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Effects of Rate and Duration of Loading on the Strength of Aircraft Structures

By

K. D. RAITHBY, B.Sc., A.F.R.Ae.S.

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Summary.—The effects of rate and duration of loading on the structural strength of aircraft have been investigated by comparing the failing loads of both wooden and metal tailplanes when tested at different rates of loading, the duration of test varying from about 6 seconds to 3¾ hours.

With wooden structures, differences in strength due to rate of loading were much less than those predicted from the results of American tests on wood.

With metal structures neither rate of loading nor sustained high loading had any appreciable effect on the failing load

1. *Introduction.*—The failing load of various materials has been shown to be increased by increasing the rate at which load is applied[1,2,3,4], some materials being more sensitive to rate of loading than others. There has been no evidence, however, to show whether the same increase occurs with complete structures; owing to their complex nature, the effects might not be the same as for small material specimens.

This paper analyses the results of tests made at the Royal Aircraft Establishment on typical aircraft components, of wooden and of metal construction, to compare the failing loads at rates of loading corresponding to flight conditions with (a) the failing loads realised in the normal type of laboratory strength test and (b) the failing loads realised at the maximum rate of loading practicable with existing test equipment.

2. *Effects of Rate of Loading on Material Strength.*—2.1. *Wood.*—According to American tests on small specimens of wood[2], the relationship between failing load and time of test is of the form:—

$$P/P_0 = A - B \log T$$

where P is failing load
P_0 failing load under standard test conditions
T time to reach failing load

A and B are experimentally determined constants.

On this basis the failing load at rates of loading corresponding to flight conditions is about 25 per cent greater than at rates of loading used in the normal type of structural strength test. American design figures[5] include a correction factor of 1·17 on standard material test results to give values corresponding to a loading time of 3 seconds.

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2.2. *Metals.*—Tensile tests on standard test pieces of various metals at different rates of loading[4] have shown that an increase in failing load occurs only when failure is reached in less than 1 second. This represents a rate of loading appreciably higher than occurs under normal flight conditions.

3. *Normal Strength Test Procedure.*—In a static strength test on an aircraft structural component, the time to reach the failing load is usually between 2 and 3 hours. Load is applied in increments, after each of which the load is maintained constant while strain gauge and deflection readings are taken, the operation of control surfaces checked, and detailed observations made.

Some British test engineers, in an effort to achieve higher failing loads, have reduced loading times to a total of about one minute of continuous loading up to failure of the specimen. Apart from introducing difficulties in the way of recording instrument readings, this means a considerable restriction on test observation, with consequent uncertainty about the behaviour of the structure under load.

4. *Rates of Loading under Flight Conditions.*—Flight measurements indicate that the normal acceleration in a pull-out, which is frequently the critical condition for wing strength, builds up roughly as a sine curve, the maximum slope occurring at about half the maximum g applied. For an average pull-out this maximum slope ranges from about $5g$ per second for a fighter down to about $1\frac{1}{2}$ to $2g$ per second for a bomber and the mean rate over the whole range is roughly half this maximum rate. Thus, for a fighter an ultimate acceleration of $12g$ would be reached in about 5 seconds ; for a bomber an ultimate acceleration of $5g$ would also be reached in about 5 seconds. These are average times and in particular manoeuvres the time may be less, but since material tests show that the higher the rate of loading the higher the failing load, considerations of structural strength should be based on the slowest rate of loading likely to occur in flight. It seems reasonable, therefore, to take 5 seconds as the minimum duration of test that need be considered in an investigation into the effects of rate of loading on structural strength.

5. *Tests on Representative Structural Components at Different Rates of Loading.*—Owing to the complex nature of a built up structure it was thought that the variation of strength with rate of loading might not be the same for complete airframe components as for simple material specimens and tests were made on representative components under the conditions given below. The main purpose of the investigation was to determine whether the normal method of strength testing gives a sufficiently accurate estimate of the failing load that would be realised under flight conditions.

5.1. *Tests Made.*—Tests were made on thirty-six *Anson* full-span wooden tailplanes and on nine *Typhoon* semi-span metal tailplanes under a simplified loading based on the design load. A résumé of each series of tests is given in Appendices I and II.

5.2. *Rate and Duration of Loading.*—Tests were made under each of the following types of loading :—

(a) *Incremental loading* to failure, the failing load being reached in about $2\frac{1}{4}$ hours on the wooden tailplanes and $2\frac{3}{4}$ hours on the metal tailplanes. This type of loading represents approximately that used in a normal static strength test on a major structural component.

(b) *Sustained high loading.* (Metal tailplanes only). Incremental loading as in (a) but the load held for one hour at approximately 87 per cent of the failing load of the tailplane. This is a severe representation of holding a high load long enough for a very thorough examination of the structure.

(c) ' 30 *second* ' *loading.* Load applied steadily to failure, the failing load being reached in about 30 seconds. This type of loading represents approximately the maximum rate of loading that can be applied to a major structural component using normal static testing equipment.

(d) '6-*second' loading*. (Wooden tailplanes only). Load applied steadily, the failing load being reached in about 6 seconds, approximating to flight conditions.

Typical load-time curves for each type of loading are given in Figs. 3 and 4.

6. *Discussion of Test Results*.—6.1. *Failing Loads*.—Results are given in Tables 1 to 5. In Fig. 5 the failing loads are plotted against the duration of test, together with an indication of the coefficients of variation. (*See* App. III).

6.1.1. *Wooden tailplanes*.—Taking the 5 per cent level of significance (*See* App. III) there is no statistically significant difference between the mean failing loads for the '30-second' and '6-second' loading rates but there are significant differences between the incremental and 30-second rates and between the incremental and 6-second rates. Under both 30-second and 6-second rates the mean failing load is about 7 per cent higher than under incremental loading. Material tests on wood[1,2] had indicated that reducing the time of test from $2\frac{1}{4}$ hours to (a) 30 seconds and (b) 6 seconds would increase the failing load by (a) 20 per cent and (b) 25 per cent.

The 6-second loading represents approximately the average rate at which load is applied to the airframe in flight. Therefore, the failing load of a particular wooden component under flight conditions would probably be some 7 per cent higher than that realised in a normal static strength test.

As there is no significant difference in mean failing load between the 30-second and 6-second loading rates, the results of both groups may be combined to give a better estimate of the coefficient of variation, if it be assumed that scatter is unaffected by rate of loading. There are not enough results to show whether this last assumption is true, although the resultant coefficient of variation of 6·8 per cent agrees well with the 7·3 per cent obtained from strength tests on sixty *Master* tailplanes[6]. Taking an average figure of 7 per cent for the coefficient of variation of wooden structures, it would be necessary to realise a test factor, *i.e.*, achieved failing load/design load, of 1·3 on the result of a single test under flight conditions to ensure that not more than one in ten components is likely to fall below 100 per cent and not more than one in a thousand below 90 per cent of the design ultimate strength[7].

The effects of both scatter and rate of loading could be allowed for by specifying a test factor of 1·21 on the result of a test on a single specimen under slow incremental loading, assuming that scatter is unaffected by rate of loading.

6.1.2. *Metal tailplanes*.—The mean failing load of all results is 9,447 lb and the coefficient of variation is 1·7 per cent. This compares with 2·2 per cent for twenty *Typhoon* tailplanes tested under incremental loading[8].

The results show that reducing the time of test to 30 seconds causes no significant difference in failing load ; all the results lie within the range of scatter to be expected.

Since for the wooden specimens there was no marked effect between the 30-second and 6-second loading and since metal is much less sensitive than wood to the effects of rate of loading except at extremely high rates, it is concluded that loading in 6 seconds would not show any increase in the failing load for metal specimens.

6.2. *Effect of Sustained High Loading*.—The method of loading used in these tests depends on the application of deflection to the specimen. The applied load therefore depends on the stiffness of the specimen ; if any creep occurs the load falls off but the deflection is maintained.

6.2.1. *Wooden tailplanes*.—With the small number of specimens available it was not possible to do sustained high loading tests such as were done on the metal tailplanes. Readings were taken, however, to determine the drop in load due to creep after the application of an increment of load. Typical curves of percentage drop in load against time are given in Fig. 6. It is seen that the load drops rapidly in the first few minutes.

Of the twelve tailplanes tested under incremental loading, four failed several minutes after the application of the final increment at a load somewhat lower than the maximum load reached, and another four failed when, on reloading, the load again reached its maximum value. These results suggest that if the load had been applied continuously a higher failing load would have been realised.

6.2.2. *Metal tailplanes.*—At 87 per cent of the failing load, the load fell some 2 per cent while the deflection was held for one hour ; this drop occured almost entirely during the first 15 minutes.

Table 5 shows that the failing loads of the three tailplanes tested in this way were not significantly lower than those achieved in the other tests. It appears, therefore, that the ultimate strength of a metal structure is not appreciably affected when as much as 87 per cent of the failing load is sustained for periods of up to one hour.

7. *Conclusions.*—This investigation into the effects of the rate of application of load on the failing loads of aircraft structural components leads to the general conclusion that with wooden structures, the failing load under flight conditions is higher than that achieved in an ordinary strength test (although the difference is much less than is indicated by material tests) ; with metal structures, the normal method of strength testing gives a reasonably accurate estimate of the strength which will be realised under flight conditions

Particular conclusions are :—

(a) *Wooden Structures.*—

(i) There is an increase in failing load of about 7 per cent when that load is reached in about 6 seconds (roughly corresponding to flight conditions) instead of in about 2¼ hours. This is very much less than the corresponding increase of about 25 per cent indicated by tests on small specimens of wood.

(ii) Increasing the duration of test from 6 seconds to 30 seconds seems to have little effect on the mean failing load, although the effect may be slightly more than indicated, since the 30-second group includes one particularly strong specimen, suggesting that the true mean for this group may be slightly lower than the apparent mean, which is based on comparatively few results.

(iii) The number of specimens tested is not sufficient to show whether scatter is affected by rate of loading.

(iv) Taking the coefficient of variation as 7 per cent and assuming that it is independent of rate of loading, the effects of both scatter and rate of loading can be allowed for by specifying a test factor of 1·21 on the results of a normal strength test on a single wooden component to ensure that not more than one in ten components is likely to fall below 100 per cent and not more than one in a thousand below 90 per cent of the strength required under flight conditions.

(v) Differences in failing load at different rates of loading are partly due to creep.

(b) *Metal Structures.*—

(i) There is no significant difference in failing load due to variation in rate of loading up to the maximum rate at which load can be applied using normal static testing equipment (duration of test 30 seconds). It is unlikely that a reduction in time of test to 6 seconds would affect the failing load.

(ii) The ultimate strength achieved in a static test is not appreciably affected when as much as 87 per cent of the failing load is sustained for periods of up to one hour.

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APPENDIX I

Tests on Wooden Tailplanes

1. *Description of Specimens.*—Each test specimen comprised a complete tip-to-tip *Anson* tailplane that had been in service. Some had suffered slight skin damage, but, in general, they were in good condition.

A typical specimen is shown diagrammatically in Fig. 1. The *Anson* wooden tailplane is of spruce and plywood construction, with a plywood skin. Four fuselage attachment fittings are bolted to the top booms of the spars inboard of rib 1, the top and bottom skins being cut away in this region.

2. *Method of Test.*—Load was applied to the elevator hinges and to the front spar as indicated in Fig. 1, the specimen being inverted for test.

The tailplanes were tested at the following rates of loading :—

(a) *Incremental loading.* Load applied in increments of 10 per cent of the estimated mean failing load, with a 15 minute interval after each increment, the failing load being reached in about $2\frac{1}{4}$ hours. At loads higher than 70 per cent of the estimated failing load, intermediate 5 per cent increments were applied, the load being held for one minute after each intermediate increment.

(b) 30-*second loading.* Load applied steadily, the failing load being reached in about 30 seconds.

(c) 6-*second loading.* Load applied steadily, the failing load being reached in about 6 seconds.

3. *Results.*—Typical load-time curves for the three types of loading are given in Fig. 3. For the incremental loading each increment was applied in about $\frac{1}{2}$ minute.

The failing loads for the three types of loading are given in Tables 1, 2 and 3. With the exception of No. 20, in which there was a glue failure on the front spar, each tailplane failed in tension at either the port or the starboard front spar fuselage fitting. A typical failure is shown in Fig. 7, taken after removal of the port fuselage fitting on the front spar.

After each test the moisture content of the spar near the fracture was determined. As the variation in moisture content was small, no correction to the failing loads has been made on account of it.

In Table 4 the mean failing load and standard deviation for each type of loading are given, together with corresponding values for the results of the 30-second and 6-second groups combined.

APPENDIX II

Tests on Metal Tailplanes

1. *Description of Specimens.*—Each test specimen comprised a semi-span *Typhoon* tailplane of the modified design (*i.e.* with strengthened spar webs). All were ex-service but were in good condition.

The *Typhoon* tailplane is of the two spar, rib, stringer and stressed skin type of construction in light alloy and is fitted with four root studs on each spar for attachment to the fuselage. A typical specimen is shown diagrammatically in Fig. 2.

2. *Method of Test.*—Load was applied to two loading points on the front spar, as indicated in Fig. 2.

Three tailplanes were tested at each of the following rates of loading :—

(a) *Incremental loading.* Load applied in increments of 10 per cent of an estimated mean failing load of 10,000 lb up to 70 per cent load, and then in 5 per cent increments, with a 15 minute interval after each increment, the failing load being reached in about $2\frac{3}{4}$ hours.

(b) *Sustained high loading.* Load applied in increments as in (a) but based on the actual mean failing load of the incremental tests and held for one hour at 85 per cent of this mean failing load (approximately 87 per cent of the actual failing load).

(c) 30-*second loading.* Load applied steadily to failure in about 30 seconds.

3. *Results.*—Typical load-time curves for the three types of loading are given in Fig. 4. For the incremental loading each increment was applied in about $\frac{1}{4}$ minute.

The failing loads for the three types of loading are given in Table 5. In each case the specimen failed by shear of the front spar web between ribs B and C. A typical failure is shown in Fig. 8.

APPENDIX III

Notes on Statistical Analysis of Results

1. *Standard Deviation and Coefficient of Variation.*—The standard deviation (Tables 4 and 5) is given by :—

$$s = \left(\frac{\Sigma(P - \bar{x})^2}{n - 1}\right)^{1/2}$$

where P is failing load of any one specimen
$\bar{x}$ mean failing load
n number of specimens

Coefficient of variation $= s/\bar{x}$

2. *Test for Significant Difference of Means.*—In the t test for significance

$$t = (\bar{x}_1 - \bar{x}_2)\left(\frac{n_1 + n_2 - 2}{\{\Sigma(P_1 - \bar{x}_1)^2 + \Sigma(P_2 - \bar{x}_2)^2\}\left(\dfrac{1}{n_1} + \dfrac{1}{n_2}\right)}\right)^{1/2}$$

where $\bar{x}_1$ is mean failing load of first sample
P_1 failing load of any one specimen in first sample
n_1 number of specimens in first sample

$\bar{x}_2$, P_2, n_2 are corresponding values for second sample

The values of t obtained are compared with standard tables[9] to determine whether the differences of the means are significant at the 5 per cent level.

TABLE 1

Failing Loads, Wooden Tailplanes, Incremental Loading

Specimen No.	Duration of Test Hr	Min	Failing Load lb	Moisture Content per cent
10	2	16	4190	16·5
11	2	30	4640	15·0
12	2	16	4190	16·5
13	2	5	3970	17·0
14	2	28	4410	16·0
15	2	1	3970	16·5
16	2	15	3970	16·0
17	2	16	4190	16·0
18	2	2	3970	15·0
19	2	17	4230	17·0
20	2	16	4210	—
25	1	48	3540	18·0

TABLE 2

Failing Loads, Wooden Tailplanes, 30-second Loading

Specimen No.	Duration of Test Sec	Failing Load lb	Moisture Content per cent
1	30·0	4610	16·5
2	30·0	4060	17·2
3	33·5	4430	16·5
4	30·0	4060	16·2
5	28·5	3990	18·2
6	31·0	4190	16·0
7	39·5	5300	15·0
8	32·0	4360	15·0
21	39·0	4720	16·5
22	39·0	4720	17·0
23	32·0	4410	16·5
24	32·0	4210	16·0

TABLE 3

Failing Loads, Wooden Tailplanes, 6-second Loading

Specimen No.	Duration of Test Sec	Failing Load lb	Moisture Content per cent
27	5·8	4190	—
28	5·6	4780	14·0
29	5·0	4120	16·0
30	6·4	4700	16·0
31	5·6	4270	16·0
32	6·2	4410	16·0
33	5·8	4430	16·0
34	5·8	4390	14·0
35	5·8	4520	15·0
36	6·4	4520	16·0

TABLE 4

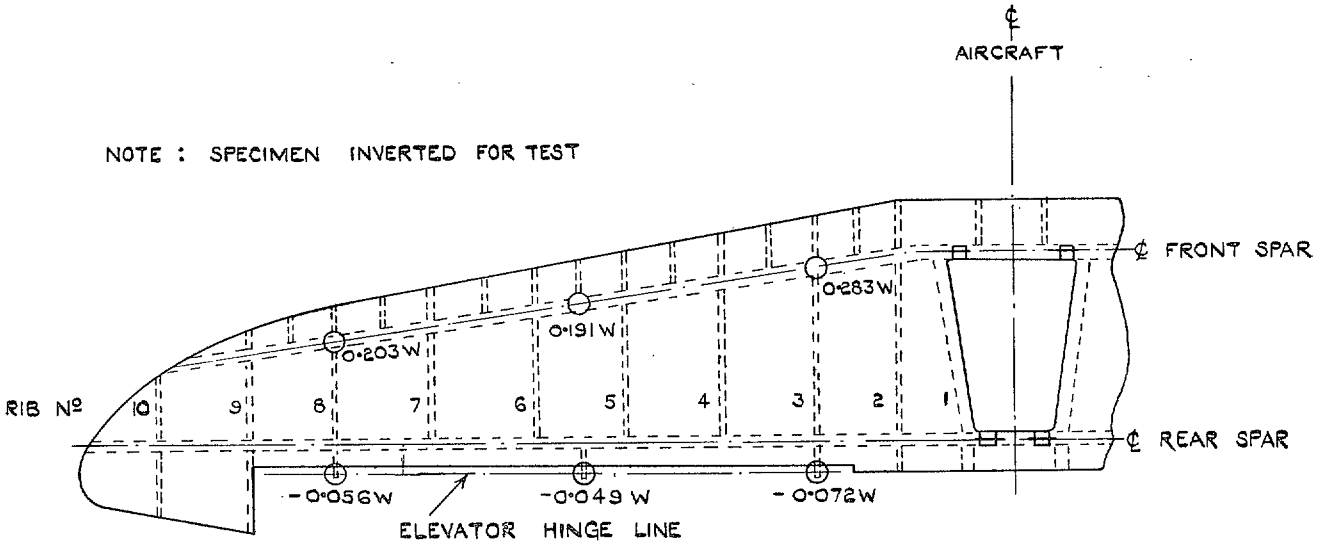
Mean Failing Loads and Standard Deviations. Wooden Tailplanes

Type of loading	No. of Specimens	Mean failing load lb	Standard deviation lb	Coefficient of variation per cent
(a) Incremental	12	4123	273	6·6
(b) ' 30-second '	12	4422	373	8·4
(c) ' 6-second '	10	4433	209	4·7
(b) and (c) combined	22	4427	303	6·8

TABLE 5

Failing Loads. Metal Tailplanes

Type of Loading	Specimen No.	Duration of Test	Failing load lb	Mean Failing load	Standard deviation lb	Coefficient of variation per cent
Incremental	2S	2h 46m	9420	9547	219	2·30
	3S	2 46	9800			
	4S	2 46	9420			
Sustained high loading	5S	3 46	9280	9303	23	0·25
	6S	3 46	9300			
	7S	3 47	9330			
' 30-second '	4Q	30 sec	9420	9490	70	0·74
	5Q	31 sec	9490			
	6Q	32 sec	9560			
	All results			9447	160	1·70

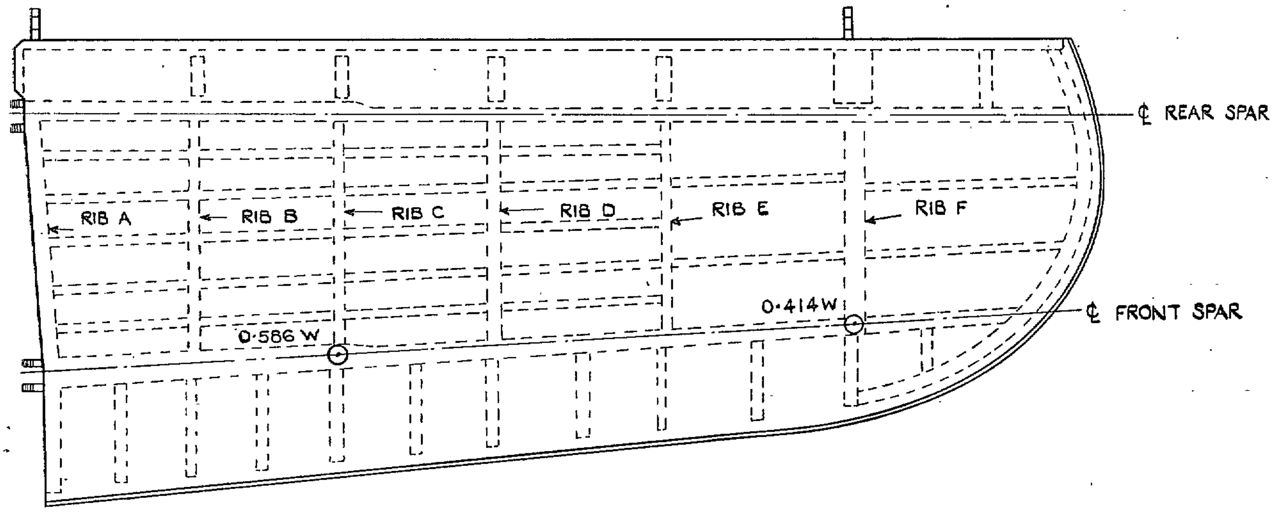


-⊟- FUSELAGE ATTACHMENT FITTINGS

○ LOADING POINTS, WITH PROPORTION OF TOTAL LOAD AT EACH (UPLOAD +VE)

RESULTANT LOAD ON COMPLETE TAILPLANE W
TOTAL UP LOAD ON FRONT SPAR 1·354 W
TOTAL DOWN LOAD ON ELEVATOR HINGES -0·354 W

FIG. 1. Applied loading. Wooden tailplanes (*Anson*).



⊙ LOADING POINTS, WITH PROPORTION OF TOTAL LOAD (W) AT EACH

FIG. 2. Applied loading. Metal tailplanes (*Typhoon*).

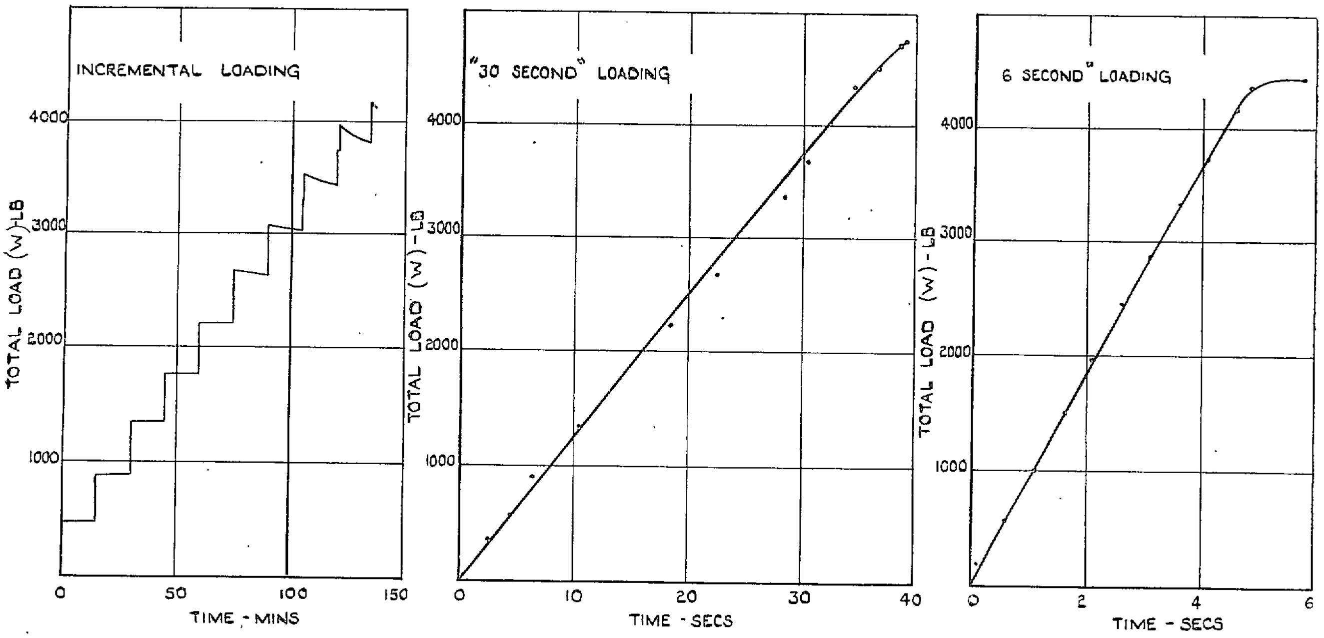


FIG. 3. Typical load-time curves. Wooden tailplanes.

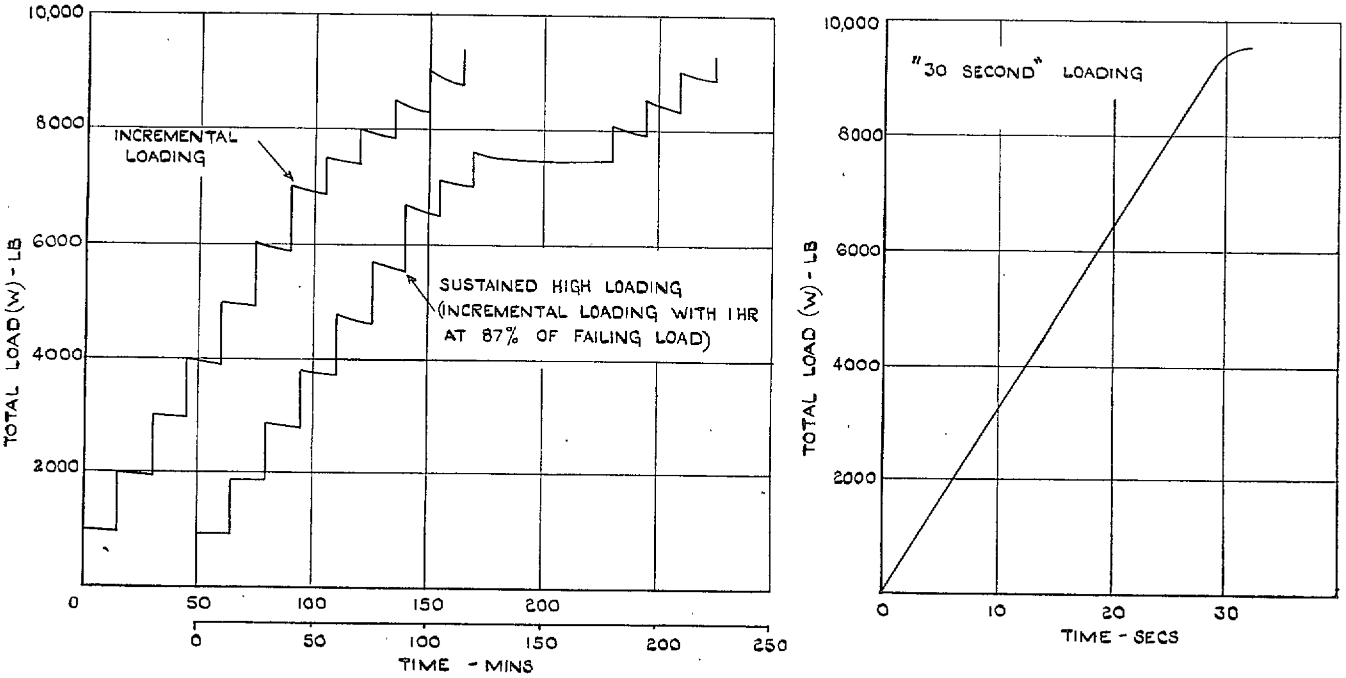
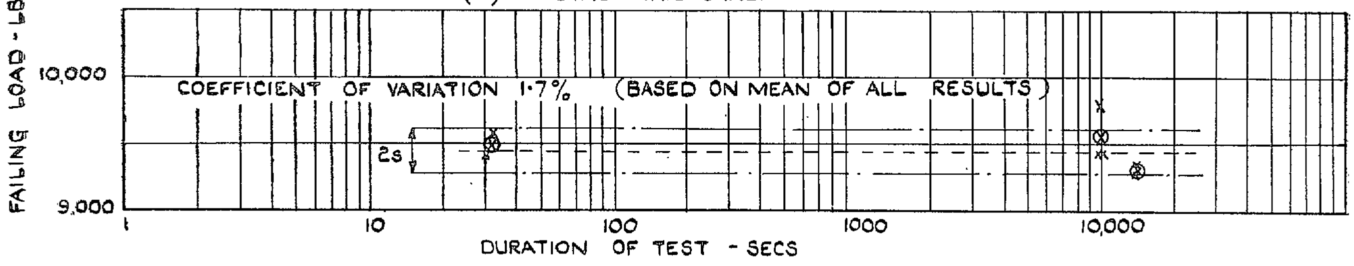


FIG. 4. Typical load-time curves. Metal tailplanes.

(a) METAL TAILPLANES



(b) WOODEN TAILPLANES

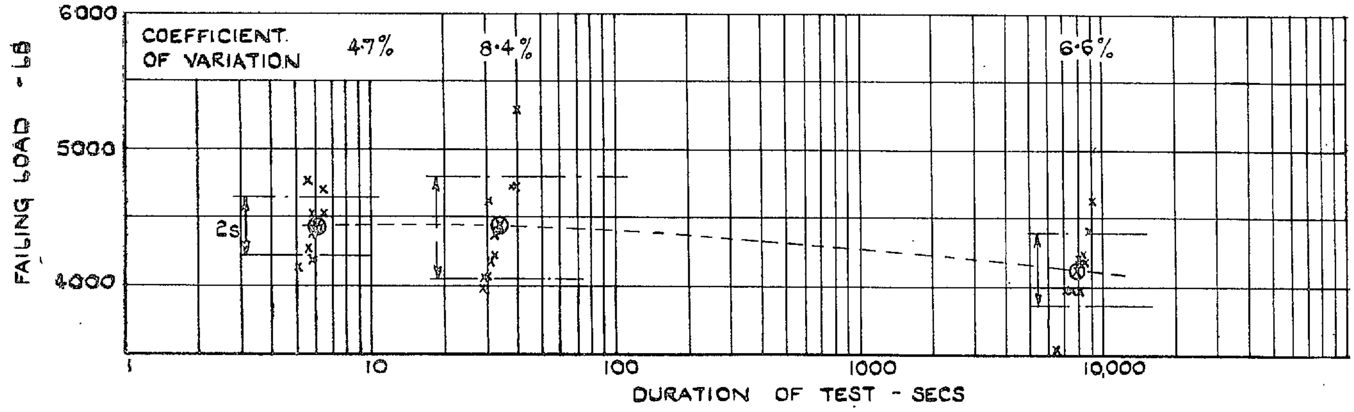


FIG. 5. Variation of failing load with duration of test.

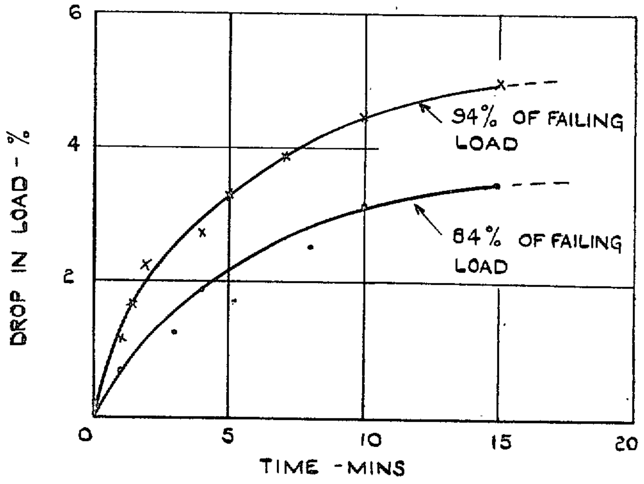


FIG. 6. Creep at high loads. Wooden tailplanes.

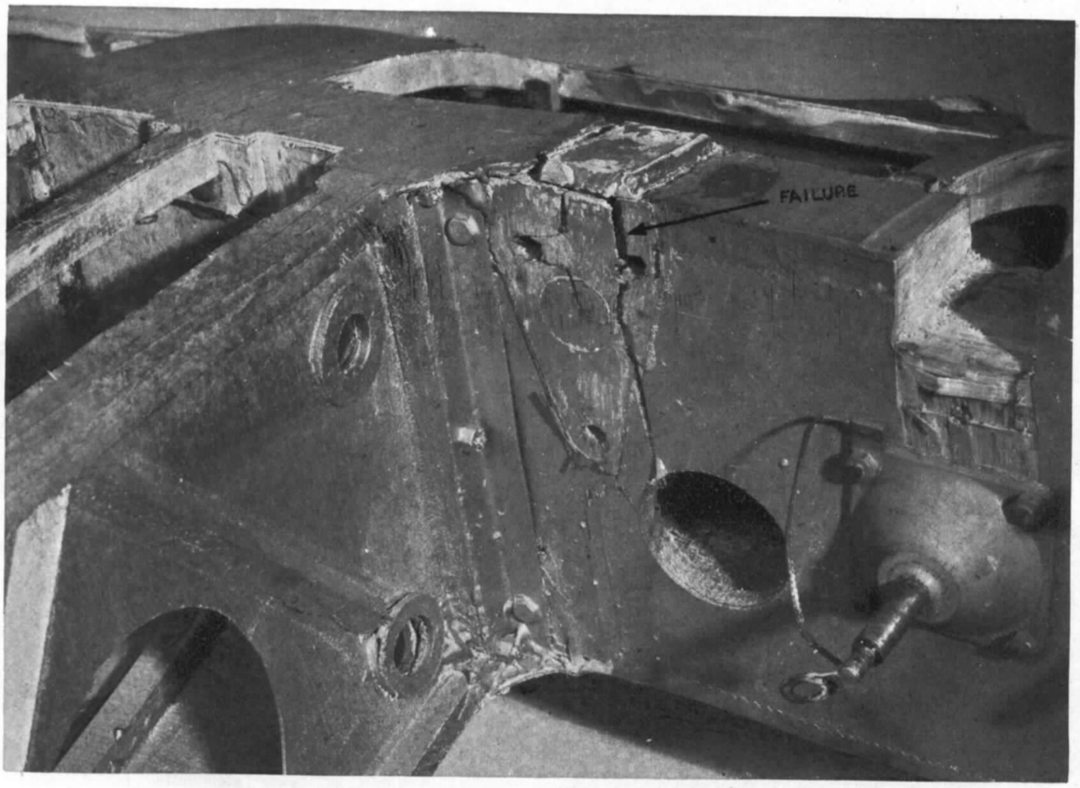


FIG. 7. Typical failure of wooden tailplane (*Anson*).

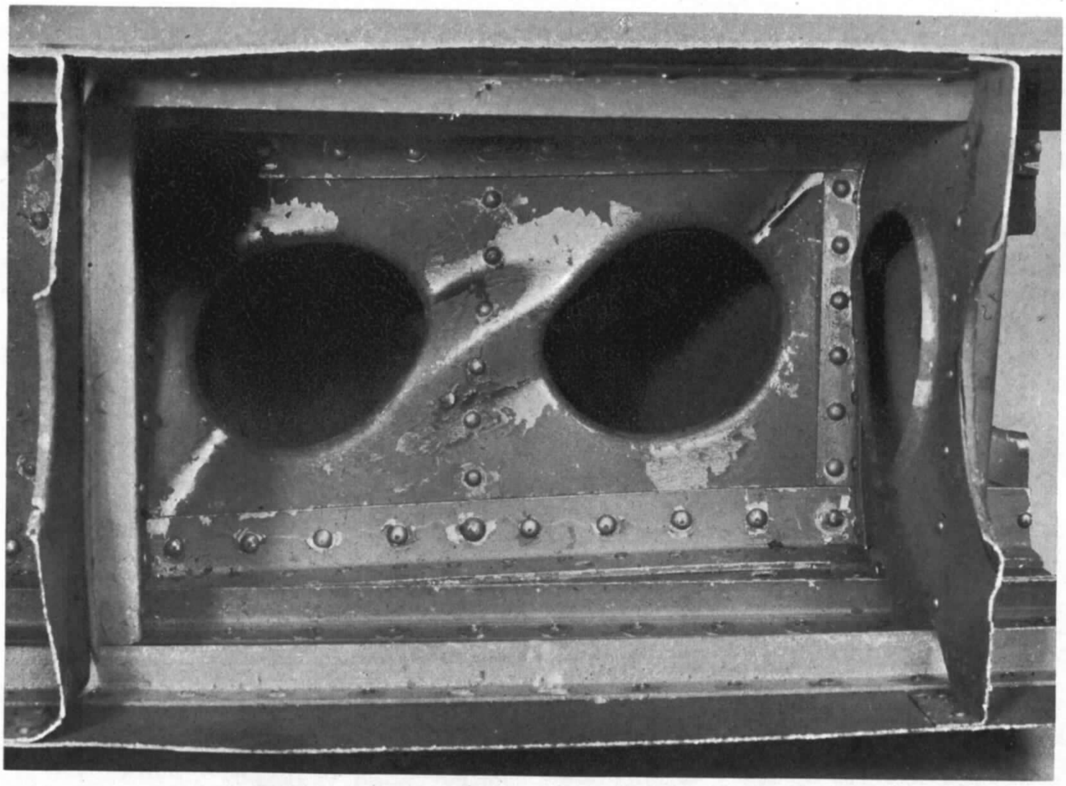


FIG. 8. Typical failure of metal tailplane (*Typhoon*).

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