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No. 538

CANTILEVER WINGS FOR MODERN AIRCRAFT

Some Aspects of Cantilever Wing Construction with Special Reference to Weight and Torsional Stiffness

By H. J. Stieger

From Aircraft Engineering, August, 1929

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The relative merits of the monoplane and the biplane have often been argued, and the respective advantages which, up to the present, have been claimed on either side still leave the solution of the question in doubt. Until now the bias in this country has been toward the biplane but, as the knowledge with regard to methods of obtaining torsionally stiff structures grows, the pendulum is bound to swing the other way.

The success of an airplane naturally depends on the skillful combination of the elements of one or the other methods of construction incorporated with the design specification, and much depends on the size and purpose of the airplane. The problem really reduces, in so far as wing structure is concerned, to the use of:

(1) An externally braced "thin" wing section, thickness ratio 6.5 per cent to 12 per cent.

(2) A cantilever "thick" wing section, thickness ratio 12 per cent to 18 per cent.

*From Aircraft Engineering, August, 1929.

In a fast Scout type or a racing airplane, where minimum drag is of the utmost importance, the advantage is usually with the externally braced "thin" wing, either monoplane or biplane. But if we consider a type of airplane of the long range, night bomber, or commercial class - that is, a type in which the total lift/drag ratio, aspect ratio, etc., are paramount - the second system of construction is the one which scores.

It must be realized that, with normal present-day airplanes, about two-thirds of the available b.hp is expended in overcoming turbulent air flow which has often been unnecessarily created. Assuming an efficiency of 25 per cent for a gasoline engine, the energy transformed into useful work is about 8 per cent of that initially available from the fuel used. Obviously there is still much to be done by both engine and aircraft designers.

These may be briefly summed up as follows:

(1) Distortion of the wing under air load causing reduction, or even reversal, of aileron control, weakness in torsion, and the probability of wing flutter.

(2) Increased profile drag.

(3) Weight.

Dealing with these items separately:

Distortion and Flutter.- A moderate deflection at the wing tip, the outcome of pure bending due to air load, is quite permissible and does not affect the aerodynamic properties of the wing, but it is absolutely imperative that torsional stiffness is maintained. Several failures have recently occurred in this country as the result of making the wing structure too flexible. This may have been due to inexperience in the particular type of design and lack of design data. As the result of subsequent investigations,* the exact nature of the phenomenon of wing flutter has been well defined. Providing that certain fundamental rules are observed, there should be now no difficulty in constructing a cantilever wing in which the likelihood of flutter is very remote.

Profile Drag.- It has often been claimed that the increased profile drag of a "thick" wing is balanced by the parasite drag due to the struts, wire, etc., in an externally braced wing system.

For the purpose of comparison, assume a biplane structure using an 8 per cent section, and a tapered cantilever "thick" wing having an 18 per cent section at the root, and a 12 per cent section at the tip (i.e., a 15 per cent average section), both having the same stalling speed. It follows that the wing area in each case is proportional to the maximum lift coefficient. The profile drag depends on the actual shape of the section, being smaller for a "thin" wing. The following figures may be taken as representing average values:

*See British A.R.C. Reports and Memoranda No. 1177: "A Brief Survey of Wing Flutter with an Abstract of Design Recommendations," by R. A. Frazer and W. J. Duncan. (1928)

	Biplane per cent	Monoplane per cent
Thickness ratio	8.0	15.0
Profile drag (at maximum speed)	0.004	0.006
Parasite drag due to struts and wires	0.002	--
Interference due to struts and wires	0.001	--
Maximum lift coefficient	0.55	0.68
Profile drag coefficient reduced to wing area basis	0.004	0.00485
Comparative values for total drag of wing structure	0.007	0.00485

Note.- The induced drag is almost zero at low values of lift coefficient, corresponding to the maximum speed flight condition.

It is obvious from these figures that the increased profile drag in the case of the monoplane is reduced to very near equality with that of the biplane when wing area is considered, and that, when the parasite drag of the biplane structure is taken into account as well, there is a very real advantage to the monoplane.

Assuming the total drag coefficient for a normal biplane to be 0.018, the drag due to struts and wires, with the accompanying interference effect, is 0.003, or 16.7 per cent of the total drag. If the biplane has wing tanks this percentage for parasite drag is greater. In a thick wing such tanks can be fitted internally.

Weight.- Up to the present the weight of the cantilever wing construction has been the main drawback and, in certain circumstances, it can eliminate the aerodynamic advantages. The weight naturally depends on the air load for the major part, but saving can be effected by skillful arrangement of the structural members. There will always be, however, the inevitable torsion load to be provided against. That, consequent upon travel of center pressure due to aileron movement, must always be present; but for the actual wing the variation of center of pressure with angle of attack, embracing the whole flight range, can be reduced by the evolution of a suitable section. In the ideal case the torsion due to aileron movement should be the governing factor. As regards the actual structure there are several schools of thought.

Utilization of Wing Covering for Strength.- The ideal solution seems to be to stabilize the wing covering so that it can transmit the air loads, and to make full use of it in taking both the bending and torsional stresses. This method has been used by both Rohrbach and Fokker. In actual practice it is very difficult to build such a structure without considerable addition to the weight. Actually it is found that the rigid skin for the most part stabilizes the spars, transmitting the torsional loads to them. As a medium for resisting bending, the wing covering is inefficient.

Multi-Spar System.- This method has been developed to a fine art by Junkers and others. The bending loads, distributed as they are over the whole chord, instead of being entirely taken by two strength members, are resisted by a number of light spars which are completely interbraced and stabilized. The main disadvantage of this type of structure, apart from the extremely light spar section required, is the lack of torsional stiffness. In most cases a rigid wing covering has to be used to supply this deficiency, with the resultant sacrifice in weight.

Two-Spar System.- With the standard method of using two spars to take the bending loads the wing suffers from abnormal torsional deflection. Even the use of box spars and braced bulkheads between them, as well as complete lateral bracing, does not suffice to reduce the torsion within reasonable limits. The wing weight involved is prohibitive, as the system depends for its success on there being sufficient depth to the airfoil section to enable bracing of economic size to be used.

Principle of the Mono-Spar System

The fundamental principles of the system are:

(1) To segregate the main and secondary structures so that each performs its function independently of the other.

(2) To transmit the load by the shortest path, and, in doing so, to make the structure as simple and straightforward as possible, in order that the strength and deflection can be accu-

rately calculated.

(3) To stabilize the main structure as fully as possible, so that a high stress can be developed in the material, with the resultant saving in weight.

The practical result is as follows:

(1) The adoption of a single spar placed at the maximum depth of the wing section - approximately at one-third of the chord - to take all bending loads.

(2) The provision of "pyramids" forming continuous tension spirals round and along the spar. These pyramids, together with drag and antidrag members, transmit all torsion and drag loads back to the spar, and at the same time stabilize it at conveniently short intervals. In virtue of this, it is possible to use an l/k ratio of about 20 on the compression flange of the spar, so that a very high stress can be developed without fear of buckling.

(3) In its simplest form the system is practically non-redundant, so that it can be easily rigged and corrected for incidence along the spar. In the event of a torsion wire being cut, there is admittedly more, but not at all undue, twist. The torque so liberated is taken by the spar itself, drag members, and also by the secondary structure over a length corresponding to the extent of half the pyramid, when it is absorbed by the next pyramid. This case has been satisfactorily investigated in an actual test.

The spiral tension members may be adjustable tie rods or simply channel or tube sections. As their main purpose is to provide torsional stiffness, the advantage of adjustable tie rods lies in the fact that by introducing initial tension the torsional deflection may be halved. There is no need for frequent adjustment of this bracing, as in the external bracing of a biplane, since the tie rods are comparatively short in relation to their sectional area - more like the spokes in a bicycle wheel.

There are obviously various possible combinations of pyramid bracing, and a redundant structure might be used, but on actual test the simplest method of bracing has given the most satisfactory results from strength, stiffness, and cost point of view.

(4) The main structure is very robust and, therefore, not easily damaged, and the pyramid points, together with the spar, form excellent points of attachment for engines, landing gear, struts, etc.

(5) The torsion bracing is not affected by the bending deflection of the spar and is, therefore, efficient under all flight conditions.

(6) Any required torsional stiffness can be achieved at the expense of a small increase in weight (See Fig. 7).

(7) The secondary structure is very light and, if damaged, does not affect the strength of the main structure; it is also easily replaced.

Comparison of Single and Two-Spar Structures

Spar weights have been calculated for the two cases by considering only the bending loads and a movement of center of pressure of ±10 per cent, representing the effect of aileron movement. I am indebted to Mr. Duncanson ("Aircraft Engineer," Flight, March 28, 1929) for the method of rapidly obtaining the ideal spar weight. In practice, of course, it is impossible to live up to this ideal, but the figures are good enough for relative comparison.

Under ideal conditions a single spar weighs only 60 per cent of the two-spar system. Actually there is always extra weight since the spar must be stabilized against buckling, it must have fastenings, and it is not practical to have the ideal sectional area and moment of inertia everywhere along the spar. The amount of extra weight is obviously greater in proportion for two spars than for one. In fact, the actual single spar weight will be less than 60 per cent of that of the actual two-spar system, assuming the extra weight per foot run to be the same for each spar (See Fig. 2).

The torsional deflection of a two-spar wing only designed to take bending loads is prohibitive and it is necessary to use some method for stiffening it. This may be done:

(1) By increasing the spar strength so as to reduce the unequal bending deflection of the spars - this is very heavy and inefficient.

(2) By the use of torsionally stiff box spars interconnected by substantial main ribs or bulkheads - this also suffers from excessive weight and inefficiency with a wing of large aspect ratio.

(3) By using "double" drag bracing - this slackens and becomes less operative under bending loads.

(4) By employing a rigid wing covering either of plywood or metal - this is effective but heavy.

(5) By the adoption of some type of pyramid bracing between the spars, using either tension or compression members.

Analyzing the weight figures for these various methods, it is found that efficient torsion bracing used in conjunction with a single spar is at least as light as, and in most cases lighter than, a system of equal efficiency used with two spars.

Of the secondary structure, only the question of rib design needs comment. The ribs may be built up as cantilevers in front of and behind the spar. However, by utilizing the drag and antidrag members, it is possible to obtain three points of support for each rib (See Fig. 2), namely, at the leading edge, the spar, and at the apex of the rear pyramid (this embraces 60 per cent of the chord). The antidrag bracing at the rear can take the form of a light auxiliary member on which the intermediate ribs can rest. This latter method gives the lighter construction, and the actual weight is no more than that of a two- or even three - spar wing.

Experimental Test Wing

A wing has been specially designed for test purposes in order to check the calculations, and the agreement between predicted and actual deflection and twist was remarkably close.

The wing weight was made up as follows:

	Test section lb./sq.ft.	Complete wing lb./sq.ft.
Spar	0.340	0.450
Torsion and drag bracing	0.199	0.269
Complete primary structure	0.539	0.719
Secondary structure	0.560	0.560
Total weight	1.099	1.279

Figure 4 gives the weight distribution along the span. It should be noted that the secondary structure weight is directly proportional to the wing area and that the weight of the torsion bracing is a linear function of the span. The criterion weight per square foot of wing area was chosen because of the tapered plan form of the wing.

The complete wing was designed for an airplane of the following particulars:

All-up weight - 13,200 lb.

Wing area - 780 sq.ft.

Load factors - C.P.F. : 4.
C.P.B. : 3.25.

Wing loading - 17 lb./sq.ft.

The complete wing would weigh 1000 lb.; that is, 7.6 per cent of the all-up weight. Further saving could be effected by incorporating the compression tubes of the torsion bracing in the bulkhead ribs.

The ideal spar weight of the test section was calculated. The actual spar, by comparison, was very heavy - nearly 200 per cent of the ideal. The inefficient spar taper - an 18 per cent section was used throughout - was partly responsible for this, and it should be possible to produce a spar such that the ideal is of the order of 70 per cent of the actual weight. Incidentally, the spar can be constructed nearer to the ideal weight at the root than at the tip (See Fig. 5).

The test spar, designed for pure bending with the C.P.F. factor in operation, was also strong enough to cover the C.P.B. case and the accompanying torsion.

The following curve shows the torsional deflection of the test section under one of the test conditions (See Fig. 6).

The twist is proportional to the span. This is explained by the fact that it is approximately proportional to the length of the torsion bracing. The magnitude of the twist depends on the thickness of wing section used, and the design stress.

The deflection quoted in Figure 6 was obtained with a certain amount of initial tension in the torsion bracing. By reducing the allowable stress in the wires, that is, by increasing their weight, the torsional deflection can be reduced to any desired degree at the expense of very little extra weight (See Fig. 7).

Wing Tip Construction

The mono-spar torsion bracing system, as with all other types of construction, is inefficient when the airfoil is of "thin" section, as at the wing tip. Here the aileron spar and the aileron itself can be made to contribute appreciably to the torsional stiffness.

Figure 8 shows one method by which this can be done. Note the torsionally stiff triangle formed by the main spar, aileron spar, and bulkhead rib.

Some of the following figures are quoted from W. S. Farren's lecture (R.Ae.S., January 31, 1929) in order to give a comparative idea of the way in which the saving in weight conferred by the mono-spar system can be utilized:

M/C type	Actual wing wt.	Corresponding mono-spar wing wt.	Nominal pay load	Pay load with mono-spar wing	Relative increase in pay load
	per cent	per cent	per cent	per cent	per cent
Fokker F VII 3M	16.1	9.3	22.2	29.0	30.6
Argosy	18.0	10.0	25.0	33.0	32.0

The mono-spar figures were based on the wing area necessary to keep the stalling speed the same as that of each prototype. It should be noted that for the Fokker F VII 3M wing the corresponding mono-spar wing is practically identical with that used in the test hitherto described. In this particular case, therefore, the weight figures are extremely accurate. The test wing, therefore, only needed reduction in the ratio of the wing areas - 780 sq.ft. to 728 sq.ft. - to obtain the above figure. The reduced wing loading per square foot of the Fokker airplane brings the load factor on the corresponding mono-spar wing up to 5.3. When reduced to the same load factor of 4, the wing weight is reduced from 9.3 per cent to about 8 per cent. The corresponding pay load is, therefore, 30.3 per cent, or an increase of 36.5 per cent.

In the foregoing remarks I have made an attempt to touch on some of the structural problems met with in cantilever wings, and dealt rather fully with a certain type of single-spar construction. The experimental test wing was a first attempt to demonstrate the principles of this departure from orthodox methods. The result was a wing both torsionally stiff and of light weight - lighter than a corresponding biplane construction.

Several new airplanes incorperating the system of construction referred to are about to be built, and aeronautical engineers will thus be able to get final confirmation of the claims made.

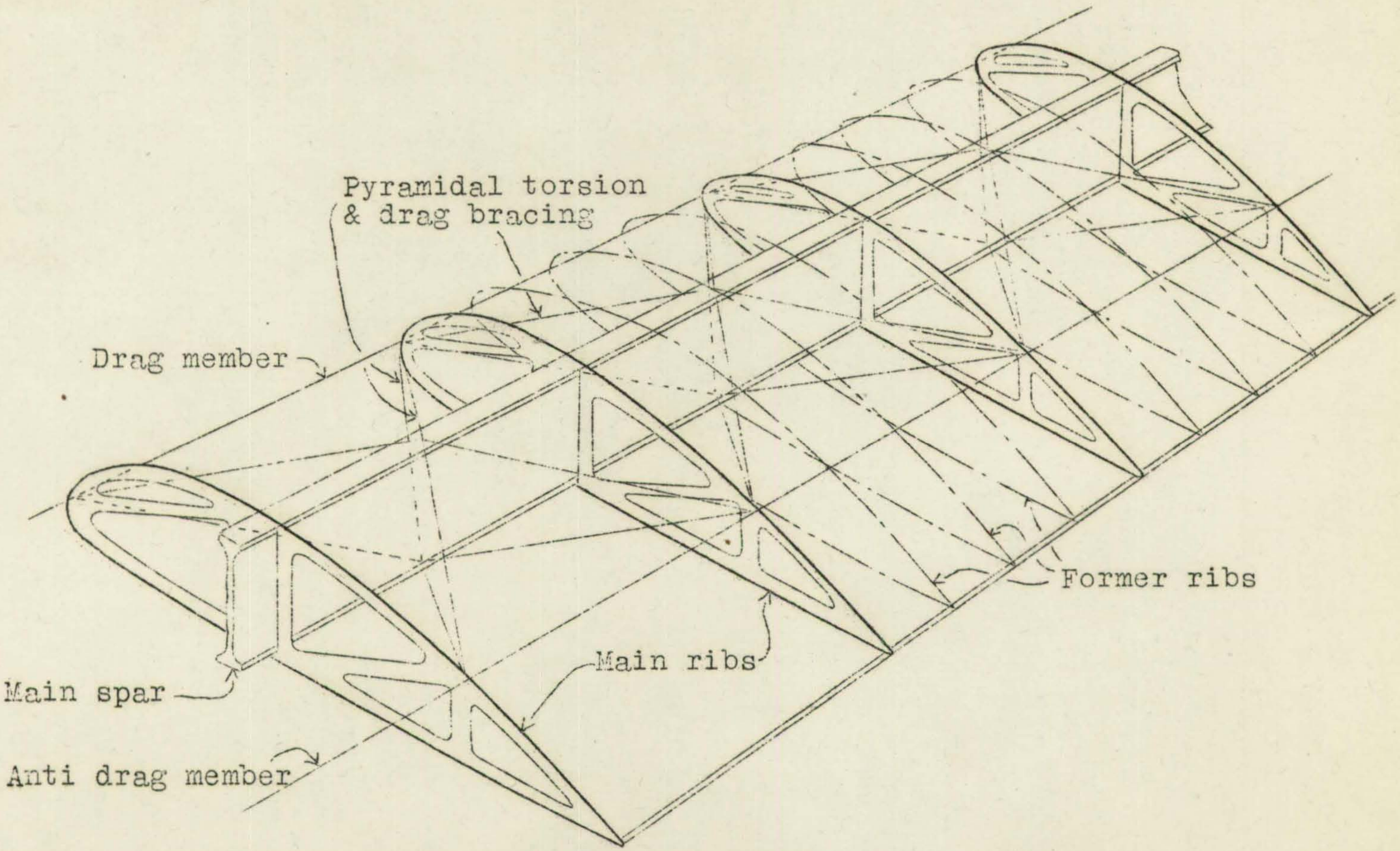
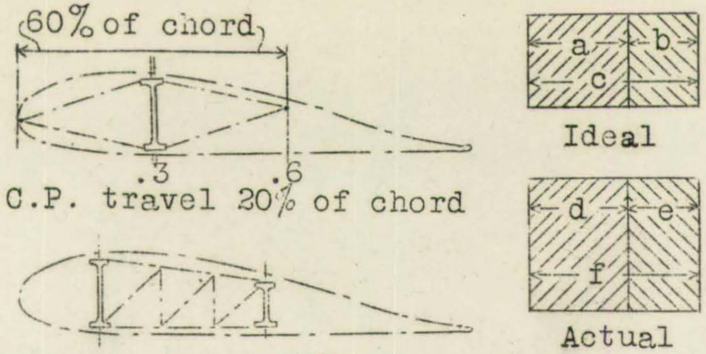


Fig.1 View showing the general arrangement of the Stieger mono-spar system of wing construction.



a, Cross-sectional area of spar in mono-spar wing, 60%
b, Saving in weight, 40%
c, Cross-sectional area of sum of spars in two spar wing, 100%
d, Cross-sectional area of spar in mono-spar wing, 58 1/2%
e, Saving in weight, 41 1/2%
f, Cross-sectional area of sum of spars in two spar wing, 100%

Fig.2 Spar weights compared in mono-spar and two-spar system.

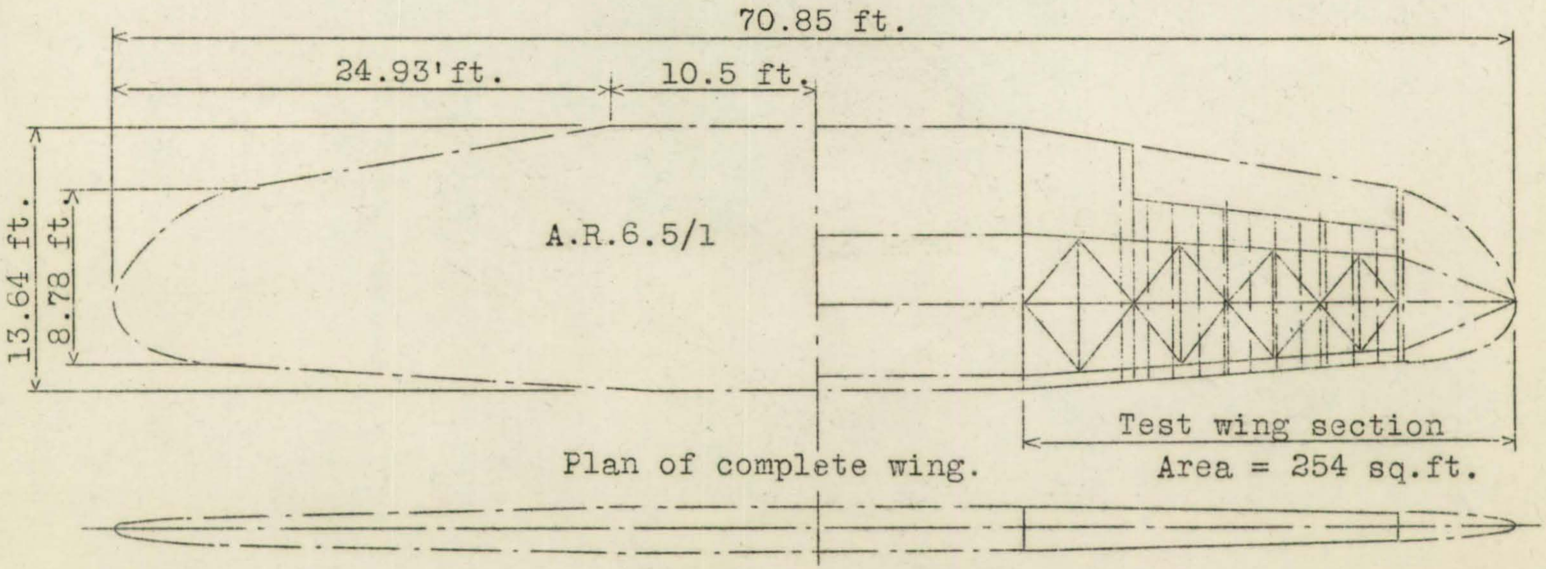
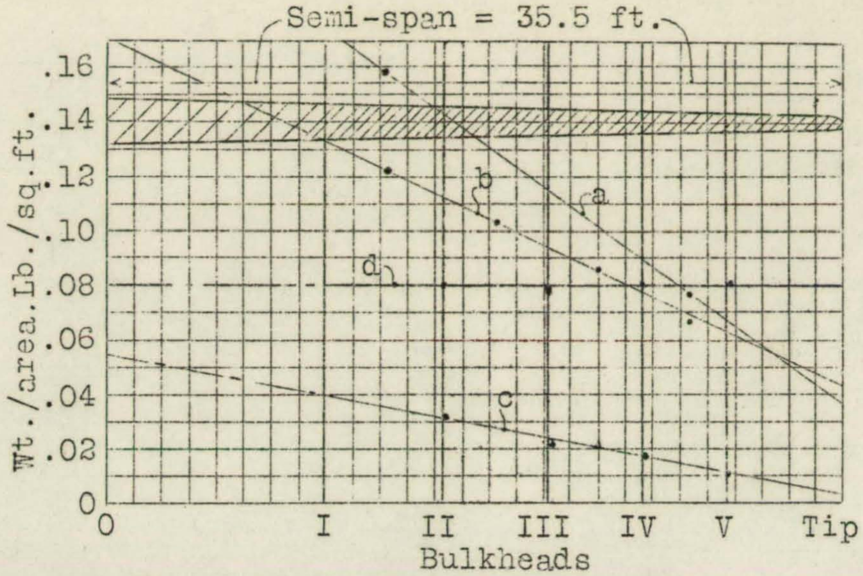
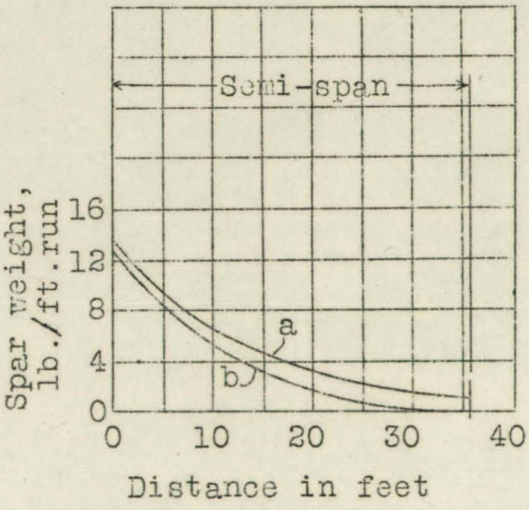


Fig.3 A specially designed test wing showed remarkably accurate results.



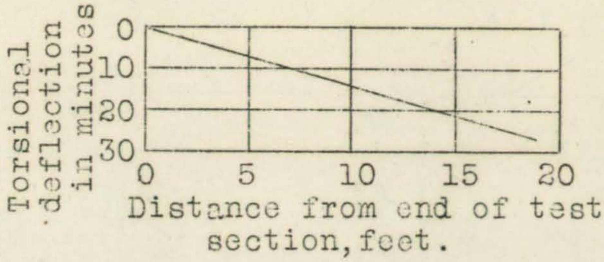
a, Drag and torsion wires
b, Compression tubes and fittings.
c, Wiring fittings.
d, Bulkheads.

Fig.4 Weight distribution of various components along the spar.



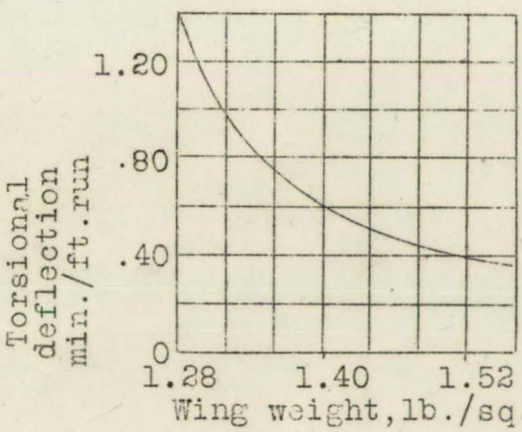
a, Actual
b, Ideal

Fig.5 Comparison between actual and ideal weights of spar.



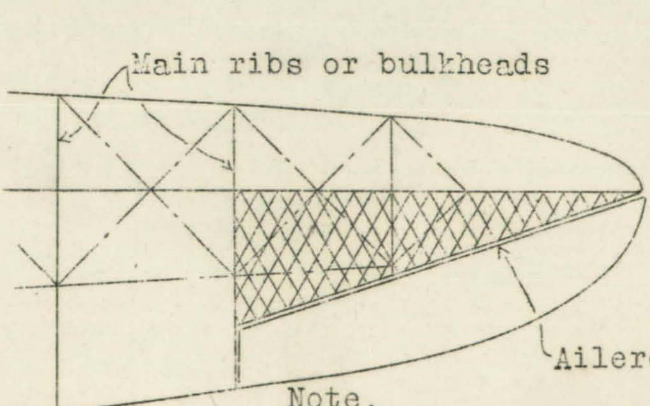
Note.
Structure designed to a factor of 3.25 W. Test section tapered in plan form and a thickness/chord ratio of 0.18 used throughout.

Fig.6 Torsional deflection for 1 W. loading and ± 10% C.P. movement.



Note
Limitation of deflection effected by increasing size of torsion bracing only, bulkhead members remaining constant.

Fig.7 Variation of torsional deflection with wing weight.



Note.
Shaded area shows torsionally stiff triangle due to aileron.

Fig.8