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MILITARY TECHNICAL COLLEGE

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FATIGUE SUBSTANTIATION OF TITANIUM LUGS

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ABSTRACT

The purpose of this paper is to calculate the fatigue life of titanium lugs from full scale fatigue substantiation tests using the stress--endurance curve together with a knowledge of the variation of fatigue strength with the mean stress. The tests were carried out using lugs with bushes whereas a helicopter components all have bushed holes.

Since, the Goodman diagram for titanium lugs has never been defined, the tests provide sufficient data to draw a Goodman diagram with confidence. A computer program for curve fitting has been designed to determine the different S-N curves from the laboratory fatigue test data.

The flight fatigue damage and the safe life for the sections of the titanium lugs as used in helicopter components are calculated on the basis of the flight load levels.

INTRODUCTION

The lug represents the simplest form of a bolted joint and its fatigue strength often indicates that likely to be obtained in an entire structure. The mean stress-vibratory stress cycles relationship for lugs is complicated by fretting effects between the pin and the hole boundary. Bushed lugs generally have some degree of interference-fit between the lug and bush. These lugs give better fatigue strength than unbushed lugs. The fatigue life of the titanium lugs is calculated from fatigue tests.

Fatigue substantiation of the lugs used in different dynamic components of helicopters is achieved by correlation of measured flight test loads with component fatigue strength determined from laboratory fatigue testing at representative multi-level loads. The cumulative damage summation used to establish the safe fatigue life of the lugs. Fatigue strength scatter and flight load variability factors are included in these calculations.

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FATIGUE ANALYSIS PHILOSOPHY

The Fatigue substantiation process of any helicopter dynamic components can be summarized by the flow diagram shown in Fig.1 which is based on the use of laboratory fatigue test results to establish the component/section fatigue endurance limit. Analysis of the results of the fatigue test consists of construction for the section under consideration of its modified Goodman diagram, which shows fatigue endurance limit as a function of local mean stress (corrected for geometric stress concentration).

From laboratory fatigue test results on each component a fatigue endurance limit may be calculated by assuming failure at each section and summing the cumulative fatigue damage as:

$$\sum_{i=1}^{m} \frac{n_i}{N_i} = 1.0 \qquad (1)$$

where:

n_i The number of load cycles experienced at a given loading

N_i The number of cycles to failure at that loading.

In these calculations material S-N (vibratory stress-cycles endurance) curves are used, which are represented in this paper by an assumed mathematical model of the form:

$$S = S_\infty \left(1.0 + \frac{A}{N^B} \right) \qquad (2)$$

where:

A,B Material constants.

S Vibratory stress.

N Endurance in megacycle at that stress.

S_∞ Fatigue endurance limit.

A computer program for curve fitting has been designed to calculate the material constants as well as the endurance limit (S_∞) from fatigue test data.

To avoid loss of accuracy in the treatment of test results the load spectra applied in the laboratory fatigue tests are designed to be as representative as practicable of those in flight. For each dynamic component sub--assembly either fifteen specimens or more have been tested and the endurance limits for the critical sections of each specimen are calculated. The section log-mean endurance limit is then calculated as:

$$S_\infty(\text{mean}) = \text{EXP}\left(\frac{\sum_{i=1}^{m} \log (S_\infty)_i}{m} \right) \qquad (3)$$

A material scatter factor (equal to 1.37 for 15 titanium specimens) which is a function of the number of tests performed and material is then applied to the section log-mean endurance limit; and this figure is further factored by 1.2 to cater for measured flight load scatter. This fully factored

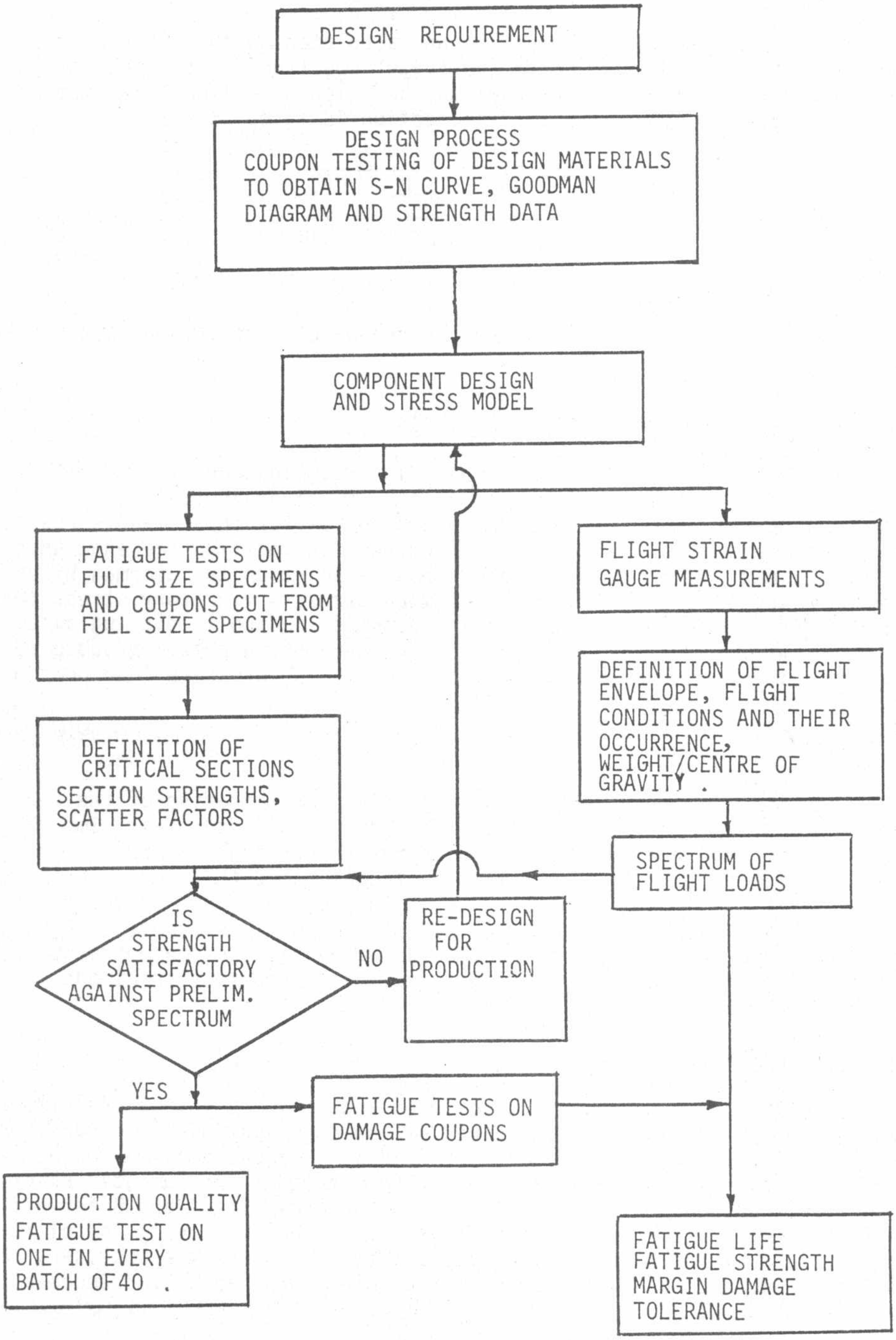

Fig.1. Flow diagram of the fatigue substantiation.

endurance limit is then used in flight fatigue damage calculations.

The flight fatigue damage rate is then calculated on the basis of the flight load levels according to the flight spectrum. The number of cycles to failure N at a given load level may be calculated from Eq.1 stated above, and therefore the safe life for the section is calculated as:

$$\text{Safe Life} = \frac{1}{\sum_{i=1}^{m} \frac{n_i}{N_i}} \qquad (4)$$

where:

$\sum_{i=1}^{m} \frac{n_i}{N_i}$ is the cumulative damage rate per hour.

FATIGUE AND FLIGHT TESTS DATA

The detail fatigue test stress which is a combination of a vibratory stress and mean stress as shown in Fig.8 is given in table 1,2,3 and 4. The aims of the tests are to produce S-N curves for three mean stresses which can be used to derive a median curve. In addition the endurance limit for each curve will be used to plot a point on the Goodman Diagram. There is one special case curve, the mean stress = vibratory stress (R=o) curve. This curve gives the limit of tensile loading in the lug since loadings with the vibratory load greater than the mean load produce no fatigue stress at the critical section for the compressive load portion of the cycle.

Fatigue Test Specimen:

The titanium test piece shown in Fig.2 is representative of the Lynx helicopter main rotor blade attachment lugs. The test lug is 13mm thick compared to 50mm for the actual lug in order that testing may be carried out at moderate load levels. It was not considered that the shape of the curves will change with lug thickness. The lugs were not subjected to out--of-plane bending loads and, since non of the lugs was clamped, there was no transfer of load by friction. The geometric stress concentration factor(K_t) was taken equal to 3.0. The total number of specimens was equal to 85.

Fatigue Test Results:

The results of the fatigue testing (endurance in megacycle) are summarised in tables 1,2,3 and 4. These values of the endurance with the corresponding vibratory and mean stresses are used as an input data to the designed computer program for curve fitting. The output of the computer program represents the endurance limit (S_∞) and the constants A and B for different values of mean stress as shown in Figs. 3,4,5 and 6. Finally by plotting the vibratory stress on the ordinate and the S_m on the abscissa, the fatigue endurance limit can be presented giving the so-called Goodman diagram as shown in Fig. 7. The endurance limit was taken as 10^8 cycles.

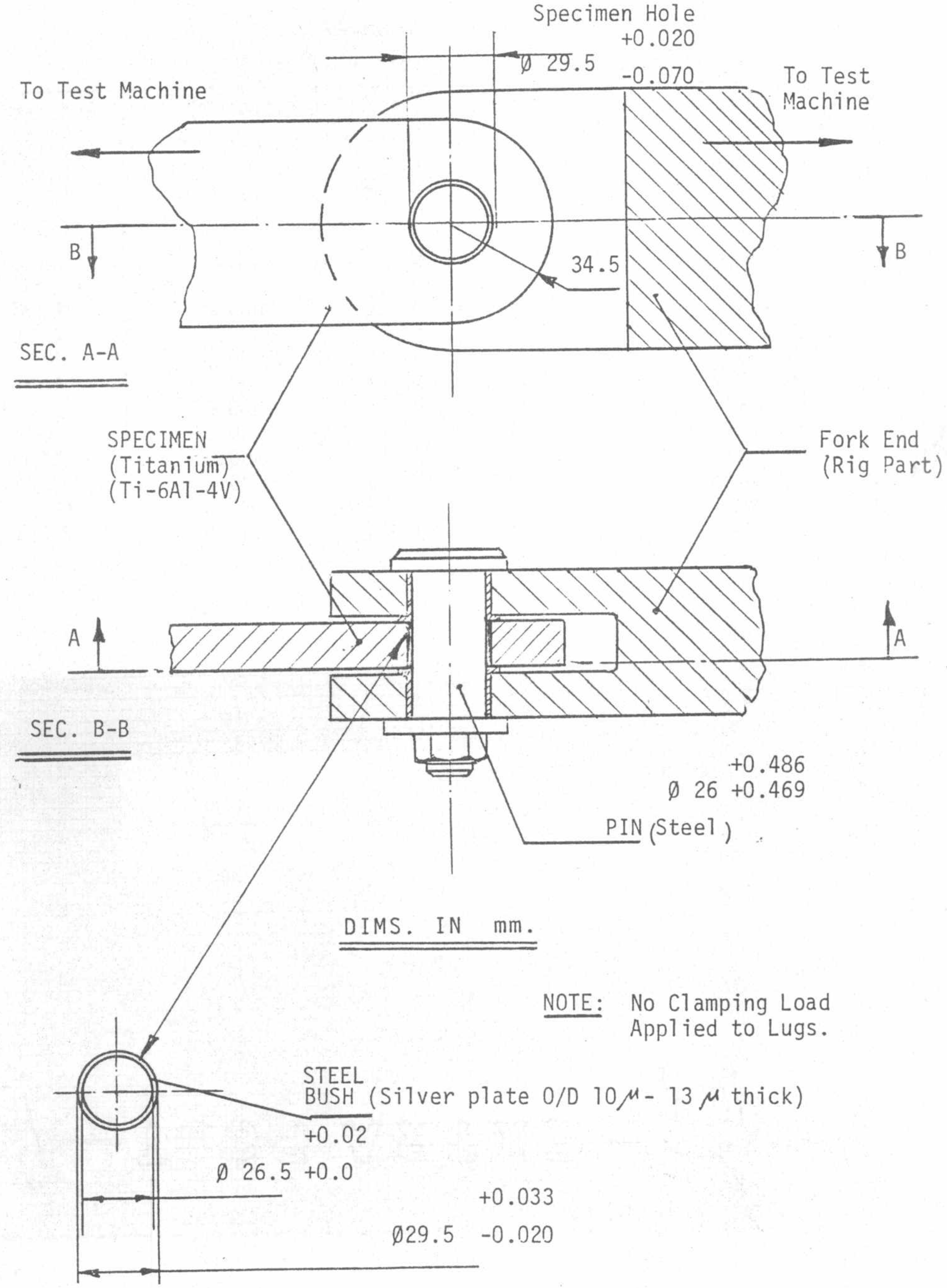

Fig. 2. Main Features of The Specimen and Assembly.

Table 1 Fatigue Test Data ($S_m = S_{Vib}$)

Test Piece No.	Vibratory Stress (Ibf/in^2)	Endurance (Cycles) X 10^{-6}	Test Piece No.	Vibratory Stress (Ibf/in^2)	Endurance (Cycles) X 10^{-6}
1	20000.0	0.11	11	9000.0	10.09
2	15000.0	0.24	12	9000.0	4.69
3	15000.0	0.30	13	9000.0	1.97
4	15000.0	0.46	14	9000.0	1.81
5	12500.0	0.30	15	9000.0	20.49
6	12500.0	0.41	16	8000.0	10.57
7	12500.0	0.86	17	8000.0	14.24
8	10500.0	1.53	18	8000.0	3.74
9	10500.0	1.48	19	7000.0	16.82
10	10500.0	2.34	20	7000.0	100.18

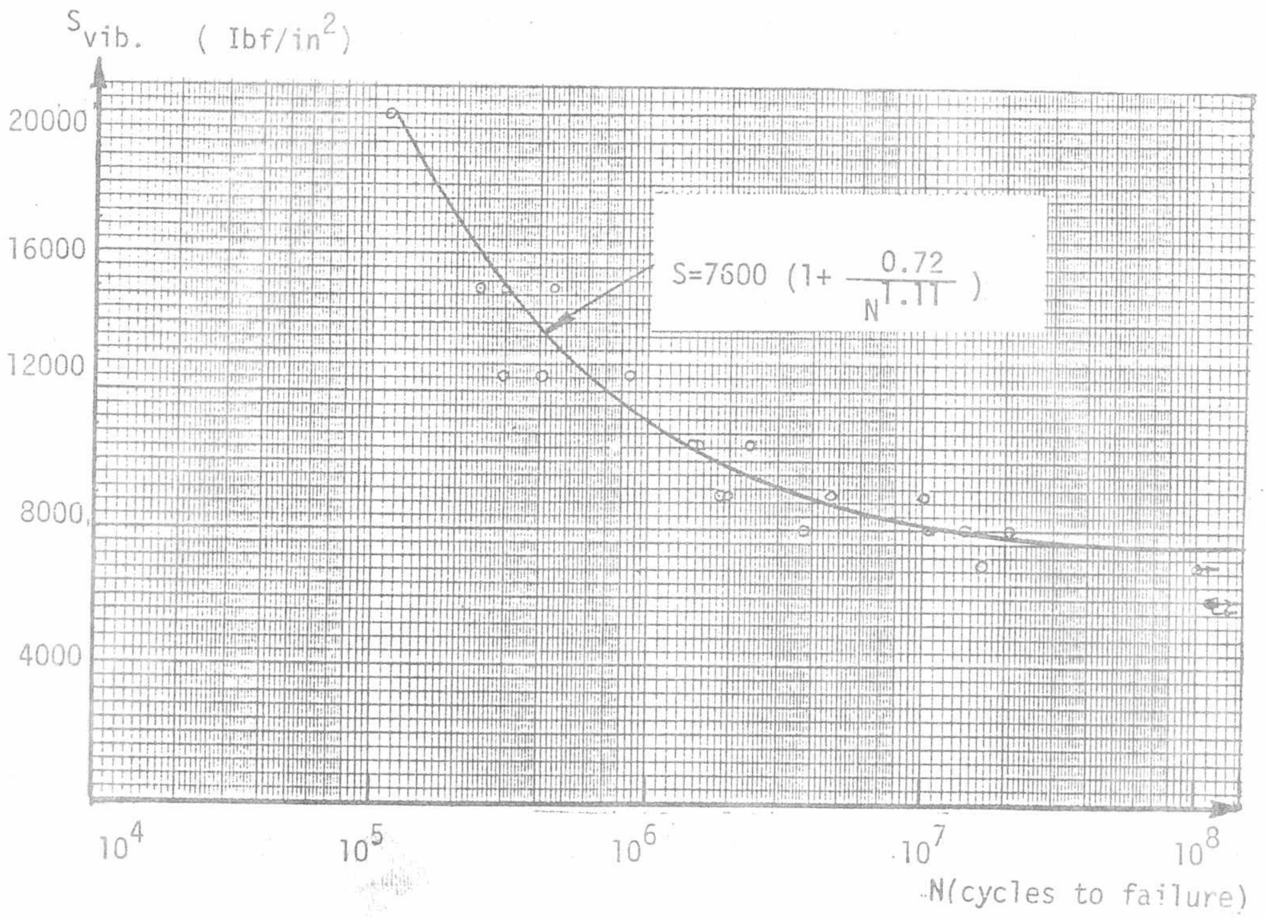

Fig. 3. Results of Fatigue Tests and curve fitting.

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Table 2 Fatigue Test Data (S_m = 12500 Ibf/in^2)

Test Piece No.	Vibratory Stress (Ibf/in^2)	Endurance (Cycles X 10^{-6}	Test Piece No.	Vibratory Stress (Ibf/in^2)	Endurance (Cycles) X 10^{-6}
1	12500.0	0.30	9	8000.0	2.09
2	12500.0	0.41	10	8000.0	13.91
3	12500.0	0.86	11	8000.0	3.12
4	10500.0	1.61	12	7000.0	10.13
5	10500.0	0.95	13	7000.0	9.75
6	10500.0	0.92	14	7000.0	9.88
7	10500.0	1.41	15	7000.0	106.89
8	8000.0	2.26			

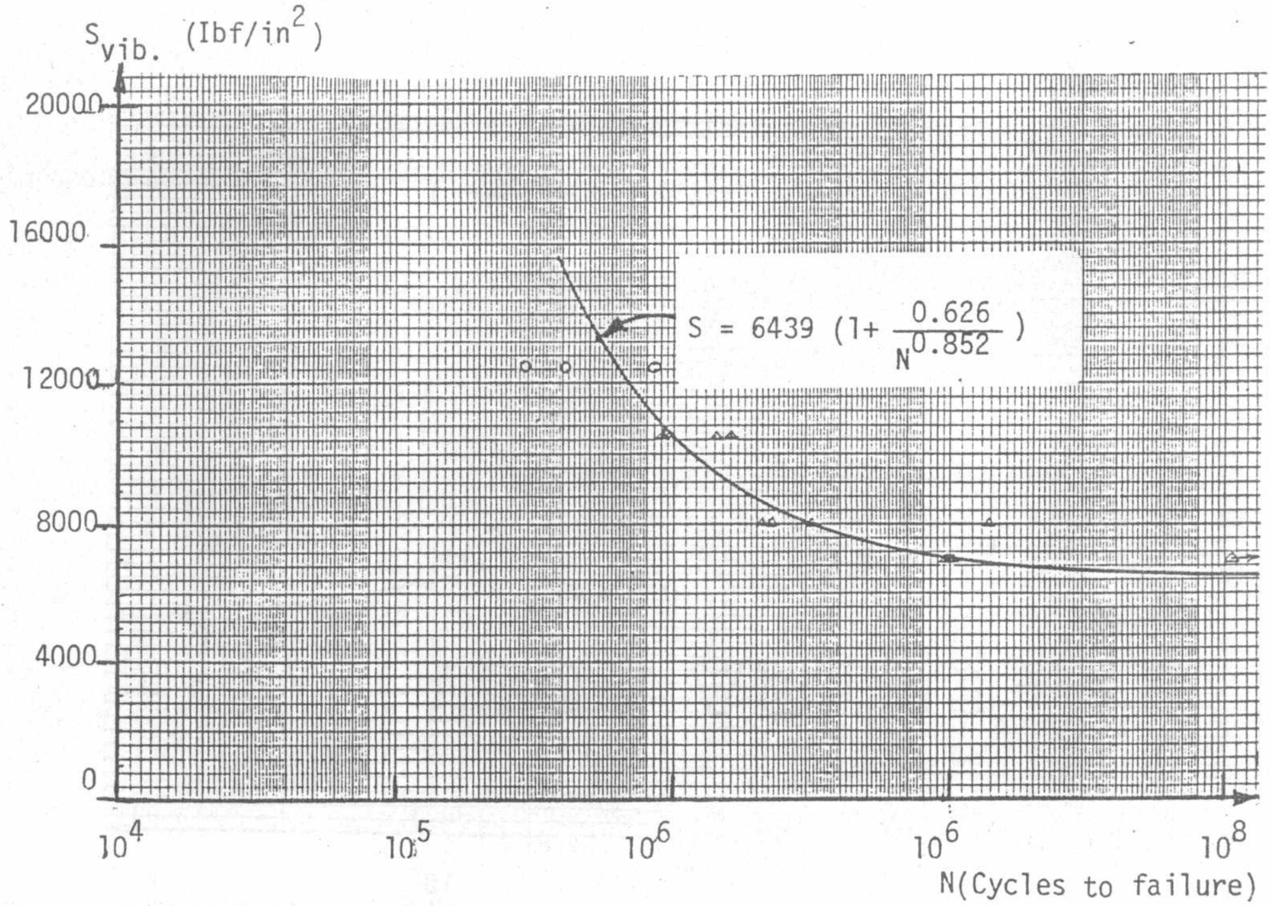

Fig. 4. Results of fatigue tests and curve fitting.

Table 3 Fatigue Test Data (S_m = 15000 Ibf/in^2)

Test Piece No.	Vibratory Stress (Ibf/in^2)	Endurance (Cycles) X 10^{-6}	Test Piece No.	Vibratory Stress (Ibf/in^2)	Endurance (Cycles) X 10^{-6}
1	15000.0	0.24	12	10500.0	1.16
2	15000.0	0.30	13	8000.0	3.72
3	15000.0	0.46	14	8000.0	3.83
4	12500.0	0.54	15	8000.0	2.26
5	12500.0	0.54	16	8000.0	3.90
6	12500.0	0.44	17	8000.0	8.07
7	12500.0	0.57	18	7000.0	22.23
8	12500.0	0.70	19	7000.0	5.50
9	10500.0	1.10	20	7000.0	9.30
10	10500.0	1.51	21	6000.0	101.14
11	10500.0	0.86	22	6000.0	100.00

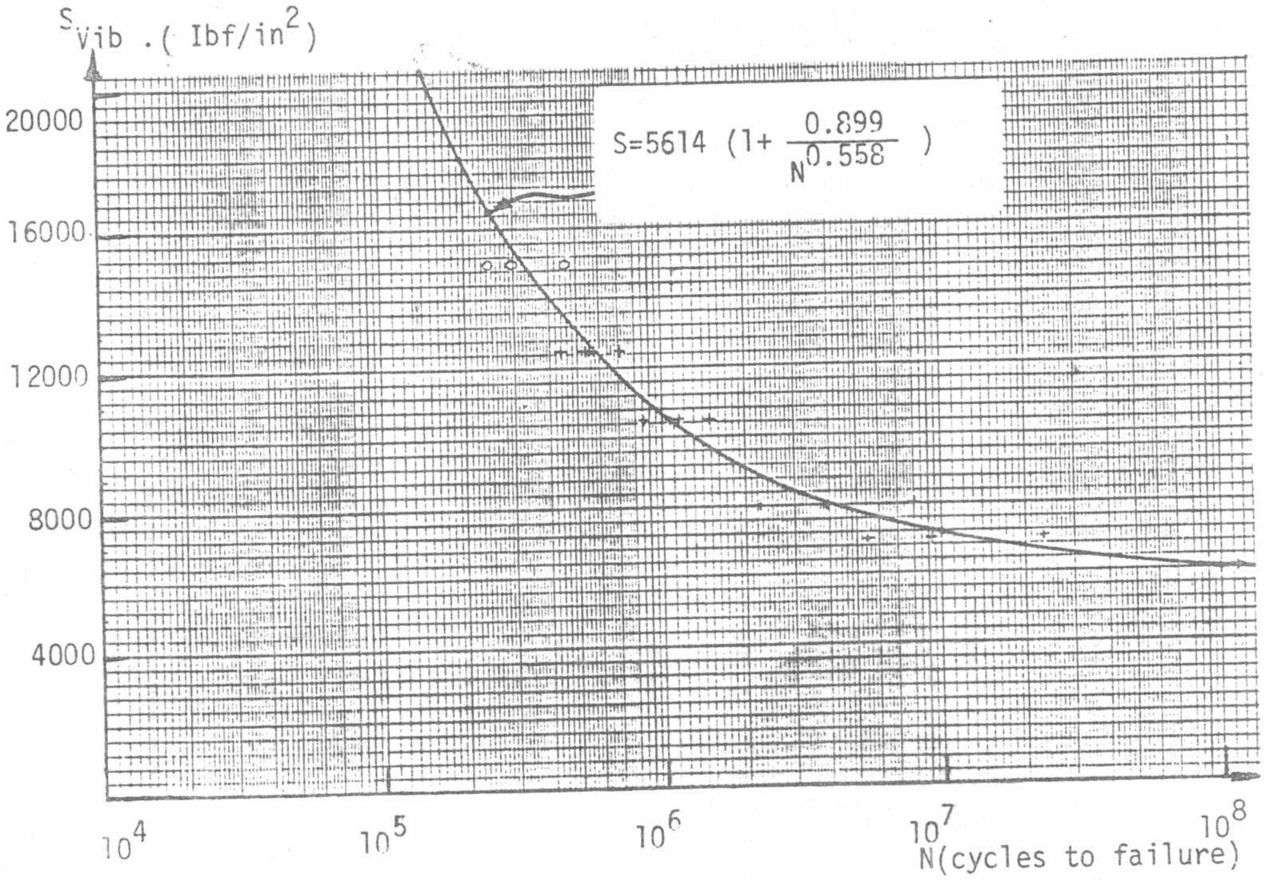

Fig. 5. Results of fatigue tests and curve fitting.

Table 4 Fatigue Test Data (S_m = 20000 Ibf/in^2)

Test Piece No.	Vibratory Stress (Ibf/in^2)	Endurance (Cycles) X 10^{-6}	Test Piece No.	Vibratory Stress (Ibf/in^2)	Endurance (Cycles) X 10^{-6}
1	20000.0	0.11	15	10500.0	0.95
2	15000.0	0.32	16	10500.0	0.85
3	15000.0	0.65	17	8000.0	1.28
4	15000.0	0.49	18	8000.0	2.23
5	15000.0	0.38	19	6000.0	15.46
6	15000.0	0.45	20	6000.0	4.23
7	12500.0	1.23	21	6000.0	6.38
8	12500.0	0.59	22	6000.0	4.82
9	12500.0	0.48	23	6000.0	5.93
10	12500.0	0.32	24	5000.0	21.64
11	12500.0	0.59	25	5000.0	9.05
12	10500.0	0.89	26	5000.0	10.98
13	10500.0	1.42	27	4000.0	111.00
14	10500.0	0.79	28	4000.0	100.00

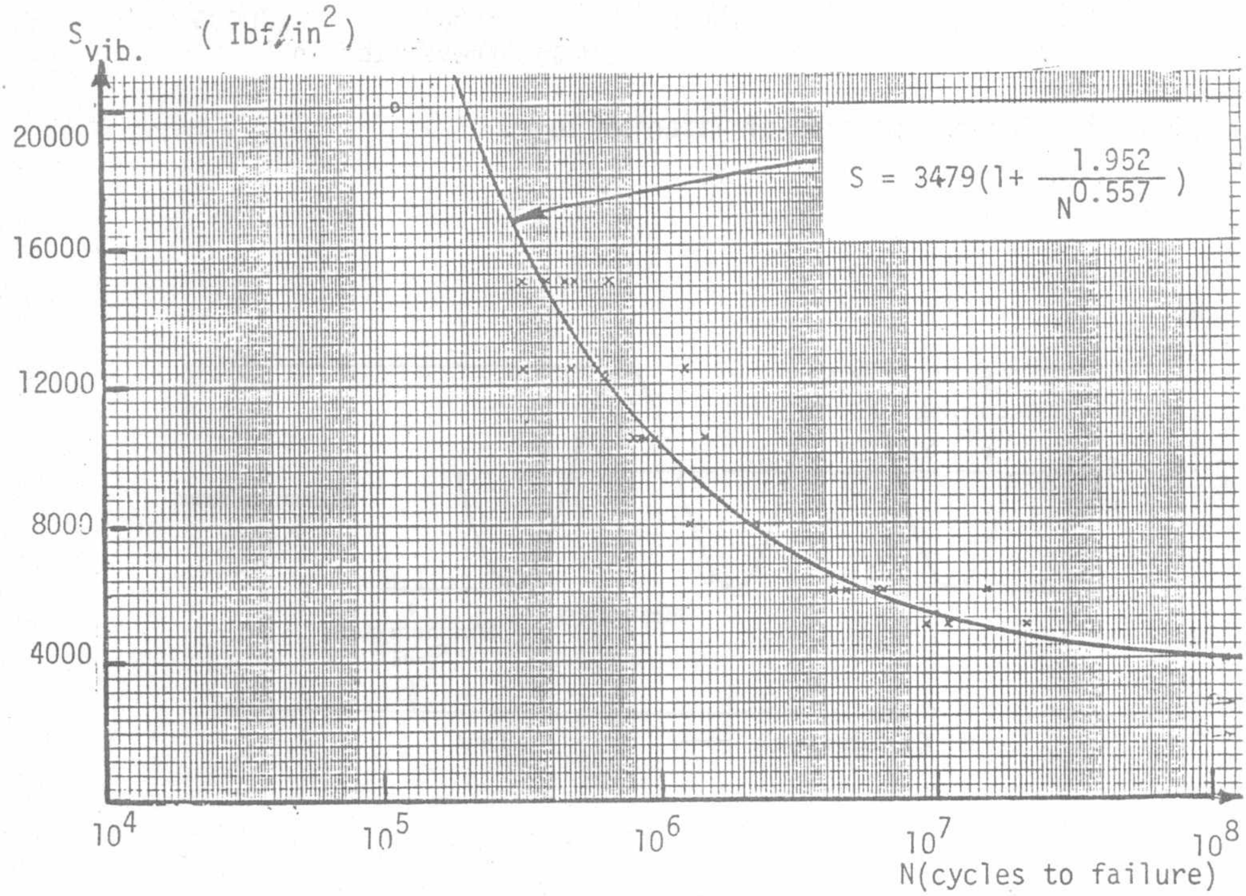

Fig. 6. Results of fatigue tests and curve fitting.

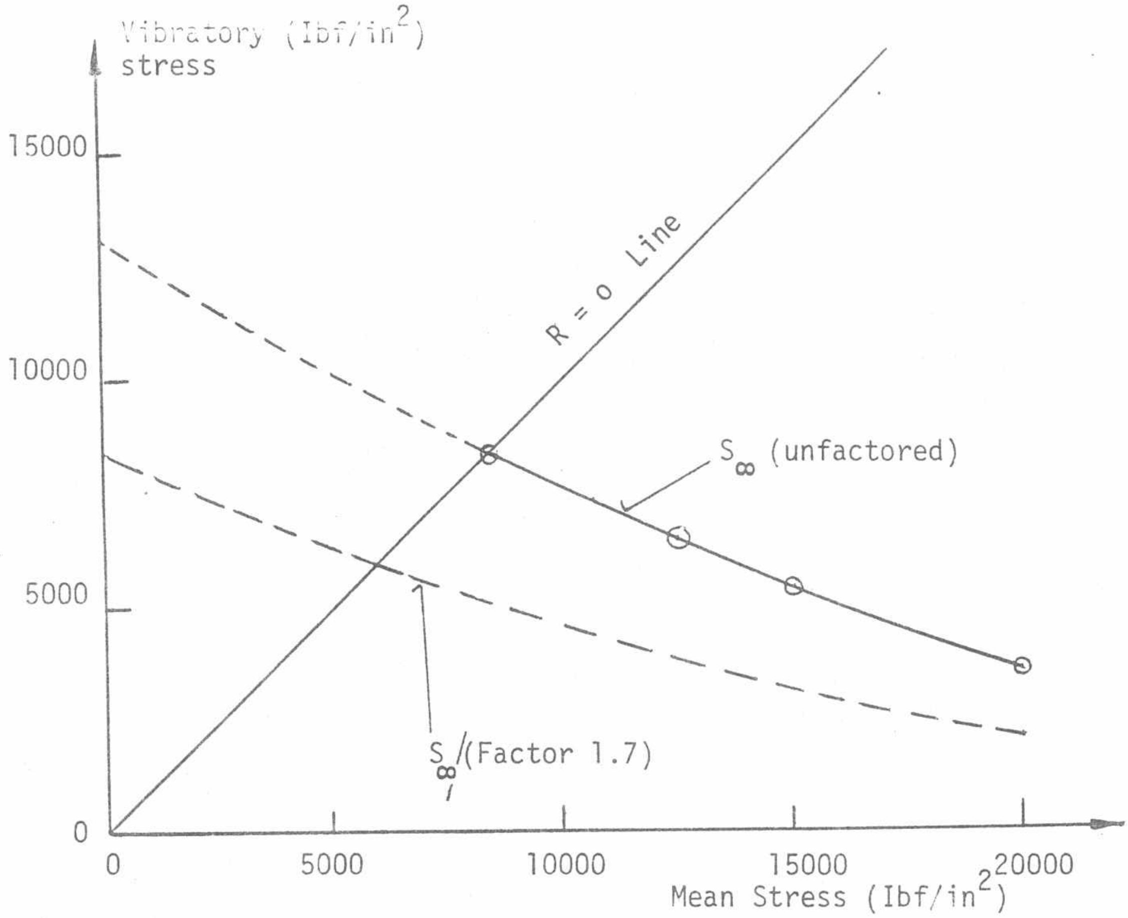

Fig. 7. Goodman diagram of Titanium lugs.

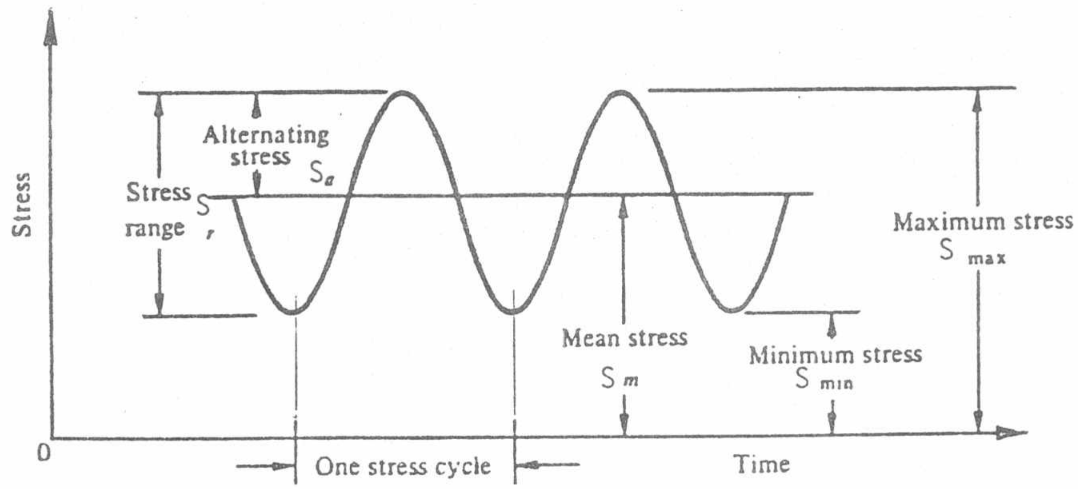

Fig. 8. Fatigue terms .

Flight Test Results:

The distribution of the flight test stresses on the titanium lugs as used in the Lynx helicopter main rotor blade attachment is obtained using the combination of all-up weight/altitude/center of gravity as:
(8600 - 9500 lb) /(0 - 2000 ft) / (forward and neutral).

The worst flight condition is defined nominally as the highest vibratory loading. However, when two similar levels of vibratory loading exist, the one with the most severe mean load is considered.

It was found from the flight tests that the mean lug stresses are in the range 5000 - 15000 Ibf/in^2 and are adequately covered therefore.

FATIGUE SUBSTANTIATION ANALYSIS

The severe flight conditions of Lynx helicopter were analysed for fatigue damage to the main rotor blade attachment titanium lugs. These conditions are:

- 1.11 V_{NE} (never exceed speed) forward flight.
- 30^0 Bank Turn at V_{No} (Normal operating speed).
- Hovering flight.

However, in order to identify the damaging conditions on a given section the maximum factors to be applied to the nominal vibratory load was determined according to the load spectrum, and the maximum cycle amplitude thereby calculated and compared with the section endurance limit. Non-damaging conditions could then be discarded and full analysis carried out on only the damaging conditions.
The damage rate per hour was calculated and the highest damage rate of 18.868×10^{-6} per hour is on the titanium lugs from which a safe life of 5300 hours may be calculated.

CONCLUSIONS

From the laboratory fatigue tests, the endurance limits of the titanium lugs vary with the mean stress where they decrease as the mean stress increases. The assumed mathematical model in the computation analysis of the fatigue test data for the S-N curves gives good results for curve fitting. The titanium lug endurance limit for the case of R=0 $(S_{min.}/S_{max.})$ is equal to 7600 Ibf/in^2 and Goodman — diagram for titanium lugs has been defined.

The minimum safe life of the titanium lugs as used in helicopter components is 5300 hours in excess of the design requirement of 2500 hours. The fatigue damage lies between V_{NE} and 1.11 V_{NE} in helicopter level flights and close to the maximum permissible speed for each bank angle.

REFERENCES

1. Lipson, C. and Sheth, N. " Statistical Design and Analysis of Engineering Experi ments ". Mc Graw - Hill, Inc. 1973.
2. Heywood, R.B, "Designing Against Fatigue" Chapman and Hall Ltd., London, 1962.