The fatigue life of wooden gliders

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Introduction

Failure by fatigue, whereby fracture occurs in a material after the application of a number of cycles of alternating or repeated stresses of a lower level than the max. static failure stress, is now a well-known phenomenon. However, little seems to have been published of its effects on wooden structures. The notes and calculations that follow show that under normal circumstances there seems to be little to worry about in a correctly operated wooden glider which has been designed to meet the Section E. of the current British Civil Airworthiness Requirements, or the slightly more severe OSTIV requirements.

The difference in approach in designing for "Safe Life" as opposed to "Fail Safe" is well known in aircraft structural circles, but perhaps not so well known outside. In essence, a "safe life" structure is one which although the effects of fatigue may be considered in its design, no account is taken of possible service failures and by combination of tests and calculations a maximum permitted flying life is laid down. In a "fail safe" design the structure is deliberately made such that in the event of a complete failure of any single primary part there is sufficient structure still available to carry a high percentage of the original design strength. In addition primary structural members must be capable of easy inspection so that developing cracks are discovered soon enough for repair to be initiated before a critical stage arises.

Until a definite attempt to design a fail safe glider is made it must be assumed that all gliders are of the safe life philosophy—certainly all older ones are, and the remainder of this paper concerns itself only with the safe life calculation.

Method of Calculation of Safe Life

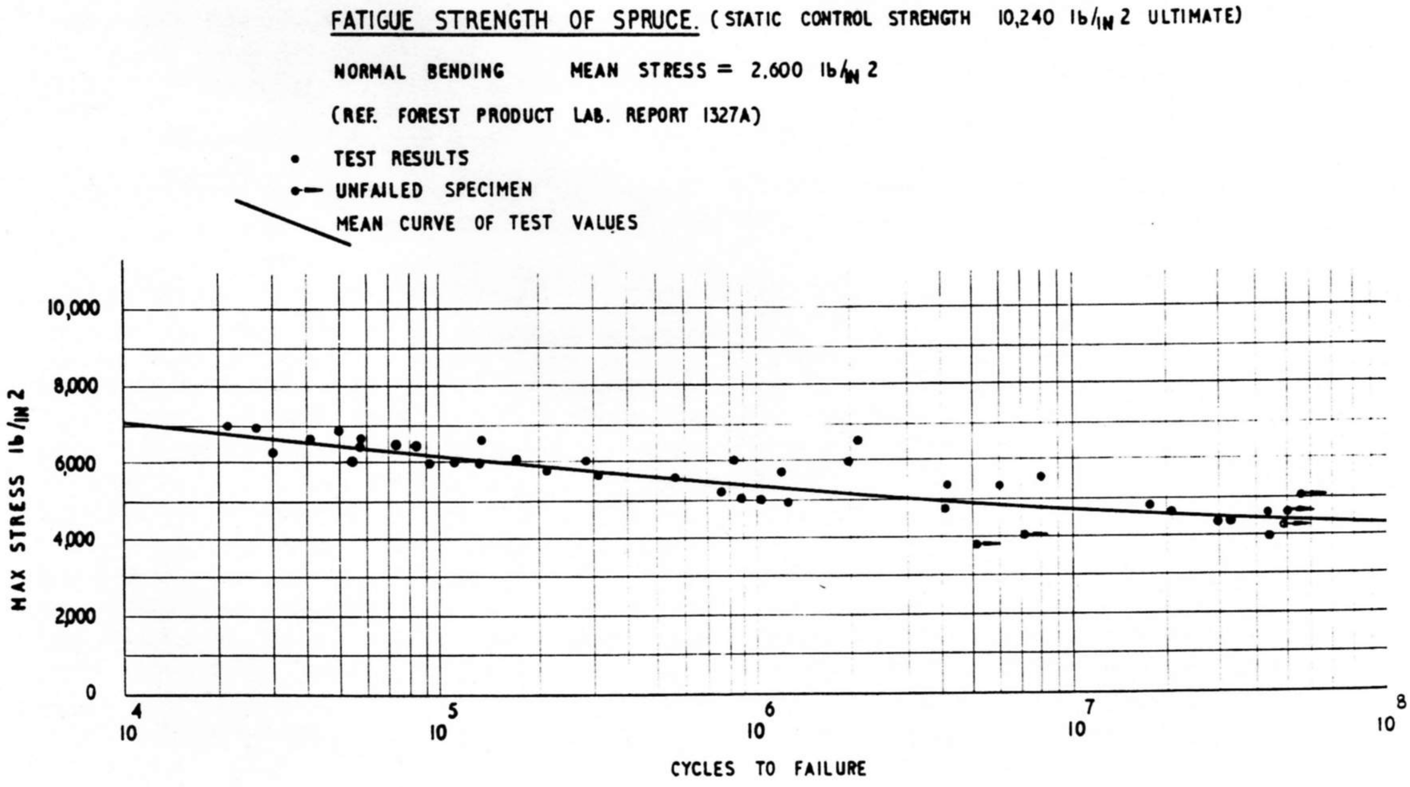
The methode of calculation currently used in the aircraft industry to estimate wing fatigue lives from test results has been developed by Raithby and it is proposed here only to offer brief comments on it. It is based primarily on the Palingren-Miner cumulative damage theory that the proportion of fatigue life used up when cycles of a particular alternating load are applied may be expressed by n/N where N = number of cycles of that load to cause failure. If a number of load levels are applied the life used is given by

$$\frac{n1}{N1} + \frac{n2}{N2} + \frac{n3}{N3} - - - - - - - = \sum \frac{n}{N} \text{ failure occuring when } \sum \frac{n}{N} = 1.0$$

Some basic data are required before embarking on the calculation:

(a) Fatigue characteristics of the structure (or at least the materials of construction). This is normally obtained from test preferably of the wing structure. For the purpose of the calculation an S–N curve is required, i.e. alternating stress plotted against the endurance for that particular stress. Published data on spruce is given in fig. 1.

Fig. 1



(b) A gust load spectrum. The best data is that appearing in Raithby's paper. This is obtained from various sources and enumerated in the Royal Aeronautical Society's Fatigue Data Sheets.

(c) A flight plan, or duty cycle. For a prediction of the safe life a crystal ball is required to forsee the type of flying, manœuvres, etc. to which the aircraft will be subjected. The calculation can, however, always be corrected later to conform with the flying already done, combined with later crystal gazing. As typical examples two different glider types can be taken, cloud flying and non-cloud flying, their usage being appropriate to soaring and training flights respectively.

	Cloud flying	Non-cloud flying
Gusts	90 % of flying life at 40 kts T.A.S. at 1000 ft. and normal gust spectrum. 10 % at 45 kts T.A.S. at 3000 ft. in rough conditions i. e. 10 times greater frequency of gust than normal spectrum	100 % of flying life at 40 kts T.A.S. at 1000 ft. and normal spectrum
Manœuvres	1,05 g at 5 per minute........ (small corrections) 1,15 g at 1 per minute........ (30° banked turn) 1,4 g at 10 per hour........ (45° banked turn) 2,0 g at 5 per hour........ (60° banked turn) 3,0 g at 1 per hour........ (Pullout)	

The Appendix para 4,2 shows that some of the manœuvres can be ignored

	Cloud flying	Non-cloud flying
Flight times	30 mins. i. e. 2 per hour	6 mins. i. e. 10 per hour
Launch	50 % aero tow 50 % winch or auto tow	Winch or auto tow
Note:	In an aero tow the loads are considered to be covered by the flight gust spectrum. In a winch or auto tow the effect of cable surging, hunting and gusts with a downward inclination of the cable is accounted for: — max cable load 90 % of weak link load and five oscillations per launch	
Landing	Airborne, but with an additional 1 g impact load	Airborne, but with an additional 2 g impact load
Towing	0.5 g inertia loads. (It is shown in the Appendix para 3.4, that in fact higher loads than this will have no damaging effect on the wings. Their frequency and time of application is therefore immaterial.)	

(d) Aerodynamic data, in order to assess the effect of gusts. The normally accepted method of dealing with gusts is to turn a graded gust into an equivalent sharp edged gust. For such a calculation the wing loading and lift curve slope ($dc_L/d\alpha$) are required.

(e) Spar stresses. These must be known for the mean and the fluctuating loads for each case in the duty cycle. In the examples calculated in the Appendix it has been assumed that a design ultimate stress of 10 000 lbs/in² is just reached in the fully factored max. flight envelope cases.

Inferences from the Calculations

The calculations for the two hypothetical gliders given in the Appendix are representative of two extremes. Study of the table in Appendix para 4. 5. shows that for the cloud flying glider used for long soaring flights virtually all the fatigue damage is done in flight and most of this in gusts. For the non-cloud flying glider, subjected to short training flights with severer handling on the launch and during landing, the flight damage is the smaller proportion.

The high proportion of damage due, in the training type, on the launch is significant. It would require only a moderate increase in the severity of the conditions assumed, to cause the safe life to tumble down. An increase, for instance in the weak link strength could easily allow the stresses in the launching case to increase by say 20 %. An increase of this amount on the critical part of the S–N curve can divide the endurance by 10, thus reducing the total life by only little less than the same factor.

There are obviously gliders which are operated between these two extremes. Their safe lives will be between the values calculated. It is unlikely that the safe lives assessed would in practice be approached, but if necessary log book and manufacturers data are likely to give increases rather than the reverse.

The extra information available from a log book to correct fatigue calculations is of course limited. It can at least corelate flying hours and number of launches. It will give a rough idea of the severity of the flight conditions met, but without a "g" recorder one will still be dependent on opinion for a lot of the important data.

The manufacturer should be able to give more exact data on stresses under the appropriate conditions than have been used in the calculations here. This will almost certainly be advantageous.

A fatigue failure in wood is described as "a fine hair-line crack across the width .... This crack is usually not visible unless the specimen is bent while viewing it". Obviously if there is any suspicion of fatigue failures being present in a glider structure it is going to be a lengthy and expensive business to find them. Better by far to ensure that the structural design is such that they will not happen.

I am indebted to the B.G.A. Technical Committee and particularly to Mr. C. D. Vernon (London Gliding Club), and to Mr. W. N. Slater (Slingsby Sailplanes) for suggestions made during the preparation of this paper.

APPENDIX

Calculation of Safe Life of Typical Gliders

1.0. *S–N Curve*

Published data are summarised in Fig. 1. This is for unnotched specimens, but it is shown that there is little reduction in endurances for V-notched specimens in wood. Nevertheless half the endurances plotted will be used. To use Raithby's paper for the gust calculation a curve of similar shape to his must be used. If we allow a "worst component" endurance of 1/6 of test on the assumption (pessimistic) of only one test result at a max. stress of (say) 5200 lbs/in^2 the endurance for calculation will be $2{,}5\times10^6 \times \frac{1}{2} \times 1/6 = 2{,}0\times10^5$. For the other parts of the duty cycle the true S–N curve with appropriate reduction factors on endurance can be used.

2.0. *Aerodynamic Data*

Assume a wing loading $(W/S) = 4 \cdot 5$ lb/sq ft. & $dC_L/d\alpha = 0 \cdot 09/\text{degree} = 5 \cdot 25/\text{radian}$

Gust alleviating factor $(F) = 0 \cdot 3\,(W/S)^{1/4} = 0 \cdot 3 \times 4 \cdot 5^{1/4} = 0 \cdot 44$.

Therefore g for 10 fps gust at 40 kts E.A.S. $= \dfrac{dC_L}{d\alpha}$

$$F.v.\ \tfrac{1}{2}\rho_0 v\, S/W = 5{\cdot}25 \times {\cdot}44 \times 10 \times \frac{1}{891} \times 68 \times \tfrac{1}{4}{\cdot}5 = 0{\cdot}42.$$

3.0. *Stresses in the duty cycle*

(Assuming the typical examples given in the main paper.)

3.1. *Flight stresses*

3.1.1. Assume the ultimate tensile stress for spruce (10 000 lb/sq. in). is achieved at an Ultimate Factor of 1.5. and max. flight envelope manœuvre load i.e. g = 5.0 and 4.0 for cloud flying gliders respectively (5).

3.1.2. *Cloud flying gliders*

Stress at $1g = 10\,000/5\times1 \cdot 5 = 1400$ lb/sq in and at other accelerations pro rata.

Stress in 10 fps gusts at 40 kts = 0.42x1400 = 590 lb/sq in.

Stress in 10 fps gusts at 45 kts $= 590\times\frac{45}{40} = 660$ lb/sq in.

3.1.3. *Non-cloud flying gliders*

Stress at $1g = 10\,000/4\times1 \cdot 5 = 1750$ lb/sq in.

Stress in 10 fps gusts at 40 kts = 0.42x1750 = 740 lb/sq in.

3.2. *Winch launching stresses*

3.2.1. The stresses due to a cable load of 90% of a weak link of 1000 lbs at an inclination of 75° to the glider datum will not only vary with the type of glider but also with the flying weight,—the net effect being less for a heavy glider. If we assume for a cloud flying glider a weight of 800 lb and a wing weight of 40% this would give net wing loads of $0.6\times800 + 900\cos 75^\circ = 1350$ lb. i.e. approx. equivalent to $(1350/480 =)\ 3$ g flight load. In a similar calculation for non-cloud flying gliders of weight 600 lb and a 30% wing weight the equivalent g load is much the same.

3.2.2. The maximum stresses involved are thus for cloud flying gliders $3\times1400 = 4200\ \text{lb/in}^2$ and for non-cloud flying gliders $3\times1750 = 5250\ \text{lb/in}^2$.

3.3. *Landing stresses*

3.3.1. *Cloud flying gliders*

If wing weight = 40% of total flying weight (W) then the net load in 1 g flight is 0.6 (W) and this corresponds to a stress of 1400 lb/sq.in.

The stress due to a 1 g wing inertia only is therefore $1400\times{\cdot}4w/{\cdot}6w = 930$ lb/sq in if we assume that wing weight and air load distributions are the same.

Assuming a "springback" load after landing equal to the inertia load, gives stresses of 1400 ± 930 lb/sq. in. for an airborne landing and a 1 g bump.

3.3.2. *Non-cloud flying gliders*

Assume a wing weight of 30%.

The stress due to a 2 g wing inertia only is therefore $2\times1750\times{\cdot}3/{\cdot}7 = 1500\ \text{lb/in}^2$ i.e. Stresses for an airborne landing and a 2 g bump = 1750 ± 1500 lb/in^2.

3.4. *Towing stresses*

3.4.1. The loading assumed is 1 g. 0.5 g on the inertia of the wing weight alone. From para 3.3 above this is for cloud flying gliders 930±460 lb/sq.in. and for non-cloud flying gliders 750±370 lb/sq.in.

3.4.2. Study of fig. 1. shows that the mean test curve is becoming asymptotic to a max. stress of about 4000 lb/sq.in. i.e. that a loading of 2600±1400 lb/sq.in. has to finite life. With due allowance for scatter it is quite obvious that the loadings of para 3.4.1. can be ignored.

4.0. *Life calculation*

4.1. *Damage due to gusts*

Assuming a flight of 1 hour: –

1 Flight Phase		2 Altitude ft.	3 T. A. S. m. p. h.	4 Time at altitude Mins.	5 Distance travelled. Miles	6 Proportion of total.	7 Stress due to 10 fps gust. lb/in²	8* Damage per 10^6 miles	9 ** Altitude correction factor	10 1 g stress ÷ curve mean	11*** Total damage per 10^6 miles
Cloud-flying	Normal gusts	1000	46	54	42	.89	590	.07	4	.54	.134
	Rough gusts	3000	52	6	5	.11	660	.10	1.7	.54	.0101
Non-cloud flying	Normal gusts	1000	46	60	46	1.0	740	.13	4	.67	.347

* From fig. 5 of Raithby's paper.

$$r = \frac{\text{Test stress at some endurance } (2\times10^5 \text{ in this case})}{\text{Standard stress at same endurance (fig. 4 — Raithby)}} = \frac{5200-2600}{4900} = 0.54.$$

K_n = Scatter factor for 1 test = 1.56 (Table 1 — Raithby)

$$\therefore \frac{r}{K_n} = 0.35$$

** From fig. 3 of Raithby's paper.

*** Columns 6x8x9x10.

4.2. *Damage due to Flight Manœuvres*

If it is assumed that the fatigue limit of fig. 1 mean curve is about 4000 lb/sq. in. we can safely ignore any manœuvres giving stresses of (say) 50% of this.

i.e. $\frac{2000}{1400} = 1.4g$ for cloud flying gliders

and $\frac{2000}{1750} = 1.5g$ for non-cloud flying gliders.

4.2.1. *1.4g Manœuvre*

Max. stress non-cloud flying glider = 2450 lb/sq. in.

Endurance is (say) 10^9 and therefore damage per 10^6 miles (10 manœuvres per hour at 46 m.p.h.)

$$= \frac{10}{10^9} \times \frac{10^6}{46} = 0.00022$$

4.2.2. *2g Manœuvres*

Max stress cloud flying glider = 2800 lb/sq. in.
non-cloud flying glider = 3500 lb/sq. in.

Endurances for both = 10^8 (say).

The damage per 10^6 miles at 5 manœuvres per hour at 46 mph = $5/10^8 \times \frac{10^6}{46} = 0.0011$.

4.2.3. *3 g Manœuvres*

Max stress cloud flying glider = 4200 lb/sq. in.
non-cloud flying glider = 5250 lb/sq. in.

Endurances 10^6 and 2×10^6 respectively.

$$\text{Damage per } 10^6 \text{ miles} = \frac{1}{10^8} \times \frac{10^6}{46} = 0.00022$$

(cloud flying)

$$\approx \frac{1}{2\times10^6} \times \frac{10^6}{46} = 0.011$$

(non-cloud flying).

4.3. *Damage due to launching*

Stresses are as for a 3 g manœuvre (see para 3.2.)

Factored damage per launch =

Cloud flying gliders: $\frac{1}{10^8} \times 1.5 \times \frac{1}{2} = 0.0075\times10^{-6}$

non-cloud flying gliders: $\frac{1}{2\times10^6} \times 1.5 \times 5 = 3.75\times10^{-6}$

4.4. *Damage due to landing*

Max. stresses are cloud flying gliders 1400+930 = 2330 lb/sq. in.

Non-cloud flying gliders 1750+1500 = 3250 lb/sq. in.

Taking endurances of 10^9 and 10^7 respectively from fig. 1 and allowing a factor of 3.0 on endurance to cover scatter together with a factor of 1.2 to cover other ground manœuvres as suggested by Raithby, damage per landing =

cloud flying gliders: $\frac{3\times1.2}{10^9} = 0.0036\times10^{-6}$

non-cloud flying gliders: $\frac{3\times1.2}{10^7} = 0.36\times10^{-6}$

4.5. *Total damage and Safe Life*

		Cloud flying	Non-cloud flying
Flight damage per 10^6 miles due to:	Normal gusts	0.134	0.347
	Rough gusts	0.0101	—
	1,4 g manœuvres	—	0.0002
	2,0 g manœuvres	0.0011	0.0011
	3,0 g manœuvres	0.0002	0.0110
	Total	0.145	0.359
Factored flight damage per 10^{-6} miles (factor 1,5) = ...		0.218	0.538
Factored flight damage per hour (46 mph)		10.0×10^{-6}	24.7×10^{-6}
Factored flight damage per flight		5.00×10^{-6}	2.47×10^{-6}
Factored damage per flight from	launching	0.0075×10^{-6}	3.75×10^{-6}
	landing	0.004×10^{-6}	0.36×10^{-6}
	towing	—	—
	Total	5.01×10^{-6}	6.58×10^{-6}
Safe Life	in flights	200,000	152,000
	in hours	100,500	15,200