THE FATIGUE SENSITIVITY OF FIBERGLASS GLIDERS

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Summary

A preliminary analysis of the fatigue strength of fiberglass gliders has been carried out in the course of a current Australian investigation to substantiate an optimum economic life and, if warranted, carry out a life extension program for fiberglass gliders in Australia. This has led to some significant conclusions relevant to the fatigue performance of fiberglass gliders, and a brief account of the project is presented here and problems it has brought out are discussed with reference to the main investigation.

The main conclusions of the paper are that the conventional view of the satisfactory fatigue performance of fiberglass structures contains some potential dangers. The flat S-N curves of this material which underlie its high fatigue performance also contribute to a very large variability in life. They also cause a large reduction in fatigue life for any increase in operating stress and with the current lack of knowledge of the effective stress concentration factor (or fatigue strength reduction factor) of complete fiberglass structures, as distinct from notched specimens, this is a major problem.

Similarly, the high residual strength maintained by fiberglass during the fatigue life until final failure is approached, also carries a counteracting disadvantage in that it reduces the advance warning available to a safety-by-inspection or fail safe approach to fatigue safety. It is suggested that the Australian Joint Program on fatigue of fiberglass gliders will help to overcome these uncertainties and provide a better understanding of the fatigue behaviour of a complete fiberglass structure.

1. Introduction

A joint investigation is being carried out by the Department of Aviation (D of A), R.M.I.T. and the Gliding Federation of Australia (GFA) into the fatigue performance of fiberglass gliders in Australia, which is designed to establish by analysis and substantiating tests, their fatigue certification to an optimum economic service life. The program includes a flight load investigation using the R.M.I.T. instrumented Janus sailplane to derive a load spectrum for Australian conditions. This has also produced a representative flight load sequence for a full scale fatigue test which is to be carried out on a fiberglass glider wing, together with a supporting test program on fiberglass specimens to obtain basic fatigue data and information on fatigue life variability.

In the course of this program, fatigue analysis has been to design the full scale fatigue test and plan for the analysis and interpretation of results. This has brought out some significant factors relating to the fatigue performance of fiberglass gliders and a report on these aspects is presented in this paper.

2. Fatigue life estimation

A load spectrum giving frequency of exceedence of c.g. acceleration has been obtained from flight load investigation and this is reproduced in Figure 1. The nominal stress per g at various potentially critical locations in the Janus flight test vehicle has been obtained in this investigation. However, the objective of Glider Fatigue Program relates to fiberglass gliders in Australia generally, and a stress of 300 MPa. (43.5 k.s.i.) at ultimate design load of 9g has been used in the calculations, since this value is widely used in current design practice.

No comprehensive data were available on the fatigue of fiberglass structures or components and since the object of the present project was to investigate the fatigue sensitivity of these structures, an effective stress concentration factor K_σ was adopted using an A-M diagram in non-dimensional co-ordinates $({}^{\sigma_{MEAN}}/\sigma_{ULT}\ {}^{\sigma_{ALT}}/\sigma_{ULT})$ for unnotched fiberglass (Figure 2) derived by C. Sue-Yek in an earlier investigation.[1]

For the life calculation, the continuous spectrum in Figure 1 was replaced by a histogram giving a series of load intervals containing a number n_s of load cycles per hour in each interval. The g load for the interval g_s is then transposed to the corresponding local stress σ_s by the relation:

$$\sigma_s = K_\sigma \cdot g_s \left(\tfrac{300}{9}\right) \text{ MPa}$$

To enter the A-M diagram, stress is transformed to non-dimensional form by dividing by the ultimate stress of the material. From Ref. 2 a typical value of ultimate compressive stress has been taken as:

$$\text{U.C.S.} = 80 \text{ k.s.i.} = 550 \text{ MPa}$$

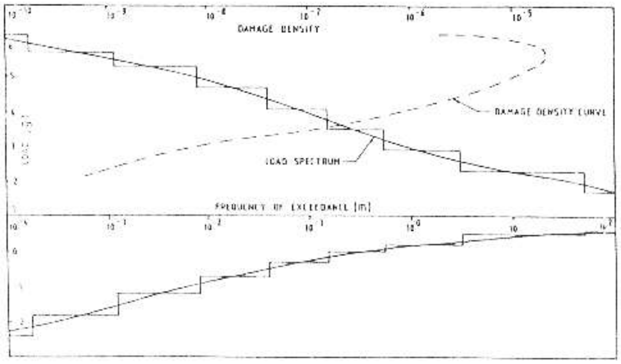


FIGURE I-LOAD SPECTRUM

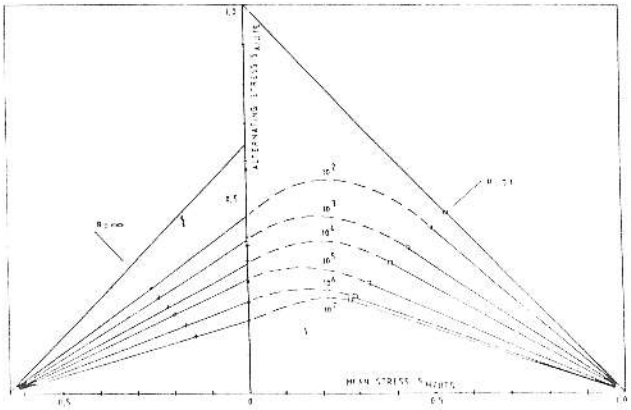


FIGURE 2-A-M DIAGRAM FOR UNNOTCHED UNIAXIAL FIBREGLASS

The fatigue life to failure N_s corresponding to σ_s having been obtained from the A-M diagram the fatigue damage is calculated from the Linear Cumulative Damage hypothesis:

$$\sum \frac{n_s}{N_s} = 1$$

shown in the sample calculation for $K_\sigma=2.3$ in Table 1. Since fiberglass is critical in compression, calculations were carried out for compressive mean stress. Fatigue life estimates were made for a number of values of K_σ, including K_σ equal to 1.) and the results are plotted in Figure 3 showing the calculated mean life versus K_σ. This graph shows how sensitive the calculated life is to the value of K_σ as discussed in Sec. 4.

3. Scatter factor

To investigate scatter in fatigue of fiberglass, a significant body of data issued by the ANC-17 Panel on Plastics for Aircraft[3] some time ago in 1956, has been analyzed. The material composition was 181 Nolan glass fabric and Epon 828 resin and approximately 60 test results are given for tests made with loading parallel to the warp direction. Although not directly comparable with the materials used in modern fiberglass glider construction, these results have been found to give a statistically homogeneous body of data and are considered to give an indication of fatigue life variation of the combined uniaxial glass fiber and glass fabric construction used in fiberglass glider wings.

A number of test replications at each stress level were not carried out, but the data present a series of approximately ten data points under each of six groups of test conditions, as shown in Table II.

For any group "r" a linear regression of the stress S_{ir} of each specimen i in the group versus the life N_{ir}, $S = a - b. \log N$, has been found to give a very good fit for each group of data, as shown by the correlation coefficients in Table II. The data have then been standardized by dividing the value N_{ir} for each stress level in a group by the mean value $\tilde{N}_{ir}$ for the stress level as found from the regression line of the group. Then, on the assumption of a logarithmic normal distribution, which often applies to fatigue life, the transformed variate,

$$X_{ir} = \log {}^{N_{ir}}/\tilde{N}_{ir} = \log N_{ir} - \log \tilde{N}_{ir}$$

TABLE I FATIGUE DAMAGE CALCULATION

Load Range					Stress Range		Cycles		Fatigue Damage		
(1) Min. Load Range g	(2) Max. Load Range g	(3) Load Range Ratio (R)	(4) Alt. Load (L_{alt}) g	(5) Mean Load (L_{alt}) g	(6) Max. Stress σ_{max} ÷ S_{ult} k.s.i.	(7) Alt. Stress σ_{alt} ÷ S_{ult} k.s.i.	(8) Exceed. per Hour (m)	(9) Counts per Hour (n)	(10) Fatigue Life (N) cycles	(11) Cycle Ratio (n/N)	(12) Damage Density Rate per g
-2.4	6.1	-.39	4.25	1.85	.543	.378	1.70E-4	1.70E-4	2.00	8.50E-6	2.83E-6
-1.8	5.7	-.32	3.75	1.95	.508	.334	1.20E-3	1.03E-3	.50E+1	1.24E-5	2.16E-5
-1.2	5.3	-.23	3.25	2.05	.472	.289	8.00E-3	6.80E-3	9.00E+2	7.56E-6	1.51E-5
- .7	4.7	-.15	2.70	2.00	.419	.240	4.00E-2	3.20E-2	1.50E+4	2.13E-6	3.55E-6
- .3	4.1	-.07	2.20	1.90	.365	.196	1.50E-1	1.10E-1	1.20E+5	9.17E-7	1.53E-6
.0	3.5	.00	1.75	1.75	.312	.156	5.50E-1	4.00E-1	6.50E+6	6.15E-8	3.03E-7
.2	2.9	.07	1.35	1.55	.258	.120	3.20	2.65	1.40E+8	1.89E-8	4.85E-8
.5	2.3	.22	.90	1.40	.205	.080	5.00E+1	4.68E+1	1.00E+11	4.68E-10	7.80E-10
.6	1.7	.35	.55	1.15	.151	.049	3.00E+2	2.50E+2	——	——	——

FATIGUE DAMAGE, D = Σ(n/N) from Column (11), Life N = 1 ÷ D =31,600 Hours
2.2 × 3.16E-5

(1),(2) = From Histogram in Figure 1
(3) = (1) ÷ (2)
(4) = [(1)-(2)] ÷ 2
(5) = [(1)+(2)] ÷ 2
(6) = (2) x K_σ x 4.83/ 125.0
(7) = (4) x K_σ x 4.83/ 125.0
(8) From Spectrum in Figure
(9) From (8) by successive difference
(10) From A-M diagram in Figure 2
(11) = (9) ÷ (10)
(12) = (11) ÷ $[L_{max}]_i$

K_σ = 2.3

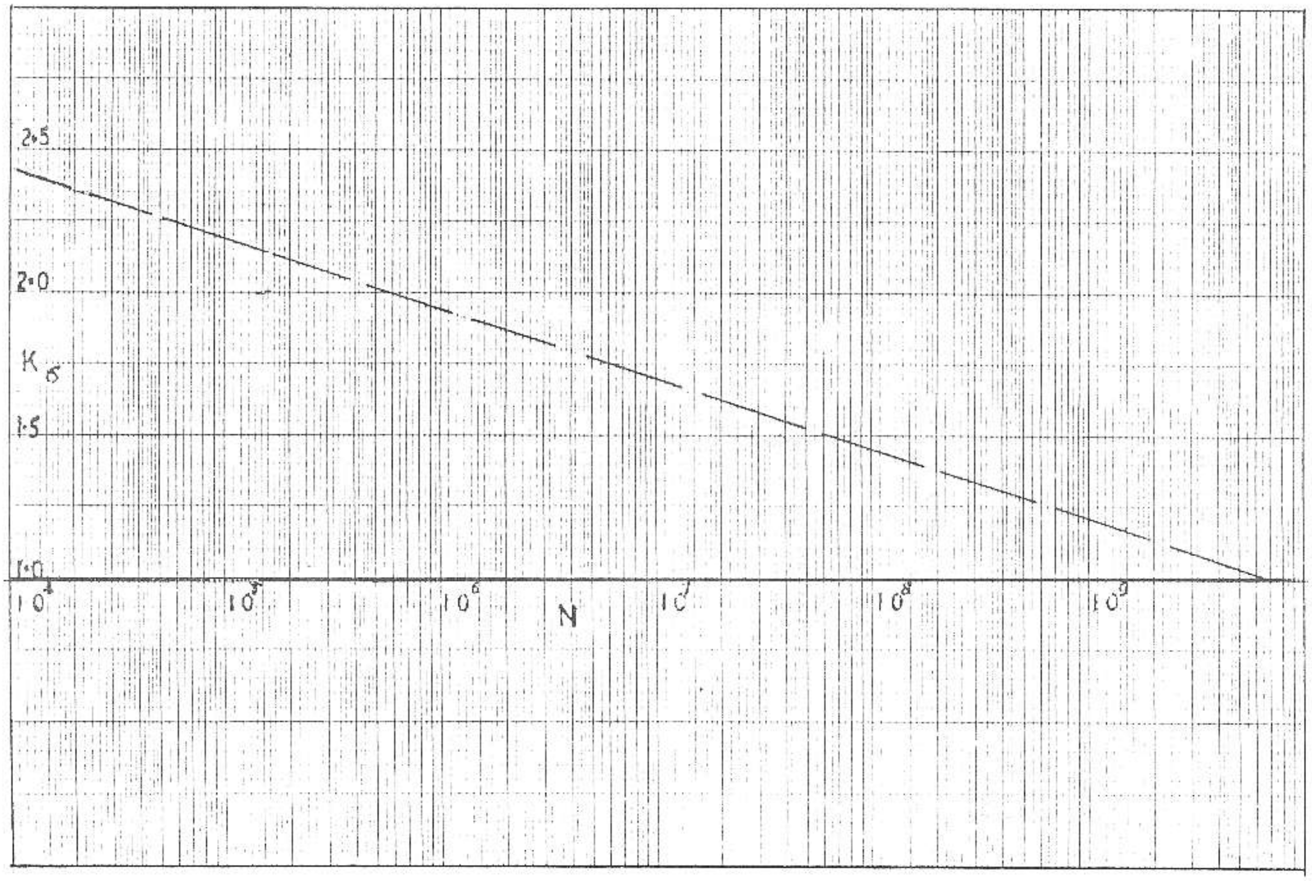


FIGURE 3-FATIGUE LIFE AS A FUNCTION OF FATIGUE STRENGTH REDUCTION FACTOR K_σ

TABLE II
SUMMARY OF TEST DATA ON GLASS FIBRE EPOXIDE LAMINATES

Group Designation	**No. of test results in group t**	**Standard deviation of log $\frac{N_{ir}}{\tilde{N}_{ir}}$ s**	**Mean S-N curve Regression line for Group (r) σ_{ir} stress in K.s.i. at mean life $\tilde{N}_{ir}$**
Group (a) Notched specimens tested parallel to the warp at 50% Relative Humidity and R = −1.	10	0.42	$\sigma_{ia} = 40{,}060 - 3378 \log \tilde{N}_{ia}$ Correlation coefficient $r^2 = 0.89$
Group (b) Notched specimens tested parallel to warp at 50% Relative Humidity and R = −1.	11	0.46	$\sigma_{ib} = 33{,}286 - 2852 \log \tilde{N}_{ib}$ Correlation coefficient $r^2 = 0.89$
Group (c) Notched specimens tested parallel to warp at 100% Relative Humidity and R = −1.	8	0.16	$\sigma_{ic} = 36{,}728 - 3670 \log \tilde{N}_{ic}$ Correlation coefficient $r^2 = .089$
Group (d) Unnotched specimens tested parallel to warp at 100% Relative Humidity and R = −1.	12	0.45	$\sigma_{id} = 34{,}652 - 2557 \log \tilde{N}_{id}$ Correlation coefficient $r^2 = 0.89$
Group (e) Notched specimens tested in bearing fatigue at 50% Relative Humidity and R = −1.	10	0.25	$\sigma_{ic} = 34{,}718 - 4071 \log \tilde{N}_{ie}$ Correlation coefficient $r^2 = 0.89$
Group (f) Notched specimens tested in bearing fatigue at 100% Relative Humidity and R = −1.	10	.044	$\sigma_{if} = 37{,}759 - 3960 \log \tilde{N}_{if}$ Correlation coefficient $r^2 = 0.89$

COCHRAN'S TEST FOR HOMOGENEITY OF VARIANCE

Ratio of largest S^2 to total of the S^2 values,
$$g = \frac{S^2_{max}}{\Sigma S^2_r} = \cdot 2426$$

From Tables in Ref. 7 for 5% Probability
$$= 0\cdot 3682 \; {}^{-}t = 10$$
$$= 0\cdot 3568 \; t = 11$$

Therefore the hypothesis of a common variance is accepted at ·05 level of significance.

would approximate a normal distribution if the six groups of data had a common variance.

The standard deviations S_r for each of the six groups have been calculated as shown in Table II and tested for homogeneity by the Cochran Test, which has supported the hypothesis of common variance. The X_{ir} for the 6 groups of data have then been pooled on the assumption that they are a homogenous sample from a Normal distribution.

The pooling assumption has been tested by plotting on Normal Probability paper in Figure 4 in comparison with the straight line for a Normal Distribution with the pooled value of standard deviation, S = 0.4 from all the test points in the 6 groups: the group a to f as designated in Table II to which the test point belongs, is listed in the same sequence as the test points on the right hand side of Figure 4. It can be seen that the 61 test points show reasonable agreement with the theoretical straight line and there is no definite tendency for the points in any group to segregate in the array.

It is, therefore, assumed that a log normal distribution with standard deviation S = 0.4 gives a good approximation to the data. On this basis, the scatter factor S.F. on fatigue life for the common assumption of 3 standard deviation from the mean[4,5] gives,

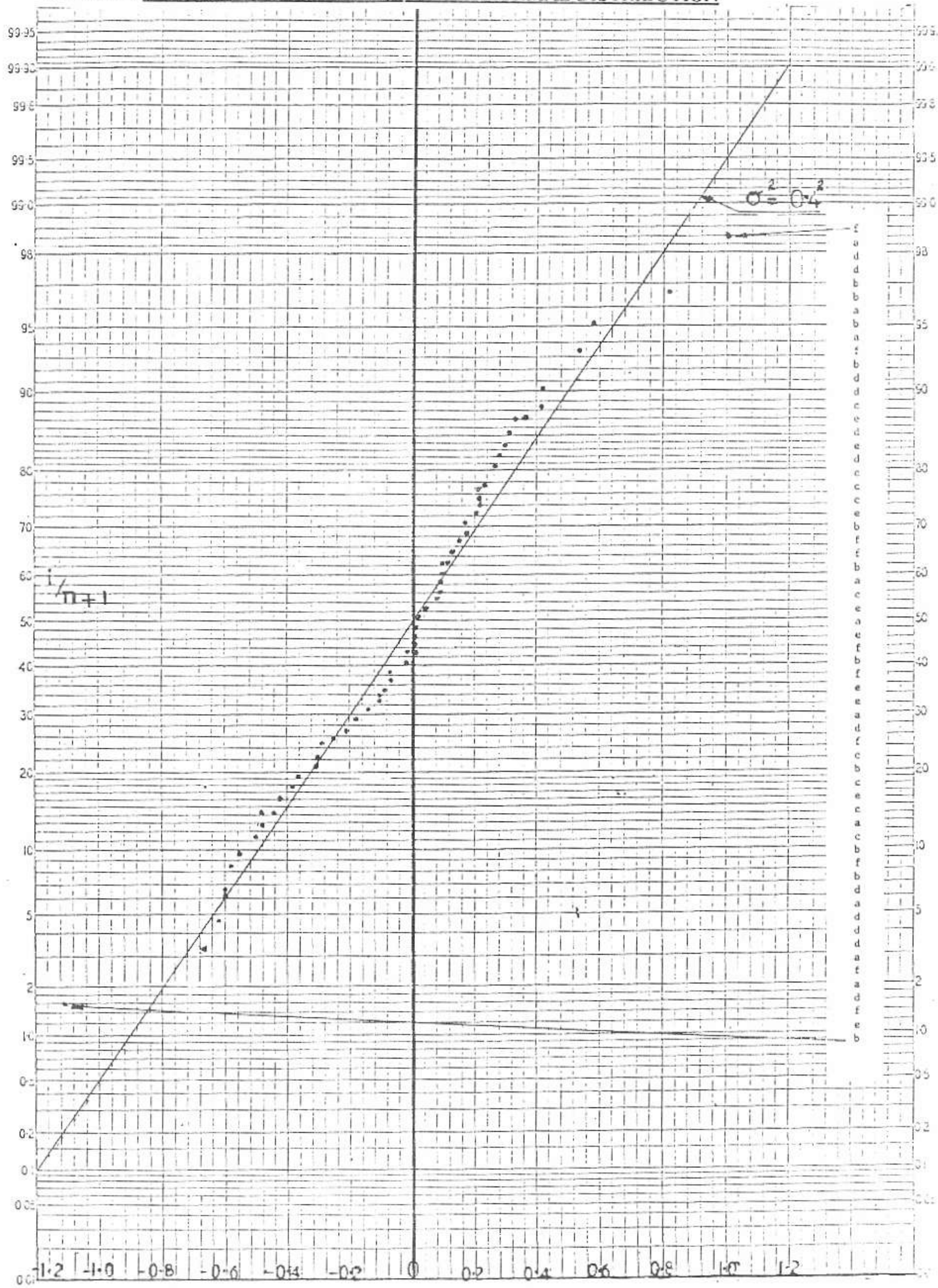
$$S.F. = 10^{3\sigma} = 10^{1\cdot 2} = 15.85 \approx 16.$$

This indicates a scatter factor of 16, which is considerably greater than for aluminum alloy construction.[5] This is discussed further in Section 4.

4. Discussion

The graph in Figure 3 gives an estimate of fatigue life as a function of K_σ for the assumed design parameters viz. nominal stress per g, f_g = 33.2 MPa (4.82 ksi) and ultimate compressive strength of the material $f_{u.c.s}$ of 550 MPa (80 ksi), or for

FIGURE 4-COMPARISON OF LOG Ni / Ñ WITH NORMAL DISTRIBUTION



LOG Ni / Ñ

the general case it shows the mean fatigue life as a function of K_σ multiplied by the relative stress per g:viz.

$$K_\sigma f_g / f_{u.c.s.}$$

However, at the present state of knowledge there are, in addition to the A-M diagram of Figure 2 which itself needs verification, a number of uncertainties involved in this approach. First, the identification of critical areas and concentration factor K_t. For an orthotropic material solutions have been derived for only a few simple stress concentrators, such as a circular and an elliptical hole[6] but for the complex three dimensional configurations n a complete structure and the changes in load path it produces finite element analysis is probably the only solution.

Secondly, the fatigue strength reduction factor K_σ does not appear to depend on K_t to the same extent as in an isotropic material. Thus, fatigue tests on notched fiberglass specimens show a relatively small effect of K_t on the fatigue life, although the stress-strain, curve of the material indicates an absence of extensive plastic yielding at high stress, which is a major factor in alleviating stress concentration in isotropic materials. Therefore, the fatigue behaviour at a stress concentration in areas of major load redistribution with high stress gradient in a complete structure needs to be investigated if a reliable relationship between K_t and K_σ is to be determined.

Third, there is the question as to whether the Linear Cumulative Damage Hypothesis is a workable approximation for fatigue life estimation of fiberglass and this has yet to be determined, even for notched specimens.

Coming to the derivation of the safe fatigue life there is also the question of the scatter factor to be applied to the mean life. Although no statistically homogeneous data involving a number of test replications could be found in the literature the investigation described in Section 3 is considered to be sufficiently well based for a preliminary estimate of fatigue life variation, covering as it does a variety of loading conditions. It gives a scatter factor of 16, supporting a widely held view of large scatter in fatigue life of composites.

From these considerations, it is apparent the safe life estimation of fiberglass structures from basic material data is subject to considerable uncertainty but it is clear that any estimate is inordinately sensitive to the value of K_σ and with the design parameters taken here a fiberglass structure could be fatigue critical.

Thus, if a value of $K_\sigma = 2.0$ is taken as realistic, bearing in mind the uncertainties in determining mean fatigue life referred to above, Figure 3 indicates a mean fatigue life for the Australian Spectrum of 600,000 hours and with a scatter factor of 16 the safe life would be 37,500 hours, which appears more than adequate. However, a 10% difference giving $K_\sigma = 2.2$ gives a mean life of 90,000 hours and safe life of 5,600 hours, which is a disturbing reduction.

Finally, there is the question of damage tolerance and detection of fatigue damage to provide safety-by-inspection. While a considerable amount of work has been done on carbon fiber composites as regards residual strength of damaged structure, particularly due to delamination, there is very little evidence available on the residual strength of fiberglass structures during their fatigue life.

Test data on small specimens indicate that there is very little reduction in strength until the fatigue life approaches the life to final failure. While this is favorable as far as achieving maximum safe life is concerned, it is unfavorable as far as providing safety-by-inspection (fail safe).

5. Australian fatigue investigation

The Australian investigation on the fatigue substantiation of fiberglass gliders referred to earlier is intended to also make a contribution to basic research on the fatigue of the fiberglass construction.

It involves a fatigue test to destruction of a fiberglass glider wing instrumented with a 300 electric resistance strain gauges and a test program on 400 plain and notched fiberglass specimens. The strain gauge data in conjunction with a Finite Element Analysis of the structure will provide information on the stress distribution in fatigue critical areas and enable an effective K_σ to be estimated by comparison with fatigue data on the plain and notched specimens.

The specimen testing program will also provide S-N data to improve the A-M diagram in Figure 2 and the program will be designed to provide data on the fatigue life distribution.

6. Conclusions

1. A preliminary investigation of fatigue life variation of fiberglass indicates a scatter factor of 16 corresponding to 3 standard deviations from the mean.

2. The fatigue life estimates of fiberglass structures using basic fatigue data on the material are very sensitive to the effective fatigue strength reduction factor assumed, but estimates based on typical design parameters suggest that the safe fatigue life could be marginal.

3. Fatigue testing of full scale fiberglass wing structures is necessary to investigate the relationship between the fatigue strength of the structure and that of the basic material and also to investigate the fail safe and damage tolerance characteristics of these structures.

4. Fatigue tests on fiberglass specimens are needed to obtain basic S-N data and information on variability in fatigue life.

7. References

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