PROBLEMS RELATING TO THE USE OF SHEET METAL IN AIRPLANE CONSTRUCTION

Thesis by

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Sheet metal as used in present airplane construction may have two separate and distinct functions. The first of these is merely to supplant fabric or other covering material on the airplane. The structure of the airplane is not altered and the load is completely taken by the framework. The added strength and durability of this type of covering is usually connected with an increase in weight which makes the practice uneconomical. This use of metal is not a very serious design problem since it is only used as a covering and fairing and its strength is not included in the calculated strength of the structure.

Secondly, the sheet metal can be designed so it will take part or all of the loads on the airplane. It is this use of sheet metal, and its attendant problems, that will be discussed here. Those problems that have been solved will be mentioned first and those yet undetermined will then be outlined. To be solved, the answer to a problem must be in such a form as to be available and understandable to the average airplane designer without the use of long and intricate mathematical calculations. This means that those problems are solved which could be incorporated in a handbook for designers and those which could not be so incorporated are not solved for the designer.

The treatment of thin sheet metal construction immediately splits into two separate fields. The first of these considers the sheet metal as supported by stiffeners and framework that the structure as a whole follows the equations of elastic materials. To this type of construction the equations of elasticity hold and allow an analysis very similar to that employed in common civil engineering construction. These stiffeners and supports tend to become prohibitively numerous as the sheets become thinner. For example, Junkers uses a stiffener spacing equal to 60 times the thickness of the material in the case of steel sheets. This means for a sheet of 0.020" thickness the stiffeners would have to be placed 1.20" apart. This allowable spacing is still smaller in the case of duralumimum sheets. The question then arises as to the action of the sheet metal without these numerous stiffeners and supporting members.

The action can be seen if one takes a thin sheet of metal and applies a load, say a shearing force, in the plane of the sheet. The sheet immediately breaks up into a series of folds. See Fig. 1. These folds are not permanent but disappear when the load is removed, indicating that the yield point of the material has not been reached. Furthermore, even after this initial buckling, the load can be increased considerably without exceeding the yield point of the material. A point will finally be reached where the folds do not disappear upon removal of the load and this means that the material has gone beyond the elastic limit. In most cases in airplane construction the structure is considered as having failed when it has reached the elastic limit, so we will consider the thin sheet as having failed when the folds do not disappear upon removing the load in the material. The above example shows that the sheet has redistributed the stresses in such a manner that even though corrugated and seemingly failed it is still capable of supporting a load. In the case of the shear stressed sheet the sheet has buckled in the direction of the compression load and the shear is then transmitted as a diagonal tension which the sheet can support.

The first problems to be considered are of course those concerning the most simple sheet metal construction, the plane flat sheet. These problems have been dealt with both analytically and experimentally and useable results have been obtained for a number of loading conditions. The plane thin sheet in compression follows the usual Euler equations and is handled as a column. The failure takes place as an Euler column and the usual engineering equations hold. The critical load is given by the Euler equation:

$$W = \left(\frac{\pi}{l}\right)^2 JE$$

where W is the load, J the moment of inertia of the section, l the length of the column, and E the modulus of elasticity of the material.

The flat plate in shear has also been treated by a number of people and consistent results obtained. The experiments have usually been conducted on sheets which were long compared to their width and the shear load was applied on the long edges. See Fig. 2. Thus the influence of the free edges could be neglected and the sheets could be treated as infinitely long strips with an applied shear load. At a certain critical load the sheet breaks up into a series of waves with a wavelength of approximately 1.6a, where "a" is the width of the sheet. (Skan and Southwell) The shearing stress for buckling is given by the formulae:

$$\tau = 5E(t/a)^2 \qquad \text{for laid on sheets,}$$

and

$$\tau = 7.5E(t/a)^2 \qquad \text{for framed sheets;}$$

where t is the thickness of the sheet. As the length of the sheet becomes comparable to the width, the edge effects begin to be of importance and one of the problems yet to be solved is to find the shearing stresses in such sheets. The distribution of stresses has been determined by photo-elastic methods and are given in Fig. 3 (from Professor E. G. Coker) but it is still necessary to determine the actual stresses in terms of the geometry of the sheet and the applied load.

The problem of the flat sheet in tension is trivial. It is handled like any other material in tension and the usual engineering formulae apply. Also the question of bending in the plane perpendicular to the sheet needs no discussion since we are dealing with sheets so thin that their resistance to bending in this plane is negligible.

Another question of interest which has not as yet been answered for the designer is the resistance of a thin sheet against combined bending and shear in the plane of the sheet. This may be considered as two problems, the first being to consider the sheet without supports, and the second, the sheet supported against rolling over. This problem is of interest to the designer of flat sided fuselages where there is a load on the tail of the airplane.

The next complication which may be added to sheet metal construction is to add a curvature to the smooth sheet. When this is done the problem is very largely in the unsolved class. The curved sheet in compression along the axis no longer obeys the Euler equations in a rigorous manner although it may do so to a first approximation if the curvature is very small. The resistance of such a sheet to a compression load perpendicular to its axis (Fig. 4) is zero.

Some experimental work has been done by the Rohrbach factory on the shearing strength of curved sheets with the shearing force acting parallel to the axis but no actual figures are available to the designer. What is necessary is experimental and mathematical work on both the compression and shearing stresses of curved sheets expressed in terms of the geometry of the sheets, particularly in terms of the thickness and the radius of curvature. Also, in the case of shear loads in curved sheets, the ratio of length to breadth is important and the exact evaluation of the stresses should be made when the length is of the same order of magnitude as the width.

The limiting case of the curved sheet is that of the cylindrical shell. This problem is important for the design of fuselages and boat hulls. These cylinders may be circular or elliptical in cross section or the treatment may even deal with forms such as airfoil sections where the sheet metal cylinder is used for a wing. The circular sections have been treated and design equations are available to the designer. The values to use for the circular sections are:

Loading	Stress	Allow. Stress
Bending	$f = My/I$	$F = 0.3Et/r$
Torsion	$f = T/2At$	$F = 0.2Et/r$
Shear	$f = S/\pi rt$	$F = 0.2Et/r$

Where M = the bending moment
y = distance to outer fiber
I = moment of inertia of the cross section
E = modulus of elasticity
t = thickness of the tube wall
r = radius of the tube
T = torsional moment
A = area enclosed by the cross section = πr^2
S = shear load

The formulae for bending have been checked experimentally and the experiments show that the formula for the allowable stress gives a very good design value. Other sections, very nearly circular, may be approximated by an equivalent circle, although it would be still better if similar equations could be found for the general ellipse since most fuselages approach the true ellipse more closely than they do the circle. In most of the cases for the cylindrical shell the stresses can be found and the main difficulty is to find the allowable stresses to use in design. This, then, is a problem for the experimentalist, to determine the allowable stresses in bending, torsion, and shear in terms of the thickness of the skin and the geometry of the cross section.

In all work on thin sheets the disadvantage that immediately appears is the very small value of the radius of gyration of such a sheet. The next step in the use of sheet metal would seem to be to find some method whereby this radius of gyration could be increased. The increased strength of the combination must be proportionally greater than the increase in weight otherwise the thin sheet alone is the most economical. There are two methods which can be used to acquire this increase in radius of gyration. The first of these is to use stiffeners which are riveted or welded to the sheet and the second is to incorporate the stiffeners in the sheet itself in the form of corrugations. We will first consider the use of stiffeners which are separate from the sheet itself.

This consideration immediately opens another field for the investigator, that of determining the characteristics of various types of stiffeners. Some of the more common types are shown in Fig. 5. The study of the characteristics of these shapes is essentially a thin sheet problem since for the type of construction under discussion the stiffeners are usually made from very thin material. The study of such shapes should include finding the resistance to direct compression, to bending, and to torsion, and then making a comparison of the various shapes on a weight basis. Another problem of importance is that of determining the most efficient length of flat section to use, for example, in a channel or Z section. The constants of such sections, such as moment of inertia, radius of gyration, and area are easily found by the usual methods, but since the material used in their construction is so very thin, ordinary engineering methods of finding their strength cannot be used. The failures of sections of this type are not beam failures but failures by local buckling which is dependent on the thickness of the sheet and the length of unsupported surface. Also, the question arises whether the compression side of the wing gives exactly the problem discussed. The problem of the curved sheet with stiffeners along the axis is also applicable to the design of the fuselage in bending since the failure is along the compression side of the shell. In the case of the fuselage these longitudinal stiffeners will also have an effect on the shearing stresses produced by the tail loads. Just exactly what these stiffeners would contribute to the shearing strength of the structure is another problem about which very little is as yet known.

For a fuselage, or similar structure, circumferential stiffeners and bulkheads must be considered as well as longitudinal stiffeners. The correct spacing of, and the loads on, these bulkheads furnishes an important problem for the designer. At the present time the structure is designed by using a great number of assumptions which all must be on the conservative side so that the structure will not fail. This very often leads to a structure weight that offsets any advantage that may have been gained in the use of the sheet metal construction. Common monocoque construction tends to use a few large bulkheads spaced at rather wide intervals with a number of smaller and lighter bulkheads or stiffeners between. Thus there are two separate problems, the first dealing with the spacing and loading of the major bulkheads and the second dealing with the problem of the secondary bulkheads, their spacing and their design loads. It is also possible that this type of design is not the most economical and that a series of circumferential stiffeners of approximately the same size would give the optimum case.

The other method of increasing the radius of gyration of the sheet is to incorporate the stiffeners in the sheet itself. This leads to the use of a corrugated sheet of one form or another. This problem has so many unknowns that at first it would seem to be impossible to arrive at a solution which would be general enough to use for design purposes. The important variables are: 1)the thickness of the sheet, 2)the form of the corrugation, 3)the wavelength of the corrugation and 4)the amplitude of the corrugation.

The form of the corrugation is limited by the fact that the sheet must be manufactured without an excessive expenditure of money for complicated dies. This limits the corrugations to those which can be made up of straight lines and circular arcs. Several possible forms are shown in Fig. 6. A series of different types of corrugations could be tested and from these tests could be determined the type which gave the best strength-weight ratio. The tests could be compression tests; the length of the specimens, the thickness of the sheet, and the developed width of the sheet being held constant, the only variable being the shape of the corrugation. The ideal solution would of course be one in which the corrugation dimensions could be given in terms of the sheet thickness, thus making the design of corrugated sheet dependent only on the sheet thickness.

The same problems appear in fuselage design when using corrugated skin as were found in the case of the plane sheet. The first problem is that of the allowable shearing stress in a corrugated sheet. In connection one should use stiffeners with curved sections or those made up entirely of flat sections. The study of these stiffeners should first be made without regard to manufacturing cost and the results then considered on the basis of economical production.

After the characteristics of the stiffeners alone have been determined they must then be combined with the sheet and the strength of the combination determined. The first problem of interest is that of the thin sheet with stiffeners subjected to a compression load in the direction of the stiffener axis. The effect of the stiffeners and the effect of the sheet could be separated by performing the test on enough specimens so the unknowns could be solved for. The unknowns would be, for a given type of stiffener and a given thickness of sheet, 1)the effect of the end stiffeners, 2)the effect of the inner stiffeners, 3)the effect of the sheet between the first and second stiffeners and that between the last and the next to the last stiffeners, and 4)the effect of the sheet between the inner stiffeners. A series of such experiments would give very valuable results regarding the most efficient stiffener spacing and the distribution of load between stiffeners and skin.

The next step would be to give the section a large radius of curvature and make enough experiments so that a correlation factor between the curved sheet and the flat sheet could be found, this factor probably being expressed in terms of the radius of curvature. These results would be very valuable since they would be directly applicable to the all-metal wing construction since with this problem it would be of interest to note the effect of the corrugations on the wave formation that was found in the case of the plane sheet under shearing load. Also, to find the difference between the effects with the corrugations in the direction of the shearing force and those with the corrugations perpendicular to the direction of the shearing force.

For cylindrical shells the method used by designers at the present time is to find the stresses in the shell by using an equivalent radius and then figuring a section of the compression side of the skin as an Euler column with a value of the radius of gyration obtained from the geometrical properties of the corrugations. One bad feature of this method is that the value of the fixity to use in the Euler equation is unknown and no logical reasoning will give a value that has any definite meaning. The column not only gets support from any intermediate bulkheads which may occur within its length but it also gets support from the side due to the rest of the cylindrical shell.

The problem in all of the above mentioned uses of sheet metal is to determine four points. The first of these is to determine at what value of the stress the initial buckling in the sheet takes place. The second is to determine what redistribution of stresses occurs when this initial buckling occurs. The third is to determine the stresses which are allowable so that no part of the structure is stressed beyond the elastic limit, and the fourth is to determine the ultimate breaking strength of the structure. All of these are necessary so that allowable stress criteria can be given to the designer using sheet metal construction. In addition to the above there must be determined the stress distribution and the actual numerical value of the stresses in the various parts of typical metal shapes. These can be determined with a fair degree of accuracy in shapes such as the circular shell and the flat sheet but they must also be found for shapes such as the elliptical shell and other curved sections.

One point in the use of this thin sheet is worth further mention. It has been assumed in the above discussion that the sheet had not failed until some portion of it had gone beyond the elastic limit of the material. This means, for severe loads, that the sheet will be acting in a buckled form. This fact must be considered by the designer and where this wave form would have a detrimental effect, enough stiffeners should be added to make the structure act as an elastic body without preliminary buckling. A case of this type would be the use of thin metal as a wing covering. Any folds which appear on this covering may have a very detrimental effect on the aerodynamic properties of the section. In this it would probably be better to increase the weight slightly in order to keep the surface of the structure smooth. Also, in cases where the surface of the structure could be seen by passengers of the airplane, any folds of a noticeable magnitude would have a bad psychological effect even though the buckling did not impair the strength of the structure. It should be kept in mind, however, that these folds are not of very great magnitude until the material is close to the elastic limit. This means that the structure would probably set up to a large percentage of the design load before the folds could be noticed unless the skin was closely scrutinized, and in fact under ordinary flying conditions the material would not be stressed to a point where the folds would appear at all.

SUMMARY

The problems relating to the use of thin sheet metal which have been solved so that the designer can use the results are:

1)The plane sheet, without stiffeners, subjected to a shear load. The results are only applicable when the length of the sheet is very great compared to the width.

2)The thin-walled circular cylinder subjected to bending, torsion, or shear but not to a combination of these loadings.

The important problems which must be solved before the use of thin sheet can become economically possible are:

1)The determination of the characteristic properties of various stiffener sections and the relation of the strength of each section to its area.

2)The effect of curvature on the compressive strength of flat sheet.

3)The effect of combining stiffeners and flat sheet. This includes the problem of stiffener spacing and the problem of the increase in the allowable load compared to the increase in weight.

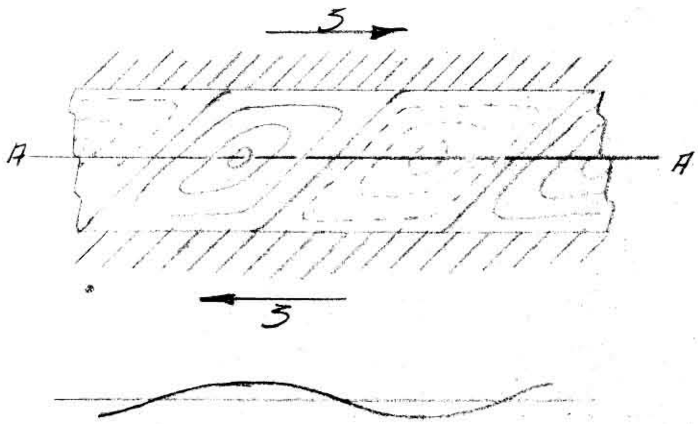
4)The problem of cylindrical sections other than circular subjected to bending, torsion, or shear, or any combination of these loads.

5)The problem of the most efficient form for corrugated sheet and the dimensions of the corrugations in terms of the thickness of the sheet.

6)The problem of determining the allowable loads on fuselages constructed of corrugated sheet.

7)The correct stiffener spacing in the case of the cylindrical shell. This includes both the longitudinal and circumferential stiffeners. Also, the problem of using major bulkheads with intermediate stiffeners, as against the method of using approximately one size of bulkhead throughout.

8)The use of stiffeners to eliminate the initial buckling of thin sheets under load is also an important problem connected with the study of thin sheet construction, and one which must be considered for reasons mentioned in the latter part of this paper.



SECTION A-A

FIG. 1.

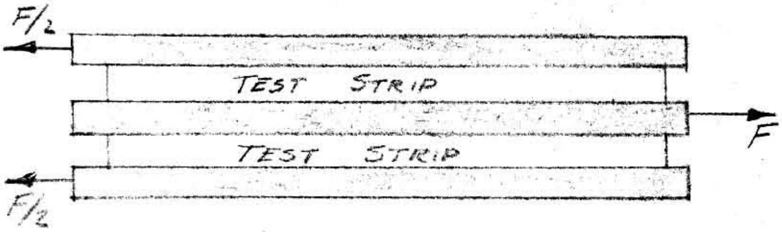


FIG. 2.

FIG. 4.

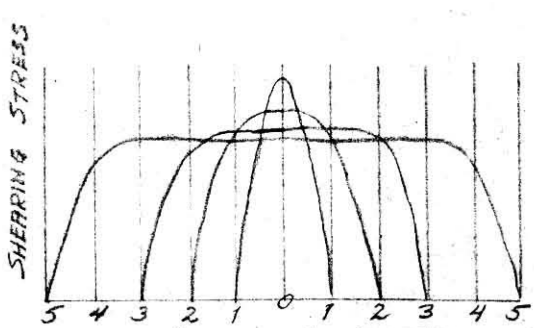
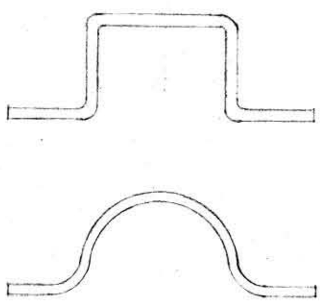
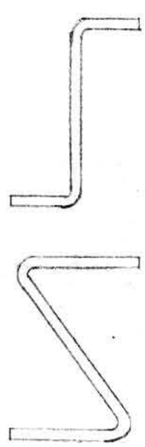


FIG. 3.

CHANNEL SECTIONS



HAT SECTIONS



Z SECTIONS

FIG. 5.

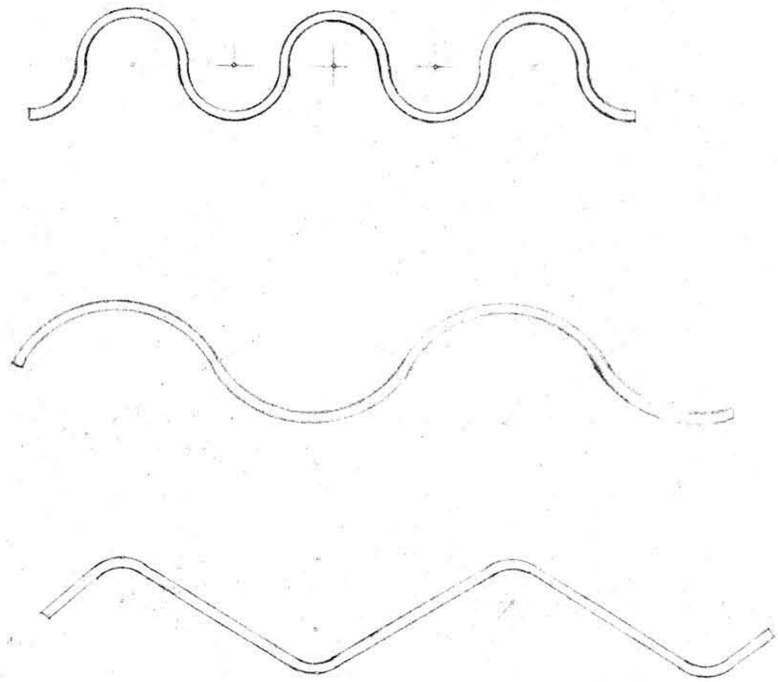


FIG. 6. TYPES OF CORRUGATIONS