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METAL CONSTRUCTION

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The future development of aerial navigation is closely connected with the condition of obtaining airplanes of great stability and sufficient strength. Formerly, the science and technical knowledge of construction were deficient and the difficult problem of the necessary lightness for being supported by an element so thin as air was solved at the expense of the strength of the entire structure. This beginning, which has led to great and undoubted progress, has resulted in many accidents and thus every advance has been accompanied by a series of mishaps. The evolution of aircraft has been quite rapid, but not so rapid as human evolution. The technician obtained a slight structural improvement, which the pilot recognized, appropriated and utilized to its fullest extent, and then sought something better. At the same time, he became more skillful and bolder, and tested the airplane more severely, so that it often gave out because it lacked just what the hand that guided it required. Thus it became necessary to make aerodynamic modifications and structural reinforcements. Abstaining for the present from taking up the problem of aerodynamic progress, we will consider more closely the problem of structural strength.

The coefficient of safety, that number which represents in

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all structures the ratio between the breaking strength of a part and the load or stress which it must normally withstand, was quite a small number for the first aircraft. The poor constructor struggled with his own ignorance and his lack of adequate means. His airplane had neither suitable finish of form nor materials of suitable strength and lightness nor reliable engines, powerful and light. Hence they were heavy, clumsy, slow, and not very strong. But with such ill-adapted means, laws were determined, flights were made, and the course to be followed was outlined. Progress was made which, by gradually eliminating the defects due to ignorance, has reached its present state. This state is not the final condition, but simply a step to be used as the basis for still greater progress. Today, the former modest coefficient of safety has been considerably raised, and is at least 10 for a swift airplane, and 6 or 7 for some parts of a good airship. These numbers, which have not yet been reached in most other kinds of construction are not, however, the maximum limits for aeronautic construction. Pilots still demand much in the way of technical improvements.

The idea here promulgated seems contrary to the general opinion. How much more solid a house or a locomotive seems than a light airplane! How much more solid an automobile or a ship seems than a fragile airship! Nevertheless, the house, the locomotive, the automobile, and the battleship have no greater coefficient of safety than is required for the modern aircraft.

The need of a very high coefficient of safety resides in the nature of the airplane which, being balanced in the air, is capable of great acceleration from the application of great forces, which necessitate coefficients greater than any hitherto obtained and which, for some aircraft, can technically assume such high values as to render their construction impossible. Able technicians are today trying to solve the intricate problem and some carry their conception to the point of claiming that the coefficient of solidity of some aircraft can be even a little higher than that of its pilot. Experiments have already been suggested for determining the coefficient of human stability, a coefficient which, for our satisfaction, we may consider, from various indications, as being quite high.

The very high value of the coefficient of safety now necessary, demands the most accurate construction, worked out in its minutest details, with materials of the very best quality - a construction which, in order to be light enough, must correspond perfectly to the theoretical conception and, in order that every part will function exactly as designed, every secondary stress must be eliminated, and every harmful strain avoided. In general, for every flexure, there is a corresponding adjustment favorable to the stability, at least when it is a question of a part being loaded to the point where any distortion indicates the beginning of excessive flexure with consequent collapse. But structures consisting of members loaded axially are ordinarily the lightest and are therefore preferred in aeronautics. Therefore every failure must, in general, be confined within the narrow limits indispensable for the strength of the member involved. The distortions correspond to the moduli of the elasticity and hence, are of the greatest importance in selecting the materials to be used in aeronautics It is not necessary to exclude all materials of great elasticity (the wood for propellers may be all the more desirable on that account), but with a low specific gravity, great strength, a high limit of elasticity and a high coefficient of expansion, there is generally combined a high modulus of elasticity.

After having thus characterized the mechanical properties of aerodynamic materials, we can immediately separate them into two categories. One category includes all those employed in parts requiring continuity of material and which may consist either of a simple covering, or also at the same time of a strong member. The other category comprises all materials especially adapted for strong parts. In this second list, on account of the mechanical properties of the materials, there is found natural extrinsicality and perfect correspondence. In the first list, on the contrary, the condition of continuity makes itself imperiously felt and to this requirement there must often be joined that of flexibility. As things are now, we would be unable to imagine an airship not covered with fabric, or its car not covered with fabric or a thin layer of wood, but, if (aside from the specific case of the envelope of an airship to which we will shortly recur) we concede that the element of shape serves a purpose, we can best employ a covering without flexibility and we can imagine a car, a fuselage, or a wing not covered with fabric, but made of strong material or metal sheets.

The case of the airship is somewhat different from the examples just mentioned, on account of the enormous size of the envelope, which, in order to be strong enough, necessitates the concentration of certain stresses in strong members, which could not be distributed along the whole surface, so that although the resistance to the normal stresses would be possible theoretically, there would still be failures due to secondary and local stresses. The non-rigid envelope is flexible by nature and withstands the stresses by reason of the tension of the inclosed gas which renders it sufficiently rigid since any force of compression at any point is always less than the pre-existing tension.

Aside from the canvas used especially for airships, the aeronautic materials which we may term non-flexible* and which are used in constructing the framework of aircraft, are: iron with its binary and ternary alloys, aluminum with its alloys, and wood. To these must be added those which are used for bushings, supports, etc., but these materials, on account of their heavy weight, are used in small quantities and only where they are indispensable.

Wood, aluminum, iron and alloys were not equally employed, during this period, in the various parts of aircraft. The progress in construction made in aeronautics before the war, was due almost wholly to the iron and metal industries. These gave us the indis-

* There are also elastic rubber cords which are used as shock absorbers and recall springs.

pensable powerful and light engines. The first aircraft employed much steel, considerable aluminum and some wood. With the advent of the war, there was a great and increasing consumption of metals in war material, leaving little for aeronautics. This fact, together with the shortage of good mechanics, led to the extensive use of wood and the limitation of metal to those parts where it was found to be indispensable, all the more, because the disadvantages due to the conservation of articles of wood were not felt during the war on account of the necessarily rapid renewal of war material. The problem now has quite a different aspect. The commercial problem has come to the front, and airplanes, besides being safe, must be able to make long trips. Wood presents disadvantages, possessed in only a small degree by metals: distortion, due to its low modulus of elasticity; excessive deterioration, from inclement weather; possibility of breaking easily from splitting; lack of homogeneity in density and strength; and ease of absorbing moisture which diminishes its strength. Hence, as in all other construction, wood has gradually yielded to metal, a like change is taking place in aircraft. It is well to remember that the advantage claimed for wood, of greater strength in proportion to its weight, no longer has any value, since I have already shown in a different article (in "L'Aeronautica," March, 1920), that good steels, duralumin, and alloys are, even in this respect, preferable to the best woods for aircraft. We will now make a little closer study of metal construction.

Fully loaded parts not exposed to the wind.- Steel and, to a smaller degree, aluminum and duralumin tubes are suitable for small loads borne for comparatively short periods. Theoretically this is shown by a formula which includes the thickness, diameter of tube and length loaded or stressed.

1. The minimum thickness is determined by conditions of indeformability from secondary stresses.- Both theoretically and practically it has been demonstrated that this minimum thickness is a function of the radius of curvature, and it appears that the minimum thickness should never be less than 1/20 of the radius of the cross-section of the tube. Under these conditions, we assume that we can adopt, for good carbon steels, or ternary steels of 50 to 60 kg per sq.mm breaking strength, a safety load of about 1/5 of the breaking strength, while for duralumin the safety load must be kept somewhat lower, probably about 1/7. When subjected to severe tests, such tubes have demonstrated the perfect agreement of the practical results with the theoretical deductions. In Fig. 1 are shown the distortion curves of several tubes which were tested, and it may be seen how little the values registered vary from the distortion curves.

These tubes are not strong enough, however, for great loads and lengths. In such cases, recourse is had to complex construction with braced girders. The theoretical conception is simple, but the external construction assumes various aspects. Ordinarily (Fig. 2) three similar members are parallel to the axis of the compressed solid and are connected with one another in various ways, which give the various methods of construction. Thus the steel tubing girders of the first Italian airships were very similar to those used in the Zeppelins (Fig. 3). Not all the connections were suitably made and we improved the construction of the various joints, thus obtaining greater strength for the same weight, and giving us the steel girders (Fig. 4) of our present airships and the duralumin girders (Fig. 5). The principal difference between the steel and duralumin girders lies in their joints. For the former, a good fastening with iron wire or tin solder (Fig. 6) answered the purpose, while the latter had to be joined with at least two rivets (Fig. 7), which necessitated the use of sheet metal members instead of tubes. Aside from the above-mentioned manner of bracing, other methods have been employed with equally good results, as shown in Figs. 8, 9 and 10, representing both square and flat girders.

We also show here some results (Fig. 11) of breaking tests. Note how accurate the agreement is between the experiments and the theory. Every distortion could have been perfectly predicted.

Parts fully loaded and exposed to the wind: Struts.- The problem of the wing struts is quite important and has thus far been chiefly solved by the substitution of steel for wood. Aluminum struts do not answer the requirements. The reason lies in the technical difficulty of production and in their rather low modulus of elasticity. But the steel struts (and those used during the war left much to be desired) behaved very well, so that at the close of the war very few airplanes had wooden struts. There was need of improving airplanes aerodynamically and metal struts were preferable to wooden ones. The fundamental principles for the construction of struts may be grouped as follows:

2. The external shape must offer the least head resistance and the cross-sections must therefore have good penetration. The cylindrical tubes, which behave the best under full load, are suitably streamlined.

3. A strut must offer nearly uniform resistance to both principal and secondary stresses or, what amounts to the same thing, the ellipse of inertia must be almost a circle, and the resistance to the secondary flexion must be equally great at all points, else the strut will give way before reaching its maximum efficiency.

Our tubes (Fig. 12) answer the condition of good penetration, but leave much to be desired in the matter of uniform strength. In one direction the strength is much greater than at right angles to this direction. Moreover, according to this, the material does not have sufficient curvature for resisting the local stresses equally well. This disadvantage is somewhat relieved by crimping, as shown in Fig. 13, a method also employed by us, but which has not given entirely satisfactory results.

The problem has been well solved technically by the English, with a known fondness for this type of construction, but with some practical difficulty in obtaining struts stronger and lighter than those of the best spruce wood or steel tubing. Thus struts for small airplanes (Fig. 14) are made in two pieces and joined, the front part of steel and the rear part of aluminum. They are also made in three pieces (Fig. 15), all of sheet steel. There appears to be no practical load limit for the struts of large airplanes (Figs. 16 and 17), while their length may be that required for the largest present-day airplanes. In the meanwhile, theory and experience enable us to establish two general principles which give values for all parts with full loads applied axially.

4. For axially compressed members composed of quite thin drawn-metal parts, with equal length of member and the same shape and size of cross-section, the allowable loads stand in direct ratio to the thickness of the drawn-metal parts.

5. For axially compressed members composed of quite thin drawn-metal parts, with equal length of member and the same shape and area of cross-section, the greatest load is borne by the member whose drawn-metal parts have the minimum (this appears to be a mistake for maximum) thickness.

Extremities of the members: Joints.- These parts, which are of capital importance in every structure, are especially important in our aircraft, since, by the proper adjustment of the axes of the members, it is possible to eliminate all the secondary (quite harmful) stresses. We will not give the theory of joints here, as it is too long, but will content ourselves with simply recording the general principles. Ordinarily the junction is made by a piece applied externally and fastened to the parts to be joined. These fastenings may be made in various ways. Steel may be soldered (with or without binding with iron wire), brazed, autogenously welded, riveted, or both riveted and soldered, while aluminum and its alloys can only be joined by autogenous welding and riveting. The general principles are however independent of the materials used. Since the strength is diminished by the first row of rivet holes, their number in the first row should be limited to the minimum and possibly to only <u>one</u>. The rivets are best arranged in quincunx.

6. <u>The allowable diameter of the rivet is three times the thickness of the sheet to be riveted</u>. This larger diameter, instead of the two and one-half times common in mechanical structures, is due to the thinness of the sheets used in aeronautics. Tin soldering gives good results. It may be employed, if well done, for surface unions up to 10 or 12 centimeters.

7. <u>A union is just so much better, the better the parts to be joined are prepared and the thinner the layer of solder between them</u>.

8. <u>In order to obtain a strength equal to that of the steel sheet or tube to be soldered, the length of the soldered part must be 100 times the thickness of the piece to be soldered</u>. This is often impossible, in which event recourse must be had to riveting.

9. <u>The best results are obtained when the rivets and solder are subjected to nearly equal forces and the first row of rivets</u>

<u>is back of the beginning of the solder, in order to offset the weakening due to the rivet holes</u>.

Sometimes, in addition to the soldering, recourse is had to winding with iron wire (Fig. 6), with very good results.

Autogenous welding and brazing always cause considerable loss of strength. It is therefore possible to employ them only in special cases and particularly in compression members where there is a general excess of strength at the ends.

For very complex and rigid structures, the members are joined by interlocking, with special recourse to the application of outside reinforcing pieces.

<u>Spars</u>.- The superiority of metal over wood is specially manifest in the spars of airplane wings and airship rudders, since in these parts, there are simultaneous compression and bending stresses. The bending of a loaded girder is inversely proportional to the modulus of elasticity and a full load introduces a new moment of flexion due to the camber. Metals are preferable to wood, on condition, however, that the maximum strength of the metal can be developed.

In order for metals to be able to compete with wood, they must be of minimum thickness. Considering the dimensions of the present parts of aircraft, steel must have a thickness of 0.35 to 0.6 mm, and aluminum from 1 to 2 mm. Such thinness conduces to local failures, which may compromise the stability of the entire structure. In order to avoid these, it is necessary to give a curvature to the member in the direction of the stress, so as to prevent the initial distortions and enable the metal to develop its maximum strength. The curvature consists of slight and continuous corrugations, with the avoidance of sharp angles which would create a tendency to crack.

In accordance with the above conceptions, it has been proposed to make wing spars of steel or duralumin. There are three fundamental kinds of construction: Plate girders with plain webs, girders with open-work webs and lattice girders. For girders with plain webs, the construction is characterized by the following properties:

10. The strips composing the spars are continuous, without holes, since breaks in the continuity would weaken the structure, and greater lightness is obtained, with equal strength, by reducing the thickness and increasing the curvature of the cross sections.

11. Absence of rivets or other means of connection on the lines of maximum stress.

12. All the metal of the section, less the transverse connections, must perform its share of the work.

13. The free edges of the flange strip are turned back toward the neutral axis of the girder, which avoids the maximum tension on the free edge and considerably increases the strength of the flange. The best disposition of the free edges of the strips constitutes one of the most important problems in light metal con-

struction. The following girders answer these conditions.

Rudge spars.- Riveted type (Fig. 18). This does not obey the condition of the flange being turned back toward the epicenter. The thickness of the flange strip is 0.01 of its width and the thickness of the web strip is 0.005 of its width. Local failure is prevented by longitudinal corrugations, the radius of each corrugation being from 30 to 100 times the thickness of the metal, a smaller radius being used where the highest compressive stresses are to be withstood.

Modified Rudge.- Riveted type (Fig. 19). The two webs are joined together at the neutral line. In case the corrugations do not meet, it is necessary to join the webs together at intervals by a cross tubular member riveted to each. The larger spars have the form of Fig. 20.

Dunlop spars.- This is a welded type which eliminates the difficult process of riveting (Fig. 21). It is produced by the welding of only three strips. It has the disadvantage that the tubular units cannot be made so large, on account of the difficulty of working high tensile strips wider than 15 centimeters, but it has the great advantage of eliminating the projecting ledges, which have a tendency to buckle under stress.

Double Dunlop.- A welded type (Fig. 22). It is like two bicycle rims straightened out and connected along their centers. Similarly to the Dunlop single spar, it requires to be supported by transverse frames at distances of not over 60 times the radius of curvature of the booms, in order to prevent the individual booms from bending transversely to the web.

For spars with open-work webs, the construction is characterized by the same foregoing properties and by the following:

14. It is possible to employ webs with plain surfaces, in the central part of which and on its neutral line are punched holes with flanges. Such are the following spars.

Boulton and Paul spar.- Riveted type (Fig. 23). This is similar to the Rudge spar, but has webs with plain central parts in which are stamped flanged holes. The edges of the webs are doubled over the flat edges of the flanges and suitably riveted.

Humber spar.- (Fig. 24).- This has a cross-section very similar to the wooden ones now in use.

For girders with lattice webs, the characteristic properties are:

15. Exact ratio between the height of the spar and the distance between the centers of zero moment in the bays, so that neither the weight of the flanges nor of the web will be excessive. The height of the spar depends therefore on the thickness of the wing.

16. Suitable inclination of the lattice bars.

17. Correct ratio between the thickness s and the width l of the flange strip. If the ratio $\frac{s}{l}$ is excessive, the radius of inertia for a given section surface is small, in relation to the distance between the zero centers of moment, and the girder bends

under a small load. If $\frac{s}{l}$ is too small, it bends with a low load from secondary stresses. The most suitable value for $\frac{l}{s}$ for a simple lattice girder seems to lie between 6 and 8 and should not exceed 10 in any case.

18. The method of joining and the rigidity of the lattice strips seem to exert no great influence on the strength of the flange strip.

19. The cross-section of the flange is corrugated and is generally improved by crimping the edges together and bending them back toward the neutral line of the girder.

20. In order to avoid local distortions, the diameter of the rivets should not exceed 15 times the thickness of the strip.

21. Since the shearing stress is very great, a lattice girder must be very rigid and well designed, especially when there is felt the need of a practically continuous girder. The girders constructed by the firm of Pratt and Temple and by Vickers answer the above conditions (Figs. 25 to 27).

From the foregoing it follows that suitable steel and duralumin spars can be made which are preferable to the wooden ones now used. Metal girders guarantee the strength of the framework of aircraft and of the control planes of airships. The distortions are less and their length of life is practically independent of the seasons and the weather.

It would seem premature to render a definite decision in favor of steel over duralumin, since the latter metal has not yet attained the industrial development that is to be expected. In any event, steel has in its favor the fact that its limit of elasticity is higher and hence may be given the preference in cases of bending stresses. On the other hand, its dimensions must be extremely small.

Ribs.- The original plans of two Italian airplanes had stamped ribs of aluminum or duralumin. These were more solid than and of about the same weight as corresponding wooden ones, but on account of the thinness of the metal, they proved less suitable, since they were easily bent under the stresses to which the aerofoils are subjected on the ground. This disadvantage may be avoided by giving the flange of the rib a longitudinal corrugation, but this, besides not affording a convenient support for the fabric, greatly increases the cost of manufacture.

Supporting and shaping surfaces.- The Germans in their Junkers airplanes, made entirely of light metal, have solved in a truly remarkable manner the problem of wing and fuselage covering. They have eliminated the parts designed to support and give shape to the covering itself, by giving the latter the requisite stiffness for withstanding the stresses to which it is subjected. This is accomplished by replacing the very light plain metal sheets with uniformly corrugated sheets, with the corrugations parallel to the longitudinal axis of the airplane. This disposition assures rigidity in one direction and enables the covering to retain its shape, provided it is supported in the direction at right angles to the corrugations.

The wing covering is supported on quite thick tubular girders inside the wing, joined by pyramidal bracing, so as to form a strong cantilever structure in the direction of the wing span. The wings of the Junkers monoplane are complete in themselves, without external struts or stay wires. The ribs of ordinary wings are completely eliminated. The tail planes are constructed in a similar manner.

The covering of the fuselage is held in the form of good penetration by braced metal frames or bulkheads (Fig. 28), with the elimination of all girders and diagonal bracing in the direction of the length of the fuselage.

This type of metal construction, which employs the covering as a part of the frame, merits special study and consideration because it involves new structural conceptions which, if properly applied, can be of great advantage in future aeronautical construction. These conceptions may be stated as follows:

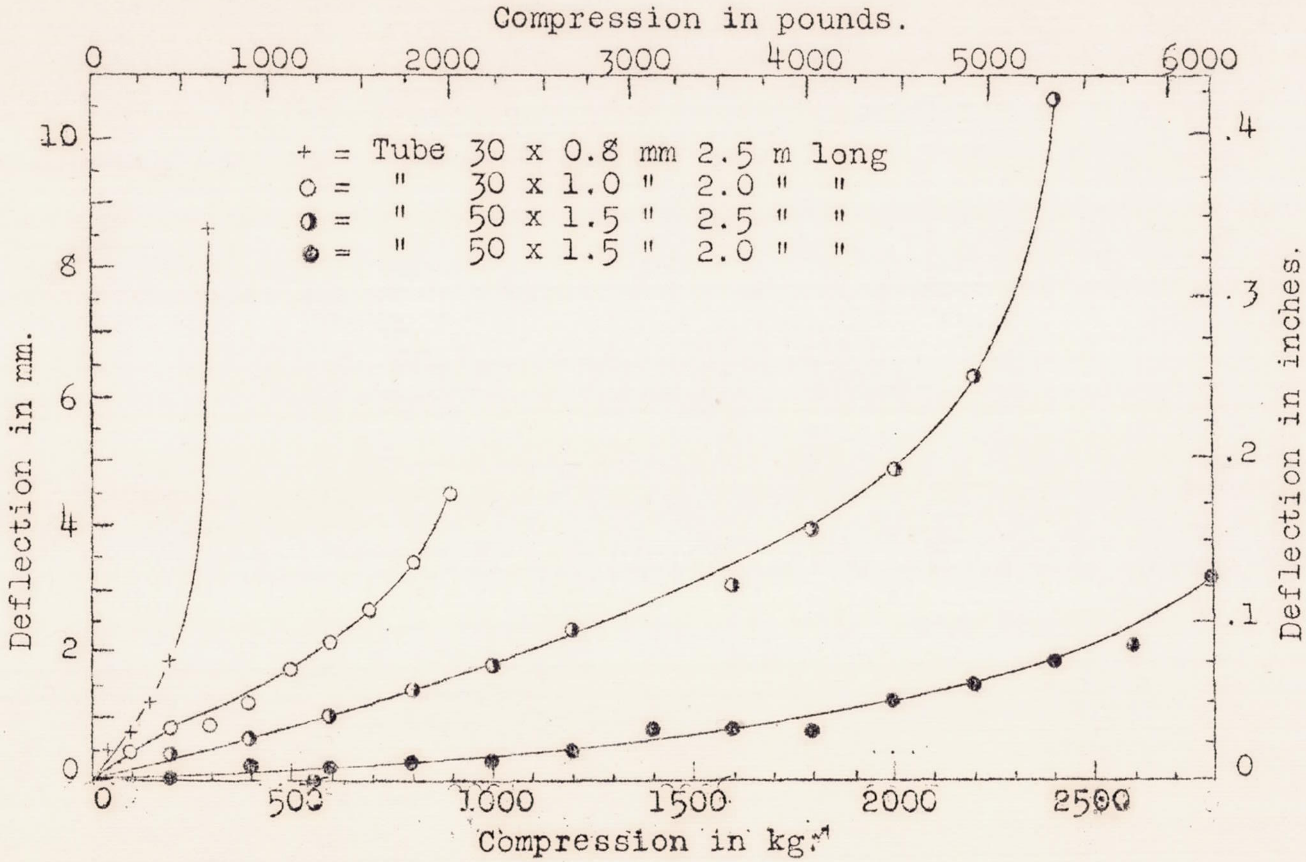
22. To try to make the covering so strong as to withstand the stresses normally exerted on the eliminated part of the framework, by taking advantage of the greater strength of the metal.

23. Any modification in the covering should not materially increase the head resistance, and hence the possible stiffening can generally be in only one direction, while at right angles to this direction recourse must be had to other rigid members.

The organs already described comprise all the parts of an aircraft, with the exception of such as have always been, and always will be, made of metal: Engines, tanks, stays, etc.

Aeronautical science has made decided progress in the study of metal construction and we have the personal conviction that practical results will confirm our faith in this branch of technics.

Translated by the National Advisory Committee for Aeronautics.



Compression in pounds.
0
1000
2000
3000
4000
5000
6000
+ = Tube 30 x 0.8 mm 2.5 m long
○ = " 30 x 1.0 " 2.0 " "
◑ = " 50 x 1.5 " 2.5 " "
● = " 50 x 1.5 " 2.0 " "
Deflection in mm.
10
8
6
4
2
0
Deflection in inches.
.4
.3
.2
.1
0
500
1000
1500
2000
2500
Compression in kg.

Fig. 1.

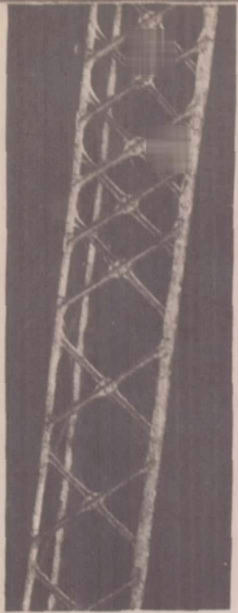


Fig. 2.

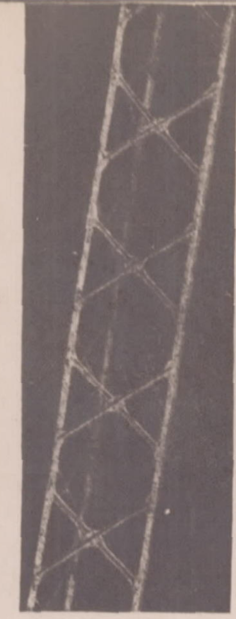


Fig. 3.

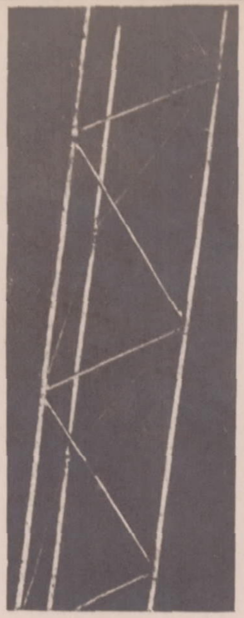


Fig. 4.

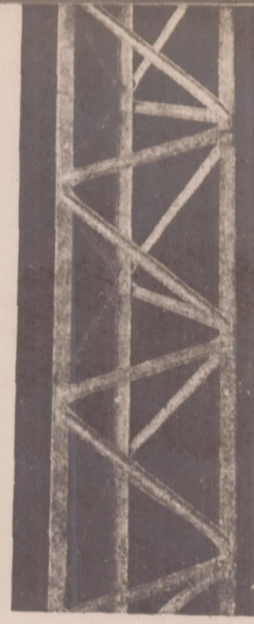


Fig. 5.


Fig. 6.


Fig. 7.

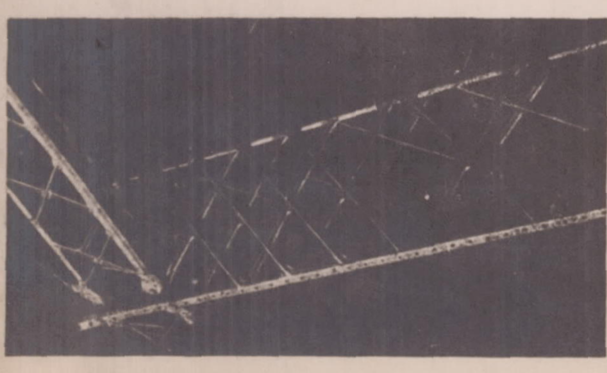


Fig. 8.

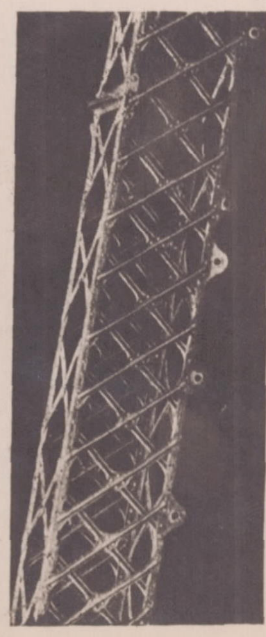
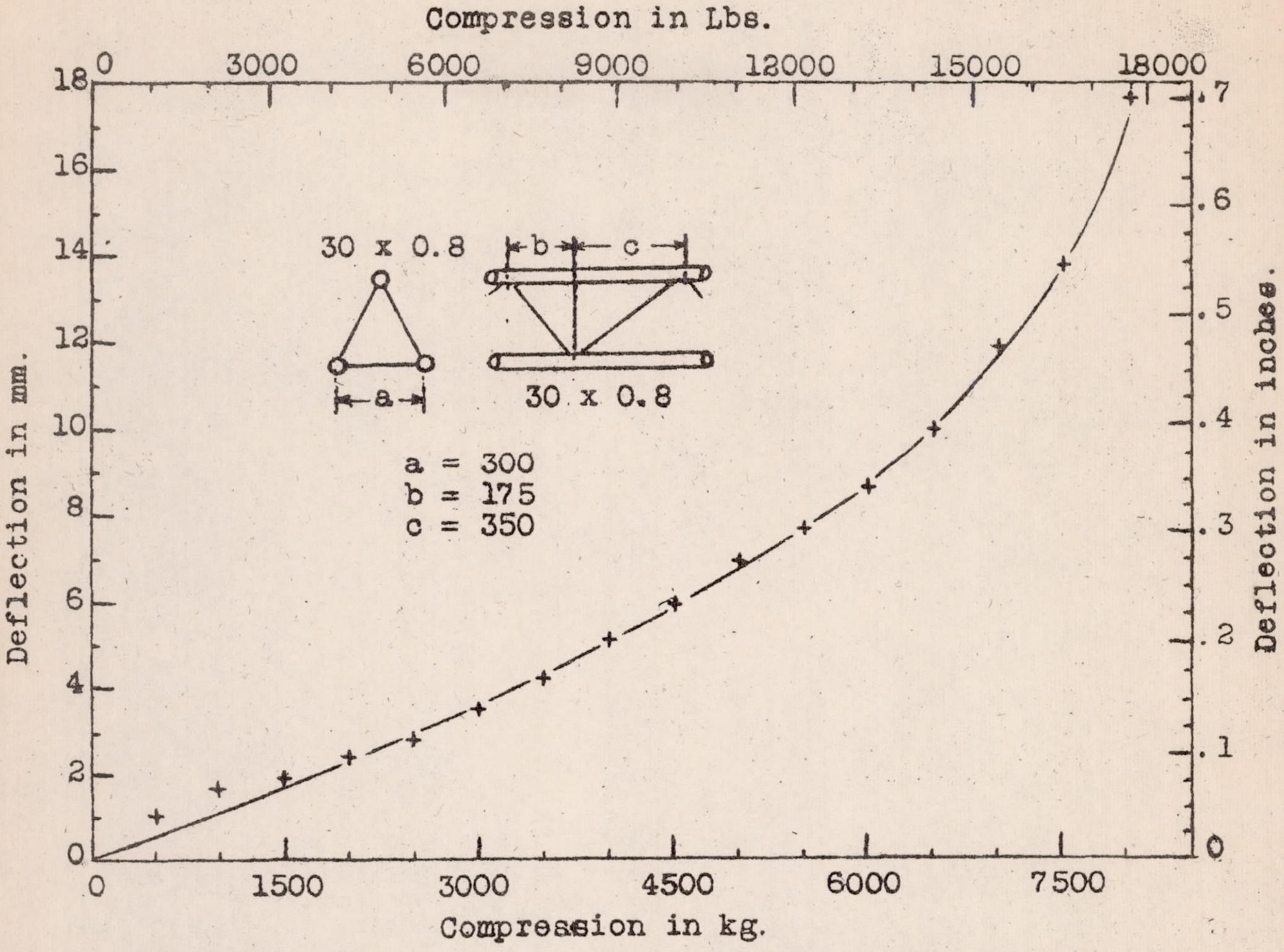


Fig. 9.


Fig. 10.



Load in kg.	Deflections in mm. Verti-cal	Hori-zontal
100	15.4	0.0
500	15.3	1.0
1000	15.3	1.7
1500	15.2	1.9
2000	15.1	2.4
2500	15.0	2.8
3000	15.0	3.5
3500	14.8	4.2
4000	14.8	5.1
4500	14.6	6.0
5000	14.3	6.9
5500	14.2	7.7
6000	14.1	8.6
6500	13.7	10.0
7000	13.2	11.9
7500	12.4	13.8
8000	11.0	17.7

A 7 m girder with lattice strips 10 x 0.5 mm on tubes 30 x 0.8 mm in equilateral triangular position of 0.3 m was designed to support 8550 kg. Weight of girder 20 kg.

Length tested, 700 mm with tubes 30 x 0.8 mm. At 8300 kg one of the tubes buckled toward the axis of the girder. It was restored and tested for tensile strength. Under 11600 kg, one of the tubes gave way at a screw. The screws were the same as used for the 30 x 1 mm tubing.

Fig.11.

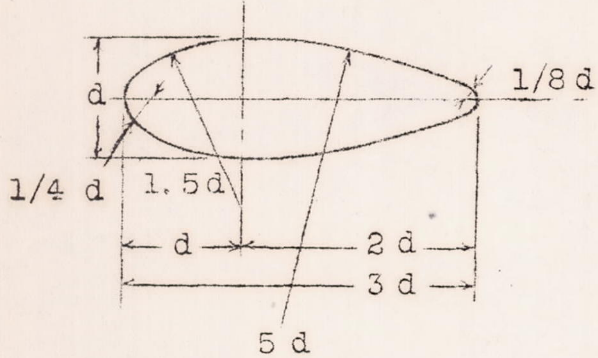


Fig. 12.

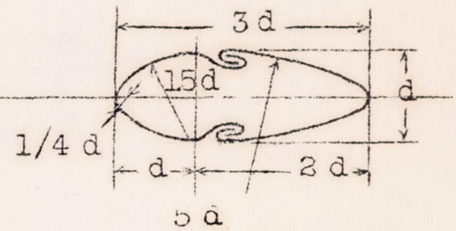


Fig. 13.


Fig. 14


Fig. 15

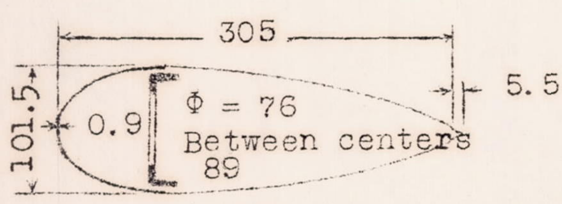
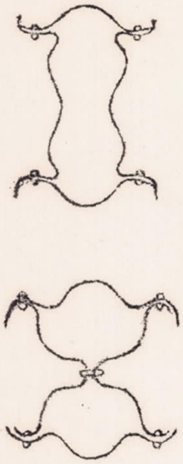


Fig. 16


Fig. 17.



Figs. 18-19

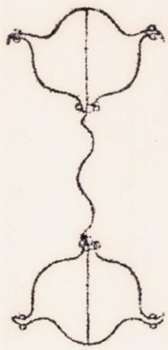


Fig. 20

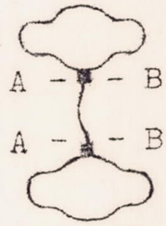


Fig. 21

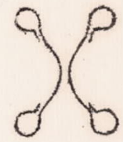


Fig. 22

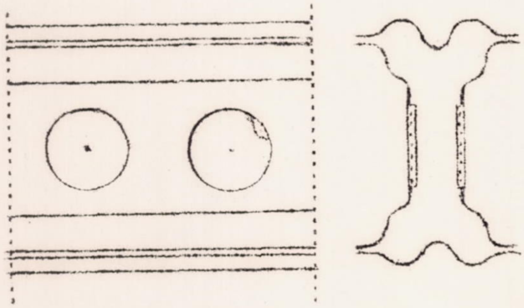


Fig. 23

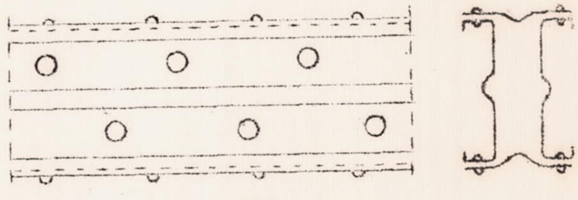


Fig. 24

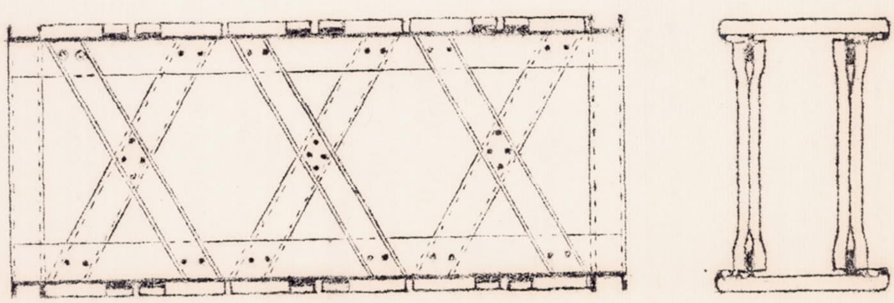


Fig. 25

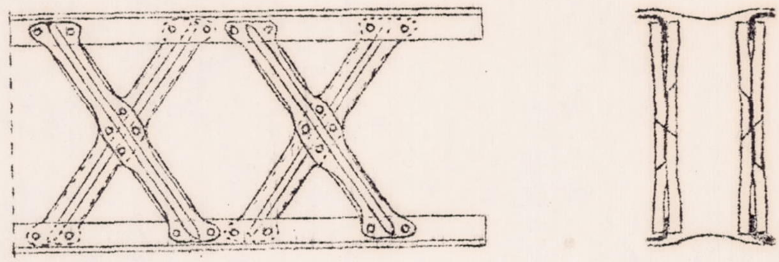


Fig. 26.

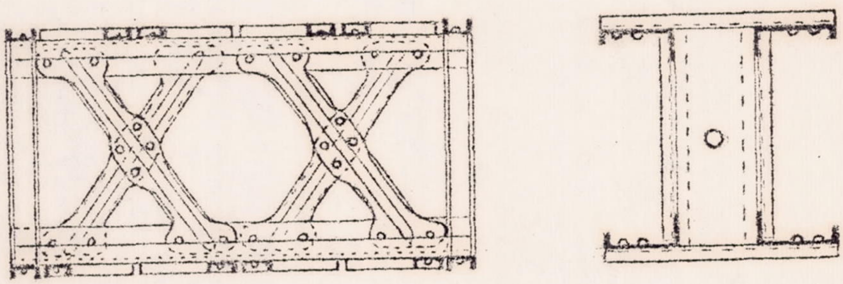


Fig. 27.

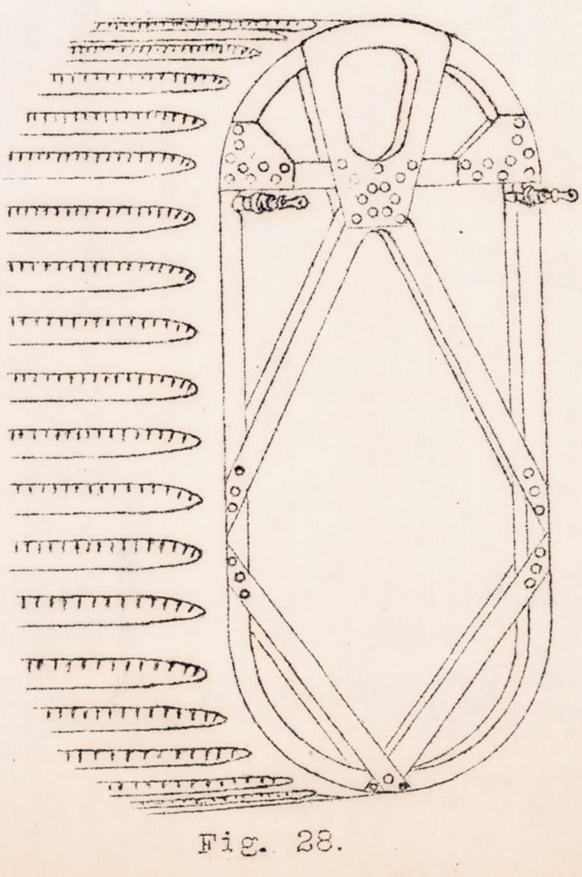


Fig. 28.