NATIONAL ADVISORY COMMITTEE
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STRENGTH INVESTIGATIONS IN AIRCRAFT CONSTRUCTION UNDER

REPEATED APPLICATION OF THE LOAD

By E. Gassner

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By E. Gassner

In the calculation of the dimensions of modern machines
and building constructions, account is taken of the frequency
of the occurrence of the anticipated loads. It is generally
assumed that these loads will be repeated an infinite number,
or at any rate some millions, of times during the total work-
ing life of the construction. When calculating the dimensions
of the structural parts of aircraft, on the contrary, a con-
sideration only of those frequencies in the appearance of the
loads which actually come into play in the various states of
stress is allowable. This is because in aircraft construction
it is absolutely essential not only to ensure adequate struc-
tural strength but also to keep down the structural weight
to the lowest possible limit. Strength tests in which this
requirement is directly taken into account have recently been
carried out by the DVL Material Strength Department.

STRESSES OCCURRING IN FLYING OPERATION

The stresses produced in an aircraft fluctuate in vary-
ing measure, according to the nature and purpose of the ma-
chine, about a mean load, which corresponds to the air forces
in unaccelerated horizontal flight, hence to the value of the
total loaded weight of the aircraft multiplied by unity.
These load fluctuations or "load multiples" do not succeed
each other in obedience to any definite law. They are pro-
duced by gusts of varying strength and direction and as the
results of the operation of the controls. Large fluctuations
occur considerably less frequently than smaller ones (more de-
tails may be found in references 1 to 5.)

Extensive statistical investigations by the DVL Flight Mechanics Institute have recently provided reliable numerical data concerning the frequency of the occurrence of these stresses. (For details, see reference 5.) Figure 1 shows, for example, the result of such stress measurements represented as a "sum curve." The ordinates in the diagram are numbered according to fractions or multiples of a load amplitude denoted by "1." The abscissas show how often the individual load "steps" are exceeded within a prescribed operational time or flying distance. In order to get an idea of the actual conditions from the diagram, a scale should be applied to the ordinates, such that the load step marked "1" gives the load applied when flying into a gust of 10 meters per second acting perpendicularly to the direction of flight ("gust load" = additional load due to gust). The frequencies plotted in figure 1 for the occurrence of loads exceeding the individual load steps then hold roughly for a transport airplane with a total service life of the order of 3000 hours with a total flying distance of the order of 1.05×10^6 kilometers at a speed of 350 kilometers per hour (European Continental air traffic).

According to Kaul (reference 5) positive and negative gusts occur with approximately the same frequency. The obvious procedure is, therefore, to count one positive and one negative gust load together as one "load alternation," although the two states of load certainly do not in reality follow each other immediately. The sum curve in figure 1, then gives both the number of the positive or negative gusts and also the number of the gust load alternations. Here, only the fluctuations of loads superimposed on the mean load are counted, and not the smaller fluctuations in the nature of harmonic oscillations otherwise produced.

STRENGTH TESTS AS INTERPRETING FLIGHT STATISTICS

If a strength test on an aircraft component is to be directly adapted to the results of flight statistics, the succession of all high and low stresses occurring in flying operations, namely, in the most haphazard order, must be imposed in this test. An example of the course of a test of this kind is shown by figure 2. For technical reasons, the total load range is subdivided into 9 load steps and the whole series of loads into 12 load cycles. Each cycle in the example selected here comprises 0.9×10^6 gust load alternations (at 350 km/hr this number corresponds to about 250 flying hours). In order to obtain a mixture of high and

low load steps conforming more or less to service conditions, all the load steps contained within each cycle were run through once in the descending and once in the ascending direction. It remains to be seen whether perhaps some other cyclic range or some other sequence of the load steps may be more suitable.

Figure 3 shows the synoptic diagram of a "strength test as interpreting flight statistics" taking as an example a perforated duralumin tube (Flieg 3115). The "sum curve of the test", namely, the stepped line k_2, indicates, by the widths ΔH of its steps, the frequencies of the load repetitions which were run through altogether in the individual load steps during a test in accordance with figure 2. As may be seen, the test was so chosen that its sum curve very closely followed the given "sum curve" of the operational loads, namely, the line k_1. (Cf. fig. 1.) To be on the safe side, the sum curve k_2 was made to coincide with the curve k_1 in the region of the highest load steps.

Comparative tests showed that the part under test would have "just" still held out in accordance with the sum curve k_2 without failure; that is, on increasing the ordinate scale, fracture would have appeared already within the total specified frequency. It may be regarded as probable, that the part under test would also have just still satisfied the sum curve k_1. The curve k_3 further drawn in figure 3, is thus the sum curve of the operational loads which the part under test would have satisfied with the requirement of a standardized factor of safety 1.35 against all load peak values (peak value = mean load + load amplitude).

It is essential that, in such a "strength test as interpreting flight statistics," all load steps are applied repeatedly to one and the same part. In order to show clearly the difference between tests of this kind and the usual treatment in strength tests, a brief survey of different forms of testing is given below.

OTHER TREATMENTS OF STRENGTH TESTS

Hitherto, the technique of tests applied to aircraft construction has been limited in the main to the single application of load, as is the usual practice in the "static strength test" in other branches of strength testing technique. In aircraft construction such static tests are intended to

show whether the specified factors of safety, in particular
1.8(sometimes also of smaller or larger value), as against
the "safe loads" exist. (For details, see reference 6.)
In machine and engine construction, generally, and in build-
ing construction at the present time, strength tests with
repeated application of the load are given preference, when
the individual part undergoing the test is subjected re-
peatedly to one and the same load amplitude till failure
occurs. The terms "fatigue strength tests" or "endurance"
strength tests are employed according to whether in such
tests the repetitions of the load applications are of the
order of 10^6, or more, or whether fewer repetitions already
lead to failure. (The results obtained from a number of simi-
lar test parts are represented graphically in the form of
"Wöhler curves".) (Cf., for example, figs. 2 to 7, also
reference 10.) These fatigue and endurance tests will be re-
ferred to as "one step repetition tests."

Neither static tests with a single application of load
nor one-step repetition tests provide direct information as
to whether and how long an aircraft part can withstand the
continued application of high and low operational loads.
For example, no rule can be given as to what number of rep-
etitions of one or more selected load steps must be endured
by the individual part under test, if the whole succession
of load applications is to be covered.

The tests carried out by French (reference 7) and Müller-
Stock (reference 8) and the studies of Langer (reference 9),
Thum and Bautz (reference 10), Kloth and Stroppel (reference
11), constitute an approach toward the realization of the
"strength tests as interpreting flight statistics."

French (reference 7) deals with the question as to how
often a load step (step 1) above the fatigue strength can be
withstood without the fatigue strength (step 2) of the part
under test being reduced. The result of "two-step repetition
tests" carried out for this purpose has been represented by
French in the form of "probable damage lines." In these a
frequency is coordinated with each stress value of step 1,
on exceeding which the (permanent) fatigue strength of the
part is reduced.

In the generalization of this conception, naturally, in
place of fatigue strength (step 2) any other stress value may
be used as the comparison step. The latter may also be se-
lected higher than step 1. In this sense, Müller-Stock
(reference 8) has carried out two-step repetition tests, which

go beyond those of French, since he not only determines the
frequency of step 1 above, which a reduction of the other-
wise tolerable frequency of a comparison step appears; but
he has at the same time sought to establish how this reduction
depends numerically on the frequency of step 1. In further
tests, Müller-Stock deals also with the question as to the
extent to which the tolerable frequency of a third step is
influenced by a load that has been previously applied alter-
nately in two steps with certain frequencies.

Direct conclusions cannot be drawn from the experimental
work of French and Müller-Stock, as they stand, with regard
to the problem as it affects aircraft construction, although
certain relations must surely exist between the results of
these two or three step repetition tests and the results of
the tests as interpreting flight statistics. In view of this
possibility, "damage lines" as interpreted by French were
determined by the Material Strength Section of the DVL for a
number of semifinished aircraft parts. As the results of
these tests will be of general interest, the damage lines for
tubes of Cr-Mo steel, duralumin, hydronalium, and electron
are shown in figures 4 to 7. The stress values of these
damage lines differ only from the corresponding values of the
Wöhler curve.

Langer (reference 9) assigns certain assessment coeffi-
cients to the different load steps of a complete sequence of
high and low loads according to the frequency with which they
are attained within the individual load cycles. According to
Langer, the load-carrying capacity of a structural part is
exhausted when the sum of all assessment coefficients has
reached a certain value. In this, account is taken of the
fact that the very frequent application of loads below the
fatigue strength may, in some circumstances, neutralize the
detrimental effect of a few applications of loads above the
fatigue strength. No account is taken, on the contrary, of
the probability that the assessment coefficient of each load
application cycle is greatly influenced by the cycles preced-
ing and following it. The order in which the different load
application cycles alternate will play a particularly impor-
tant part in this connection.

Thum and Bautz (reference 10) seek to interpret a sequence
of high and low loads by tests with repeated stress in one
step only selected out of the whole load cycle, that is, by
one-step repetition tests. Load steps above the one selected
for the test are taken into consideration by increasing the
frequency of the test load step to a value above that which
it reaches in reality. Such considerations, however, hold

only for the case where the test load step lies above the fatigue strength. As in Langer's work, here again the influence of all preceding and following load cycles on the assessment coefficient of each individual load cycle is neglected. Thum and Bautz still give no clear rules of any kind for the execution of the strength tests concerned nor for the determination of the dimensions of the structural part.

Kloth and Stroppel (reference 11) were the first to utilize the sum curve of the operational stresses for the assessment of the strength characteristics of land machine parts. They came to the conclusion, however, that, in view of the "interference stresses," the structural parts should be so dimensioned that their fatigue strength lies above all otherwise "normal operational stresses." (Such a rule for dimensioning would not be suitable in airplane construction.)

CONCLUDING COMMENTS

As opposed to the otherwise usual utilization of strength tests, the recent tests of the Material Strength Section of the DVL are characterized by the fact that they are directly adaptable for the whole sequence of all loads occurring under operational conditions. Today, the usual methods of fatigue and endurance testing cannot in any way take the place of tests of this kind, that is, by making one- and two-step repetition tests. The results of such strength tests will probably show certain relationships with "Wöhler" and "damage" lines.

The tests now in progress at the DVL Material Strength Section are intended first to provide information on fundamental questions: for example, on the influence of the order of sequence and distribution of the individual load cycles within the total cycle, on the influence of pauses of rest, and so forth. So far as it is possible now to make any statements, it would appear as though a sequence of load application descending in monotone, beginning with the highest load would be considerably less favorable than, for example, a sequence as represented in figure 2. If the continuity of the load sequence is interrupted by relatively long pauses, it may be expected, according to trial tests carried out with duralumin (Flieg 3115) with a two-day interruption after each complete cycle, that there will be a reduction in the total tolerable frequency.

Translation by M. Flint.

REFERENCES

General considerations on the stresses occurring in flying operation are contained in the following papers:

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2. Teichmann, Alfred and Michael, F.: Safety and Design in Airplane Construction. NACA TM No. 755, 1934.

3. Küssner, Hans Georg: Häufigkeitsbetrachtungen zur Ermittlung der Erforderlichen Festigkeit von Flugzeugen. Luftfahrtforschung, vol. 12, no. 2, May 16, 1935, pp. 57-61. (Air Corps Trans. No. 308)

4. Neesen, Arthur and Teichmann, Alfred: Bemerkungen zu den Vorschriften für die Festigkeit von Flugzeugen. Luftwissen, vol. 2, no. 8, Jan. 1935, pp. 201-214 and vol. 2, no. 9, Sept. 1935, pp. 251-254.

Detailed statistical considerations on the load frequencies in operational flying are contained in:

5. Kaul, Hans W.: Statistical Analysis of the Time and Fatigue Strength of Aircraft Wing Structures. NACA TM No. 992, 1941.

Details on the present strength requirements of aircraft are to be found in:

6. Bauvorschriften für Flugzeuge, No. 1: Vorschriften für die Festigkeit von Flugzeugen. Edition   Dec. 1936.
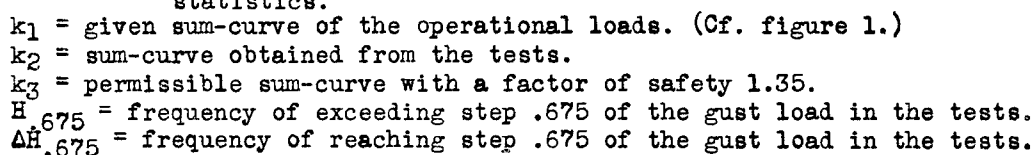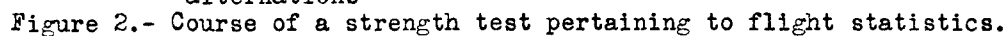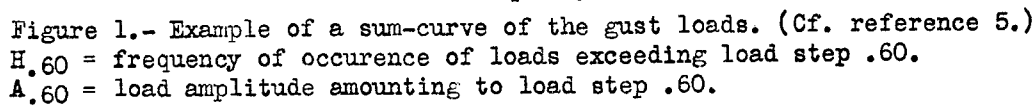
Recent strength tests in machine construction and materials are described in:

7. French, H. J.: Fatigue and the Hardening of Steels. Trans. Amer. Soc. Steel Treat., vol. 21, 1933, p. 899.

8. Müller-Stock: Der Einfluss dauernd und unterbrochen wirkender schwingender Überbeanspruchung auf die Entwicklung des Dauerbruchs. Mitt. Kohle- und Eisenforschung, vol. 2, no. 2, March 1938.

9. Langer, B. F.: Fatigue Failure from Stress Cycles of
      Varying Amplitude. Jour. of Appl. Mech., Trans.
      A.S.M.E., vol. 4, no. 4, Dec. 1937, pp. A-160-A-162.

10. Thum, A., and Bautz, W.: Zeitfestigkeit. ZVDI., vol. 81,
      1937, p. 1407.

   Statistical data on the load frequencies were employed
for the first time in strength considerations in:

11. Kloth and Stroppl.: Kräfte, Beanspruchungen und Sicher-
      heiten in den Landmaschinen. ZVDI., vol. 80, 1936,
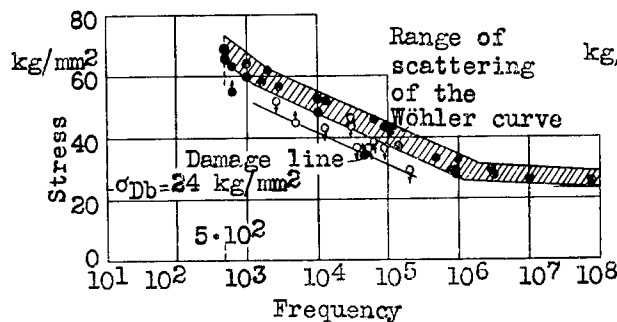   p. 85.

Figure 1.- Example of a sum-curve of the gust loads. (Cf. reference 5.)
$H_{.60}$ = frequency of occurence of loads exceeding load step .60.
$A_{.60}$ = load amplitude amounting to load step .60.

Figure 2.- Course of a strength test pertaining to flight statistics.

Part under test, tube 50.1 of dural
(Fleig 3115) with 5 mm bore in the
highest stressed fibres. σ_B=46 kg/mm^2,
$\sigma_{.2}$=34 kg/mm^2 (permissible minimum value
of material; σ_B=40 kg/mm^2,
$\sigma_{.2}$=28 kg/mm^2).

Figure 3.- Synoptic diagram of a strength test as interpreting flight
                statistics.
k_1 = given sum-curve of the operational loads. (Cf. figure 1.)
k_2 = sum-curve obtained from the tests.
k_3 = permissible sum-curve with a factor of safety 1.35.
$H_{.675}$ = frequency of exceeding step .675 of the gust load in the tests.
$\Delta H_{.675}$ = frequency of reaching step .675 of the gust load in the tests.

Figure 4.- Wöhler and damage curves for smooth steel tube 38·1 under alternate bending.
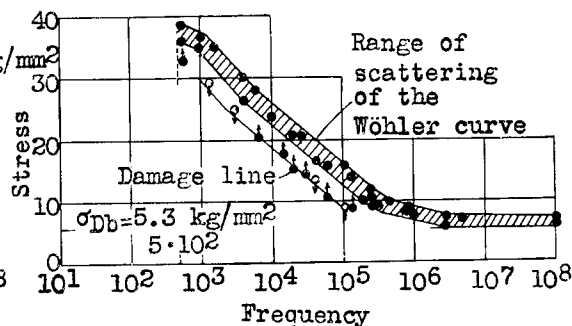Material: Cr-Mo-steel (Flieg 1452.9) with σ_B=70 to 82 kg/mm^2 and $\sigma_{.2}$=63 to 76 kg/mm^2.

Figure 5.- Wöhler and damage curves for smooth duralumin tube 50·1 under alternate bending.
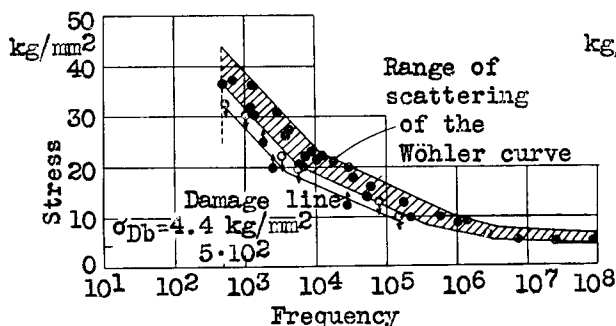Material: Duralumin 681 (Flieg 3115) with σ_B=40 to 43 kg/mm^2 and $\sigma_{.2}$=28 to 32 kg/mm^2.

Figure 6.- Wöhler and damage curves for smooth hydronalium tube 50·1 under alternate bending.
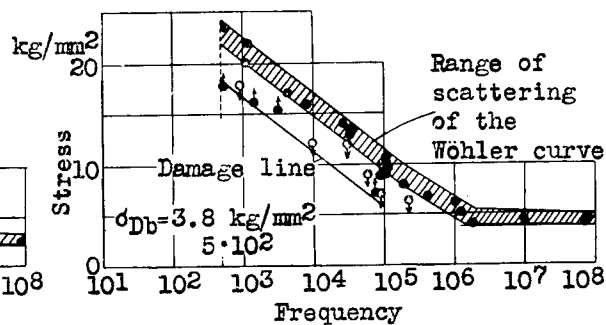Material: Hydronalium Hy 9 (Flieg 3315.7) with σ_B=38 to 39 kg/mm^2 and $\sigma_{.2}$=28 to 30 kg/mm^2.

Figure 7.- Wöhler and damage curves for smooth electron tube 50·1 under alternate bending.
Material: Electron AZM (Flieg 3510.1) with σ_B=29 to 30 kg/mm^2 and $\sigma_{.2}$=16.5 to 17.5 kg/mm^2.

Figures 4 to 7.- Wöhler and damage curves for smooth tubes (alternate bending).

● Wöhler test.
Tests for recording the damage line.

⬥ Not yet fractured in the 2nd step with 2·10^7 load alternations.

○ Fractured already in step 2 before reaching 2·10^7 load alternations.
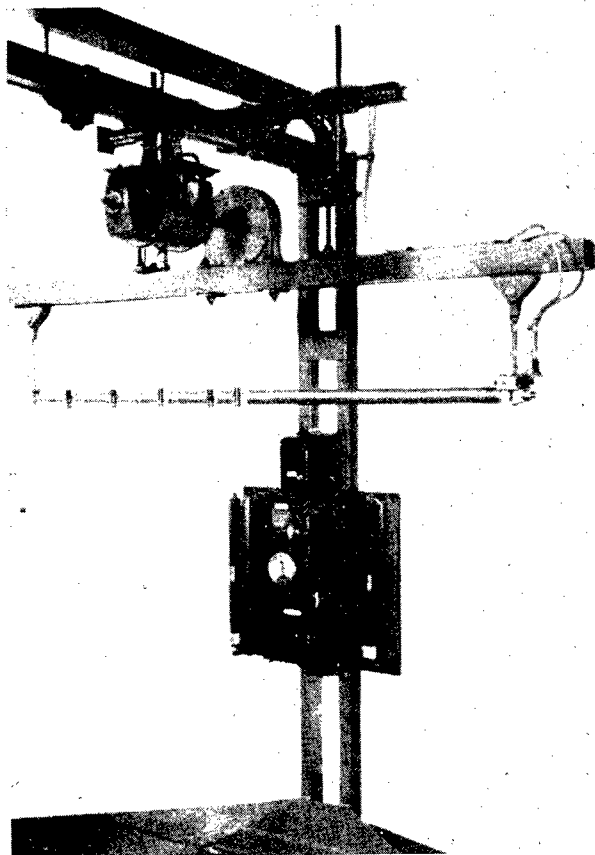
Figure 8.- DVL bending oscillation
        test machine for tests with
a large number of load alternations.

The part under test (tube) is sus-
pended from a flexibly mounted
carrier and is set in oscillation by
a rotating flywheel which is fixed to
the carrier. As the rpm of the fly-
wheel is made by a suitable mechanism
to approximate the natural oscillation
frequency of the part, the oscillation
stresses of the latter can be stepped
up or down arbitrarily. Their value is
calculated from the amplitudes of the
part. Constant amplitude values are
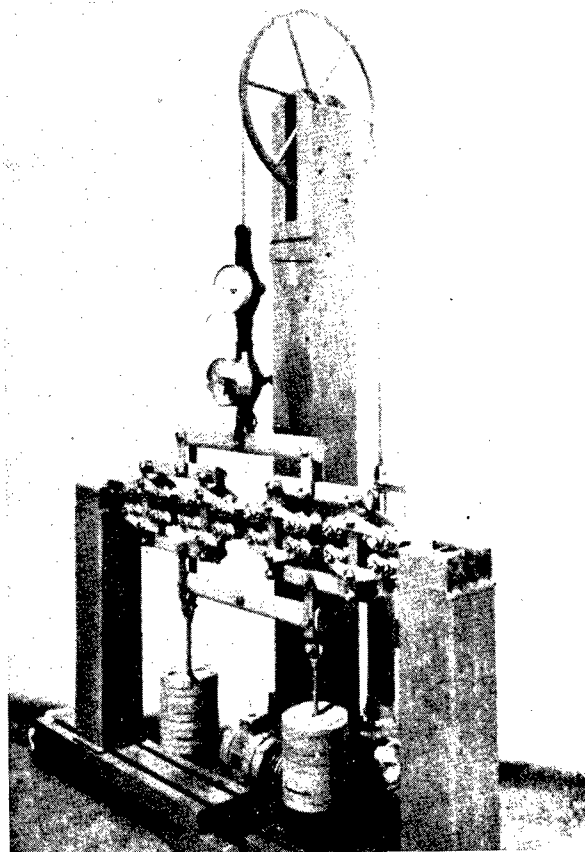obtained with the aid of a Schenck
regulating apparatus.

Figure 9.- DVL alternating winch for
        tests with a small number
of load alternations.

The part under test (tube) is loaded
through a suitable system of levers
in one direction by weights and in
the other direction by a screw
spindle. The latter is driven by a
reversing motor. On reaching the
upper and lower load limits, the
motion of the spindle is reversed
by means of a contact dynamometer.