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FOREWORD

The purpose of ICAO Circulars is to distribute information bearing upon the progress of ICAO's work more widely than would be possible for the ordinary series of documents.

The present Circular is a republication of a national study on a matter of fundamental importance that has also been considered at the First and Second Sessions of the Airworthiness Division of ICAO, during the discussions on the determination of minimum structural load factors for aeroplanes.

The report reproduced in this Circular was first issued by the Aeronautical Research Council of the United Kingdom as Reports and Memoranda No. 1906.* Consequent upon recommendations made by the Airworthiness Division, the report was submitted to ICAO for publication, has been translated by the Secretariat into French and Spanish and is being published as an ICAO Circular in English, French and Spanish.

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A PHILOSOPHY OF AEROPLANE STRENGTH FACTORS

By A.G. Pugsley, D.Sc.

SUMMARY

This report attempts, in a preliminary and elementary way, to bring aeroplane structural strength and loading statistics together into a logical and practical philosophy of strength factors. By correlating such statistics with structural accident rates, the influence of various design parameters is demonstrated and a new view of some past difficulties obtained.

1. - INTRODUCTION

The specification of strength factors for the design of engineering structures has for long presented theoretical difficulties, and many efforts have been made to formulate clear principles for their choice. The aim has always been to apply new knowledge to reduce the element of ignorance and so help to avoid having to regard strength factors as purely empirical or as factors of safety or factors of ignorance. As examples of such efforts we may note the introduction of allowances for dynamic loads and for fatigue effects.

In aeronautical work the general engineering outlook has been supplemented by an appreciation of the unusually variable nature of the loads coming upon the aeroplane structure. Accelerometer records have been taken in flight and expressed and used as "load" factors. The choice of strength factors has indeed been more influenced by the load aspect of the matter than by consideration of the properties of the structure used. The two questions have generally been treated as separate ones, and it is only recently that efforts [1,2] have been made to bring them together by relating both to accident rates. In doing so we have on the one hand to allow for the frequency of occurrence of loads of different magnitudes and on the other hand to allow for the variation in strength among aeroplanes produced to a given design. The purpose of this report is to try, in a preliminary and elementary way, to weld these various aspects of the design of aeroplane structures into a logical and consistent whole - a philosophy of strength factors - and, by so doing, to reduce accident rates, to bring into better perspective some of our past problems, to point to ways of further development, and to prepare for making the fullest use of the speed and acceleration loading statistics now accumulating.

2. - THE BASIC AIM

Let us start with the simple assumption that, in deciding upon the strength of an aeroplane structure, we are aiming primarily to ensure that the aeroplane shall be able to perform its duties efficiently without breaking. In practice, because of the importance of minimising structure weight, an aeroplane cannot be made so strong as to be unbreakable, and structural failures occasionally occur under extreme conditions, such as may arise if a pilot attempts to manoeuvre a large bomber too violently or if he makes a very bad landing. Structural accidents may also sometimes occur due to errors of design or workmanship or to the use of faulty material. It is natural to consider all such accidents in relation to the hours flown, and to express the history of structural failure among aeroplanes by the number of structural accidents arising in a given number of flying hours, i.e. by a structural accident "rate". Expressed in more precise terms, then, our basic aim is to learn how to choose aeroplane strength factors so that structural accident rates shall be as small as possible consistent with efficient production and operation. To help to do this, we study in the succeeding paragraphs the accident rate that may be expected to arise when aeroplanes made to a specified strength factor are used for duties involving a given range of loads, concentrating attention upon wing strengths and flight loads as most important and typical. We then see how the accident rate would probably change were the specified factor altered or the wings constructed more accurately to the strength desired.

3. - PRIMARY LOAD AND STRENGTH STATISTICS

To study the liability of a wing to fail in flight we have on the one hand to estimate the load history to be expected, having regard to its duties, and on the other hand to estimate the probable effective life of any aeroplane structure designed to meet such a load history. In our present state of knowledge this is obviously a matter for successive approximation, but that does not mean that it cannot be placed on a logical basis.

To attempt this in a preliminary way, let us disregard as secondary such matters as the influence of wing elasticity, of variation of load distribution and of fatigue effects, and concentrate upon total loads on the one hand and wing strengths on the other. Let us assume we have continuous accelerometer records for a set of aeroplanes of comparable type and duties. From these we can prepare a table of the number of times (n) the total wing load passes upwards through a given value (x) in a given flying time (large). An imaginary table of values collected in this way for a fighter is given below:

TABLE I

Wing load (x)	Frequency (n) in 10^4 flying hours
1	--
3	30,000
5	5,000
7	100
9	10
11	1
13	0
15	0

Suppose now we design a wing structure with a strength corresponding to a breaking load of about 13 (on the scale of Table I). If we make a number of aeroplanes to this design, the actual strength of the wings will vary somewhat on account of size tolerances and material variations. If we tested the wings of 100 such aeroplanes, we might find their strengths to be as tabulated below:

TABLE II

Wing strength (in intervals of 2 units of load)	No. of wings with strengths in each interval
0-2	0
2-4	0
4-6	0
6-8	0
8-10	2
10-12	12
12-14	72
14-16	12
16-18	2
	100

Average strength = 13
Standard deviation = 1.26

Thus, although the average strength of the wings is 13, of a hundred such wings two would have a strength of only about 9 (i.e. in 8 to 10 interval) and two would have a strength of as much as 17 (i.e. in 16 to 18 interval).

4. - CORRELATION OF LOAD, STRENGTH AND ACCIDENT STATISTICS

Consider now the 100 aeroplanes of Table II, and concentrate on those falling in a particular strength group, say the two aeroplanes with wing strengths between 8 and 10 - i.e. of mean strength 9. Now these two aeroplanes will, from Table I, on the average only meet a load sufficient to break them (i.e. a load passing upward through 9) ten times in 10^4 flying hours, so that if the 100 aeroplanes of Table II started flying together, and each flew for 10^4 hours, then the two aeroplanes concerned would probably have failed in the early stages of the flight. Before we can estimate the accident rate to be expected under the conditions of Tables I and II, we have to decide over what times the aeroplanes do their flying, and when and why new aeroplanes are brought into service. Thus all the aeroplanes could be produced together and start flying at the same time; or some could start together and others join them later. To make the problem at once amenable to simple probability theory and also approximate to practical service conditions, let us assume that the original 100 aeroplanes are continuously replenished as structural and other failures* occur, so that at any moment in the long 10^4 hours flying time the constitution of the 100 is according to Table II. Then we can say that the chance of an aeroplane having a strength in the class 8 to 10 is 2 in 100, and the chance of that aeroplane being broken is 10 in 10^4 hours. Treating these two chances as quite independent, the chance of a failure of an aeroplane of the specified class is $\frac{2}{100} \times \frac{10}{10^4}$ - i.e. 20 in 10^6 flying hours. We may regard this as meaning that, if a large number of aeroplanes of the design and duties represented by Tables I and II were flying in service, structural failures would occur to those in the 8 to 10 strength group at the rate of 20 in 10^6 hours. Applying the same argument to each strength group, we obtain Table III.

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* In practice few structural failures occur and replenishment is largely necessary for quite other reasons. This replenishment problem has interesting common features with other such problems in statistics.[3]

TABLE III

Strength group	No. of wings from Table II	Load frequency from Table I	Accidents in 10^6 hours (= product)
0-2	0	--	0
2-4	0	30,000	0
4-6	0	5,000	0
6-8	0	100	0
8-10	2	10	20
10-12	12	1	12
12-14	72	0	0
14-16	12	0	0
16-18	2	0	0
	100		32

Thus there would be 32 structural failures every 10^6 flying hours, of which failures 20 would be found to have occurred to aeroplanes with wing strengths of 8 to 10 and 12 to those with strengths of 10-12. This structural accident rate is actually a little above the average for modern aeroplanes - the figures in Tables I and II have been chosen to produce such a rate. We have thus arrived, upon certain simplifying assumptions, at an easy way - given the data - of roughly estimating structural accident rates.

5. - INFLUENCE OF DESIGN PARAMETERS

With the aid of Tables such as I, II and III, we can examine the influence upon the accident rate of various broad design parameters and so understand better the part played by them in preventing accidents. Suppose, for example, the structure was such that the mean strength of the wings was 11 instead of 13, the distribution about the mean being kept much the same, and the duties being unaltered. Then instead of Table III we might have Table IV, thus:

TABLE IV

Strength group	No. of wings	Load frequency	Accidents in 10^6 hours
0-2	0	--	0
2-4	0	30,000	0
4-6	0	5,000	0
6-8	2	100	200
8-10	12	10	120
10-12	72	1	72
12-14	12	0	0
14-16	2	0	0
16-18	0	0	0
	100		392

Thus the broad result of a decrease of mean strength from 13 to 11 would be a serious increase of the accident rate from 32 to 392 in 10^6 flying hours.

Alternatively, we might leave the mean strength of the wings unaltered, but choose the materials and size tolerances to reduce the scatter of strengths in Table II. Assuming we can thus roughly halve this scatter (as measured by standard deviation), we would then have Table V in place of Table III.

TABLE V

Strength group	No. of wings	Load frequency	Accidents in 10^6 hours
0-2	0	--	0
2-4	0	30,000	0
4-6	0	5,000	0
6-8	0	100	0
8-10	0	10	0
10-12	5	1	5
12-14	90	0	0
14-16	5	0	0
16-18	0	0	0
	100		5

Thus by halving the variation of strength about the mean of 13 we have reduced the accident rate from 32 to 5 in 10^6 flying hours.

The foregoing examples of the use of a correlation table of the form of Tables III, IV and V could be extended in various ways. We might, for example, examine the effect of variations of the load frequency table. Such variations might result from a change of duties, an alteration of the flying controls - as by an inertia device -, or from a change of pilots.

6. - SOME PAST AIRWORTHINESS DIFFICULTIES

When specifying strength factors for a particular design it has been customary to allow for variation of the strength of the finished structure in production by saying that a certain factor must be achieved by a standard test specimen; and this standard specimen has been defined as one constructed of members having the specified lower limits of both size and material properties. Unfortunately, while such limits could be embodied in strength calculations, it was never practicable to make such a standard specimen for test. Strength tests have therefore been made on specimens selected at random and the specified standard specimens have then been assumed to have strengths 20 per cent. less than the test values.

If we approach this problem in the light of the foregoing paragraphs, we may decide first that for convenience we wish to represent the strengths of the wings of Table II by a single strength value; and may then proceed to choose this value so that, coupled with the load frequencies of Table I, we derive the same accident rate as the "real" one given by Table III. In other words, let us aim at a strength value such that, if applied to all the aeroplanes concerned, it would lead to the real structural accident rate. To do this, we have to consider the numbers in the second column of Table III replaced by a single number of 100 and find its level in relation to the strength groups so that, when multiplied by the number (or interpolated number) in the load frequency column on the same level, it gives an accident rate of 32 in 10^6 flying hours. It is clear from Table III that this equivalent strength level is between 10 and 14, and by rough graphical interpolation it is found to be about 12. That is, if all the aeroplanes concerned had a strength of 12 and underwent the loads of Table I., then the accident rate would be 32 in 10^6 flying hours. This equivalent strength is about 7½ per cent. below the mean strength of 13, and corresponds to the mean less 0.8 times the standard deviation of Table II. It will be noted that, as in a random test there is a good chance that the specimen will approximate to the mean, these figures of 12, 7½ per cent. and 0.8 may roughly be compared with the figures that would result from the present 20 per cent. rule, i.e. 10.4, 20 per cent. and 2.1 respectively. It should also be noted that the former set of figures are strictly a function of the loading frequencies as well as of the degree of strength variation.

Another problem of the past, though worked on more in Germany than elsewhere, is how to allow for the effects of load repetition on the behaviour of complete aeroplane structures. Even if such effects were large and sufficient data were available, it was always difficult to see how any allowance could be brought into a logical system of strength factors; but with Table III before us there seems more hope of this. It may be practicable to scheme an enlarged version of Table III to make full provision for repetition effects, or alternatively to devise an approximate process by suitably "weighting" or adjusting the figures in the second or third columns.

7. - CONCLUSION

No attempt has been made in this exploratory report to state the frequencies and probabilities concerned in the mathematical terms of statistical theory. But it is clear that the simple examples discussed in the Tables could all be cast into algebraic form, using appropriate generalized frequency laws, and the relative importance of design parameters discussed in general terms. Such an analysis, whether graphical or algebraic, would have complicated this first simple discussion of the matter, but might form the basis for a useful series of wing strength, load frequency and accident rate curves for use in the review of design factors. The effects of different systems of replenishment to the simple one adopted in #4 for Table III are already being examined.

Another point, to which this attempt to state a possible practical philosophy of strength factors draws special attention, is the fundamental importance of collecting load and strength statistics.

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