Library L. M. a. L.

TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 490

STRUCTURES OF THIN SHEET METAL

THEIR DESIGN AND CONSTRUCTION

By Herbert Wagner

Washington
December, 1928

3 1176 01353 1653

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

TECHNICAL MEMORANDUM NO. 490.

STRUCTURES OF THIN SHEET METAL, THEIR DESIGN AND CONSTRUCTION.

By Herbert Wagner.

Introduction

The advantages of light metals for airplane construction outweigh their disadvantages, at least for many airplane types. Consequently, many airplane builders, both at home and abroad, have adopted metal construction, either in whole or in part. On investigating the sheet-metal construction of a number of such airplanes, we are surprised at the great variety of methods employed. Every constructor holds a different view of the possible stresses and reactions in a piece of sheet metal and of the nature of their transmission.

From the standpoint of strength the fundamental difference between an all-metal airplane and, e.g., a steel-tubing airplane, consists in the coverings. In contrast with a cloth-covered steel-tubing airplane, in which the stresses are simply transmitted by the inner structure, an all-metal airplane enables the transmission of a portion of the stresses by means of the outer sheet-metal coverings. Since these coverings constitute a large share of the weight of the cell, the economy of this type of construction depends on how far the greater weight of the

*"Ueber Konstructions- und Berechnungsfragen des Blechbaues," a preprint received from the Paris Office of the National Advisory Committee for Aeronautics, August 15, 1928.

sheet-metal covering, as compared with fabric covering, can be offset by reducing the weight of the interior structure.

I believe it is not going too far to say that the most important characteristic of any type of all-metal construction is the manner of applying the sheet-metal covering. It not only determines the inner structure of the airplane, but greatly affects the choice of the aspect ratio, the external bracing of the wings, etc.

It would lead me too far if I should now take up in detail the relations between the inner and outer structure. I will therefore confine my remarks to a brief survey of the uses of sheet-metal coverings in conjunction with the inner structure. I will then elaborate on a special method of construction, on which I have worked during my connection with the Rohrbach firm and which enables simple and cheap shop work combined with great simplicity and lightness. Dr. Rohrbach has been so kind as to allow me to use photographs of some of the experiments I performed while with the company. These photographs will make my descriptions clearer.

In connection with the discussion of this method of construction, I will also touch upon other important questions regarding the strength of sheet metal. I shall, however, only indicate the most essential principles. As regards more detailed considerations and calculations, I refer you to the articles to appear later in the Zeitschrift für Flugtechnik und Motorluftschiffahrt. I shall not discuss the question of compressive strength, which is also important in the construction of all-metal airplanes.

Constructional Methods

The first successful builder of all-metal airplanes, Professor Junkers, made a special study of the method of attaching the sheet-metal covering to the framework. His conclusions found expression in the constructional method of his 1915 iron monoplane and in a patent of that year.

Two kinds of stresses are developed in the sheet-metal wing covering:

1. Longitudinal stresses produced by the bending of the whole wing by the air forces (e.g., compressive stresses on the upper side and tensile stresses on the lower side of the wing);

2. Shearing stresses, chiefly due to torsion.

The numerous stiffeners, which are welded to the sheet-metal covering, afford the only way to obtain buckling strength, both against the shearing and against the compressive stresses. In order, however, to enable the stresses in the sheet-metal covering to approach the yield point and thus utilize the material to the best advantage, the distance between these stiffeners in the case of steel, must not be over sixty times the thickness of the sheet metal and still less in the case of duralumin.

For these thin steel sheets the distance between the stiffeners is 15 mm (0.59 in.). The inherent difficulties are thus already apparent in this first solution of the problem. In changing to duralumin, which cannot be welded, Professor Junkers abandoned this method of construction and used the sheet metal in the corrugated form. Since the corrugations on wings run in the direction of the air flow, they do not help to take the bending stresses in the direction of the span, but they do resist the torsional stresses in the direction of flight. I will not go farther into the strength problems of this successful method of construction, which is not simple, especially in its application to the fuselage where, due to the position of the corrugations, it can assist in resisting the longitudinal stresses and must therefore always be considered in stresses resulting from the simultaneous action of longitudinal and shearing stresses.

In the Dornier type of wing the metal skin serves principally as a covering. Great torsional moments, which could hardly be absorbed without the aid of the metal skin, are avoided by bracing the wings with struts. Even in the fuselage of a Dornier airplane, the full utilization of the metal skin is more or less dispensed with. Especially in the more highly stressed fuselages, for which these problems first rightly assume importance, i.e., in the fuselages or hulls of large flying boats, the lateral stresses are absorbed by a system of compression struts arranged in the form of a K. This is assisted only by the narrow strip which rests on the stiffeners and is riveted to them.

Another interesting type of construction, which resembles in its effect the Junkers corrugated sheet metal, is used by Breguet in his duralumin fuselages. The bottom surfaces of the U frames, adjoining one another in the longitudinal direction, form the outer surface of the fuselage. The lateral ends of the U frames are bent inward and serve to hold them together.

Flat Sheet-Metal Girders with Very Thin Webs

I now come to the constructional type I wish to discuss in greater detail. In the above-mentioned experiment of Junkers, we saw that it was hardly possible to reinforce a smooth outer skin with stiffeners close enough together to resist torsional and compressive stresses. I have put myself the question: "What is the behavior of a sheet-metal skin, which is so thin that it offers no appreciable resistance to buckling?" In this extreme case the bending strength of the metal skin is zero.

Figure 1 represents such a sheet-metal girder. It has an upper and a lower flange, a very thin sheet-metal web and vertical reinforcing strips or stiffeners. It is here subjected to the action of a weight P. Even with a very small load, oblique folds begin to form in the web. After this buckling of the web, however, the load can be greatly increased, e.g., 100 to 500-fold, without causing the girder to fail and without the folds forming any excessive unevenness. The depth of the folds may reach 5 mm (0.2 in.) and their width, perhaps 100 mm (3.94 in.). They are therefore quite small corrugations. I will briefly discuss the principle of this formation of folds.

Figure 2 represents a square piece of very thin sheet metal. It is as thin as paper. We can then make folds in this sheet, whose bending strength is zero, without exerting any appreciable force, as shown in Figure 3, thus somewhat lessening the distance between the edges A. We can then apply tensile stresses to the upper and lower edges of the sheet (Fig. 4). This does not change the direction of the folds, but their depth is somewhat diminished by the lateral contraction. There is no force exerted on the sheet perpendicular to the direction of the folds. Under these conditions the greatest elongation is in the direction of the tension. This tension, in the sense of the strength of the material, is therefore a principal tension. Since there is no tension perpendicular to this, i.e., since the second principal tension is zero, we here have to do with a state of uniaxial tension.

I here call your attention to a disturbing phenomenon, when the edges are not free but are riveted to the sides of a frame. It is then apparent from Figure 5 that the edges cannot fold. It can be demonstrated, however, that this effect disappears with an infinitely thin sheet. The above statements therefore hold good even for this case of rigidly held edges.

Figure 6 represents a square field enclosed by four bars hinged together at the corners. We will assume these bars to be perfectly rigid. A thin metal sheet receives the transverse or shearing force. The load P then produces shearing stresses τ in the metal sheet. The direction of the principal tensions is at 45° to the direction of these shearing stresses. The principal tension σ_1, is a tensile stress in the direction of the greatest elongation of the sheet. The other principal tension σ_2 is a compressive stress. If the sheet is very thin, it will soon buckle under the compressive stress and form folds in the direction of the tensile stress (Fig. 7). On further increasing the shearing force P, the tensile stress σ_1 rapidly increases, until, under a very large force, it absorbs nearly the whole shearing force P. The field has thereby developed uniform folds. This is called a diagonal-tension field.

The value of the tensile stress σ_1 can be easily calculated. It is $\sigma_1 = 2 \frac{P}{a\ s}$, in which s represents the thickness of the metal sheet. It is therefore twice as great as the shearing stress would be, if the metal sheet were subjected to the latter.

If the upper and lower bars (Fig. 8) are connected by another rigid bar hinged to their central points, no change occurs in the direction of the greatest elongation of the sheet, which remains at 45°, as likewise the direction of the folds.

Figure 9 shows the model of a sheet-metal girder supported at the right-hand end and loaded with bags of shot with the aid of transmission levers. The upper and lower flanges and the thin metal web are easily recognized. The vertical bars are on the back side, their location being indicated by the rows of rivets. All dimensions are proportional to those of the full-sized girder.

We can clearly see the folds, which are quite uniform over the whole web. Since the shearing stress in the girder increases toward the right, due to the loading of the individual bars, the folds are somewhat deeper in the right portion of the web than in the left. As shown in the photograph, the load already greatly exceeds the one at which the first buckling occurred. The initial buckling could be produced by a slight pressure of the hand on one of the levers, representing only a very few kilograms of transverse or shearing force. The folds shown in this photograph still fall far short of being permanent deformations. After removing the load they completely vanished. Permanent folds are formed only when the tension in the metal sheet has nearly reached the yield point. The local bending stresses, resulting from the formation of the folds, hardly affect it.

Figure 10 shows the back side of the sheet-metal girder under a much greater load. The diagonal-tension field is very clearly indicated by the folds. The angle between the flanges and the direction of the folds (which, as mentioned above, is 45° for perfectly rigid bars) is somewhat smaller for a sheet-metal girder with bars not perfectly rigid, due to the compressive stress in the vertical bars, which makes the direction of the greatest elongation in the web with respect to the flanges somewhat less than 45°. In accord with the calculation, this angle of the folds is always somewhere between 40 and 42°.

At the load shown in this picture, the yield point of the web has been somewhat exceeded. For simplicity of calculation of such sheet-metal girders, the fact is very important that, even when the yield point of the web is exceeded, the state of tension of the whole is not essentially altered. On the contrary, the hypothesis of the negligibly small bending strength of the metal sheet applies better than before.

Figures 11-12 show the girder after the yielding of the vertical bars, whose admissible load was being tested in this experiment.

Figures 13-15 show a similar sheet-metal girder, which is loaded by a single weight at one end, under two different loads and after the rupture of the web.

Figure 16 shows how the flanges are bent inward between the vertical bars by the tension exerted on the flanges by the web. The vertical bars which support the flanges against these forces are subjected to compressive or buckling stresses.* All these stresses can be easily calculated. In accord with the experiments, the calculations give the following results.

*As easily shown, the compressive force in a vertical bar is $V = P \frac{t}{h} \tan\alpha$, in which P denotes the transverse or shearing force, t the distance between the vertical bars, h the height or thickness of the girder, and α the angle between the direction of the folds and that of the flanges. If α is 40-42°, then $V = 0.9\, P \frac{t}{h}$.

If the distance between the vertical bars is kept within reasonable limits, say from 1/6 to 1/2 of their length, the bending moments produced in the flanges by the tension of the web have no practical effect on the strength of the flanges. On the contrary, the buckling strength of the flanges is very great, due to the relatively narrow spaces between the vertical bars. Especially with bars of open cross section, the buckling strength is increased by the fact that the tension in the web prevents the flanges from turning.

Also due to the tension of the web between two vertical bars, the deflection of the flanges is so slight that the latter may be regarded as rigid. Were large deflections to occur in the flanges, the tensile stresses in the web would not be uniform and their directions would no longer be parallel. In accordance with the calculation, however, such phenomena do not occur and even in case the flanges should happen to be so weak that these phenomena would be produced to some degree, they can be quite simply determined by calculation, at least in so far as they are of any practical importance.

I consider this unexpectedly high resistance and rigidity of the flanges, with respect to the above-mentioned bending forces, important. Thus, for example, as I recently learned, it was stated by Mr. Rode with reference to the ideas of American engineers in the Austrian magazine "Der Eisenbau" (Iron Construction) in 1917, that a sheet-metal web, even after buckling, can still withstand shearing forces, because it still has tensile strength. Mr. Rode did not conclude, however, that such a method of construction would be desirable, because he feared insufficient bending strength of the flanges.

As regards the compressively stressed vertical bars, it may be remarked that the buckling of these bars, out of the plane of the stretched web to which they are fastened, is rendered considerably more difficult. The calculation shows that their buckling load, depending on the spacing ~~according to the wide intervals~~ between the bars, is four to seven times as great as the Euler buckling load for unstressed rods. In reality, however, this buckling strength is not utilized since, due to its magnitude, it is always possible to make the inertia moment of these bars so great that, even with the use of sufficiently solid cross sections which preclude buckling, the yield point is reached before the calculated buckling load. Sheet-metal girders of this type are not only very light, but are also very rigid in proportion to their weight.

The folds produced by the stressing of such girders hurt neither their appearance nor their aerodynamic behavior. In uncovering the wings, care must be taken, however, that this buckling is only slight in the position of normal flight. This is always easily attainable, however, since only slight torsional moments are produced in box wings in this flight position.

For comparison, I will add a few words regarding other types of sheet-metal girders. A transition between the type, in which the shearing forces are absorbed by special diagonal braces (tension strips or compression struts) and the above type is formed by the type in which, with relatively long intervals between the vertical bars, a portion of the sheet-metal covering is regarded as tension diagonals, whose width is then generally about 1/5 of their length. In comparison with the latter type, the above-described type is preferable, not only because the whole web is involved in the transmission of the shearing stresses, but still more because of the less weight of the vertical bars due to their greater buckling strength.

I wish to call attention to one more structural method in which flat metal sheets are laid over a complete framework as an outer covering, these sheets being reinforced by stiffeners at quite long intervals. The stiffeners running parallel to the spars do not indeed protect the sheets against buckling under the shearing stresses, because they are too far apart for that purpose. On the other hand, they prevent the formation of an effective diagonal-tension field, because the tensile stresses must be transmitted along the stiffeners lying obliquely to them. These stiffeners offer no resistance to such a tensile stress, but are only loosened somewhat. This type of construction prevents all cooperation of the sheet-metal covering and is therefore only superfluous weight. I would either put the stiffeners or corrugations so near together as actually to prevent buckling or leave them out entirely. The "golden mean" would seem to be of no advantage in this case.

Figure 17 illustrates another type of construction. It is a transverse frame of an old Rohrbach flying boat with lattice-work at the bottom. The transverse frame in Figure 18 has a sheet-metal girder at the bottom. This type is not only less expensive to make, but is also stronger than any other type in proportion to its weight.

Figure 19 shows the uncovered side of a seaplane fuselage and Figure 20 shows it after the outside covering has been added. Attention is called to the perfectly regular riveting and to the absence of all gussets and diagonal bracing in this highly stressed fuselage.

Figure 21 shows the inside of the fuselage of a Rohrbach-Rocco seaplane, with its sheet-metal floor, girders and walls. The longitudinal walls of the wings are also advantageously built in the form of sheet-metal girders, thus obtaining lightness and the possibility of making the box girders of the wings water-tight.

In the above-described type of construction, the weight is not increased by the sheet-metal covering, since, in most cases, it is hardly possible to find any other type so light as a sheet-metal girder. This statement is true at least for large airplanes. On small airplanes the metal covering cannot for other reasons generally be so thin as would be allowable from strength considerations alone.

Buckling Strength of Flat Metal Sheets

Thus far I have spoken only of metal sheets which are so thin that their buckling strength is negligible. There are sheet-metal girders, however, which, with only a small height, have to absorb such great shearing forces that their webs must be relatively thick and therefore secure against buckling, provided the stiffeners are not altogether too far apart. In the short time at my disposal, I cannot further discuss the laws governing the construction of such girders, but must content myself with calling your attention to the problems involved regarding the strength of metal sheets.

Such a sheet is first subjected to shearing forces. The buckling strength of a flat sheet in opposition to shearing forces can be calculated, with the aid of the theorem of the minimum work of deformation, by methods which were chiefly developed by Timoschenko. The shearing stress involved in the buckling is given for laid-on sheets by the formula $\tau = 5\ E(s/t)^2$ and for framed sheets by the formula $\tau = 7.5\ E(s/t)^2$. Here E represents the modulus of elasticity of the material, s the thickness and t the width of the sheet, its length being assumed to be very great. Since the difference in the buckling stress between the laid-on and framed sheets is not great (only 50%) the estimation of the degree of rigidity of such sheets plays a much less important role than in the case of compression struts.

Figure 22 shows a device used to verify the calculation for framed sheets. Each of the four edge pieces consists of two steel bars between which the metal sheet is clamped with the aid of strong screws. The four bolts at the corners are not tightened, but act simply as joints. By means of a pulley block and tackle, one steel bar was pulled longitudinally, thereby subjecting the metal sheet to a shearing stress. An observer, placed at some distance from the sheet with an electric lamp, could quite easily determine the instant of the inception of the folds by the distortion of the image of the lamp in the metal sheet, especially as the formation of the folds began quite suddenly. The result agreed very well with the calculation, in which connection your attention is called to the fact that a similar result has been obtained by similar experiments elsewhere (in England, if I mistake not).

Now the web of such a sheet-metal girder is not subject simply to shearing stresses. Due to the longitudinal stresses in the flanges and also in the vertical bars, the web is also subjected to longitudinal stresses and it is necessary to investigate the buckling strength of flat sheets simultaneously subjected to shearing and longitudinal forces. This calculation, made with the aid of the principle of the minimum work of deformation, gives a simple result. If σ_x and σ_y denote the longitudinal stresses and if these stresses act simultaneously with a shearing stress τ, then the shearing stress at which buckling occurs can be calculated, for a laid-on sheet, from the equation

$$\frac{\tau^2}{\kappa^2} = \left(2\sqrt{\frac{\sigma_y}{\kappa} + 1} + 2 + \frac{\sigma_x}{\kappa}\right)\left(2\sqrt{\frac{\sigma_y}{\kappa} + 1} + 6 + \frac{\sigma_x}{\kappa}\right)$$

and, for a framed sheet, from the equation

$$\frac{\tau^2}{\kappa^2} = \left(\frac{4}{\sqrt{3}}\sqrt{\frac{\sigma_y}{\kappa} + 4} + \frac{4}{3} + \frac{\sigma_x}{\kappa}\right)\left(\frac{4}{\sqrt{3}}\sqrt{\frac{\sigma_y}{\kappa} + 4} + 8 + \frac{\sigma_x}{\kappa}\right)$$

in which

$$\kappa = \frac{s^2}{t^2}\ \frac{\pi^2}{12}\ E\ \frac{m^2}{m^2 - 1}$$ (m = coefficient of lateral contraction).

The results of these calculations can be plotted on coordinate axes. The shearing stress, at which buckling occurs with the simultaneous operation of all these stresses, can then be determined from the plotted curves. Nevertheless, τ and σ_x can also be given. Then the σ_y at which buckling occurs can be determined from the diagrams. These values can therefore be determined in the construction office by a glance at the diagram, almost without numerical computation.

In this connection, however, it must not be forgotten that the problem is not always so simple. The stresses are not always the same over the whole field and the shape of the field does not always correspond to the one on which this calculation is based. In this case it is of advantage to use considerations similar to the ones employed in the previously mentioned article by Rode and to which you are here referred.

It is not so easy to answer questions regarding the state of tension in metal sheets after buckling, when the buckling strength cannot be disregarded, for such disregard is permissible only when the sheets are stressed far beyond their buckling strength. For relatively thick sheets, however, in which the yield point is reached soon after buckling, deeper considerations are involved, which extend even to their behavior beyond the yield point and to combinations of stresses. It is possible, however, to select simple viewpoints which I will consider in a future discourse.

Curved Sheet-Metal Girders

In conclusion I will say a few words on the behavior of curved metal sheets. If a sheet-metal cylinder of circular cross section is subjected to pressure in the direction of its axis, the thickness s of the metal being very small with relation to the radius r of the cylinder, buckling will occur in such a sheet long before the yield point is reached, and the supporting power of the cylinder is thereby exhausted. From general considerations it follows that the compressive stress $\sigma_D = k_D E \frac{s}{r}$, in which k_D is a constant. This constant k_D, as Lorenz says, can be calculated, on the assumption of symmetrical deformation with reference to the axis, to about 0.61.

In order to test these considerations, we tried, among others, an experiment with a compressed sheet-metal cylinder (Fig. 23). After the formation of several local humps, the cylinder suddenly buckled. There was no sign of symmetrical deformation from the beginning and there is none to be seen in this picture. Since the compressive stress is always too high in a buckling calculation in which a false deformation is assumed, I wish to warn against the use of the above value, at least for the conditions existing in airplane construction. This value k_D can be much more simply and reliably obtained from such an experiment than by calculation.

Also for curved sheets subjected to a shearing force, the shearing tension τ at the instant of buckling can be calculated from the equation $\tau = k_s E \frac{s}{r}$, whereby, according to approximate mathematical considerations, k_s is found to be somewhat less than $k_D/2$. Figure 24 shows an experiment with such a metal sheet subjected to shearing stresses. The angle at the center of the sheet was 90°. With this large angle the buckling occurred very suddenly and immediately caused permanent deformation. I here call your attention to the fact that, in such experiments with curved sheets, the compressive or buckling stresses scatter greatly and that a large number of experiments must be tried, in order to obtain a clear idea of the relations.

The above-mentioned shearing stress $\tau = k_D E \frac{s}{r}$ simply gives the resistance resulting from the curvature of the metal sheet. If the sheet is laid on marginal bars or secured between them, and especially if the thickness s is not too small in relation to the developed length t between the two bars, the metal sheet (due to this laying on or framing, then offers the same resistance as a flat sheet. At the instant of buckling we can therefore write:

For the laid-on sheet $t = k_s E \frac{s}{r} + 5 E\left(\frac{s}{t}\right)^2$ and

" " framed " $t = k_s E \frac{s}{r} + 7.5 E\left(\frac{s}{t}\right)^2$

With such sheets, therefore, especially when the angle at the center is not too great and the metal is thin, the first deformations do not occur immediately on buckling, but considerably later and only after the formation of deep folds. As to when such a sheet is to be regarded as broken, depends on how it is being used and is, in the last analysis, a matter of personal judgment.

Figure 25 shows a metal sheet with a smaller angle at the center, which can probably be designated as already broken, while Figure 26 shows two sheets which were stressed far beyond the permissible degree. At this point I may perhaps call attention to the fact that it is easy to calculate, on simple assumptions, the direction of these folds, at and after the time of buckling, in very good accord with the experiments, which is also important for the computation of the stresses in all the adjoining members.

The curved sheet shown in Figure 27 has a longitudinal stiffener as indicated by the row of rivets. This sheet has just buckled, but the folds do not yet represent any permanent distortion. Nevertheless, the sheet must probably be already designated as broken. In Figure 28, where the longitudinal stiffeners are closer together, the first folds are just forming. The load can therefore be considerably increased without causing permanent and excessive deformations. Such a sheet then forms a diagonal-tension field, as in the case of the previously discussed flat sheet-metal girder, which naturally leads to permanent deformations on further increasing the load (Figs. 29-30). Figure 31 shows the sheet after rupture.

The longitudinal stiffeners of such a sheet must, when the buckling point has been reached, divert the tensile stresses and thus undergo bending stresses from the forces acting perpendicularly to the sheet. The stiffeners must therefore be quite large and strong.

On the other hand, in the case of a curved sheet with circumferential stiffeners (Fig. 32), these stiffeners, after buckling begins, are not subjected to bending stresses, but only to compressive stresses, even when the sheet is not cylindrical but of any other cross-sectional shape. This reinforcement method is stronger in still another respect, but the curved shape of the stiffeners make more work. I will discuss all these strength problems in greater detail at some future time.

Summary

In conclusion I will say that the task devolving on the constructor of all-metal airplanes, is to utilize the strength of the outer covering to the greatest possible degree. I have therefore indicated a method which meets this requirement in a very perfect manner, and which, moreover, is simple, economical, and mathematically easy to control.

I have then discussed other important strength problems which arise in the construction of all-metal airplanes with smooth sheet-metal covering. In particular, these are the problems concerning the behavior of flat and curved sheets subjected to longitudinal and shearing stresses, both during and after buckling. I have also shown how a general idea of these relations can be obtained by simple experiments in conjunction with theoretical considerations, and I have called attention to the fact that, in most cases, simple viewpoints can be easily selected which furnish a basis for the constructive development of simple strength formulas for use in the designing room.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

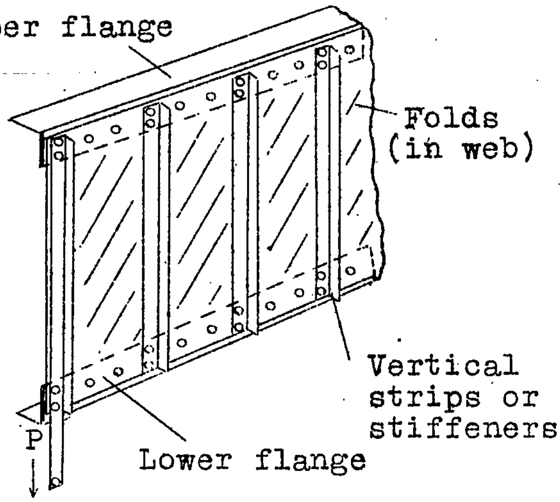

Fig.1 Sheet metal girder.

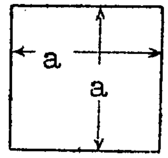

Fig.2

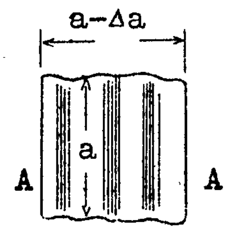

Fig.3

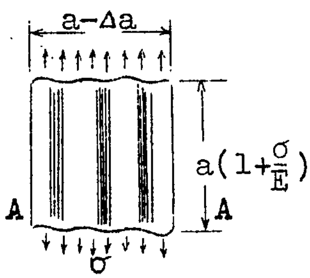

Fig.4

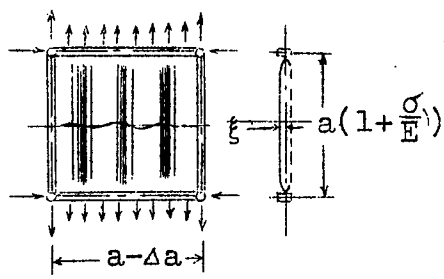

Fig.5

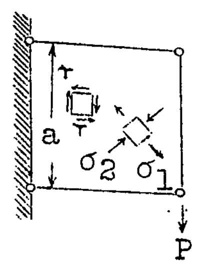

Fig.6

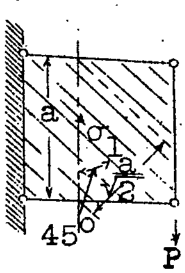

Fig.7

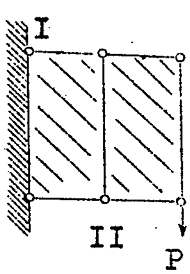

Fig.8

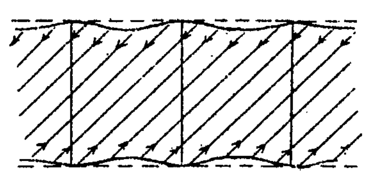

Fig.16

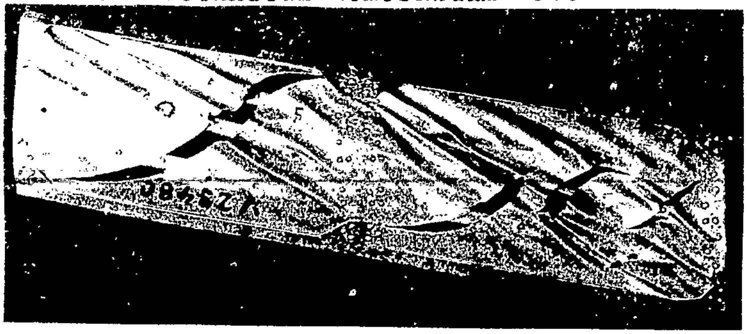

Fig.31

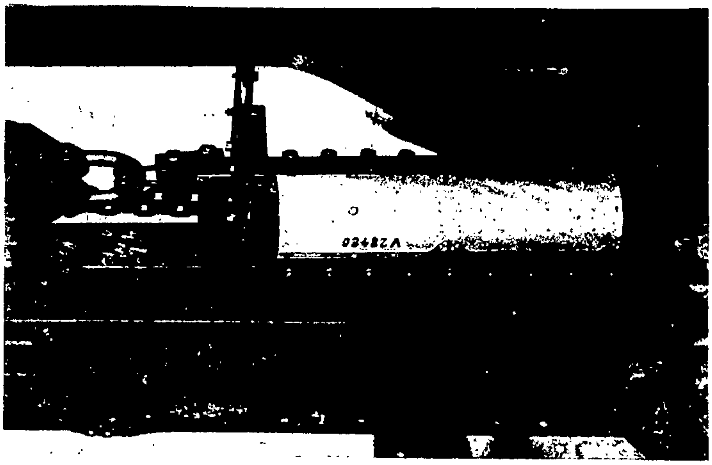

Fig.28

Fig.29

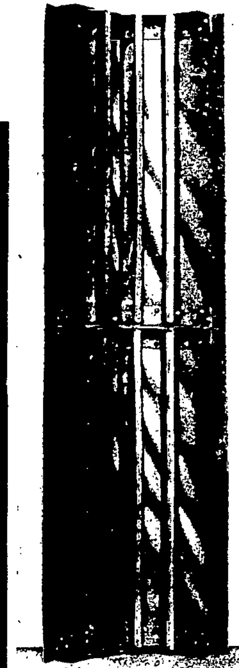

Fig.30

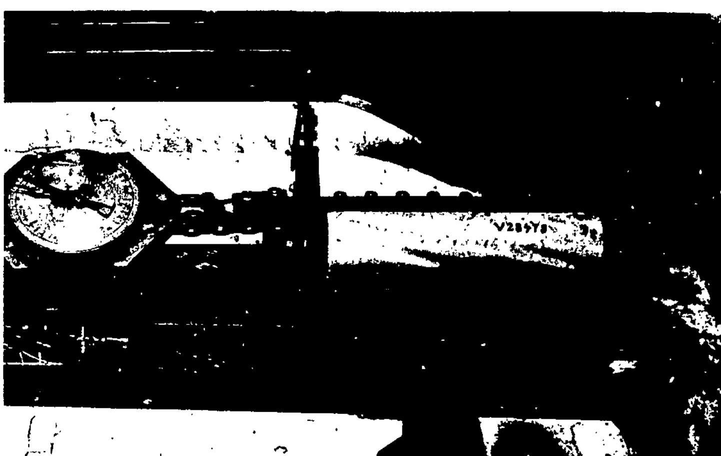

Fig.27

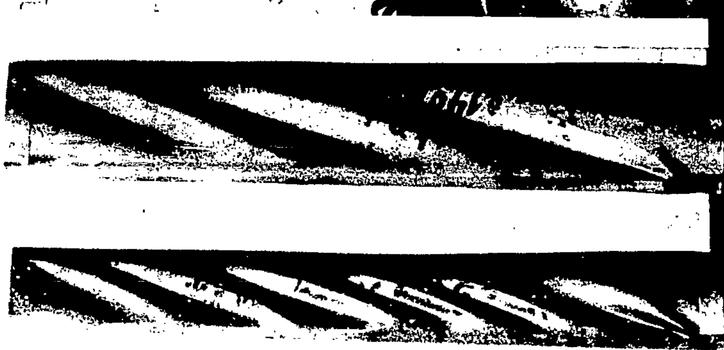

Fig.26

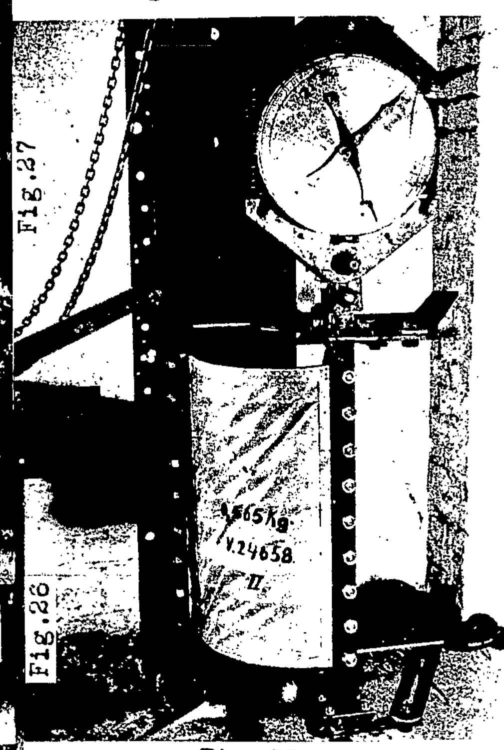

Fig.32

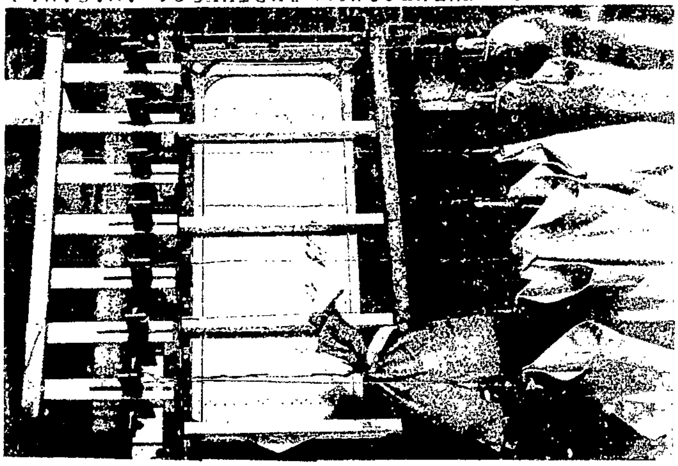

Fig.9

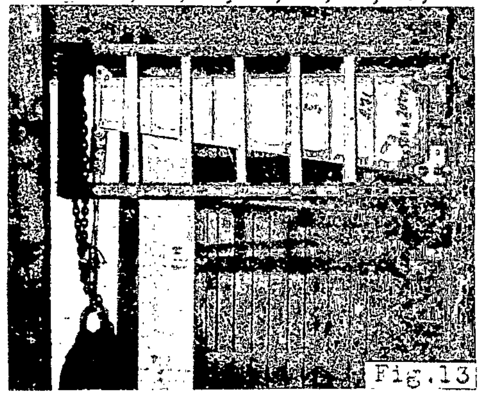

Fig.13

Fig.14

Fig.10

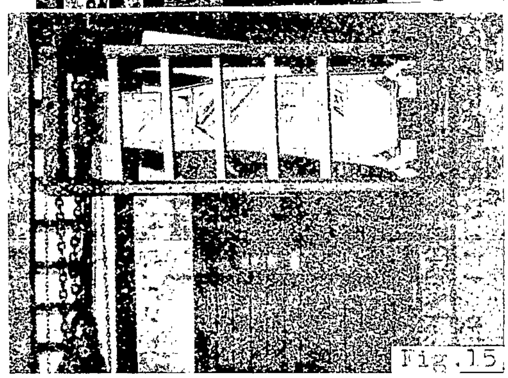

Fig.15

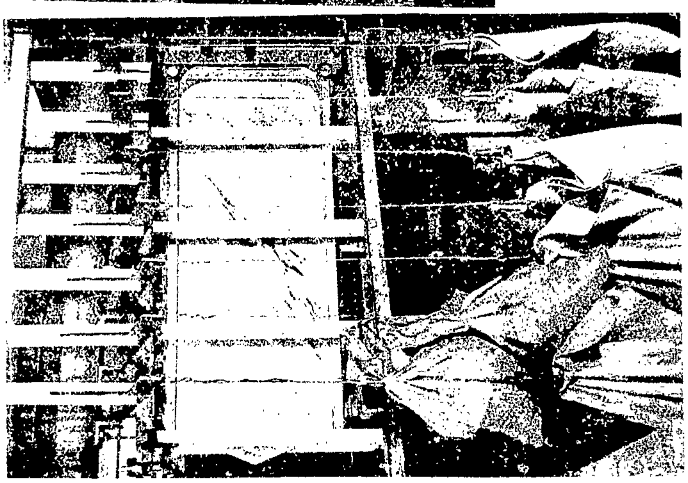

Fig.11

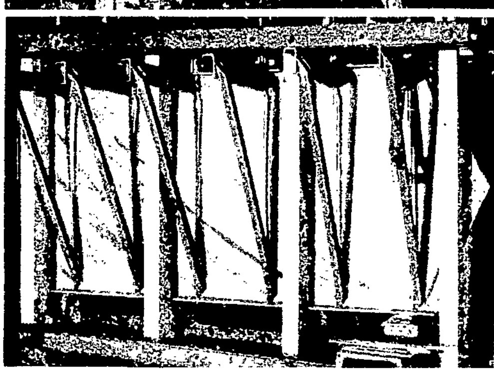

Fig.12

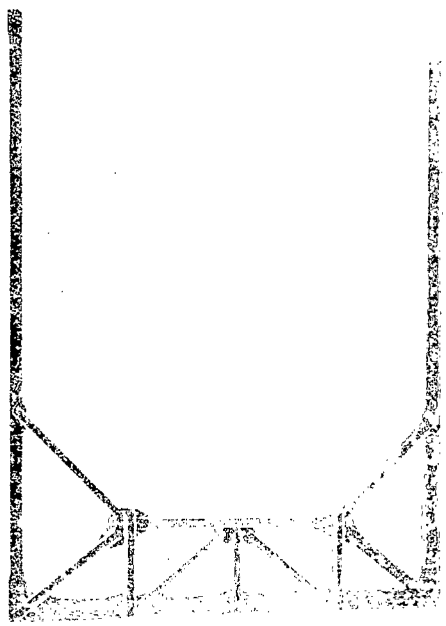

Fig.17

7398 A.S.

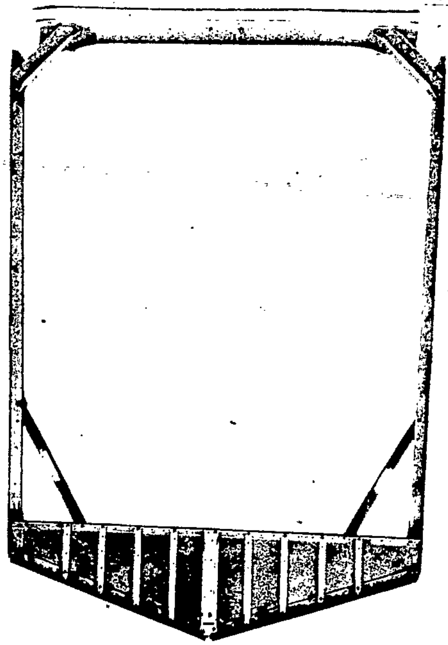
Fig.18

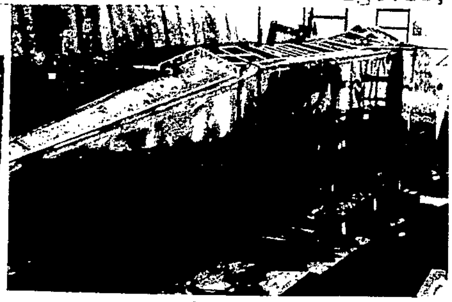
Fig.20

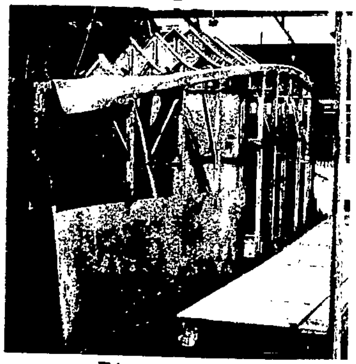
Fig.19

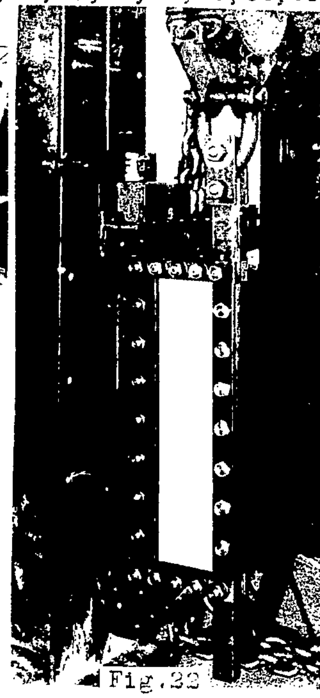
Fig.22

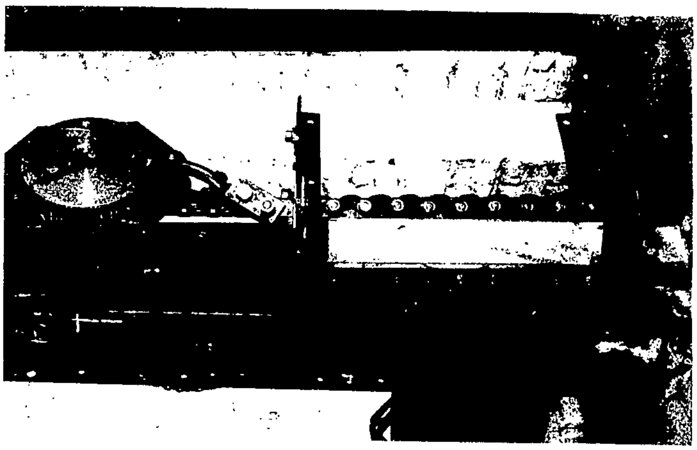
Fig.35

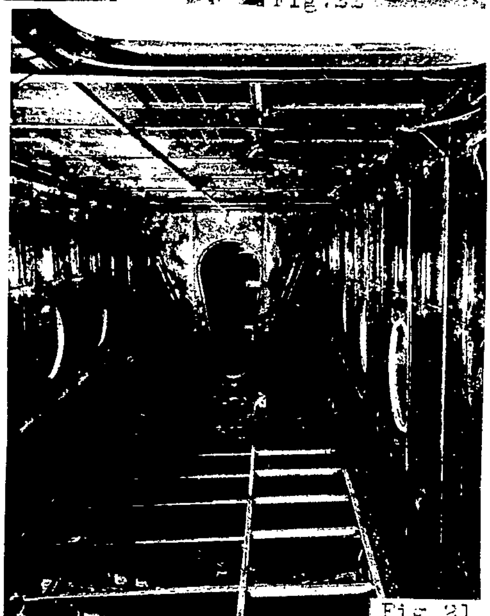
Fig.21

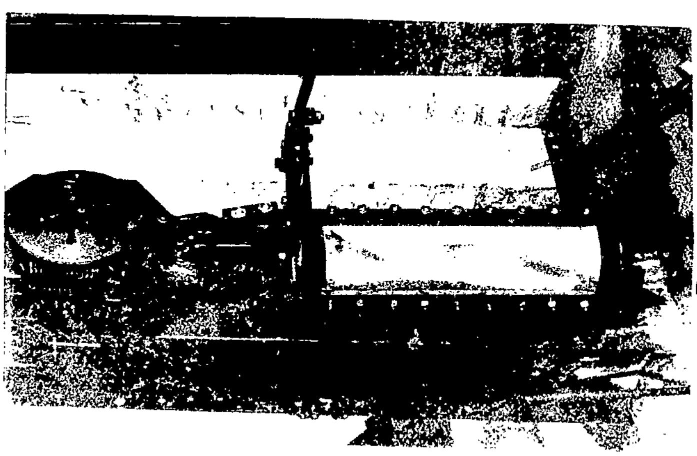
Fig.34

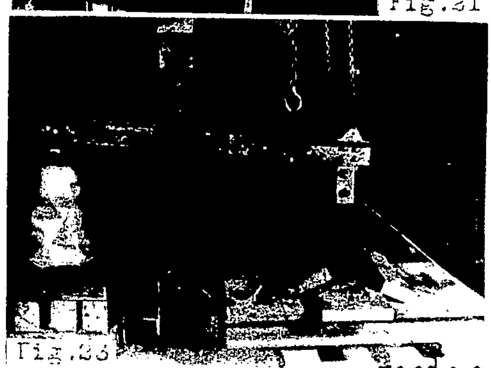
Fig.23

7399 A S.

LANGLEY RESEARCH CENTER
3 1176 01353 1653

DO NOT REMOVE SLIP FROM MATERIAL

Delete your name from this slip when returning material to the library.

NAME	MS
H. Rush	432

NASA Langley (Rev. May 1988) RIAD N-75