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SAFETY AND DESIGN IN AIRPLANE CONSTRUCTION

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SUMMARY

The author gives a survey of the principles of stress analysis and design of airplane structures, and discusses the fundamental strength specifications and their effect on the stress analysis as compared with the safety factors used in other branches of engineering.

PART I. FACTORS OF SAFETY

The problem of appropriate safety factors in general machine design in the light of modern progress in material research (references 1, 2, 18, and 21) has been treated in various publications during the last few years (references 3, 4, and 5), so that the following discussions of the principal requirements for airplane design should form a suitable counterpart on this interesting subject.

The demand for minimum weight makes the utmost use of the strength characteristics of each structural component imperative. This also explains the strict specifications in force in airplane design. During the war these specifications were issued by the General Staff; after the war the control was placed in the hands of the DVL (Deutschen Versuchsanstalt für Luftfahrt). A new, revised edition is at present being formulated by the DLA (Deutschen Luftfahrzeug-Ausschuss (references 15 and 16).

The design of an airplane is contingent upon well-defined flight conditions:

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*"Sicherheit und Gestaltung im Flugzeugbau." ATZ (Automobiltechnische Zeitschrift), January 25, 1934, pp. 28-31.

pull-up, glide, dive, inverted dive, sudden pull-out from inverted flight, gust stresses, landing, elevator operation, etc. The air or shock loads and the resultant of full load and inertia forces acting during these attitudes in different direction and different distribution over the airplane, are generally expressed in multiples of the flight weight - the so-called "load factor n."

These load factors vary with the prevailing speed and acceleration attitude. They scatter about certain mean values, depending upon the type of airplane in the individual flight and landing cases. Discrepancies from these mean values occur less as the magnitude of the discrepancy increases, so that as a rule the physically possible limit values are not attained (except in a dive). Load factors which exceed stipulated boundaries are accordingly considered as unfortunate exceptions.

Stated values of the load factor - themselves already so high as to render their occurrence feasible only a few times during the prescribed total life of an airplane - are denoted as "safe load factors." They are graded according to airplane types (speed, weight, purpose, and stress category), and according to the individual flight and landing attitudes. The counterparts of these rare - and then of short effective period only - safe loading conditions are the continuously active operating loads during flight, which change with the momentary gross weight of the airplane.

The certain occurrence of the safe loads being anticipated at some time or another during the life of an airplane, every airplane must be so designed as to prevent any major permanent deformation. Even if plastic deformations do not necessarily presage any imminent danger (references 6, 7, and 8) in many cases, they nevertheless may induce changes in the static characteristics of an airplane which are vitiating in view of the thin walls and the alternating stress of the individual structural components. They may even cause untoward aerodynamic changes in the outer shape of the airplane.

In consequence, it would be logical to demand that the elastic limit of metal or some equivalent allowable stress be not exceeded under safe loads. But, as such material stress limits are difficult to define and in most cases also vary considerably, this requirement is modified into a specification which is referred to the readily determinable 0.2 limit. According to it, metal parts must not reach this limit at less than 1.35 times the safe load:

$$\sigma\,(1.35\text{ safe}) \leqq \sigma_{0.2} \qquad \text{(a)*}$$

The factor 1.35 allows for the fact that permanent deformations can occur even below the 0.2 limit as well as that an exact determination of the stresses in a structural component is impossible. If the stresses are assumed to increase proportional to the load factor and the stress of the material at the 0.2 limit equals 2/3 times the ultimate stress, the latter is not reached at 2 times the safe load, according to specification (a).

However, this specification (a) is not valid for points of locally restricted stress increases, at which the maximum stress values drop to lower stressed adjacent points as, for example, on rivet holes; neither does it apply to wood structures.

Outwardly, specification (a) is similar to the German State Railway specification (references 9, 10, and 11) for iron railroad bridges, according to which the loads shall not exceed 1/1.71 times the yield-point stress. But this rule is primarily intended to insure that the original strength** is not exceeded. The design loads of bridges may occur each time the bridge is loaded, and therefore <u>frequently</u>, in view of the assumed long life of the bridge, and most members are loaded only in one direction and then largely unloaded. Logically, the allowable stresses are lower for members which may receive either tension or compression.

In rare cases it may, of course, happen that the safe load is exceeded. Besides, it should be borne in mind that the material may be defective, the dimensions inexact; that some parts may be weakened by corrosion, and that the static and aerodynamic analysis is always afflicted with inaccuracies.

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*In the strength specifications for airplanes (reference 15) the safety requirements are categorized differently.

**"Original strength" is the stress which can be carried for infinitely many cycles of repetition when the stress varies constantly from zero (the origin) to a maximum and back to zero, but does not reverse its sign.

In order to prevent the material from reaching its ultimate strength under such circumstances, each individual component must be so designed as to insure that the highest stresses under safe load do not exceed 50 percent of the ultimate stress of the material:

$$\sigma\,(\text{safe}) \leqq \frac{1}{2}\,\sigma_B \qquad \text{(b)}$$

This is primarily directed against the appearance of abnormally high loads, for static tests as well as accident investigations have revealed that only subordinate importance attaches to the inaccuracies attributable to manufacture, servicing, and stress analysis.

On the premise of stress increase in proportion to the load factor, this specification stipulates a twofold security against stress failure; and if, in addition, $\sigma_{0.2} \leqq \frac{2}{3}\,\sigma_B$, the specifications (a) and (b) are practically identical. On the other hand, since according to the location of the 0.2 limit in comparison to the ultimate stress, either (a) or (b) is decisive for the design, materials having a high 0.2 limit do not utilize the height of this limit. Specification (b) may therefore be considered as directive for the desired elastic properties of the material, and for that reason could equally well (just as in bridge design) be replaced by stated regulations governing the elastic and plastic properties of the approved structural materials (reference 10); but such a limitation in material selection was not advisable because the material with comparatively high yield and 0.2 limit is exactly the one that would be favorable for short columns.

For wooden structures, specification (b) need only be considered because wood has no fixed limits at which permanent deformations occur.

Up to now we considered only the rarely effective "safe" loads. But there may also be lower loading conditions which decisively affect the design, i.e., when such loads occur "frequently" and thus become a potential source of fatigue failure.

To illustrate: There are the recurrent alternate stresses due to engine and propeller vibrations, or even due to periodic breakdown of flow. Then, in freight and passenger airplanes, the regularly occurring air and shock loads in normal operation are substantially closer to the "safe" loads than in an acrobatic airplane, for instance, designed for high-peak performance.

To assure a sufficient distance between the occurring stresses and the critical limits in cases where a frequently occurring alternate stress superposes itself on a constant fundamental stress, it must be proved that a 35 percent higher basic load and superposed reversal load does not exceed those limit stresses which would cause fatigue fracture:

$$\sigma\ (1.35 \text{ frequently occurring}) \leqq \sigma_D \qquad (c)$$

This specification is chiefly for the test or inspection section, to be used in cases where an airplane in operation habitually reveals alternating stresses due to oscillations. Its application to the design of the individual parts is generally confined to attachment fittings, sectional changes, etc., which may promote fatigue failure. However, for materials with high ultimate limit and yield point and comparatively low fatigue strength, this specification (c) may become of fundamental importance for the whole design.

In contrast to (c), Professor Rötscher (reference 4) recommends for general engineering design, safety factors graded between 1.4 and 2.4, depending on the ratio of static fundamental to superposed reversal stress. This corresponds to the greater danger in pure reversal stress. The 1.35 airplane factor of safety, low in comparison to it, is based upon the fact that the regularly recurring stresses are decisive for the endurance strength, whereas the rarely occurring, more or less accidental maximum load figures are covered by (a) and (b). Added to that, the oscillations are generally noticed during the test, so that their timely removal may be effected.

The design of a member against stability failure, such as buckling, wrinkling, crushing, is again governed by the "safe" loading conditions. The stability of a structural member depends on integral terms extending across its entire length, as a result of which local defects in material or design are less important in stability failure than in stress failure. Besides, the stresses of a member designed for stability failure are generally far below the individual danger limits of the material stress. For that reason, structural members may reach their stability limits at 1.8 times the safe load:

$$\sigma\ (1.8\ \text{safe}) \leqq \sigma_K \qquad (d)$$

whereas a safety factor of the order of 2.0 would correspond to specification (b). This lower safety against stability failure also corresponds to the well-known fact from the exact buckling theory, according to which the resistance of a bar, after beginning to buckle, slightly increases against any further buckling. Besides, it may be argued that buckling requires a certain time interval, whereas the peak loads are of short periods. From the economical point of view, the lower safety factor against stability failure is propitious because the design of the greater majority of parts of an airplane is governed by their stability.

Specification (c) is inapplicable to thin walls stressed in shear, which already buckle elastically under very low loading in one principal stress direction without affecting their power to take up tensile stresses in the other principal stress direction (reference 24).

In contrast to (d), bridge design rules (references 9, 10, and 11) specify safety factors for buckling struts graded according to the fineness ratio; that is, factor 1.71 for fineness ratio $\lambda = 0$, but factor 3.5 for the highest fineness ratio in bridge design, $\lambda = 150$. The former (1.71) equals the previously cited ratio of yield-point stress to allowable stress. This grading is based on the fact that the inevitable bar curvature and eccentricity of the applied loads increases with the fineness ratio (reference 14a). The same applies to buildings (reference 12).

But in airplane design, such preference is not shown to short columns because it is precisely in such members that the effect of eccentricity, etc. - especially in view of the thin-walled parts - is more unfavorable than for thin bars (references 10 and 13). Professor Gehler (reference 13) also objects to this grading even in bridge design, and recommends a standard buckling safety of 2.5, that is, about the same safety factor as that of the ultimate tensile strength of structural steel, i.e., $1.5 \times 1.71 = 2.56$ when assuming it at about 1.5 times the yield-point stress. The equivalent factor in airplane design would be 2.0 instead of 1.8.

In airplane design the members stressed in combined bending and compression, such as strutted spars, or eccentrically attached truss members, assume a particular significance (fig. 1). The deflections y postulate the occurrence of additional bending moments $S\ y$ due to longitudinal force S; consequently, the stresses of such members do not increase in proportion to the load factor. When computed on the basis of Navier's bending theory as customary with the simplified differential equation of the elastic line, they approach with hinged end support, for instance, infinity, when S reaches the Eulerian load $S_E = \frac{EJ\pi^2}{l^2}$ (references 14 and 17). Of course, failure occurs before that.

When such a member stressed in buckling is so designed as to exactly meet conditions (a) and (b), it manifests, as seen on the dashed line of figure 1, a lower ultimate tensile strength than a tension member designed according to those specifications.

This is the reason why the new strength specifications for airplane designs stipulate, aside from (a) and (b), a determination of the required safety against exceeding the ultimate stresses of the structural material. According to it the ultimate stress in the tension fibers of a structural component shall not be reached at less than 2.0 times the "safe" load, whereas in compressive fibers, it may be reached at 1.8 times the safe load:

$$\sigma_+ \text{ (2.0 safe)} \leqq \sigma_{+B} \qquad (e')$$

$$\sigma_- \text{ (1.8 safe)} \leqq \sigma_{-B} \qquad (e'')$$

The requirement (e') corresponds to that stated relative to (b), while (e") is generally restricted to wood designs, for in metal design the stability limit governs the compressive fibers, hence is controlled by (d). The safety factor 1.8 in (e") is justified because local defects in the structural material have less significance in compression than in tension; furthermore, the rapid stress rise due to $S\ y$ follows the same arguments as those advanced relative to (d).

A member stressed in combined bending and tension manifests the line showing the stress rise versus load factor with a downward curvature (fig. 1) on account of the then produced unloading moments $S\ y$. Then, as with vanishing or low tension the rules (e') and (e") are no longer applicable.

There is no direct relationship between stress and load factor in buckling, consequently specifications (a), (c), (d), and (e) are referred to multiples of the safe load and not perhaps as (b), to certain "allowable" stresses under safe load. This is the reason why they necessitate the information regarding the stress of a component after exceeding the elastic or proportionality limit. From the point of view of unequivocal strength proof, this is disadvantageous because the usual methods for computing statically indeterminate or solid wall systems are based on Hooke's law. Here the point is often made that it suffices to give by the conventional method, "mathematical" values for stresses at 1.35, 1.8, and 2.0 times the safe load; even a seemingly more exact method of calculation could only be interpreted as estimation, since no great plastic deformations occur during the short-period action of the peak loads. Moreover, the inaccuracy of the conventional method of calculation had already been allowed for in the safety factors. Further, it is pointed out that, ordinarily the "actual" ultimate load of statically indeterminate and solid wall systems is higher than that obtained by the conventional mathematical methods; for, if with increasing load the proportionality limit, or yield point, or crushing limit is reached at any point, the stress at that point thereafter increases very little or not at all. In that case the adjacent fibers or members not stressed as highly are used to take up the stress to a greater degree (references 6, 7, and 8).

With a view to plastic deformation, the members stressed in buckling, however, do not fare as well. In these the deflections increase more strongly after locally exceeding the proportionality limit, and with it the additive moments $S\ y$, than corresponds to the analysis with constant elasticity modulus. As a result, the ultimate load is reached much sooner (fig. 1).*

The unrestricted application of the method based on Hooke's law is therefore unacceptable, especially since in the limiting case of pure buckling, it would logically lead to computing the short buckling struts also according to the Eulerian formula with constant elasticity modulus.

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*In designing members stressed in buckling (more exact, compressive bending), it is advisable to consider the carrying capacity as being exhausted when the highest stressed fiber reaches the 0.2 limit.

The most acceptable method of obtaining reliable data on the actually existent strength is, of course, the destruction test. But it entails considerable expense, so that the research of strength characteristics in the plastic deformation range should proffer a profitable field for modern airplane research.

The destruction tests on airplanes and airplane parts designed according to the customary stress analyses have, on the whole, shown a surprisingly close agreement between "mathematical" and "actual" ultimate load.

The above discussion is confined to the fundamental principles in airplane design from the point of view of safety factors, hence makes no mention of the various special regulations, such as of lower safety factors on parts of the landing gear where so-called theoretical points of failure are stipulated to protect the rest of the airplane, of specifications regarding the highest permissible permanent deformation due to safe load, and of the permissible minimum stiffness characteristics.

The future draft of the safety regulations will be largely contingent upon the results of extensive measurements of airplane stresses. They should make it possible to allow for "expectancy" much more than heretofore, with which the individual loading conditions and load factors occur during the prescribed life of an airplane (reference 16).

Translation by J. Vanier,
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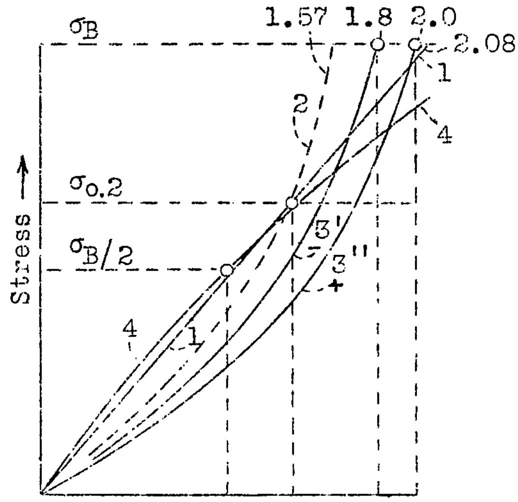

1. Bar stressed in bending, dimensions according to(a)
2. Thin bar stressed in buckling, erroneous dimensions according to (a)

3' and 3". Compression and tension flange of a thin bar stressed in buckling, dimensions according to (c)

4. Thin bar stressed in tension and bending, dimensions according to (b)

Figure 1.- Stress of varyingly loaded bars, computed on the premise of unlimited validity of Navier's bending theory and the simplified differential equations for the elastic line.