Sheet-Metal Airplane Construction

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ONE of the first successful attempts to manufacture all-metal planes in Germany was made by the airplane branch of the Zeppelin Works at Lindau, later known as the "Dornier-Metallbauten." This firm had the advantage of the experience of the Zeppelin Works in the use of the light-weight metal duralumin. Entirely new principles of construction were applied in Professor Junkers' "Iron-Monoplane" (Eiseneindecker) built in 1915. Up to that year the covering of airplane wings served essentially the sole purpose of giving them a certain shape and of providing a surface for maintaining the supporting air pressure. The distribution of the stresses was assigned to a special supporting structure which also included the external wiring and struts. Junkers made the external fairing of the wings of metal and, at the same time, combined it with the internal supporting structure so as to form a strong integral supporting body.

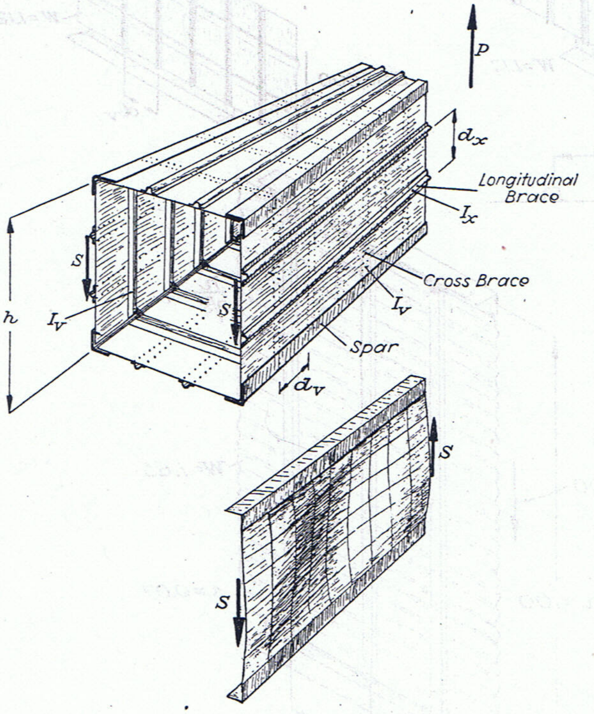

Fig. 1 Box Fuselage
(The lower part of the picture shows the side wall buckled due to shear S.)

Thus the increase of weight of the fairing as compared with a cloth covering was at least partially saved, in the internal structure.

These principles prepared the way for the development of all-metal planes in Germany, and in the course of years various forms and types of such supporting fairings have been developed. Inasmuch as the use of sheet-metal fairing for support is the outstanding constructional characteristic of such structures, it is the object of this paper to discuss the possibilities of building such sheet-metal walls.

Fig. 1 shows a hollow fuselage consisting of spars and sheet-metal walls. These walls are stiffened by means of braces, made of rolled shapes and riveted to the walls. For convenience the transversely arranged braces will be called "cross braces" and those running in a longitudinal direction "longitudinal braces." Such a fuselage will be subjected to bending stresses by forces exerted by air pressure on the tail plane or by the tail skid in the course of landing. The side wall will therefore be subjected to the shear S, and the top and bottom walls, together with the spars, serve as tension and compression members.

Consider first the strength of such a sheet-metal wall subjected to a shearing stress. With the shear S increasing, the sheet-metal wall finally breaks and buckles diagonally. This, like any other collapse or buckling, happens suddenly with the load increasing only slightly.

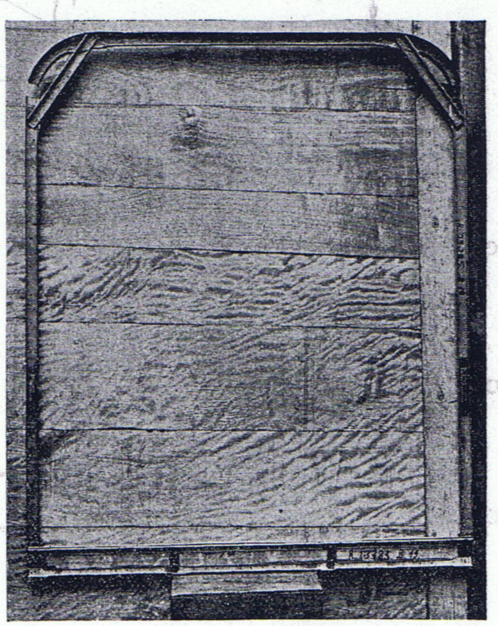

Fig. 2 Fuselage Frame of a Rohrbach Land Plane
(The bottom beam is fitted with a web securely braced against shear.

In cooperation with Dr. Schmieden[2] the author has made calculations of this problem of strength, the results of which give the basis for the following considerations.

When the walls buckle out the braces are bent, the load S depending on the bending strength of these braces. The numerical value of S may be calculated as follows:

$$S = \frac{33E}{h}\sqrt[4]{\left(\frac{I_v}{d_v}\right)^3 \frac{I_x}{d_x}}$$

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[2] "Das Ausknicken versteifter Bleche unter Schubbeanspruchung," by C. Schmieden, in the *Zeitschrift für Flugtechnik und Motorluftschiffahrt*, vol. 21 (1930), no. 3. A supplementary treatise by Dr. Schmieden and the author will soon be published in the same magazine.

In this formula E is the modulus of elasticity of the material; h is the height of the fuselage or beam, I_v is the cross-sectional moment of inertia of a longitudinal brace, and d_x is the distance between these braces. At a given external load S and for a certain height h of the beam, the moments of inertia of the bracing, therefore, have to be chosen so that

$$\left(\frac{I_v}{d_v}\right)^3 \frac{I_x}{d_x} \geq \left(\frac{Sh}{33E}\right)^4$$

Assume an external shear S of 10,000 kg. (22,000 lb.), and using the above formula, the problem is to determine which type of construction may be used to best advantage with different beam heights.

First, if this beam is to be constructed without bracing, how small must this height h be? Such a beam may be represented by the floor-beam of a Rohrbach land plane, as shown in Fig. 2. The value of the shearing stress τ at which such an unbraced sheet collapses and buckles diagonally has been determined by theoretical calculations as well as by experiments. This value (see Fig. 3) depends on the ratio of the distance d between the bracing members to the thickness s of the metal sheet. For all values of d/s higher than about 50, τ can be calculated from the following formula given by Southwell-Skan:

$$\tau = \frac{5E}{(d/s)^2}$$

For $d/s = 50$ the buckling stress of duralumin is about equal to the yield point (approximately 1500 kg. per sq. cm. = 21,330 lb. per sq. in. shearing stress) and consequently its increase is not worth considering even with smaller distances between the bracing members. To get a light structure, i.e., to subject the sheet to the highest practically obtainable stress, the distance between the bracing members must not be made greater than 50 times the thickness of the sheet.

If, now, the beam with a shear load of 10,000 kg. (22,000 lb.) has a total height of 22 cm. (8.66 in.) and a height of about 15 cm. (5.9 in.) between the spars, then a desired shearing stress of 1500 kg. per sq. cm. (21,330 lb. per sq. in.) will call for a thickness of about 3 mm. (0.118 in.) so that the sheet is sufficiently braced to resist buckling. For such beams, and of course for beams of smaller height as well, special bracing can be eliminated.

Considering, however, a beam with a height of 33 cm. (approx. 13 in.) with the same shearing stress of 1500 kg. per sq. cm. (21,330 lb. per sq. in.), the sheet need only be 2 mm. (0.079 in.) thick, while the distance between the bracing members must not exceed 110 mm. (3.95 in.) to give the sheet sufficient resistance. As the spars are already too far apart in this case, bracing must

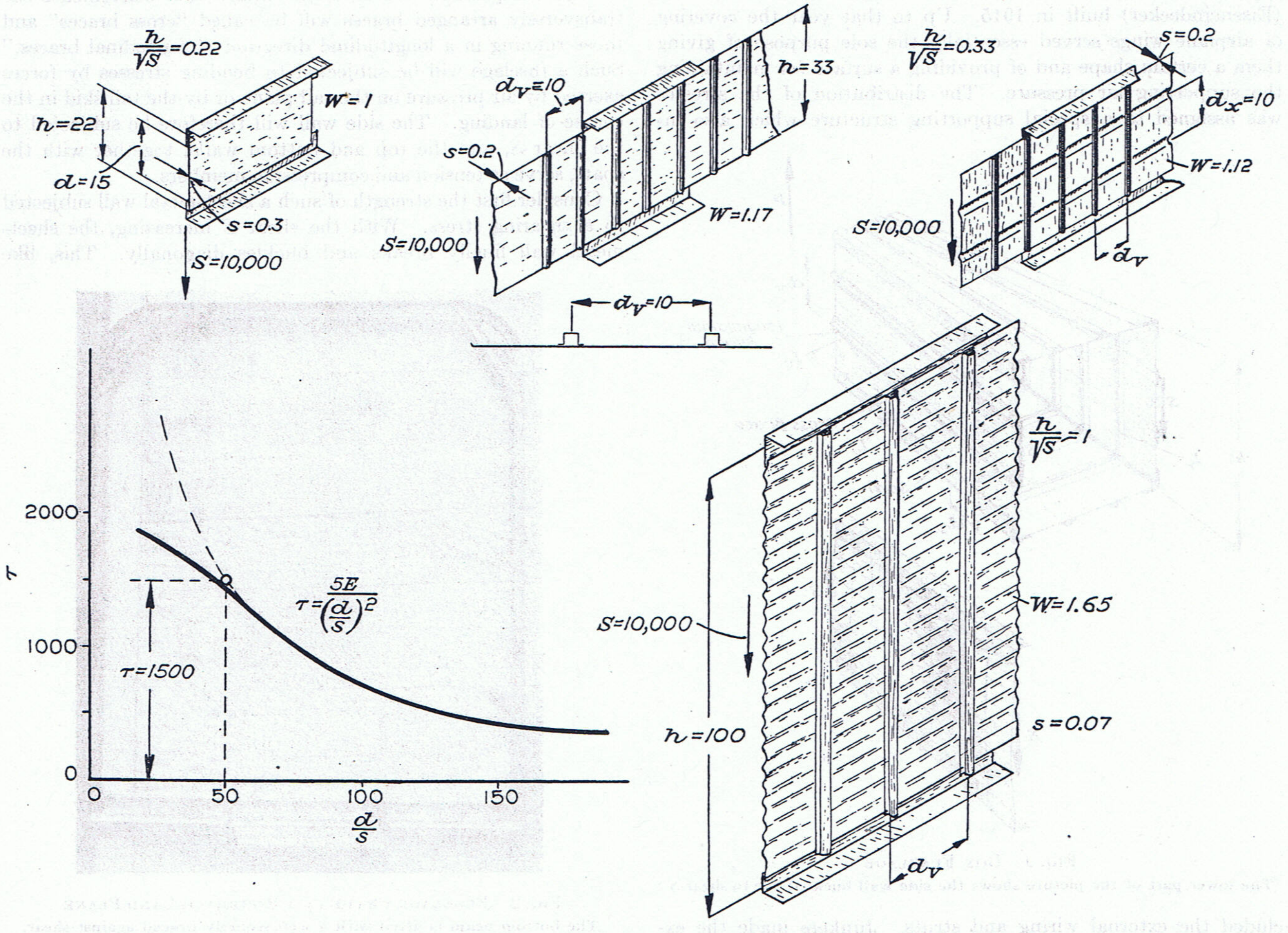


Fig. 3 Details of Side Wall

(In the lower left-hand corner the shearing stress τ is given, under which plane sheets with a wall thickness s buckle, if the distance between the bracing members is d. The other illustrations show the most favorable forms of design of sheet-metal walls securely braced against shear, dependent on the value of $h/\sqrt{S}$. W indicates the ratio of the weight of the sheet wall (exclusive of the spars) to the weight of a sheet secure against shear (exclusive of the weight of the bracing), so that the figures after the decimal point give approximately the comparative weight of the bracing. The weight of the sheet only is, at a given shear load, approximately the same for all heights of the beam.)

be provided. If, for example, cross-braces are chosen, the moment of inertia of these braces has to be determined from the formula previously given, in which the resistance to bending of the sheet proper, namely, the value $s^3/12$, must be inserted for I_x/d_x.

$$\left(\frac{I_v}{d_v}\right)^3 \frac{s^3}{12} = \left(\frac{Sh}{33E}\right)^4$$

If such cross-braces are chosen as are customarily used for airplanes, it will be found that they can be very light, their weight amounting to about 17 per cent of the weight of the metal sheet. Bracing the sheet also in a horizontal direction, most easily and simply accomplished by corrugations or by the use of corrugated sheet metal, would result in an additional reduction of the weight of these profiles. By these means the moment of inertia in horizontal direction is materially increased so that now the stiffness of the cross-braces may be decreased. Then the weight of the cross-braces amounts to only about 12 per cent of the weight of the metal sheet.

At the given shear load of 10,000 kg. (22,000 lb.) the thickness s of the wall is decreasing more and more with increasing height of the beam. If no special longitudinal braces are provided the moment of inertia I_v of the cross-braces would, according to the equation, have to increase disproportionately fast in order to provide sufficient resistance to buckling. For beams of such a height only corrugated sheet is used. Then the weight of the

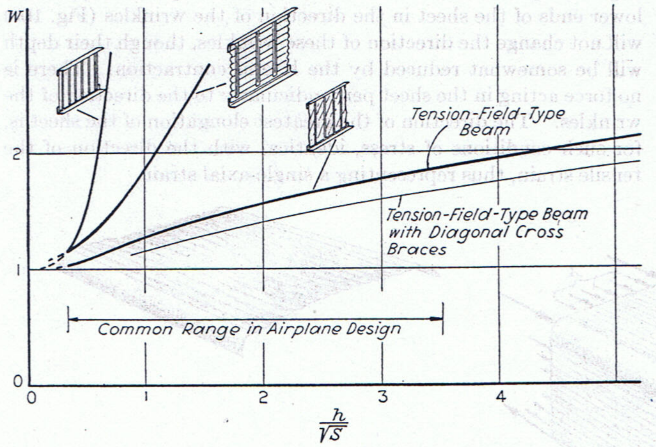


Fig. 4 Relation Between W and $h/\sqrt{S}$

(The ratio W of the weight of the sheet wall, without spars, to the weight of a sheet secure against shear, exclusive of the weight of the bracing, is plotted against the factor $h/\sqrt{S}$ for various designs of sheet-metal beams (plane sheet metal securely braced against shear by cross-braces; corrugated sheet with longitudinal corrugations and braced by cross-braces; tension-field-type beams with vertical cross-braces; tension-field-type beams with cross braces arranged at an angle of 120 deg. to the spars). In this sheet, which is secure against shear, the allowable shearing stress τ is equal to 1500 kg. per sq. cm. (21,300 lb. per sq. in.). See also Fig. 3.)

cross-braces rises only slowly with increasing height of the beam, amounting to about 65 per cent of the weight of the metal sheet for a beam 100 cm. (39.37 in.) high, which should be 0.7 mm. (0.0276 in.) thick.[3]

These examples show how the design of beams with various heights may be determined when they are subjected to a shear of 10,000 kg. (22,000 lb.). These most favorable types of design also hold true for any other values of shear as long as the value $h/\sqrt{S}$ is the same as in these examples. This can easily be understood from the law of similarity[4] as applied to the science of the strength of materials.

In Fig. 4 W, the ratio of the weight of the sheet wall, exclusive of spars, to the weight of the sheet secure against shear, exclusive of bracing, is shown to rise with increasing value of $h/\sqrt{S}$.

The values of $h/\sqrt{S}$, which are common in airplane design, vary between about 0.3 and 4 cm. kg.$^{-1/2}$. For the side wall of a fuselage having a height of 200 cm. (78.74 in.) and which has to resist a shear of 3600 kg. (7920 lb.) the value of $h/\sqrt{S}$ will be 3.3. As, for such high values of $h/\sqrt{S}$, the added weight of the bracing would be quite considerable, the construction is modified by making some of the cross-braces especially stiff (see Fig. 5).[5] Such strong frames are also often necessarily employed for other

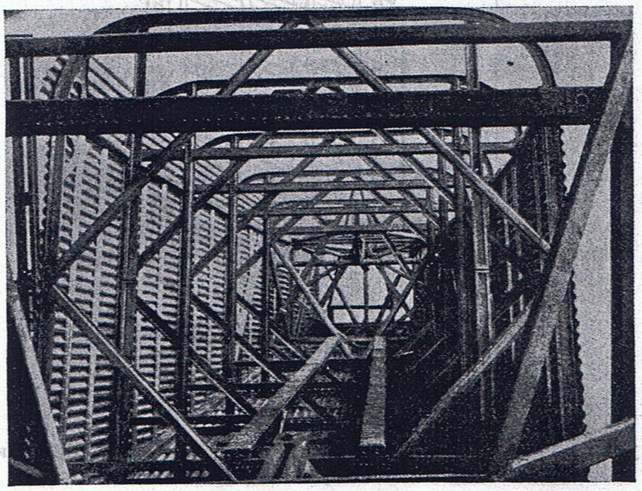


Fig. 5 Interior of the Fuselage of a Junkers Airplane, Showing the Strong Frames, Between Which the Corrugated Sheet Is Stiffened by Braces

purposes, as, for instance, in the passenger cabin for taking up the loads.

The strength of such a construction can likewise easily be determined. (See Fig. 6.) According to well-known principles a shearing stress in a vertical direction is always accompanied by an exactly equal shearing stress in a horizontal direction. The sheet-metal wall between two strong frames, therefore, has to be considered as a beam with the height d, which has to transfer the horizontal shear $\left(S\frac{d}{h}\right)$ from the bottom spar to the top spar; and the corrugated sheet with its bracing must be dimensioned accordingly.

Thus far the resistance of braced sheet-metal walls to shearing forces has been considered. There follows now a discussion of the resistance to compression forces in the direction of the spars.

Consider, for instance (Fig. 7), the top of a square fuselage subjected to the stress set up by an elevator reaction, which produces compression stresses in the upper sheet-metal wall and the upper spars. If the upper sheet-metal wall were not sufficiently braced it would buckle as indicated in Fig. 7. The pressure X, at which this occurs, may be comparatively easily calculated as follows:

[3] The weight of the sheet wall is, of course, also dependent on the kind of corrugations. In the case under consideration, corrugations having a depth of 15 mm. (0.59 in.) have been assumed. For the same reason the curve for corrugated sheet in Fig. 4 is true only for certain dimensions customarily used for airplane design. The curve of the value W for tension members, however, is only slightly dependent on the cross-sectional form of the cross-braces.

[4] For details see Professor Wagner's treatise, "Einige Bemerkungen über Knickstäbe und Biegungsträger," in the *Zeitschrift für Flugtechnik und Motorluftschiffahrt*, vol. 19 (1928), no. 11.

[5] The illustrations of the Junkers designs have been taken from Langsdorff's book "Fortschritte der Luftfahrt," by courtesy of H. Bechhold, Frankfurt am Main.

$$X = \frac{20E}{h}\sqrt{\frac{I_v}{d_v}\frac{I_x}{d_x}} + \frac{10G}{h}\frac{T_v}{d_v}$$

From this equation the relations of the weight of the material and the height and pressure, i.e., $h/\sqrt{X}$ may be derived; these relations being quite similar to those assumed when the effect of shear was studied. A brief discussion of the equation will suffice. The first half of the equation contains the moments

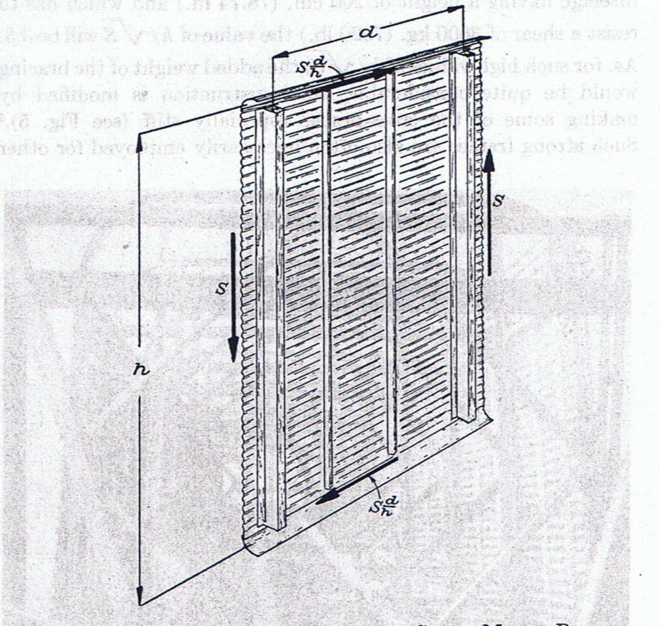


Fig. 6 The Direction of Forces in the Sheet-Metal Beam of Fig. 5.

of inertia of both bracing members, both factors being of the same power. In the second half of the equation GT_v is the resistance of a cross-brace to torsion. This half of the equation may be neglected if the cross-braces have so-called "open sections" (see Fig. 7), which have little or no strength in torsion. Cross-braces, however, built up of closed (tube-shaped) profiles or which together with the corrugated sheet form a channel-like cross-section, as shown in Fig. 7, have considerable resistance to torsional stress. A numerical evaluation makes it apparent that the compression strength of the wall is thereby approximately doubled. At all events, closed profiles are to be preferred for corrugated sheet-metal structures.

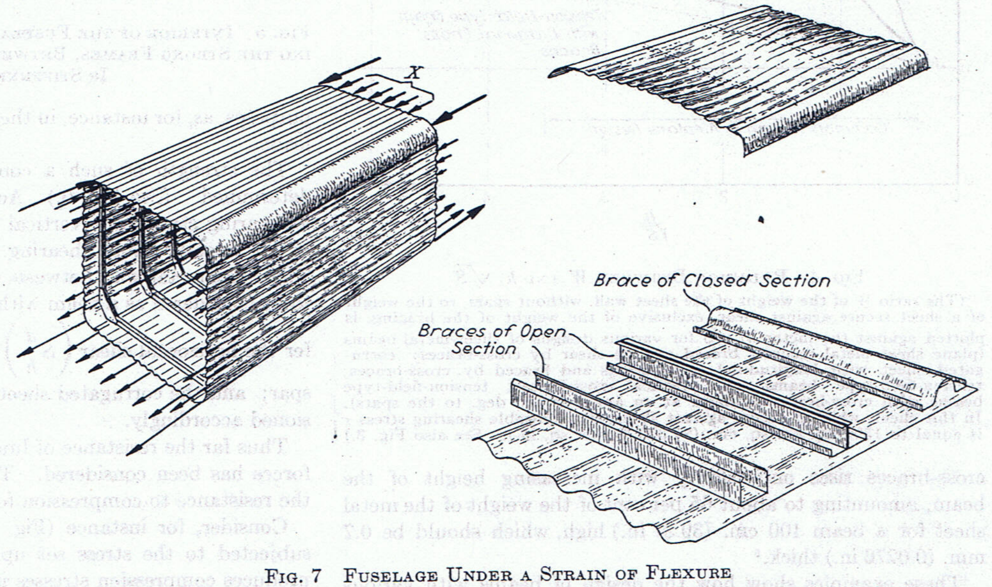


Fig. 7 Fuselage Under a Strain of Flexure

(The upper right-hand corner illustrates the buckling of the upper sheet-metal wall due to the shear S. The lower right-hand corner shows braces of open and closed sections.)

An examination of the equation furthermore shows that even when using comparatively heavy cross-braces and coarsely corrugated sheet the compression strain in the corrugated sheet metal lies, in most cases, well below the yield point (about 2600 kg. per sq. cm. = 36,972 lb. per sq. in. for duralumin), which means that the material may not be used to its full advantage. These difficulties can be evaded by curving the surfaces as in Fig. 8. Although numerical data on this type are not available it is certain that the resistance to compression forces is considerably increased.

So far sheet-metal walls which are braced against forces of shear and compression have been discussed. The following discussion covers another type of design developed years ago by the author when he was with the Rohrbach Metallflugzeugbau and described in 1929.[6] The present discussion is limited to the most essential points.

Fig. 9 illustrates a sheet-metal wall, consisting of upper flange, lower flange, a thin sheeting, and cross-braces subjected to a shear S. At a very small load the thin sheet will buckle diagonally.

It has been shown that the sheet may be prevented from buckling by arranging cross-braces very close to each other. What will happen if the distance between the bracing members is so large that the sheet may buckle almost unhindered?

After the first buckling the load may be considerably increased, for example, a hundred or thousand times, without collapsing the beam or rendering the surface excessively uneven. The wrinkles in the surface may attain a depth of perhaps 3 mm. (0.118 in.) and a width of perhaps 100 mm. (3.94 in.), thus representing only very slight corrugations.

Fig. 10a shows a square sheet of very thin metal, which is assumed to be as thin as paper. This may be wrinkled (Fig. 10b) without applying much force, thereby somewhat diminishing the edge-to-edge distance a. Tensile stresses acting at the upper and lower ends of the sheet in the direction of the wrinkles (Fig. 10c) will not change the direction of these wrinkles, though their depth will be somewhat reduced by the lateral contraction. There is no force acting in the sheet perpendicularly to the direction of the wrinkles. The direction of the greatest elongation of the sheet is, for such conditions of stress, identical with the direction of the tensile strain, thus representing a single-axial strain.

Attention is called to a phenomenon of disturbance caused by the fact that the edges are not free, but are riveted to braces. It will be noted from Fig. 11 that the edges themselves cannot

[6] "Ueber ebene Blechwandträger mit sehr dünnem Stegblech," by Herbert Wagner. *Zeitschrift für Flugtechnik und Motorluftschiffahrt*, vol. 20 (1929), nos. 8 to 11. See also the Jahrbuch der Wissenschaftlichen Gesellschaft für Luftfahrt, 1928, p. 113.

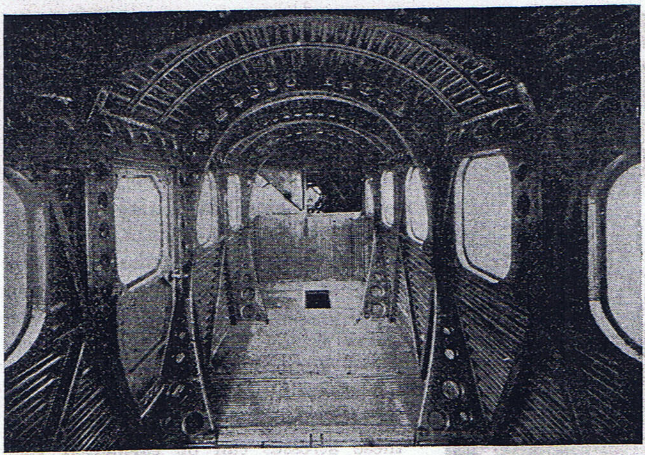


Fig. 8 Interior of the Fuselage of a Junkers Airplane
(The upper surface is curved, which increases the resistive strength against forces of compression. The braces can be clearly distinguished.)

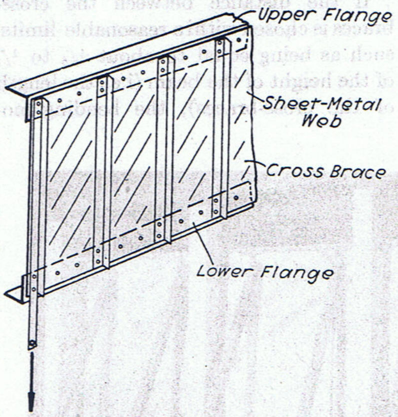
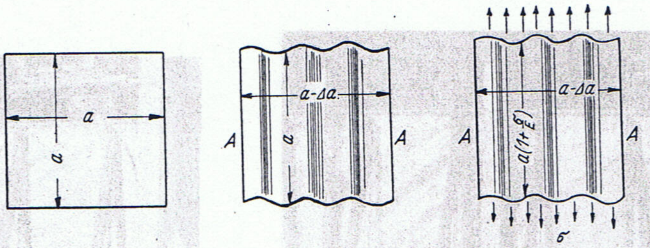


Fig. 9 Tension-Field-Type Beam



10-a 10-b 10-c

Fig. 10 Conditions of Strain and Deformations in a Tension-Field-Type Beam

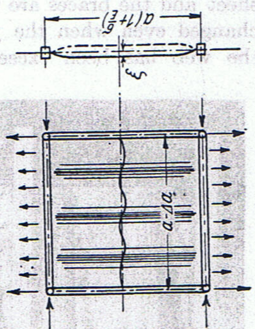


Fig. 11 Disturbing Influence of the Edges

wrinkle. It can, however, easily be shown that this disturbance is of no importance to further considerations.

A simple but important practical example may be illustrated by Fig. 12. Fig. 12*a* shows a frame formed by four rods which are to be pin-jointed to each other and are assumed to be perfectly rigid. A thin sheet is to take up the shear. Because of this shear S, shearing stresses τ will become effective within the sheet metal. The direction of the main stresses is at an angle of 45 deg. to the direction of these shearing stresses. The main stress σ_1 sets up a tensile strain, its direction being identical with the direction of the greatest elongation of the sheet metal. The other main stress σ_2 causes a compression strain. If the sheet is very thin it will soon buckle under the effect of the compression strain and wrinkle in the direction of the tensile strain, σ_1 (Fig. 12*b*). With further increase of the shear S the tensile strain σ_1 will rise rapidly until, at very high loads, it will take up nearly all the shear. Thereby the field has buckled uniformly. Such a field is called a "tension field."

The value of the tensile strain σ_1 can easily be calculated as follows:

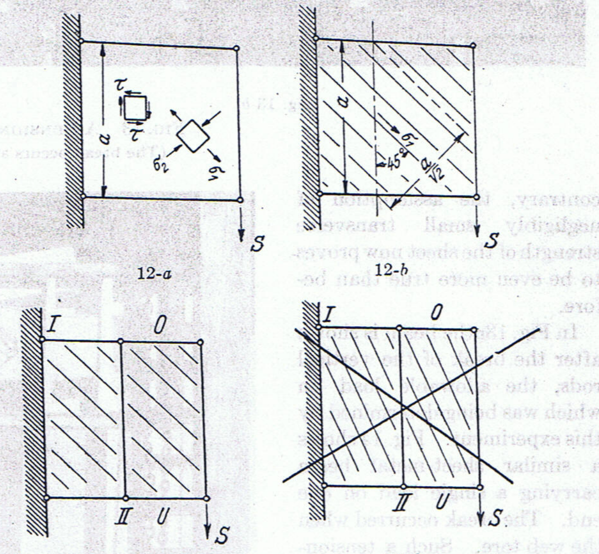
$$\sigma_1 = \frac{2S}{as} = 2\tau$$

The equation shows that the tensile strain is twice as great as would be the shearing strain, if the sheet would withstand shear.

Adding (see Fig. 12*c*) another equally rigid rod to the four rods and pin-jointing the new one to the rods O and U naturally would not change the direction of the greatest elongation of the sheet or the direction of the wrinkles, which remains 45 deg. This means that the diagonals are not running from I to II (see Fig. 12*d*), but at an angle of 45 deg., their direction being, in the case of rigid rods, independent of the distance between the rods.

Fig. 13 et seq. illustrate a few experiments with "tension-field-type" beams made several years ago at the Rohrbach Works.[7] Fig. 13*a* shows a sheet-metal beam supported at the right end and carrying a load of shot-bags by means of levers. Upper flange, lower flange, and the thin sheet-metal wall can easily be recognized. The position of the cross-braces on the back of the beam is recognizable from the riveting. All dimensions of the experimental model are to scale.

The tension wrinkles are distinctly visible and appear rather uniformly over the whole sheet. The shear in the beam increasing to the right, because of the load on the different rods, the wrinkles in the right part of the sheet are more strongly formed than those in the left one. The difference, however, obviously is not great. The load shown on this picture is far beyond that at which the first buckling of the sheet occurred. This initial buckling could be caused by slightly pressing one of the levers by hand, i.e., by a shear of very few pounds. The wrinkles shown in this illustration do not represent permanent deformations. They disappeared entirely after the load had been



12-a 12-b 12-c 12-d

Fig. 12 Thin Sheet With Rigid Rods at the Edges and Loaded by a Shear S

[7] On the occasion of a lecture delivered in Danzig, Dr. Rohrbach permitted the author to publish the pictures of these tests.

removed. Permanent deformations appear only when the tensile strain in the sheet has nearly reached the yield point. This is hardly influenced by the local transverse strains which are caused by the formation of the wrinkles.

Fig. 13*b* shows the beam from the back, under an appreciably higher load. The tension field, indicated by the wrinkles, stands out very distinctly. The angle between the spars and the direction of the wrinkles, which, as stated, is 45 deg. in the case of perfectly rigid rods, is in this case somewhat smaller on account of the flexibility of the cross-braces. It is about 40 to 42 deg., which is in accordance with the calculation.

At the load applied in Fig. 13*b* the yield point of the sheet has already been somewhat exceeded. It is of great importance to the simplicity of calculation that the conditions of the stress in the sheet and the braces are not essentially changed even when the yield point in the web has been exceeded. On the contrary, the assumption of negligibly small transverse strength of the sheet now proves to be even more true than before.

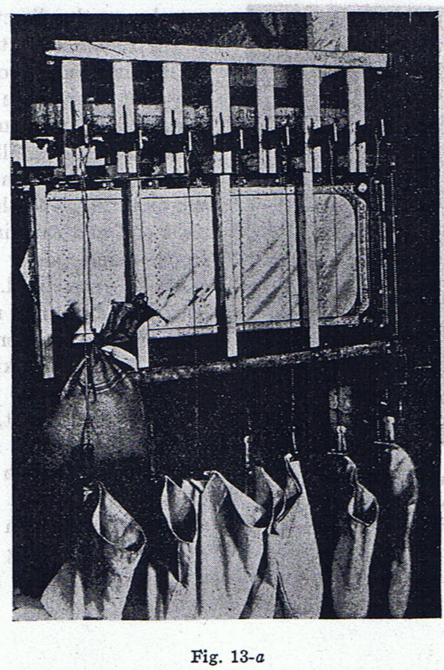


Fig. 13-*a*

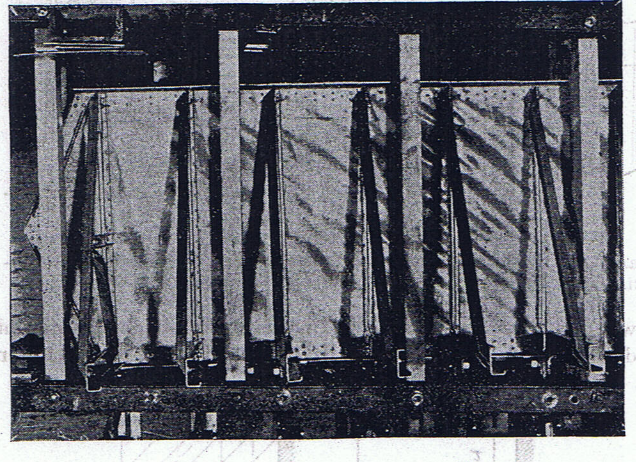


Fig. 13-*b*

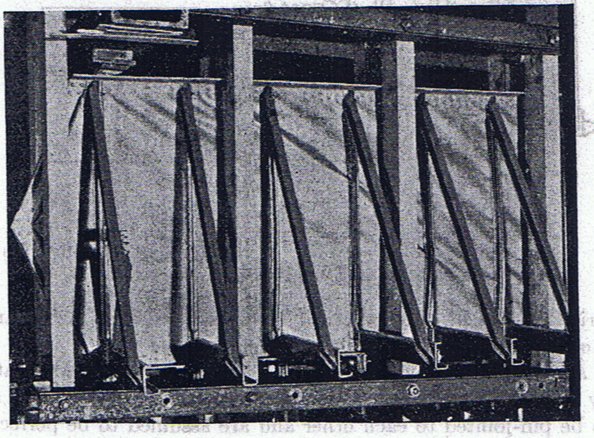


Fig. 13-*c*

Fig. 13 A Tension-Field-Type Beam Under Load
(The break occurs after buckling of the cross braces.)

In Fig. 13*c* the beam is shown after the break of the vertical rods, the allowable load on which was being determined by this experiment. Fig. 14 shows a similar sheet-metal beam carrying a single load on one end. The break occurred when the web tore. Such a tension-field-type beam may be compared with a framework having cross-braces placed in the same direction and diagonals at the same angle of 40 deg. as that of the tensile strains in the web of the beam (see Fig. 15). If, for the diagonals in a framework, straps are used of such a width that two adjacent ones just touch each other, and provided that they are of the same thickness as the sheet of the beam, these straps will be stressed to the same extent as the sheet.

In a tension-field-type beam the spar of each field between two cross-braces (see Fig. 16) is bent toward the sheet metal by the tensile strains in the web acting at the spars. The cross-braces which support both spars against these forces are subjected to compression loads which tend to cause buckling. Any of these stresses can be calculated very easily. The results of such calculations are, in accordance with the results of the tests, the following:

If the distance between the cross-braces is chosen within reasonable limits, such as being equal to about $1/6$ to $1/2$ of the height of the beam (i.e., the length of the cross-braces), the bending moments in the spar caused by the pull of the sheet have practically no effect upon the strength of the spars. On the contrary, the resistance of the spars to breaking strain is very high because of the comparatively close arrangement of the cross-braces which support the spars.

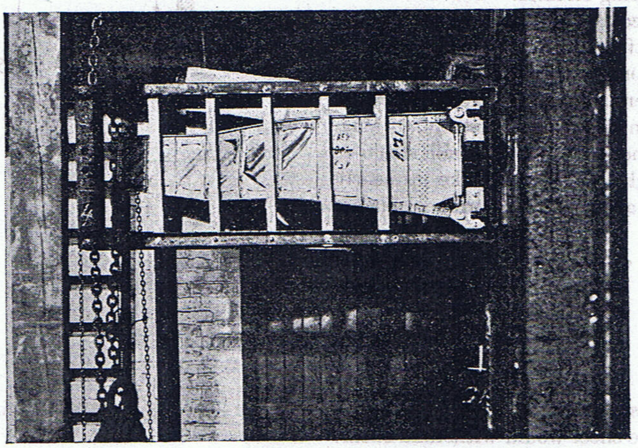


Fig. 14 A Tension Field Under Load
(The break occurs when the web tears.)

Furthermore, the deflection of the spars between two cross-braces on account of this pull of the sheet is so small that the spars may be assumed to be rigid. If great deflections of the spars were to occur the tensile strains in the web would become unequal and the directions of the wrinkles and tensile stresses respectively would no longer be parallel. In accordance with the calculation, such things, however, do not happen. Yet should this happen to a certain degree, due to the weakness of the spars, this problem could be checked comparatively easily by calculation, at least as far as this is of practical importance.

This unexpectedly high stiffness and resistance of the spars to bending forces is an essential fact. Thus, for instance, as the author subsequently heard, a Mr. Rode, in referring to deliberations of American engineers, called attention, in the Austrian magazine, *Der Eisenbau*, in 1917, to the observation that a web, after buckling, could still transmit forces by resisting tension. But, as Mr. Rode fears the insufficient transverse strength of the

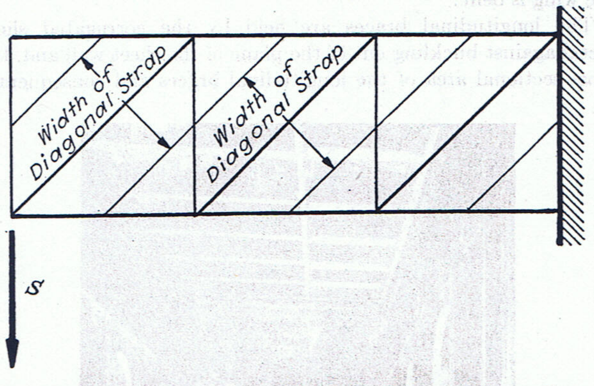


FIG. 15 COMPARING A TENSION-FIELD-TYPE BEAM WITH A FRAMEWORK BEAM

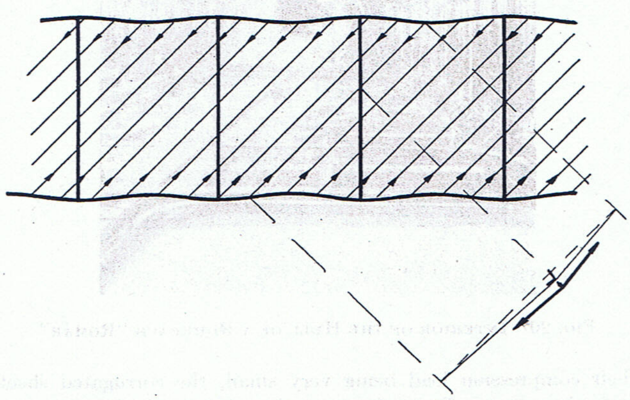


FIG. 16 SPARS AND CROSS-BRACES OF A TENSION-FIELD-TYPE BEAM UNDER STRAIN

(The strained sheet complicates buckling of the cross-braces.)

spars, he consequently does not conclude that such a design can actually be carried out to advantage.

It has been shown that the cross-braces are under compression strains. (See Fig. 16.) They must, therefore, be stiffened to prevent buckling. However, this stiffness can be comparatively small since the strained sheet metal holds them in place. For when a cross-brace buckles and moves out of the plane of the sheet metal it must also move the sheet to which it is riveted. Thereby the tension lines of the sheet suffer a displacement at the cross-brace with the result that the reaction of the stress lines against the cross-brace exert a force which is opposed to the buckling force. This essentially increases the resistance of the cross-braces to buckling stresses. This resistance has been calculated by the author. Depending on the distance between the cross-braces, it is about 4 to 7 times as great as Euler's buckling load for unsupported columns.

The cross-braces may also be arranged at an angle to the spars (see Fig. 17), in which case, under certain conditions, the member may be built lighter. Arranging the cross-braces at an angle of 120 deg. to the spars will have the least weight. The total weight of the web plus the cross-braces is thereby decreased by 15 per cent as compared with a sheet-metal wall having cross-braces arranged perpendicularly to the spars. However, this advantage can be used to the full only when the external shear S_1 acts essentially in one direction only. For this beam with diagonal cross-braces is considerably less resistant to the shear S_2 in the opposite direction. The shear S_2 in the direction shown must not exceed a value equal to about $^1/_3$ of the shear S_1.

In Fig. 4 a curve has been plotted which represents the weight required for such tension members. It will be noticed that

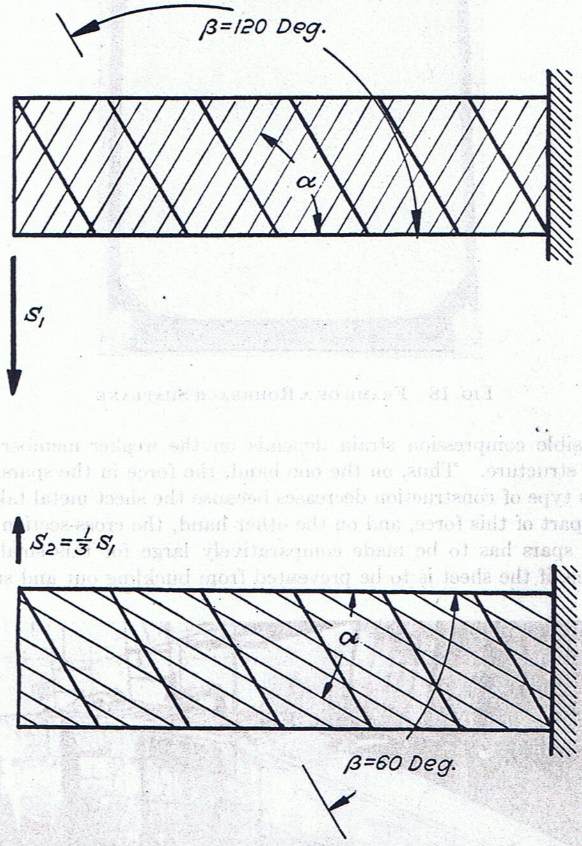


FIG. 17 EFFECT OF REVERSING LOAD

(The direction of the wrinkles [tensile strains] is changed if the external load S is reversed. The direction of the wrinkles approximately bisects the angle between the spars and the cross-braces, $\alpha = {}^1/_2\beta$.)

beams of great height and comparatively small shear, i.e., with high values of $h/\sqrt{S}$, are essentially lighter, for example, than corrugated sheet metal amply stiffened against buckling. Since these high values of $h/\sqrt{S}$ are frequently encountered in airplane design these tension-field-type beams are particularly suitable for airplane design.

Fig. 18 shows a frame of a Rohrbach seaplane, whose bottom beam has been designed as a tension-field-type beam. Figs. 19 and 20 show the hull, the walls of which represent tension-field-type beams.

The weight requirements for sheet-metal beams (Fig. 21), which must resist, in particular, longitudinal forces in addition to the shearing forces, will now be discussed.

In a fuselage made up of sheet-metal walls which are braced to resist buckling not only the spars but also the corrugated sheet-metal sides resist longitudinal forces. It should be observed that as the spars used at the edges of the fuselage are directly restrained against buckling in both directions, they can resist a much higher compression stress than can the sheet-metal wall which is held against buckling only by comparatively easily bending beams, namely the cross-braces. Naturally the permissible compression strain depends on the weaker member of the structure. Thus, on the one hand, the force in the spars of this type of construction decreases because the sheet metal takes up part of this force, and on the other hand, the cross-section of the spars has to be made comparatively large for this smaller force, if the sheet is to be prevented from buckling out and sustaining greater and permanent deformations before the calculated breaking load is reached.

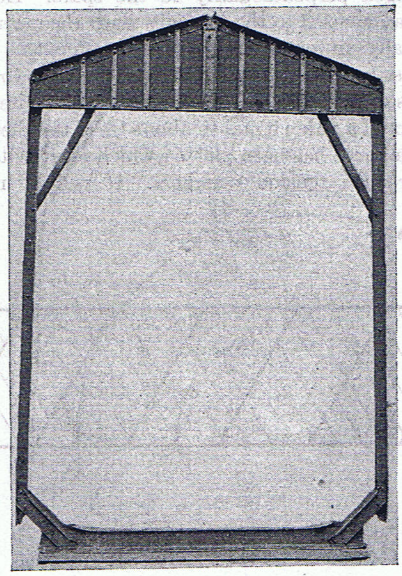


Fig. 18 Frame of a Rohrbach Seaplane

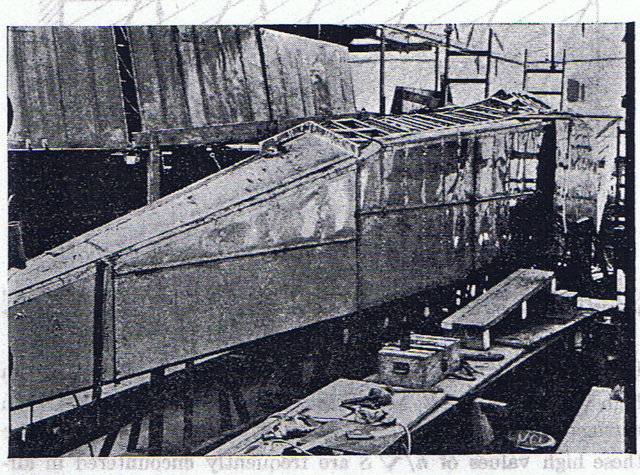


Fig. 19 Hull of a Rohrbach Seaplane
(The surface walls are designed as tension-field-type beams.)

In the tension-field-type beam the sheet metal buckles under a very small compression load and therefore does not resist compression loads to any appreciable extent. But as this buckling of the thin sheet metal takes place without appreciable strain and no permanent deformations remain after removing the load, the spars may be loaded as highly as warranted by the fact that they are supported by the adjacent walls of the fuselage. Though they must resist all of the longitudinal force in the tension-field-type beam they may, nevertheless, under certain conditions, be lighter than the spars of the sheet-metal beam which is securely braced against shear and compression.

Consider now the stresses in a wing of the Junkers type such as is shown in Fig. 22. The corrugated sheet metal, the corrugations of which are in the direction of flight, is fastened to strong spars that resist the bending moment. The torsional moment appearing during a vertical dive puts the corrugated sheet under a shear load. The sheet, therefore, has to be braced between the spars by longitudinal braces. These braces, running parallel to the spars, can be noticed in Fig. 22. How do these longitudinal braces behave under compression forces when the wing is bent?

The longitudinal braces are held by the corrugated sheet metal against buckling out of the plane of the sheet wall and, the cross-sectional area of the longitudinal braces and consequently their compression load being very small, the corrugated sheet metal is such an effective support that the permissible compression strain in the longitudinal braces is hardly lower than that in the spars. This can easily be proved with the help of the equation previously given for the compression forces in such sheet-metal walls.

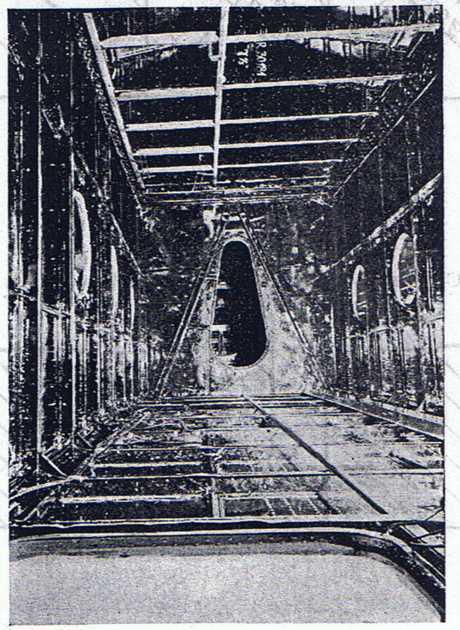


Fig. 20 Interior of the Hull of a Rohrbach "Romar"

We have thus arrived at a result quite similar to that obtained for the tension-field-type beam, i.e., the sheet-metal wall serves only to resist the shearing forces. The spars resist nearly all the longitudinal forces, but, on the other hand, may be loaded as highly as conforms to their being well supported in two planes.

Fig. 23 shows a Junkers wing which has the spars spaced so closely that the corrugated sheet need no longer be stiffened by special cross-braces.

It has been shown that sheet-metal beams may either be fitted with sheet metal which is securely braced against shear or be designed as tension-field-type beams. A warning should be issued against the middle course. If a web is made with corrugations, as shown in Fig. 24, and if the distance between these corrugations is made larger than would conform to the optimum strength of the plain, smooth part of the sheet between the corrugations against shear, then this part of the sheet will buckle and exert tensile forces on the corrugations. This stretches out the corrugations, and ugly bumps or protrusions will remain in the sheet when the load is removed. Even in the case where special diagonal bracing is used to resist the shearing forces, the distance between the corrugations must be chosen cautiously.

Thus far the structural weights of different sheet metal constructions have been compared with each other. There remains the comparison between the weight of these constructions and that of fabric-covered structures. This comparison will give different results, depending on the size of the airplane. Since the external forces exerted by the air on the plane and, consequently, the shearing stresses in the sheet-metal beams are rising at least with the square of the lineal dimension, the thickness of the sheet required for taking up the shear increases at least in direct proportion (linear) to the size of the plane.

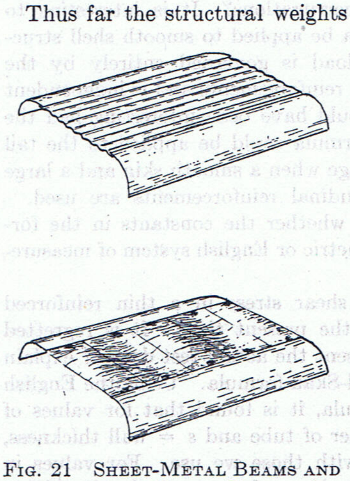


Fig. 21 Sheet-Metal Beams and Tension-Field-Type Beams Securely Braced Against Shear and Compression and Under a Load of Compression Forces Acting in Direction of the Spars

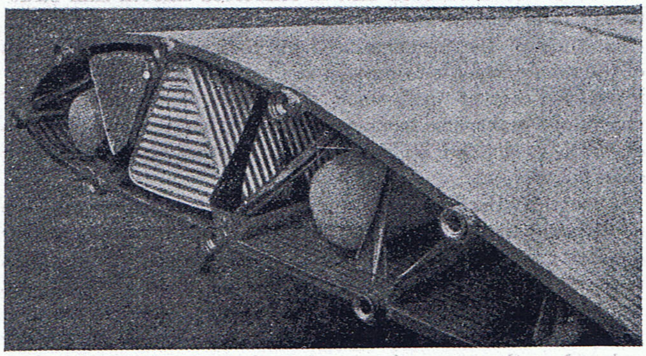


Fig. 22 Interior of the Wing of the "Bremen" (Junkers W 33)
(Note the longitudinal bracing running parallel to the spars.)

For small airplanes the required thickness of the sheet is so small that the sheets must be made thicker than this calculation would demand in order to make them secure against accidental local stresses. Moreover, sheets less than 0.3 mm. (0.0118 in.) thick are difficult to manufacture in sufficiently large sizes and such a sheet-metal construction will, under these conditions, of course, be heavier than a small fabric-covered plane. It should be added that for small and medium-size airplanes, corrugated sheet metal appears to be preferable to smooth sheet metal because it has a higher resistance to local stress and because very thin plane sheets are easily deformed in riveting.

However, for larger airplanes the strength in shear is the deciding factor as far as the thickness of the sheet metal is concerned. Such fully utilized sheet beams are, at all events, lighter than a framework, if they are, for example, built as tension-field-type beams. For heavily loaded, very large planes, therefore, the metal-covered type may be the most favorable solution in so far as weight is concerned. However, those parts of the wings, even of large planes, which are under little strain, particularly in the neighborhood of the trailing edge, may be covered with fabric, as it has been done, for example, on the huge Dornier seaplanes "Superwal" and "DoX."

Fabric-covered airplanes have been compared in this paper with metal-covered ones only with regard to their respective weights. The other advantages and disadvantages are so well known that only brief mention is necessary.

Metal-covered planes require a greater amount of work in the design room and the shop and are a little more difficult to repair. The construction of the wings of very small planes is particularly difficult.

Metal-covered wings have a greater air resistance than those covered with fabric. This holds true not only for corrugated-sheet-metal but also for smooth-sheet-metal covering, as this deforms under the strain of the air pressure and because the frictional resistance is increased on account of the rivets and especially bracing placed on the outside. The advantages of metal-covered airplanes are their durability and lower fire hazard. Very large all-metal airplanes are lighter than fabric-covered ones. The use of wood for pontoons as compared with the use of metal has the disadvantage of water-logging and thereby increasing the gross weight.

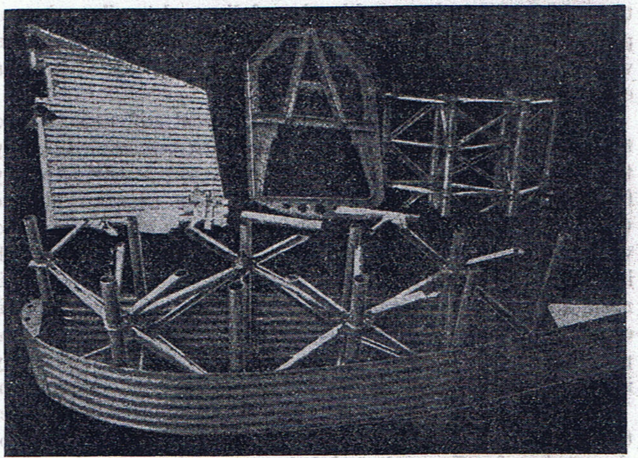


Fig. 23 Junkers Wing
(The spars are arranged so closely that the corrugated sheet is secure against shear even without special bracing.)

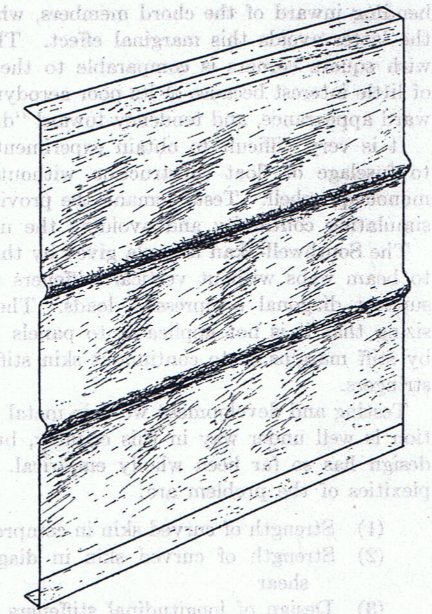


Fig. 24 Sheet-Metal Beam With Longitudinal Corrugation
(If the distance between the corrugations in a plane sheet is too great the sheet will buckle between the corrugations and exert tensile stress on the corrugations in a manner similar to the tension field. These are thereby stretched out.)

An attempt has been made in this short paper to survey the most important problems of strength encountered in the design of metal-covered airplanes. The discussion has been restricted to plane sheet-walls, because the problems of strength of curved sheet-walls have not yet been settled entirely.

Discussion

Col. V. E. Clark.[8] The paper is most interesting and valuable at this time because of the rapidly increasing use of duralumin and "Alclad" monocoque construction in this country.

It is believed that there is at present more need for experimental data on the sheer strength of thin plate girders and reinforced shells than on any other phase of airplane structure. In a way the use of the term "sheer" is an unfortunate habit among engineers as it tends to obscure the fact that shear in the web of a beam is a combination of diagonal tensile and compressive forces acting at right-angles to each other. A thin web without vertical stiffeners is buckled in compression at a comparatively small stress.

In the case of a girder employing vertical stiffeners refitted to a thin web, the compressive stresses must be confined largely to the stiffeners and the chords, since the web is effective only for tensile stresses. There is no sharp division between the case where the web will support the compressive component and where it will not. The allowable compressive stress in the web is gradually reduced as the d/s ratio is increased. (d = minimum spacing of reinforcing members.) The addition of vertical stiffeners to a thin web not only provides additional compression-resisting cross-sectional area, but also undoubtedly increases the ability of the web to support diagonal compression.

Credit is due Dr. Wagner for inviting attention to the fact that the shear strength of thin webs is a function, not only of the spacing of stiffeners, but of their compressive strength as well.

There is an important difference between the plate girder and the side wall of a stiffened monocoque shell of curved cross-section. The shear strength of the former is reduced by the bending inward of the chord members, while the continuity of the latter avoids this marginal effect. The flat-sided fuselage with square corners is comparable to the plate girder, but is of little interest because of its poor aerodynamic qualities, awkward appearance, and tendency toward "drum-head" vibration.

It is very difficult to obtain experimental results applicable to fuselage or float construction without testing a complete monocoque shell. Tests demand the provision of a plate girder simulating continuity and avoiding the usual marginal effect.

The Southwell-Skan formula given by the author is applicable to beam webs without vertical stiffeners where the web must support diagonal compressive loads. The fact needs emphasizing that it is not applicable to panels bounded on all sides by stiff margins or to continuous skin stiffened by frames and stringers.

Testing and development work in metal monocoque construction is well under way in this country, but the application to design has so far been wholly empirical. A few of the complexities of the problem are:

(1) Strength of curved skin in compression due to bending
(2) Strength of curved skin in diagonal tension due to shear
(3) Design of longitudinal stiffeners to withstand inward component of tension in skin
(4) Strength of main bulkheads
(5) Loads on and strength of curved frames.

The writer would like to put a few questions regarding details and uses of the formula presented by the author that do not seem clear.

In the formula giving the shear force S required to buckle walls, I_x and d_v are not explained. Is the assumption correct that I_x is the moment of inertia of the section of the longitudinal reinforcements, d_x the distance between them, and I_v the moment of inertia of the transverse reinforcements, and d_v the distance between them? If this is true, how would the value of I_x/d_x be calculated in the tail portion of a monocoque fuselage where there are no longitudinal reinforcements and the skin is corrugated? Could each corrugation be treated as a reinforcement and d_x be the pitch of the corrugations? It is interesting to note that, should this formula be applied to smooth shell structures, the maximum shear load is governed entirely by the properties and location of the reinforcements and is independent of the skin thickness. It would have been interesting had the author explained how this formula could be applied to the tail section of a monocoque fuselage when a smooth skin and a large number of equal size longitudinal reinforcements are used.

The article does not state whether the constants in the formulas are calculated for the metric or English system of measurement.

The subject of allowable shear stress in a thin reinforced sheet is very interesting at the present time. It is regretted that Dr. Wagner did not present the actual test data or explain the deviation of the Southwell-Skan formula. Using the English system of units in this formula, it is found that for values of $d/s = 50$, where d = diameter of tube and s = wall thickness, it gives values comparable with those we use. For values in tubes with d/s less than 50, it gives values proportionally higher than those now recommended in this country. For values in thin web beams and monocoque shells with cross-bracing, where d/s = 100 to 350, it gives values far below those based upon our test data. It is believed that in reinforced smooth skin structures d/s is seldom less than 100.

A study of the formulas used for computing the properties of the reinforcements to prevent the buckling of the web is very interesting. It is understood that I_x/d_x = the moment of inertia of a transverse section of a longitudinally corrugated web of width d_x divided by the width or the height, as in a wing spar.

Apparently the deeper the corrugations, the greater will be the shear load capacity of the web. It is regretted that the author did not give this optimum depth for the best strength-weight ratio—the depth governed by the sheet thickness and d_x. It would be interesting to know if the same formula may be used for the so-called "wandering web" used sometimes in wing spar webs where the corrugations are large in proportion to the sheet thickness and lie normal to the plane of horizontal shear. If it is applicable, then d_v must be the pitch of the corrugations and I_v the moment of inertia of a cross-section of a complete corrugation, about its neutral axis.

The author's formula giving the allowable compressive load presents a very interesting question—whether the sectional properties and spacing of the longitudinal and transverse reinforcements have an equal effect in calculating the allowable compressive load. It appears that the material in the longitudinal reinforcements, if any, has a dual purpose—that of preventing the skin from buckling and that of carrying some of the compressive load directly while the transverse reinforcements simply prevent the skin and longitudinals from buckling and do not carry any of the compressive load which is acting normal to the transverse members. The same formula contains another very interesting factor—that of the effect of the torsional strength of a transverse reinforcement. Is it correct to calculate T_v as the torsional moment that the section of the transverse member will carry at the ultimate or yield point and G as the torsional modulus of elasticity? It is not clear in the paper how this strength affects the allowable compressive load normal to the reinforcement. It is noted that the author did not compare the diaphragm or bulkhead type of transverse reinforcement with the ring type. In the design of a bulkhead

[8]Buffalo, N. Y. Mem. A.S.M.E.

is I_v calculated for a section from the center to the outer fiber at a point in question?

In applying this formula to a monocoque fuselage covered with corrugated sheet and not employing any longitudinal reinforcements, is it correct to calculate I_x as the moment of inertia of a cross-section through one corrugation of the skin and d_x as pitch of corrugation? Again, it is interesting to note that in applying this formula to a smooth-skin monocoque structure the thickness of the skin does not enter into the calculations for the maximum compressive load when I_v and I_x apply to the transverse and longitudinal reinforcements, respectively.

The writer agrees with Dr. Wagner that the radius of curvature has an important influence on the allowable compressive stress in the region of small radii.

It has been our experience that the effect of the radius of curvature on the allowable compressive stress in a smooth metal monocoque shell cannot be plotted as a linear function. From test data available it appears that the effect of an increase in the radius of curvature is practically negligible when the radius of curvature is greater than 1300 times the skin thickness, while the reduction of the radius of curvature from $300t$ to $200t$ increases the allowable compressive stress about 9 per cent, where t = sheet thickness, and for smaller radii the rate of increase is greater.

It has been found that failure in compression in metal monocoque structures results in an inward buckling of the skin and reinforcements. This is apparently due to the eccentric loading of the reinforcements.

The author has made detailed reference to square-section bodies where four main longerons are used to carry the principal stresses. It would have been interesting had he treated a round or elliptical section with a number of longitudinal reinforcements all having the same section. In such structures there are regions of the skin that lie between the regions supporting maximum shear and those supporting maximum compression that are subjected to both shearing and compressive forces. It is believed that in these regions a careful study should be made to select the proper amount of skin or shell reinforcement.

It is interesting to note that the author gives an angle of 120 deg. between the longitudinal and transverse reinforcements as the best angle to take shear in one direction. Since in the opposite direction we require in the case of wing spars about one-half the main strength and this angle reduces the strength to one-third, this rule might not be applicable to wing-spar design.

The author's reference to "tension field type" beams apparently applies to all reinforced thin sheets where d/s is large and the sheet wrinkles under a light shear load which is actually carried by tension lines. The author states that beams built as the "tension field type" are "lighter than a framework." This might open a discussion for those who are fostering the truss type of construction for very deep units. It is assumed that the author means "truss" when he uses the word "framework."

It would have been interesting had the author given a general idea regarding the amount of reduction in performance when corrugated covering is used on fuselages. The increase in drag may be partly due to the angle existing between the line of air flow and the axis of the corrugation.

Closure by J. Otto Scherer[9]

Colonel Clark's discussion of the paper brings up a number of interesting points. The writer is sorry that he cannot answer the questions as to the derivation of the formulas, etc., but believes such should be answered by Dr. Wagner himself.

Dr. Wagner, it appears, has rather slighted two important forms of all-metal construction, forms which are steadily increasing in popularity in this country, while making a case for the "tension field" beam, with which he has had extensive experience and which has given very good results.

With regard to the increased drag caused by the wrinkles appearing in the "tension fields" of Dr. Wagner's beams, it might be pointed out that about two years ago the D.V.L. published the results of rather extensive full-scale tests conducted to determine the effect of skin smoothness on drag.

These tests showed that an absolutely smooth surface gave a considerably lower drag. However, as soon as this surface was marred, if even only to the extent necessitated by countersunk rivet heads, the drag increased to a "normal" figure, which varied but little for all the usual types of covering.

By "usual types of covering" are meant a fabric covering, as normally applied and finished, a plywood covering with its ever-present small unevennesses, a smooth metal skin with either countersunk or round-head rivets, and the corrugated Dural skin. The "tension field" construction would probably present surfaces about the same as a normal plywood wing covering.

With regard to the corrugated-skin construction, it may be of interest to mention that the Junkers Works use two depths of corrugation, depending on whether the structural stresses carried by the skin are relatively high or low. On such parts as the fuselage and the portions of the wing near the fuselage, the corrugations have a depth equal to $1/3$ the pitch, while on the outer parts of the wing, etc., the depth of the corrugations is only $1/5$ pitch.

The metal monocoque fuselage employing a corrugated skin is usually strong enough to carry all the flying loads, even though no longitudinals are incorporated. Experience, however, has shown that it is desirable to run a rather stiff longitudinal along the bottom center of fuselages of oval section or along the lower corners of those of rectangular section. Such longitudinals are of considerable value in protecting the fuselage against damage incident to accidental mishandling on the ground.

In conclusion may one take the liberty to remark that, though designers in this country are, on the whole, inclined toward types of all-metal construction in which the skin is designed to carry the compression as well as the tension components of the shear stresses, Dr. Wagner's type of construction is well worth consideration and well applicable to good advantage on a number of types built in the United States today.

The "tension field" construction could nicely be applied to almost all jobs which make use of a rectangular welded steel-tube fuselage with fabric covering. The fabric, with its dope, weighs just about as much as a thin Dural sheet, but does not contribute anything to the strength of the structure. The Dural sheet, on the other hand, can safely be included in the structure, making possible a reduction in the weight of the trussing without any sacrifice of strength.

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