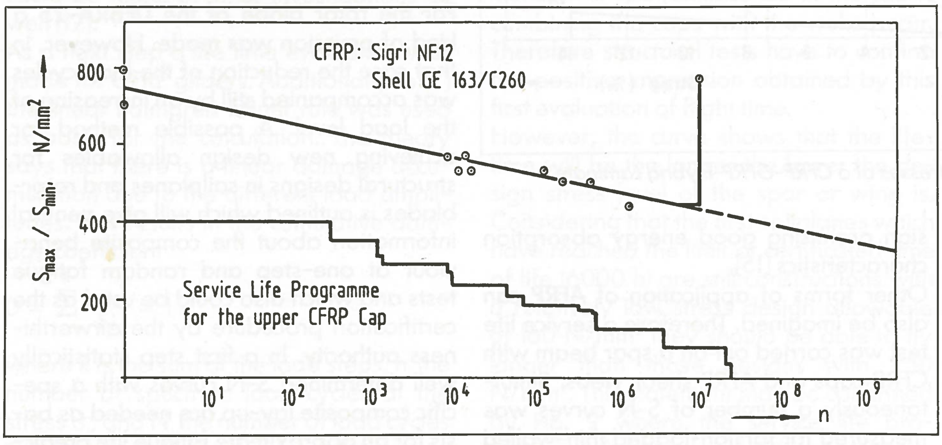

Fig. 15: S-N Curve of UD-CFRP Compared with a Fatigue Programme for a 12 000-Flight-Hour Certification

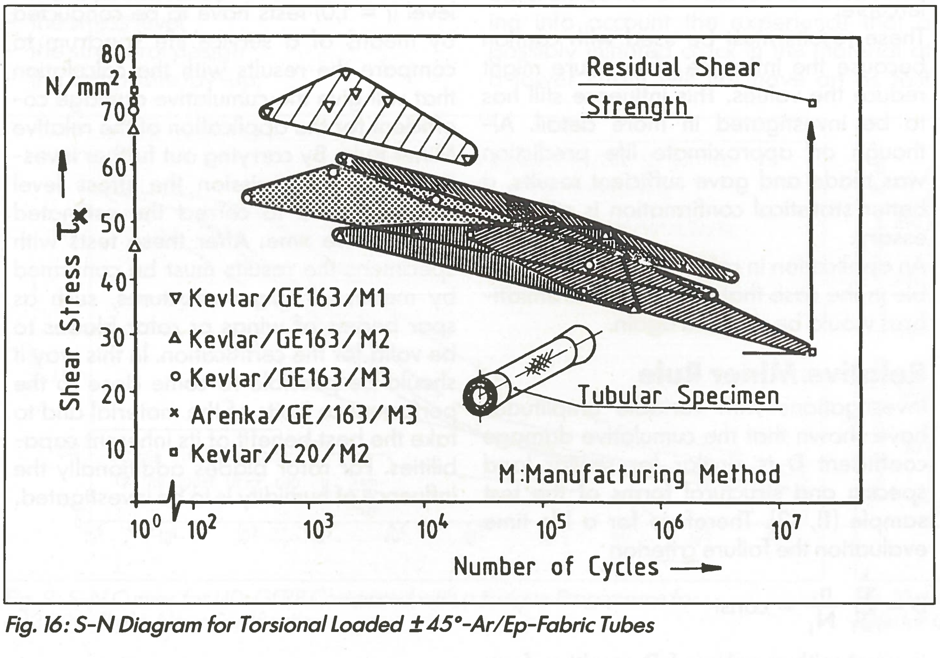

Fig. 16: S-N Diagram for Torsional Loaded ±45°-Ar/Ep-Fabric Tubes

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