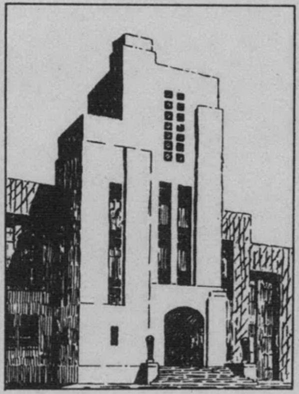
THE DAVID W. TAYLOR MODEL BASIN

UNITED STATES NAVY

FACTORS AFFECTING THE TIME AND FATIGUE STRENGTH OF MATERIALS

BY F. BOLLENRATH



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FACTORS AFFECTING THE TIME AND FATIGUE STRENGTH OF MATERIALS

(EINFLÜSSE AUF DIE ZEIT- UND DAUERFESTIGKEIT DER WERKSTOFFE)

by

F. Bollenrath

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Translated by F.A. Raven

David Taylor Model Basin
Bureau of Ships
Navy Department, Washington, D.C.

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FACTORS AFFECTING THE TIME* AND FATIGUE STRENGTH OF MATERIALS**

ABSTRACT

Several cases are cited to show how widely time and fatigue stresses under working conditions differ from those under the conditions that usually exist in laboratory tests. Some of the factors that cause these differences are work interruptions, periodic changes in limit stresses and mean stresses with a few groups and load conditions in periodic sequence, statistical variations and sequence of limit stresses and mean stresses, fretting erosion at fixation points, and effects of notching. By several examples drawn from aeronautics it is shown how data on these factors, obtained from alternating load tests by a variation of Wöhler's technique, now in general use, can be utilized by the engineer to achieve greater economy of materials. Numerous data are given to show recent trends.

INTRODUCTION

Wöhler's technique is usually preferred to test the strength of structural materials under cyclic loading. Simple test rods are subjected to periodically alternating loads between fixed stress limits either to failure or at least for several million load cycles. The average stress limit as a function of the number of load cycles up to failure indicates that up to a certain stress limit practically any desired number of load cycles can be sustained. These test methods have served well in the development of materials of high fatigue strength, and are indispensable in comparing various materials with one another.

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* Translator's Note: The term "Zeitfestigkeit" is discussed in the following excerpt from Volume 2, Chapter III, B, 1, c, of Handbuch der Werkstoffprüfung, Erich Siebel, Berlin, 1939, pp. 181-182.

"If the amount of stress is greater than that which belongs to the endurance limit, we speak of time strength, since then the life-span only amounts to a limited number of load cycles, i.e., for practical purposes only a definite number of operating hours. After the number of load cycles determined from the S-N curve (Wöhler-Kurve) have been run off, fracture must occur. In this respect it must be noted that by comparison of the number of load cycles at failure, which are found for various materials under identical load conditions, i.e., by comparison of time-strength values, the ratio of their fatigue strengths cannot be determined directly, since the S-N curves (Wöhler-Kurven) of various materials can intersect." See Figures 11 and 12.

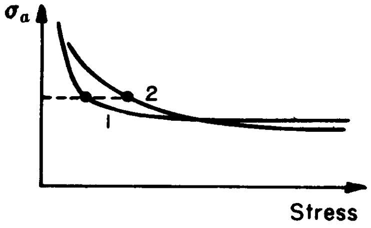

Figure 11 - Various Forms of S-N Curves (Wöhler-Kurven)

A comparison of the number of load cycles at fracture at a definite stress does not always permit conclusions to be made as to the fatigue strength of the materials.

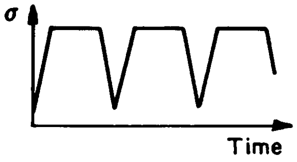

Figure 12 - Loading Scheme

** Delivered at the 28th meeting of the "Deutscher Verband für die Materialprüfung der Technik" (German Association for Material Testing in Engineering), Munich, June 12 and 13, 1940.

There are many factors in applied mechanics which to varying degrees modify the strength of structures under cyclic loading, but which sometimes are considered only in part or even wholly ignored in strength tests. Among these, for example, are shape and size of the structural member, surface conformation, methods of fabrication, temperature, chemical reactions, mode of stress distribution due to shape and external loading as well as internal stresses, and stress as a function of time.

It is beyond the scope of a report to discuss the effects of these factors even without great attention to detail. Moreover, the general aspects of a number of mechanical factors are taken into account in testing materials for specific uses. Therefore the following discussion will be limited to several factors whose growing importance is due to the fact that modern engineering structures are designed, to the best of our present knowledge, to utilize materials to the limits of their capacity and thus to economize material and weight. This is a characteristic of modern light-weight design. It is particularly evident in the most recent engineering achievements in fast transportation, the motor car and the airplane. In the future, economy and efficiency will demand even closer adherence to this trend than at present.

LOADING IN OPERATION AND IN TESTING

The structure of fatigue testing machines almost universally produces a sinusoidal pattern of stress alternations between fixed limits, so that considering the frequency, a cosine curve of the load velocity results. Moreover, as far as I know, the changes of the S-N curve with respect to changes in the time-stress curve have been studied very little, although deviations from the sinusoidal pattern often occur. This subject will be discussed later. Repeated impact tests, which are concerned with the effect of impact loading, constitute a borderline case. In such tests, however, the effect of the impact rate is not noted particularly. With respect to the load limits, one-stage tests are sometimes run to failure or until the fatigue limit has been found.

The S-N diagram is the result of numerous one-stage tests. Similar loads naturally predominate in engines and machine tools which run for long periods at fixed output. In this field, by considering a few additional factors which vary from case to case, such as dimensions or shape, the fatigue strength is an adequate criterion for the choice of materials and dimensioning of structural members. This is particularly true of many stationary machines designed for long life and industrial use where weight is unimportant, and where in order to avoid excessive wear, only small loads are permitted.

Special conditions may occasionally require that constant stress amplitudes greater than the fatigue strength be admitted in spite of the shorter life span of the structure which this entails. In such cases the problem of time strength (Zeitfestigkeit) must be considered, and the question arises whether the S-N curve can still be regarded as a satisfactory basis of design. To estimate the factor of safety even for a limited number of load cycles to failure, it seems necessary first to plot the S-N curves for stress amplitudes exceeding the actual design loads. Moreover it is necessary to determine the extent of the zone of fracture by numerous tests. This will give S-N curves of the form shown in Figure 1, which extend from the static strength to the fatigue strength and define the fracture zone.

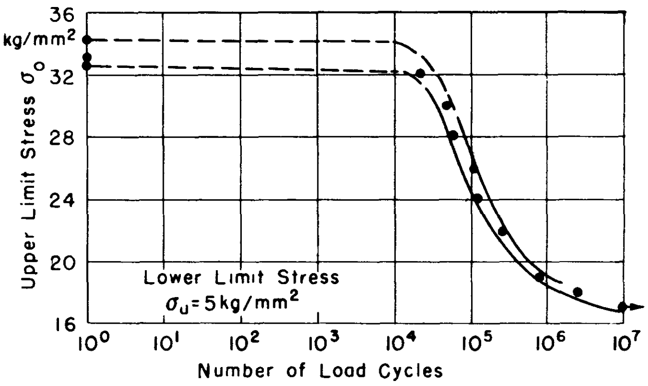

Figure 1 - S-N Curve for a Ductile Aluminum Alloy Containing 6 Per Cent Magnesium and 1 Per Cent Zinc

Complete S-N curves are also a necessary basis for strength tests where stress limits change because of operating conditions. This will be reserved for more detailed discussion. The S-N curve shows essentially that the factor of safety can better be judged by the intensity of stress than by the number of load cycles up to failure. The complete S-N curve also reveals only a slight change in stress amplitude from the condition of static strength up to the point where the curve begins to drop sharply after many thousands of load cycles. However, the fatigue failures scatter over a rather broad range, the so-called fracture zone. Hence, only those critical load cycle values which are denoted by the lower limit curve of the fracture zone can be regarded as reliable.

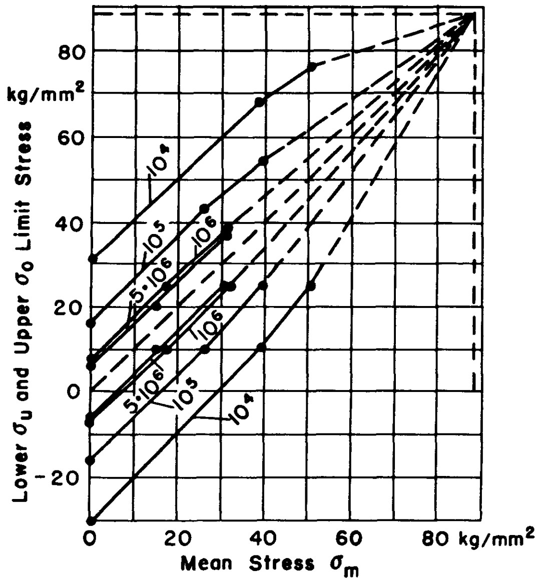

Figure 2 - Chart of Time Strength and Fatigue Strength of Hardened Chrome-Molybdenum Steel Tubing

The steel tubing has an outside diameter of 28 mm (1.10 inch), a wall thickness of 1 mm (0.04 inch), and a transverse bore of 2 mm (0.08 inch) at the midpoint.

By combining a number of S-N curves for various lower limit stresses, complete time-strength and fatigue-strength graphs can be plotted. An example is given in Figure 2, which shows conditions for hardened chrome-molybdenum steel tubing of 28 mm (1.10 inch) outside diameter and 1 mm (0.04 inch) wall thickness and having a transverse bore of 2 mm (0.08 inch) at the midpoint. The upper and lower limit stresses are plotted as functions of the mean stress for fatigue strengths based on 5 × 10^6 load cycles and further for stress limits which belong to the lower limit of the range of failure at 10^6, 10^5, and 10^4 load cycles. Various types of S-N curves which are generally not plotted in material testing, but which are of practical value, can be obtained from such graphs. Examples include those for fixed mean stresses or for constant upper-limit stresses. The loading range covered by such a graph is not used in actual practice because it is restricted by certain safety factors, which may depend on the tensile limits, failure strength or deformation, etc., beyond the load limits corresponding to particular types of materials and the reliability of the underlying principles.

Actual fracture is merely the culmination of a protracted phenomenon of failure extending over many load cycles. The latter may vary greatly, depending on the nature of operating conditions. For this reason, the number of load cycles when failure begins could be taken as the index of safety. However, the early stages of failure can scarcely be determined, and up to the present no generally suitable method has proved reliable. Contemporary data chiefly concern the extent to which a series of load cycles affect the fatigue strength between high stress limits or the time strength between low stress limits. Collaterally, the studies of H.F. Moore and H.B. Wishart (1),* H.F. Moore and I.B. Kommers (2), H.F. Moore and T. Jasper (3), I.B. Kommers (4), H.B. Wishart and S.W. Lyon (5), H.J. French (6), Müller-Stock (7), and others should be mentioned. These methods may be termed "two-stage tests." They are specially characterized by the uninterrupted succession of load alternations in the individual stages, and where the higher stage may precede the lower and vice versa.

Any number of load cycles which results in decreased fatigue or time strength lies on a so-called "damage line." Whether or not this "damage line" indicates the number of load cycles at which the fibers part, i.e., where actual fracture or failure

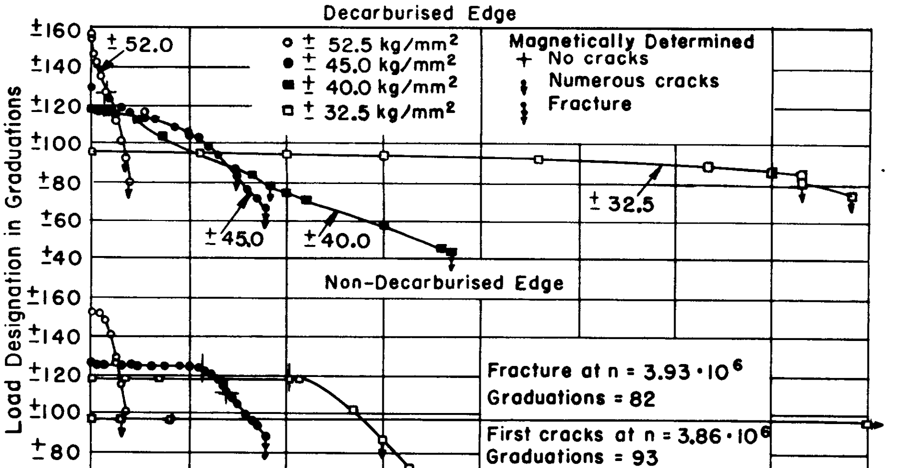

Figure 3 - The Torsional Stress Limits as a Function of the Number of Load Cycles for Stay Wire at Varying Limits of Deformation

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* Numbers in parentheses indicate references on page 18 of this translation.

occurs, has not been definitely proved. The sensitivity of other methods to determine initial damage has only been slightly clarified as yet by comparative tests. In this respect reference may be made to a study by F. Oshiba (8) who investigated the problem dealing with the number of impact load repetitions as a function of the bending strength of notched bars. Disadvantages of the test methods to which reference has just been made are the large number of specimens required, and the length of time consumed in testing them.

F. Bollenrath and W. Bungardt (9) approached the problem from a different direction. They studied the stress as a function of the number of load cycles between various fixed limits of the amount of deformation, see Figure 3, and simultaneously recorded the appearance of cracks by the magnaflux method. The greater the deformation, the sooner the tensile stress begins to slacken and a decrease in the breaking strength becomes apparent with resultant damage. The damage can be determined very similarly from a deformation which increases with the number of load cycles at constant stress. In this way, for example, the sharp increase of deformation which appears in the deflection curves for rotary deflection after a certain number of load cycles indicates a drop in load capacity, Figure 4. Comparative tests have proved that the amount of damage, determined by the methods described, is not constant. This is obvious, if it is considered that each method deals with a different problem; i.e., whether the one-stage test emphasizes the fatigue strength, a definite time strength, resistance to the impact notch bending test, or continued load capacity. For example, the fatigue and time strengths decrease long before the deflection appreciably begins to rise. Therefore, considering these various problems, it is doubtful whether the various damage curves can be made to agree. Hence, the task of finding the "damage line" needed to determine the size and dimensions of a structural member needs special attention.

The type of "damage line" which was just described can rarely be of use in practical load conditions. There are but few structural members which are first stressed by a definite number of uninterrupted load cycles in the field of time strength and subsequently in that of fatigue strength. However, the importance of such research for the strength testing of materials under changing loads should not be underestimated. All studies of the type previously mentioned are indispensable for research in basic theory. At the same time, however, it is necessary to explain the relationships between the results of these studies and the

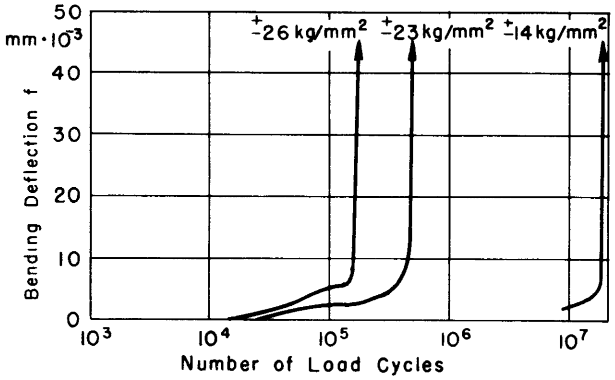

Figure 4 - The Increase of Deflection of Duralumin as a Function of the Number of Load Cycles in Rotary Deflection

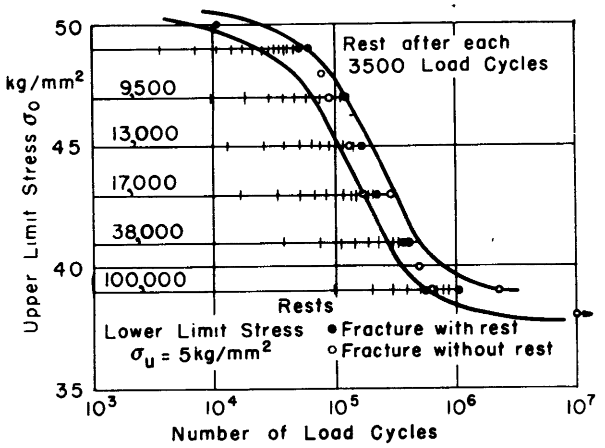

Figure 5 - Effect of Interrupted Operation on the S-N Strength of an Austenitic Chrome-Nickel Steel (18 Per Cent Chromium and 8 Per Cent Nickel)

problems arising under practical operating loads. Some of these problems will be taken up in greater detail.

In the first place, the total number of load changes scarcely ever occurs without interruption, even if the stresses remain within fixed limits. This gives rise to the problem of the effect of interrupted operation on time and fatigue strengths. This problem can be considered solved for ferritic steels by the studies made by K. Daeves, E. Gerold and E.H. Schultz (10) and for the most varied types of materials by research at the "Institut für Werkstofforschung der Deutschen Versuchsanstalt für Luftfahrt" (German Aeronautical Research Institute, Division of Material Testing). According to these investigators interruptions in work seem to increase the number of load cycles up to fracture in mild or unalloyed steel containing "free ferrite," and tests by the first-named authors (10) indicate that this increase is augmented by allowing the parts to rest at raised temperatures during the interruptions.

In their reports of tests with alloy steels and other materials, F. Bollenrath and H. Cornelius (11) state that work interruptions had no other effects on the shape of the S-N curve, as is shown by Figure 5 for an austenitic steel containing 18 per cent chromium and 8 per cent nickel. All the critical load cycles in this example are within the range of failure for uninterrupted operation.

Under actual operating conditions, uniform amplitudes at a mean load, such as are maintained in material strength testing, do not often occur. For example, the pressure curve, Figure 6, of the master bearing of a radial airplane motor during a single revolution of the crankshaft

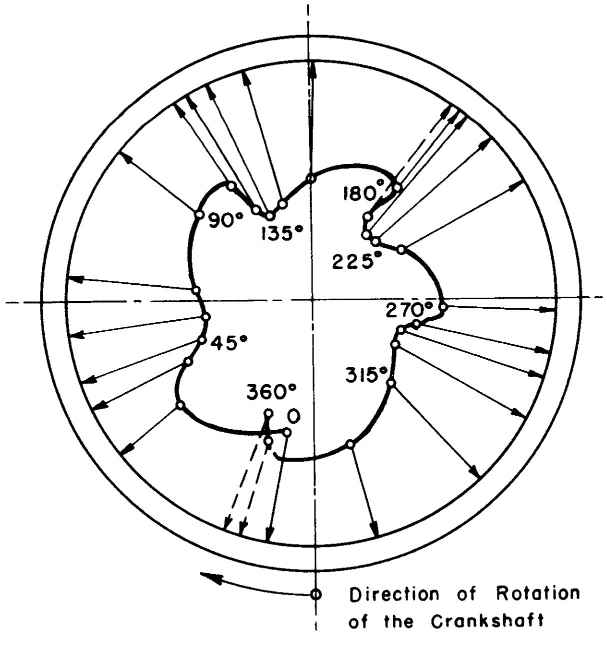

Figure 6 - Pressure Curve with Respect to Magnitude and Direction for the Master Bearing of a Radial Motor during a Single Revolution of the Crankshaft

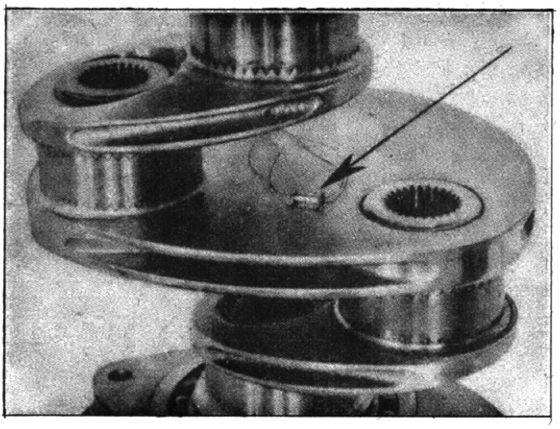

Figure 7 - Electric (Inductive) Strain Gage of the German Aeronautical Research Institute, Division of Propulsive Mechanics

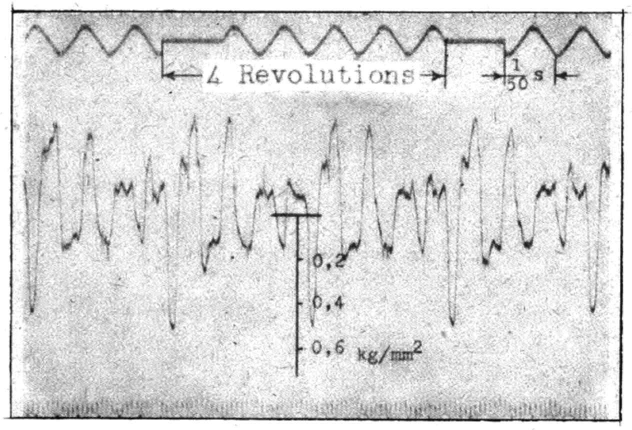

Figure 8 - Stress-Strain Curve of the Base of an Airplane Propeller Blade, Recorded by the Instrument Shown in Figure 7

Motor B M W 132, n = 2150 RPM

shows a periodic succession of load changes at constant frequencies within a limited range and at graduated mean loads. Due to the fact that the motor is of the 4-cycle type, the frequency is equal to one-half the RPM. Another example shows how actual operating conditions differ from strength testing technique, i.e., that of the base of a blade of an airplane propeller attached to the shaft of an in-line motor. First, however, a strain gage will be described which permits the stress-strain curve of moving parts to be recorded in actual operation. Figure 7 shows such a recording strain gage mounted on a Hirth crankshaft. It is a tiny inductive electric instrument developed by the "Institut für Triebwerksmechanik der Deutschen Versuchsanstalt für Luftfahrt" (German Aeronautical Research Institute, Division of Propulsive Mechanics). It weighs only 0.5 gram (0.017 ounce) and is 10 mm (0.39 inch) long. It is cemented on to the part to be tested and will withstand a load of 1500 grams (3.30 pounds). The stress-strain curve at the base of a propeller blade was recorded with this extremely sensitive and accurate instrument. Figure 8 shows such a recording at 2150 RPM. It is evident that the stresses are sinusoidal and that the frequency is equal to one-half the number of revolutions because the propeller is driven by a 4-cycle motor. Superposition of various sinusoidal vibrations produces a beat, from which it is possible to derive in close approximation stress changes which can be divided in uniform groups among a few graduated stress limits.

To investigate the suitability of a material for such loading, if the test is not made within the motor itself, stresses of equal amplitudes should always be collected in groups and tabulated in the same way for reasons of testing technique. The number of equal amplitudes which should be included in a group and the order in which the groups must be arranged to most closely approximate practical load conditions is yet to be determined.

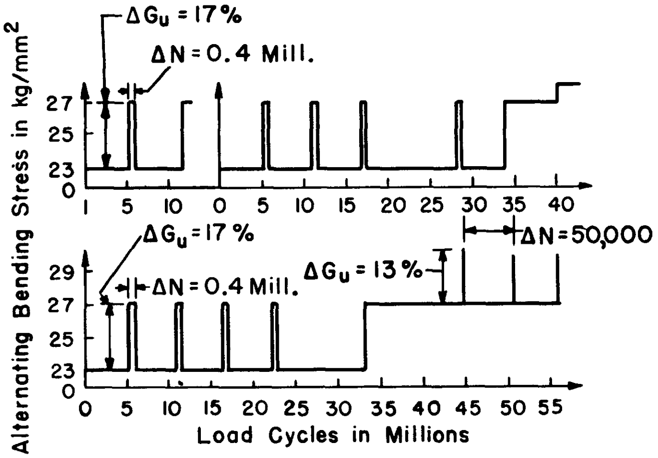

Figure 9 - Variation in the Strength under Alternating Bending Load of an Unalloyed Annealed Steel Containing 0.20 Per Cent Carbon through Conditioning by Overloading (F. Körber)

Studies which have already been made, such as those by B.F. Körber and M. Hempel (12) already give an idea in this respect. Figure 9 shows the result of several multiple-stage tests which were conducted to simulate actual operating conditions. They consist chiefly of two-stage tests in which two dissimilar groups of bending-stress cycles follow each other. Therefore the number of load cycles in each group is important. By subdividing into smaller groups a far greater number of load cycles can be carried above the fatigue strength of 23 kg/mm^2 (32,700 pounds per square inch), than is possible when large numbers of load cycles are grouped. In the given example, it is interesting to note that those groups whose load is at the fatigue strength level and which are interspersed between groups of high stress variation, can appreciably increase the endurable number of stress variations lying in the field of time strength. This phenomenon will be reserved for detailed discussion.

A load on an airplane engine similar to the experimental conditions just described occurs rarely. With respect to the crankshaft of an airplane engine, there are several intervals at which resonance occurs, lying within the range of the practical RPM's. The RPM's which lie within the ranges of resonance are always traversed as rapidly as possible, since they produce the absolute maximum loads. The normal RPM's, e.g., cruising speed, are fixed to lie somewhere outside the resonance ranges. Thus the maximum number of load cycles is kept within rather low stress limits. However, when the engine speed (RPM) is changed, or in starting (warming up), some resonance ranges must be traversed. Therefore, a small number of multiple-stage load cycles lying between high limits are interspersed among a large number of load cycles lying between low, regular load limits.

Disregarding this, occasionally even higher loads are encountered, as for example, in taking-off at full power or diving. No rating based on any arbitrary, large number of load cycles encountered while traversing the resonance ranges is made,

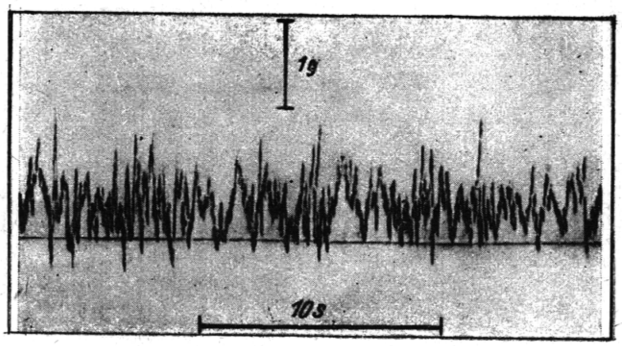

Figure 10 - Acceleration Curve of an Airplane while Cruising, Showing the Effect of Up and Down Drafts (He 70 UDAS)

because it is unimportant. If an engine were allowed to run continuously at such a critical speed the crankshaft would possibly last 10 or 20 hours, whereas at some other critical speed it might last 50 hours, and at some speed lying between these figures, it might last many hundred hours, or not fail at all. Therefore, the problem chiefly consists in studying and comparing the behavior of materials as determined from test results with that under actual operating conditions, especially with the occasional higher loads encountered at cruising speeds.

The loading conditions on the wing unit of an airplane, for example, differ basically from those described for engines. This difference becomes most apparent, perhaps, by comparing the loading curve or loading record of a propulsive part, such as the previously described propeller, with that of a portion of a wing unit. Figure 10 shows the acceleration record of a Heinkel 70 airplane of the Lufthansa made while cruising straight ahead on an even keel. It depicts vertical accelerations (up and down drafts) due to squalls. The accelerations, from which the acceleration curve can be directly deduced, were recorded with a DVL (Deutsche Versuchsanstalt für Luftfahrt) accelerometer. The mean load corresponds to an acceleration of 1 *g* (acceleration of gravity). Here complete irregularity rules both with respect to the order and size of loads, as well as with respect to the mean load at any given moment.

This brings up extremely important questions of aircraft construction, namely: How should structures be designed to withstand such loads with maximum economy of material, and to what extent do experimental results in the field of material testing contribute? These questions cannot immediately be answered definitively. In discussing them, it is important to consider that the life of airplanes need not be long, for reasons having to do with engineering and technical development, economy and specific use. Numerically expressed, this means that an airplane must only have a reasonably sufficient factor of safety for a given number of flying hours or for a limited flight range depending upon the flying speed.

The course pursued in aircraft construction to determine the strength of materials or structural components necessary to bear such loads as are shown in Figure 10 will be briefly outlined in the following discussion. By statistical methods depending on test accuracy, the accelerometer readings are analyzed for the frequency with which acceleration peaks occur within given stages (13). The tests are based on the acceleration of gravity. Since the ratio of the accelerations to the stresses is known, statistics stating the frequency with which certain stress peaks will recur

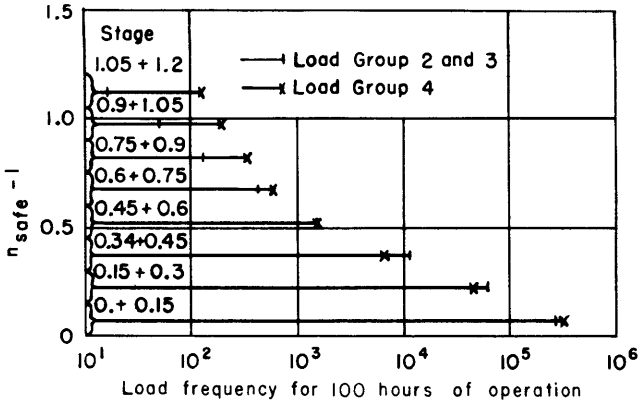

Figure 11 - Load Frequency in Multiples of (n_{safe} - 1) for 100 Flying Hours

The load due to squalls (n_{safe} - 1) which may be safely superimposed on the load in undisturbed and unaccelerated straight flight, according to the structural code for airplanes, is converted for a flying speed of 350 km/h (217.5 miles per hour).

within fixed stress gradations can be obtained. Figure 11 gives an example of such statistical data. Since the unit distribution was found to be approximately symmetrical to the basic load, W. Kaul (13) developed a simple and dependable rule for loading tests. His method consists in combining two equal, opposite, but not necessarily consecutive squalls into a load cycle, using the undisturbed cruising speed on a straight course as the mean load. For Groups 2, 3, and 4, in accordance with usual practice in S-N diagrams, Figure 11 shows how frequently such load cycles fall within the gradations of the arbitrary group division.

The question which needs to be answered more exactly in such cases is: For what total frequency does a material or structural component withstand the statistically determined loads at a given stress standard, or what stress standard is to be assigned to a given statistical total frequency? Experiments designed to answer this question are termed strength tests in a statistical sense. In discussing these problems, the author follows principally hypotheses established by A. Teichmann and E. Gassner of the DVL Strength Testing Institute. In Figure 12 the arbitrary sequence of load gradations occurring in actual operation are compared with an ideal sequence; direct repetitions of identical stages occur only on the lowest level, slowly rising or falling sequences are found only between the lowest and next to the

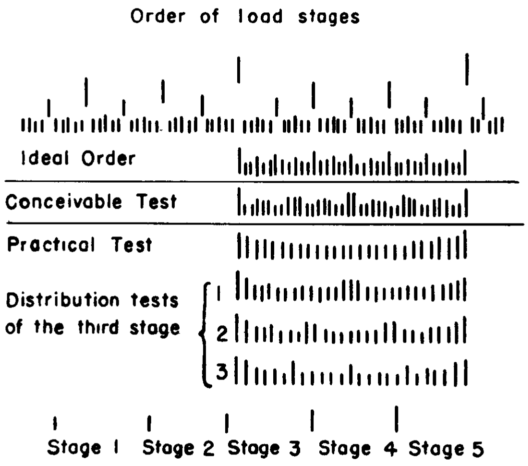

Figure 12 - Sequence of Loading Gradations (A. Teichmann)

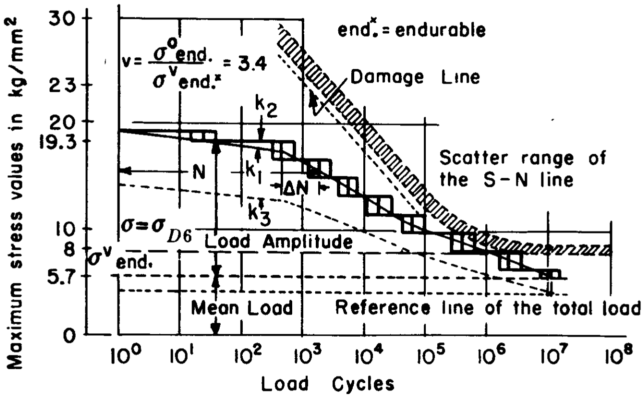

Figure 13 - E. Gassner's Summarized Presentation of Strength Data from Statistical Methods

Test specimen: Duralumin tube 50 × 1 (Flieg 3115) having a 5 mm (0.19 inch) bore in the most highly loaded fiber;
σ_B = 46 kg/mm^2 (65,425 pounds per square inch)
$\sigma_{0.2}$ = 34 kg/mm^2 (48,360 pounds per square inch)
Permissible minimum value of the material:
σ_B = 40 kg/mm^2 (56,890 pounds per square inch)
$\sigma_{0.2}$ = 28 kg/mm^2 (39,825 pounds per square inch)

K_1 = given summation curve of operating loads (see Figure 1)
K_2 = test summation curve
K_3 = permissible summation curve for a safety factor of 1.35
H = the frequency with which a definite stage of the supplementary load due to squalls is traversed in the test
A_H = the frequency with which a definite stage of the supplementary load due to squalls is reached in the test.

lowest stages. In view of the fact that several million cycles are necessary, tests with such an ideal sequence are not feasible. Therefore, if identical stages are grouped, and moreover, if they are grouped·according to certain regularities of rise and fall, the series is appreciably simplified for both purposes of theoretical and practical tests. The latter hereby require less time and material than otherwise. By selecting a group, in this case that of the third stage, and by scattering it over the range of the series to be tested with varying distribution, the effect of deviation from the ideal series can be determined.

For practical test purposes, A. Teichmann and E. Gassner (14) derived a summation curve K_1 from the flight record for an arbitrary time or distance, which is represented in Figure 13 in the usual form for S-N diagrams. To save time, the loads are first divided into groups capable of duplication in tests. The continuous summation curve K_1 is then replaced by a step-shaped line K_2 in closest possible agreement with K_1. The K_2 curve shows the frequency with which the load exceeds a given step. The step-shaped lines to the right and left of K_2 show the scatter range of the frequencies. After a number of test repetitions, this scatter range rather closely resembles that of an S-N curve. In the tests the loads·are produced as a series of summation curves, each of which contains the statistical load record for 250 hours

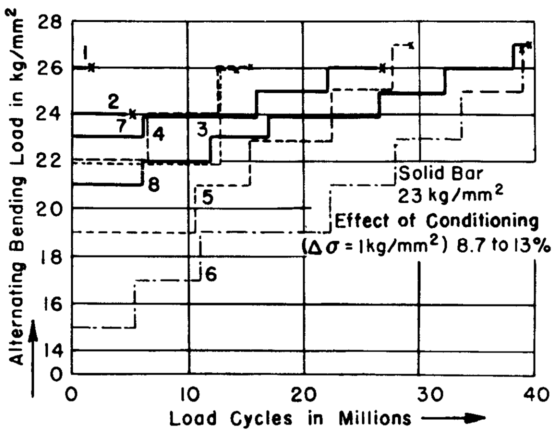

Figure 14 - Change in Bending Strength under Alternating Load, due to Conditioning

The test specimen was of unalloyed steel with a 0.2 per cent carbon content. (F. Körber)

of operation. Hence, over a proposed operating period of 3000 flying hours a structural member must be able to endure 12 such partial summation curves with safety.

In view of the foregoing, how must the loads be applied for test purposes? What effect does the sequence of load cycles have between regularly increasing or decreasing, or alternately increasing or decreasing limits? The effect of rising load gradations is evident in tests made by F. Körber (12) and M. Hempel. Figure 14 shows their results for an unalloyed, annealed steel having a 0.2 per cent carbon content. The bending strength under alternating load is ± 23 kg/mm^2 (32,700 pounds per square inch). Due to the fact that the load changes to which it was first subjected lie between limits which are below the fatigue strength, a conditioning effect occurs which is evidenced by an 8.7 per cent to 13 per cent increase of the cyclic strength (Wechselfestigkeit).* According to this, greater numbers of load cycles above the fatigue strength are endured as the load stages increase. According to investigations of structural members of steel and duralumin, carried out by A. Teichmann and E. Gassner, the stress scale which can be endured at a given number of cycles, increases in this order: regularly falling, alternately rising and falling, and regularly rising limits. In this way the stress scale or unit may increase about 70 per cent to 80 per cent.

Strength testing sequence is like that in an operating record, as Figure 15 shows. The loads fluctuate around the mean load, which is the flying weight on a straight course in undisturbed flight. The start lies at an average stage of the maximum stress values. In the test here cited a partial sequence includes 0.9×10^6 cycles. In this case it is desired to find a stress scale which can be used for a total of 10.8×10^6 load cycles, corresponding to 3000 flying hours at 350 km/h (217.50 miles per hour).

Figure 16 shows a somewhat more generalized treatment of the problem in which the study is extended to greater ranges of the number of flying hours. Therefore a series of tests was made on duralumin tubes 50 mm (1.96 inch) in diameter, with walls 1 mm (0.03 inch) thick and notched with three 5 mm (0.19 inch) transverse drill holes in the zones of maximum stress under bending alternation. These tests showed the maximum load occurring in the statistical data σ^0, and hence all remaining maximum stress values, to be a function of the number of hours of operation. The ratio between the statistically determined maximum stress and the stress σ^v which pre-

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* Translator's Note: This conditioning effect appears to be a form of "work hardening."

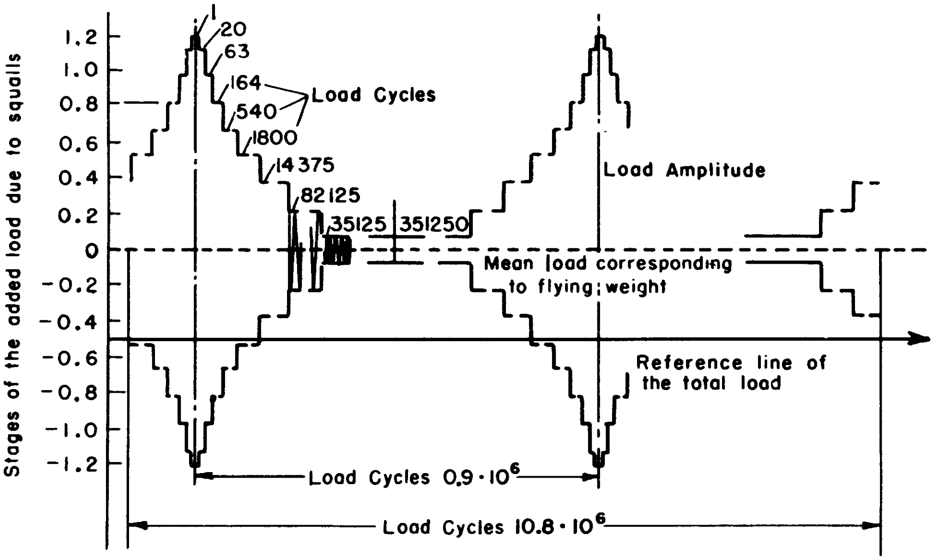

Figure 15 - Curve of a Strength Test Made in the Same Sequence as a Flight Record

vails during undisturbed cruising on a straight course, i.e., the mean load or stress, is 1:3.4. This is the reason the test series simultaneously shows the mean stress, or differently stated, the stress during undisturbed flight on a straight course, as a function of the number of flying hours or the desired life span of the airplane. Studies in the nature of operating statistics have additionally shown that the load capacity of a test specimen does not have to be exhausted at all, when the summation curve K_2 exceeds French's damage line by 10 kg/mm^2 (14,225 pounds per square inch) as it does here in the stage of maximum stress values, as shown in Figure 13.

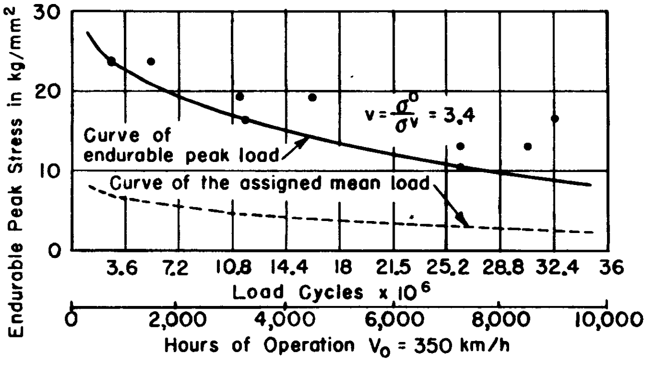

Figure 16 - Curve for Duralumin Tubes Showing Scale Effect (E. Gassner)

Test specimen: Duralumin tube (about Flieg 3115.5) with 3 transverse bores of 5 mm (0.19 inch) diameter each in the most highly loaded fiber. Permissible minimum values of the material: σ_B = 40 kg/mm^2 (56,890 lb/in^2), $\sigma_{0.2}$ = 28 kg/mm^2 (39,825 lb/in^2). Values obtained from 18 test bars: σ_B = 40 kg/mm^2 (56,890 lb/in^2), $\sigma_{0.2}$ = 28 kg/mm^2 (39,825 lb/in^2). Type of load: Bending alternations.

Various additional parameters, such as load sequences, variable mean load, interruption of operation and others arising from operating conditions can be included in this type of study. However, a discussion of these topics would lead too far afield.

Sometimes, due to a few local conditions, a structural member must be more carefully designed than generally prevailing stresses require. These local conditions include individual stress peaks at notches and fixed joints or supports, i.e., clamped joints, etc. In the latter case, there is added to these the effect of sliding

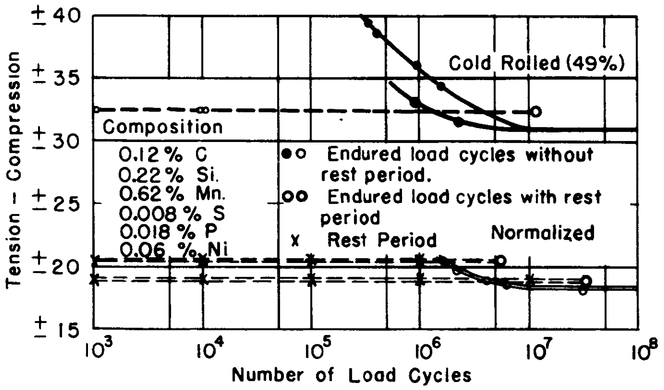

Figure 17 - Effect of a Cold Working and of Interrupted Operation on the S-N Strength of Steel (H.J. Gough and W.A. Wood)

friction resulting from varying alternating strains in the clamped or fixed joints. A few tests made by the "Institut für Werkstofforschung" (Institute for Material Testing) concerning these subjects are briefly reported in what follows.

A careful study of the effect of surface pressure on transversely bored shafts under alternating torsional loads was made by O. Föppl and A. Thum (15). Their tests were intended to help determine to what extent surface pressure at notches (in this case at the transverse bore) contributes in improving durability by cold working or the related natural stress condition (16). The test bars were made from two malleable allows of light metal which were chosen because the changes in fatigue strength due to cold working were known by tests (17).

The fatigue strength of steels can be increased greatly by cold working. Figure 17 shows the result of tests made on a low-alloy steel by H.J. Gough and W.A. Wood (18). By 49 per cent cold rolling, the endurance limit was increased 70 per cent. Therefore, it is difficult to decide here to what extent cold working due to pressure improves fatigue strength.

For aluminum-copper-magnesium alloys and malleable alloys of aluminum-magnesium, in contrast, the endurance limit of smooth bars is raised only 10 per cent, or else not raised at all by 60 per cent cold rolling, while that of notched bars is even lowered, Figure 18. In conformity with knowledge obtained from tests on transversely bored steel shafts, the shafts were pressed at the transverse bore with a pyramidal stamp having rounded corners. Figure

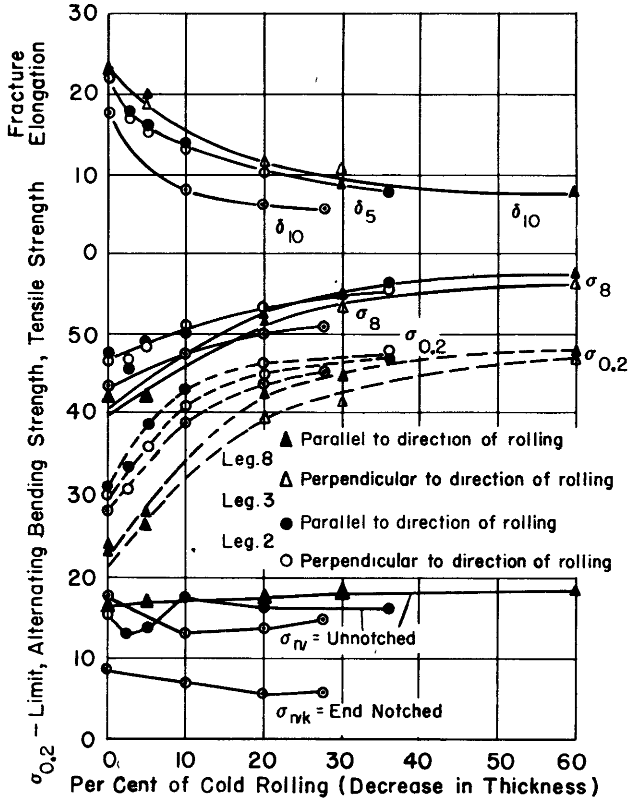

Figure 18 - The Strength Properties as a Function of the Degree of Cold Working for Several Aluminum Alloys

19 shows some results of the alternating torsional tests. The improvement of the S-N strength as a percentual increase of the torsional time strength as a function of the number of load cycles is plotted. The improvement of Material A (type Al-Cu-Mg) is greater than that of Material B (type Al-Mg); however, it is quite considerable in each case. As the number of load cycles increases up to the point of failure, the improvement decreases and has almost entirely disappeared after 20,000,000 load cycles for Material B.

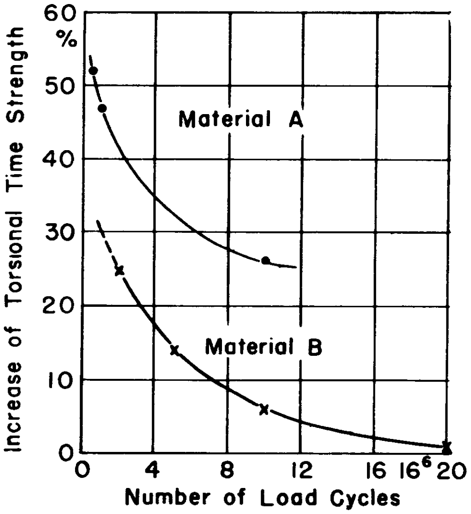

Figure 19 - Effect of Pressure on the Edge of the Bore on the Torsional Time Strength of Transversely Bored Shafts Made of Two Aluminum Alloys

F. Gisen and R. Glocker (19) performed radiographic stress measurements on a steel shaft with a transverse bore. Moreover, this bore was loaded by pressure around the edge. Test results showed that the natural stresses produced by pressure on the edge of the bore change as the number of torsional cycles increases. Similar radiographic tests to measure the inner stress change of test bars made of various types of steel were performed by F. Wever and G. Martin (20). These studies indicate that the improved S-N strength due to pressure is more to be attributed to the natural stress condition developed, than to strain hardening and the elimination of surface flaws. The latter is no essential trait of surface pressure, according to tests by G. Sachs (21) on the fatigue strength in the fixed joints of propellers made from a magnesium alloy. He determined, namely, that the fatigue strength in clamped or fixed joints was very much improved by compression, although the fretting corrosion in the clamped joint did not appreciably decrease.

The effect of various factors, such as the type of material, the surface finish, sliding friction, erosion, fretting corrosion (frictional oxidation), etc., which concurrently affect a clamped joint, has been the object of numerous studies (22). The phenomena which occur in fixed joints under fatigue loading have thus been basically explained. However, it is still necessary to explain the quantitative effect of the individual parameters.

A recently completed report of the "Institut für Werkstofforschung" (Institute for Research on Materials) contributes to this problem (23). A few results of this study will be briefly described. The part played by stress peaks produced by clamping and alternating sliding friction in lowering the fatigue strength are of special interest in this field. Tests on flat bars composed of an aluminum-copper-magnesium alloy and having turned flanges were made by W. Müller (24). The mean pressure was 0.53 kg/mm^2 (750 pounds per square inch). The S-N curves for these bars, which are shown in Figure 20, give the impression that there is no fatigue

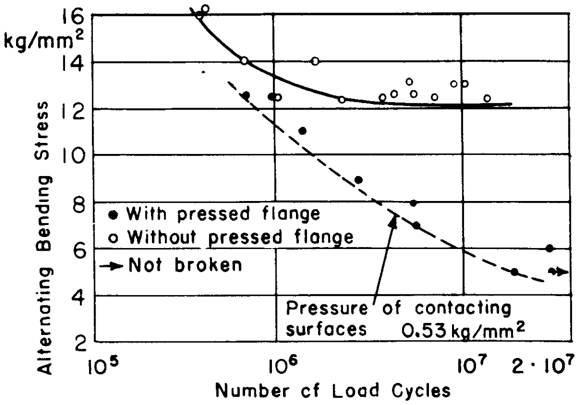

Figure 20 - Effect of Clamping on the S-N Strength of an Aluminum Alloy (Type Al-Cu-Mg) under Alternating Bending Load (W. Müller)

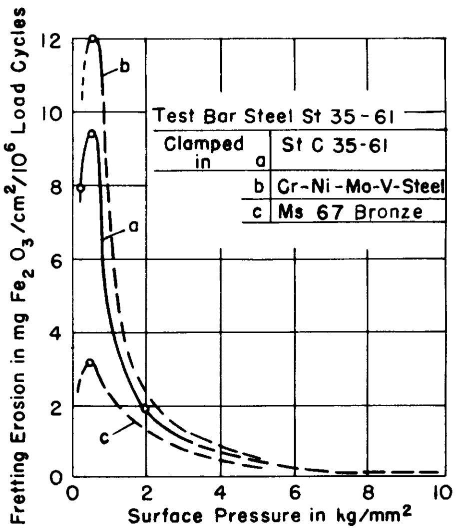

Figure 21 - Fretting Corrosion as a Function of Surface Pressure and Pairing of Materials for Steel C 35 – 61

strength for flat, clamped bars. At high numbers of load cycles, the S-N curve still shows no tendency to approach a limit value. Moreover, it shows great similarity to S-N curves which are derived under condition of erosion. Therefore, it borders on ascribing an important part of the decrease of the S-N strength to the constant fretting corrosion, whose extent depends on the number of load cycles.

Results of special tests on flat bars composed of a normally annealed, unalloyed steel (Steel C 35 – 61)* under an increasing tensile load are shown in Figure 21. The curves show the fretting corrosion (frictional oxidation) as a function of the surface pressure at 10^6 load cycles. Steel C 35 – 61 was tested with itself in clamped condition (Curve a), with a hardened and subsequently drawn chrome-molybdenum steel having a Brinnell rating of 400 kg/mm² (570,000 pounds per square inch), (Curve b), and with bronze 67,** (Curve c). At first the fretting corrosion increases very strongly with the surface pressure in clamped condition, reaching a maximum value at about 0.5 kg/mm² (710 pounds per square inch). As the surface pressure increases, the fretting corrosion again decreases strongly and becomes negligible at 5 kg/mm² (7000 pounds per square inch). The fretting corrosion is greatest when clamped with the hardened chrome-molybdenum steel, somewhat less when clamped with Steel C 35 – 61

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* Translator's Note: Steel C 35 — 61 - DIN (Deutsche Ingenieur-Normung - German Engineering Standards) 1661, Group 6. This group includes ingot steels, medium and high carbon steel, forged or rolled, unalloyed steels for charging or hardening with subsequent drawing. This steel contains 35 per cent carbon. Hütte I, 26th edition, Berlin, 1931, p. 964.

** Translator's Note: Ms 67 - a bronze composed of 67 per cent copper and 33 per cent zinc, having a specific gravity of 8.6 per kg/dm³. Its special properties are that it is suitable for deep drawing and that it can be cold worked. It is used for bars, tubes, sheets, wire, wood screws, springs, and cartridge cases. Hütte I, 26th edition, Berlin, 1931, p. 811.

(itself), and when clamped with Ms 67 (bronze) it is only 25 per cent of that for chrome-molybdenum steel. Figure 22 shows the clamped-original-tensile strength as a function of the surface pressure in clamped condition. According to this, the fatigue strength linearly decreases generally with the surface pressure. This can be seen to be a result of the rising local stress in the clamped condition, which increases with surface pressure. The decrease is sharper only at low pressures in the clamping or fixed joint.

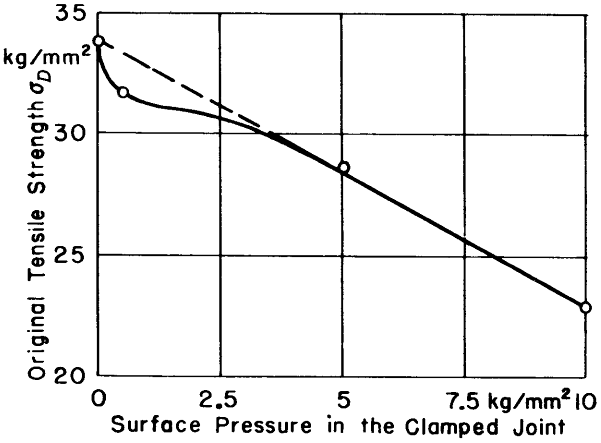

Figure 22 - Original Tensile Strength as a Function of the Surface Pressure in Clamping for Steel C 35 — 61

According to the relationships between fretting corrosion and contact pressures in the clamped joint, which have just been shown, the difference between the linear and actual decrease in original tensile strength is to be attributed to fretting corrosion. Since the fretting corrosion, as well as the notch effect and diminution of the cross section which it produces are a function of the number of load cycles, it seems advantageous to use clamping pressures no smaller than 4 kg/mm² (5700 pounds per square inch) for Steel C 35 — 61, if the structural member is to be designed for fatigue strength. In designing for time strength, it would be conceivable that lower surface pressures are advantageous, in spite of the strikingly higher fretting corrosion then produced. Tests of this kind on other materials have not yet been completed.

SUMMARY

The curve of actual operating conditions is compared to that derived by usual test methods employed to determine the strength of materials under alternating loads. First, a differentiation must be made between two different types of alternating loads to which structural members may be subjected. One of these is an alternating load which is predominantly regular within a few graded limits or groups of limits and a very high number of cycles; the other differs in that the load changes occur between irregular changing limits with greatly varying, but restricted frequency, although a frequency which corresponds to prescribed life span. The foregoing gives rise to two problems encountered in judging materials. In the first mentioned case the problem is: What is the endurance of the material between multiple-stage limits of stress amplitude, and what effect does any particular order of limit groups of varying frequency produce? The contrasting question in the second case is: Assuming a statistical interpretation of operating loads, how can the endurable stress standard at a prescribed and predetermined frequency standard be determined without unfavorably affecting the safety factor? In the discussion of these problems, the effect of interrupted operation on the S-N strength and how test methods can be made to more closely approximate actual operating conditions are treated. How materials may be tested by statistical methods is shown by several examples from the field of aircraft construction. If strength testing of materials follows the methods herein outlined, a broader basis on which to compare test results with actual operating loads with reliable estimates of safety may be expected. This will make efficient and economical use of materials possible. In conclusion the results of some tests are reported which dealt with the problem of fatigue strength in fixed or clamped joints and the effect of surface pressure on the time and fatigue strengths of the materials.

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