AIAA 81-0366R

Structural Weight Comparison of a Joined Wing and a Conventional Wing

Mary Fairchild Samuels*
University of Texas, Arlington, Tex.

A structural weight comparison was made between a new concept wing design, called a "Joined Wing," and a reference conventional wing-plus-horizontal tail (Boeing 727). The joined-wing analysis includes two cases that differ only in minimum gage skin thickness. The comparison was accomplished by constructing finite-element computer models of each wing configuration, analyzing each for optimum skin thickness, then determining the structural weight of each wing. The optimizations were based on a fully stressed design concept using a Von Mises criterion for maximum allowable stress. The joined wing was found to be lighter by 12-22%.

Nomenclature

b = span dimension, ft
c_{fe} = equivalent skin friction coefficient
e = span-efficiency factor
n = load factor, g load
S_{wet} = wetted area, ft^2
v = airspeed, ft/s
W = weight, lb
ρ = air density, slug/ft^3

Introduction

General Description of Joined Wing

THE "Joined Wing"† is a revolutionary new design most simply described as two wings joined together at or near the tips. There are numerous configurations of this concept imaginable in which the positions, shapes, and sizes of the wings vary greatly. One rather basic configuration will be studied throughout this report.

The joined wing has a distinctive diamond shape that is immediately recognized when viewing the wing from either above or in front of the airplane. This shape is obtained by attaching the forward wing low on the fuselage, then sweeping backward and upward while tapering it to the tip. The aft wing is attached high on the vertical fin. It too tapers to the tip, but it sweeps forward and downward to join the forward wing.

Suggested Advantages

The diamond shape of the joined wing has the primary structural advantage of strength. This is achieved by each wing bracing the other against the lift loads. In order for this to be beneficial it must be coupled with a significant weight advantage. Dr. Julian Wolkovitch, the inventor of this joined-wing configuration believes that there can be a weight advantage if the internal wing structure represents an optimum skin thickness taper.[1,2]

Purpose of Study

To check the validity of these weight claims, Dr. Wolkovitch requested that two parallel structural analyses be done. The basic objective was to compare the structural weight of the joined wing with the weight of a conventional wing-plus-horizontal tail. This was done by constructing a computer model of each wing configuration, then optimizing the skin thickness of each based on a fully stressed design concept. To make the wing designs comparable aerodynamically, the two wings were designed to have similar lift and drag characteristics.

The Wing Configurations

Reference Conventional Wing

The Boeing 727 was chosen as the basis for the transport airplane wing design to be compared to the joined wing. In order to simplify the analysis, only the torque box was used to represent the wing. There are two differences from the actual Boeing 727 design that should be mentioned: 1) omitting the slight (7 deg) dihedral angle, and 2) bringing the structural box into the fuselage with a constant slope. These changes were made for ease in model construction under the guidance of structure experts at Vought Corporation.[3] Based on their experience with this wing, it is assumed that neither change will have a significant effect on the structural comparison.

A scaled drawing of the conventional wing is given in Fig. 1. As illustrated, the quarter-chord of the wing sweeps backward at a 32-deg angle over the semispan of 648 in. This wing has a taper ratio of 0.304, with no built-in twist.[4] For ease in placement of boundary conditions (to be explained later) the exterior surface of the fuselage is located 54 in. from the centerline.

The airfoil of this wing is approximated by a NACA 23012 airfoil, with the structural box extending from 15 to 65% chord. This is the optimum box size for this wing. This airfoil has a thickness ratio of 12%, which yields maximum root and tip thicknesses of 36.39 and 11.03 in., respectively. All these dimensions will be constant throughout the study.

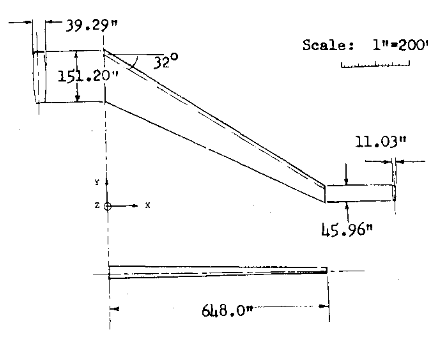

Fig. 1 Conventional wing box: three views.

Presented as Paper 81-0366 at the AIAA 19th Aerospace Sciences Meeting, St. Louis, Mo., Jan. 12-15, 1981; submitted March 4, 1981; revision received Sept. 16, 1981.

*Graduate Student. Presently, Structural Analyst, Hunt/Leslie Associates, Dallas, Tex. Member AIAA.

†Wolkovitch, J., Joined Wing Aircraft, U.S. Patent 3,942,747, 1976 (others pending).

Comparison Standards

In order to compare two wing configurations, some standard had to be established. It was decided that the basis for the comparison would be the performance class of the wings. This meant that the lift and drag characteristics of each wing configuration had to be the same.

The lift produced by an airfoil is defined as the net force produced perpendicular to the relative wind. For the two wings to have the same lift characteristics, the airfoil profiles of each have to be the same. Thus the NACA 23012 airfoil was used on each airplane.

The drag of an airfoil is the net force produced parallel to the relative wind. It is affected by the pressure distribution and the skin friction of the surface. The total drag of a wing in flight is said to be the sum of the drag due to lift (called induced drag) and the drag due to frictional effects (called parasitic drag). In terms of the factors involved:

$$D_{\text{tot}} = D_{\text{ind}} + D_{\text{par}}$$
$$= \frac{1}{\frac{1}{2}\rho v^2}\frac{(nW)^2}{\pi e b^2} + c_{fe} S_{\text{wet}} \tfrac{1}{2}\rho v^2$$

To determine equivalent dimensions for the joined wing, each term must be equated.

Previous work on the joined wing has shown that this new wing has a higher span-efficiency factor than a conventional wing.[1,2] Thus, when equating the induced drags for each wing style, a smaller span dimension must be used for the joined wing. For a dihedral angle of 17 deg, the joined wing semispan dimension should be 0.8971 of the reference wing semispan dimension. This ratio was derived from wind tunnel data and theoretical analyses.[1,2]

In matching the parasitic drag of the joined wing with that of the conventional wing, the same overall average equivalent skin friction coefficient was assumed. Since the parasitic drag is primarily influenced by the wetted area of a wing, the joined wing was constructed to have the same wetted area as the Boeing 727 wing-plus-horizontal tail. Reference 4 indicates that the tail area of the Boeing 727 wing is 21.2% of the wing area. Therefore, using the same airfoil for both wings, and a 17-deg dihedral angle for the joined wing, the equivalent joined-wing chord dimensions were calculated to be 0.646 of the reference chord dimensions.

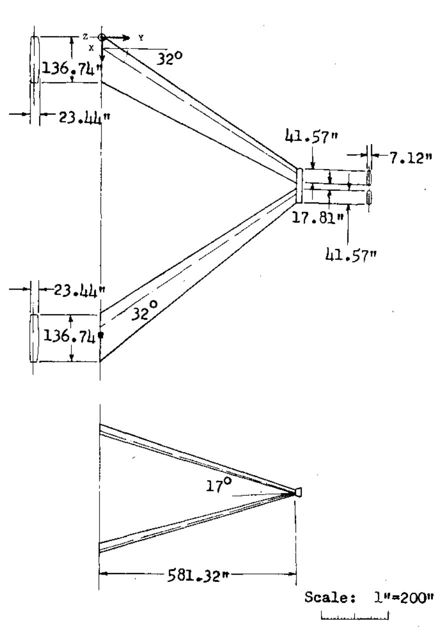

Fig. 2 Joined wing box: three views.

Joined Wing

Using the above calculations, the structural box of the joined wing was given the dimensions shown in Fig. 2. As in the reference wing, each joined wing has a quarter-chord sweep of ±32 deg, no built-in twist, and zero incidence on each wing. The dihedral angle is ±17 deg, as opposed to the 0-deg angle on the reference wing. The semispan dimension is 0.8971 of the Boeing wing, smaller because of the calculated higher span efficiency. The full airfoil chords are each 0.646 of the reference wing. In both the forward and aft wing, the torque box extends from 5 to 75% of the full airfoil. Thus it includes more of the airfoil than does the conventional wing. Again, for ease in placement of boundary conditions, the fuselage wall was located at 48.44 in. from the centerline.

The tips of the two wings are joined by a structural member which is to transmit the high torques from one wing to the other. The tip member is a closed-ended tubular member of trapezoidal cross section. This tip member was assumed to be infinitely rigid, therefore it will not affect the analysis of the wing. Using this tip design by no means suggests that the author feels that it is the optimum design. It was simply chosen as a rough structure to transfer the load from one wing to the other.

Computer Analysis

SAP V: The Input

Computations for the static analysis of the wings were done using an expanded version[5] of the finite-element code of Structural Analysis Program Version Five (SAP V). SAP V is a self-contained static and dynamic program with its own plotting routine. For the static analysis of the wings, SAP V, type 3 quadrilateral membrane elements were used. These are plane stress elements, thus they are capable of carrying in-plane axial and shear loads, but no out-of-plane loads. Type 3 elements are isoparametric, which means the displacement functions are of the same order as the lines connecting the nodes. This gives better results where the model is not straight. Also, second-order bending modes were included in the analysis.

SAP V: The Output

The results of the static analysis include node deflections, element stresses, and, if requested, a weight calculation and any number of model plots. The shear stress output includes the normal stress (S_{11}, S_{22}) and the shear stress (S_{12}). It is calculated at each element's centroid, as an average of the stress over the element.

The Models

Three models were analyzed in this study. The first was a conventional wing represented by a Boeing 727; the second two were joined-wing models. Joined-wing case I was given the same minimum thickness as the conventional wing, while case II used a smaller minimum. The reason for this smaller gage case was due to the decrease in box chord dimensions of the joined wing compared to the conventional wing. Thus, if an equal number of supporting ribs were used in each configuration, a smaller minimum skin gage thickness is required to support a panel. Both the Boeing 727 and each of the joined wings are represented by a semispan of the structural box. Each is built with a single cell representing the skin, with spars located at the leading and trailing edges. For stiffeners, ten vertical ribs are spaced evenly along the span. The skin is segmented into five equally spaced compartments to represent the chordwise cross section. Each rib and spar section is divided at the chordline into upper and lower elements. For the joined wing, a trapezoidal-shaped tube connects the fore and aft wing tips. This element extends 12 in. spanwise from the tips and 12 in. from upper to lower edges. It is composed of only one element spanwise, two elements deep, and eleven elements fore and aft.

The models contained a sizable number of nodes and elements. For the reference wing, 234 nodes and 298 elements were used. The joined wing however, required more since it has two wings plus the tip member. This meant a total of 504 nodes and 666 elements for the model. Each wing of the joined wing was constructed identically to the conventional wing.

Since half-wing models were used, boundary conditions had to be applied to simulate the symmetry of a wing. First, all centerline nodes are restrained in the spanwise direction. For the conventional wing and the forward wing of the joined wing, two nodes along the fuselage are restrained from vertical movement and one node is restrained from fore-aft movement. For the rear wing of the joined-wing configuration, these restrictions are placed at the centerline instead of the fuselage, since that is where the attachment would be. No restraints are applied to the tip member. All other nodes can translate in the X, Y, and Z directions. Because of the nature of membrane elements, however, no rotational degrees of freedom are permitted. (If rotation were allowed, discontinuous element slopes would be possible at the boundaries.) Additional details of the model are given in the author's M.S. thesis on which this paper is based.[6]

Physical Properties

The physical properties of the two wing types are the same. The material is aluminum with a modulus of elasticity of 10.6×10^6 psi, modulus of rigidity of 4×10^6 psi, and Poisson's ratio of 0.33. Finally, the weight density of aluminum is 0.1 lb/in.[3]

Loading

The total load applied on each wing configuration was based on a limit load (or actual takeoff weight) of 170,000 lb. To this load, a 2.5g maneuver factor and a 1.5 factor of safety were applied. This results in a total vertical lift load of 637,500 lb for the full-span wing, or 318,750 lb for the semispan wing. The manner in which these loads were applied will now be explained.

In a conventional wing, the lift load is opposed by the weight of the airplane and a downward lift on the tail. For this analysis, this downward force on the tail was not included. (Note that if this downward load were included, it would have been necessary to increase the total vertical lift load on the wing to a greater value than 637,500 lb.) In the joined wing, both the fore and aft wings provide lift. The percentage carried by each wing was chosen to be 60% fore, 40% aft.

The true aerodynamic load distribution was simplified since the data had to be input by hand as point loads. The typical elliptic spanwise loading was simplified as three straight lines. Chordwise, the distribution was approximated by a step loading function. Both of these load distributions are illustrated in Fig. 3 as normalized functions. These loads would actually be distributed over the entire airfoil, but in fact, they were converted to point loadings and applied along the structural box only. These simplifications will approximate the true airload to give a slightly heavy measure of the weight. In fact, concentrating all the load on the structural box results in a box able to carry more load than it would normally. Thus this will act as an additional safety factor to yield a stronger, heavier wing.

Since SAP V is a discrete analysis program, the loads, too, had to be discrete. Using the normalized distributions, the normalized loads were calculated at each node and converted to point loads.

After calculating each load, the angle of loading had to be considered. It was necessary to keep the summation of the vertical loads equal to the total inertia load. For the conventional wing, the load was applied to the lower surface in the vertical direction. This gives a load which is perpendicular to the midsection of the chord.

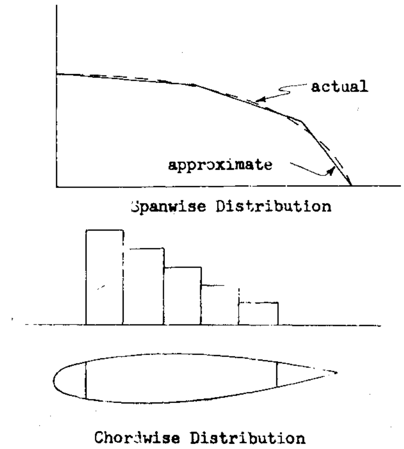

Fig. 3 Normalized load distributions.

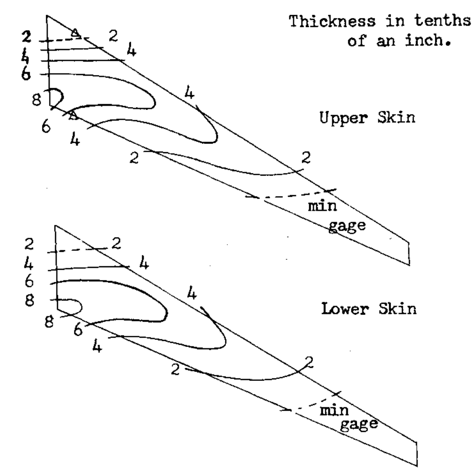

Fig. 4 Skin thickness distribution for conventional wing.

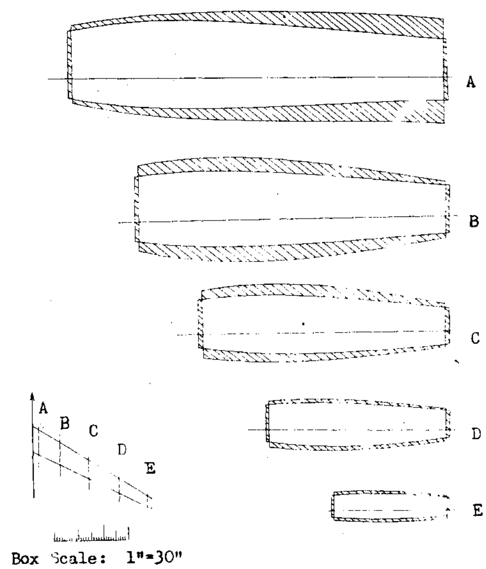

Fig. 5 Cross-sectional thickness distribution for conventional wing.

The joined wing required more consideration. The joined wing must be loaded perpendicular to the dihedralled wing surface. From the vertical components of the load, the spanwise horizontal components of load were calculated to yield the desired perpendicular loading along the dihedral. To be consistent with the conventional-wing loading, the angle of loading in the chordwise direction was not accounted for from

15-65% chord. But, from 5-15% and 65-75% chord, the loads were applied perpendicular to the airfoil surface. Because the loading on the joined wing was applied perpendicular to the surfaces, the total load was higher (333,592 lb compared to 318,750 lb), but the total vertical load was kept the same.

Method of Solution

Optimization

The configurations described in previous sections were used throughout the optimization procedure. Thus, only the distribution or thickness of the material was optimized. Whether or not the configurations chosen were the best for the structural design of each wing is not discussed in this study.

The basis for the optimization was Von Mises' criterion for allowable stress. This is given by the equation

$$\sigma_{\text{allow}} = \sqrt{S_{11}^2 + S_{22}^2 + 2S_{12}^2}$$

where the allowable stress for aluminum was taken as 28,000 psi. The optimization was based on the fully stressed design concept, that is, all elements within the wing were stressed so that the Von Mises stress limit was not exceeded. All skin and tip elements were optimized, but the wing ribs were kept at the initial thickness value.

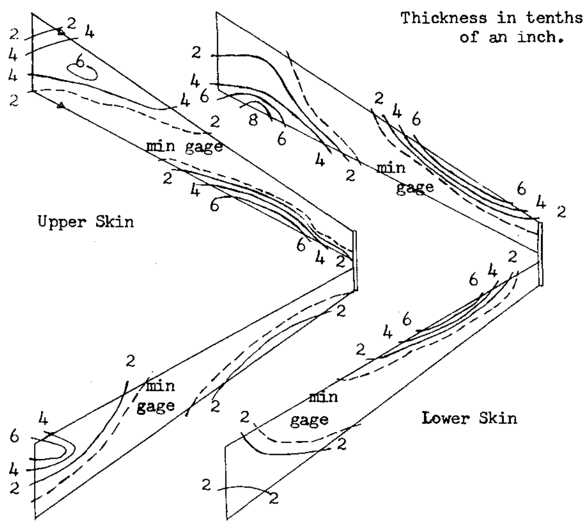

Fig. 6 Skin thickness distribution for joined wing.

In order to have a feasible model, minimum thicknesses were established for the skins, ribs, and tip members. The minimum gage thickness for all elements of the reference wing was 0.125 in. Two different cases of minimum gage were used in the joined-wing analysis. Case I represented a joined wing with a minimum thickness identical to the reference wing (0.125 in.). Case II, however, used a smaller gage (0.070 in. for the skin and 0.025 in. for the ribs). The reason for this smaller gage case was discussed previously.

The optimization procedure utilized is as follows. First, all elements were given appropriate minimum thicknesses. Using the SAP V element stress output for S_{11}, S_{22}, and S_{12}, the Von Mises stress was calculated for each element. To evaluate the new thicknesses, the ratio of the Von Mises stress to the allowable stress was multiplied by the old thickness. This represents the inverse relationship between stress and thickness. These new thicknesses were then input into the SAP V element code, except when the new thickness was less than minimum gage, in which case, minimum gage was used. All of the optimization was automated with one program to calculate the new values and an interactive editing terminal to input them.

Weight Calculation

The structural weight was found by obtaining the structural volume of each element and multiplying it by the weight density of the material. The structural volume was taken to be the area of an element multiplied by its thickness. Summing the structural weight of all the elements yielded the total structural weight. The rib weights were not included in this total because they were not necessarily the optimum shape, size, or position.

Results

Skin Thickness

Plating diagrams for the fully optimized wing configurations are given in Figs. 4-7. These represent the "smeared" thicknesses that meet the Von Mises criterion. Note that the boundary conditions applied at the fuselage (marked Δ) slightly affect the position of the maximum thicknesses.

The thickness distribution obtained for the conventional wing is consistent with the known distribution for this type of wing. The joined-wing thickness distribution, however, gave unorthodox and unexpected results. The two most obvious differences from a normal wing distribution are 1) the

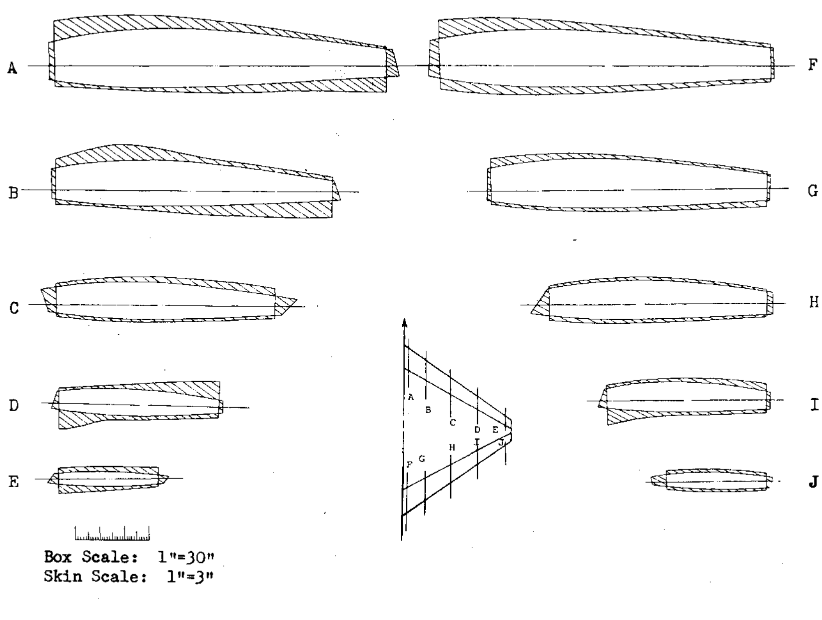

Fig. 7 Cross-sectional thickness distribution for joined wing.

evidence of two distinct maxima on each wing surface (this was not expected); and 2) the different chordwise taper on the upper and lower skins (this was predicted by the designer). These features are perhaps clearer in the cross-sectional views of Figs. 5 and 7.

To address this second difference, reference is made to reports by Dr. Wolkovitch,[1,2] in which he predicts such a chordwise taper from this truss-like wing. By breaking down the lift load at any chordwise section of the joined wing into "in-plane" and "out-of-plane" components, it is easy to see that the joined wing is very stiff in the plane of the truss (the plane formed by A-A and perpendicular to the plane of the paper in Fig. 8). Note that A-A joins the centroids of areas of the fore and aft wing boxes. In the plane that is perpendicular to the page and 90 deg to the plane of the truss, though, the structure is not inherently very stiff. To strengthen the structure in this direction, the material of each wing should be concentrated as far as possible from the line A-A. This is the reasoning behind the prediction of a chordwise taper of material. By inspecting Figs. 5 and 7 more closely, one can see that this theory is valid only near the root. At the tip, a complete reversal of this trend was discovered for the tapered wing analyzed.

To explain this reversal, represented by the occurrence of two maxima, it was necessary to investigate the effects of the applied load on a tapered wing. The normalized airload at each section along the wing span was divided by the taper ratio at that section. This yields representative values of the effective load, as illustrated in Fig. 9. Note that the effective load acting is not the elliptic load that was applied, but is a function that has a maximum at approximately 75% of the span. Returning to the joined-wing plating diagram of Fig. 6, it can be seen that the second maxima are also at approximately 75% of the span dimension. This similarity is not thought to be coincidental. The effective load is believed to be the cause of this trend. To confirm the relation, a case of an untapered wing was briefly studied, since in that case, the airload is identical to the effective load. No second maxima were found.

Deflections

First, it should be noted that the deflections found by SAP V will be conservative. This is because it approximates the wings by finite models rather than a continuous model. This results in models stiffer than the actual structures, and thus, smaller deflections result.

The vertical deflections of the conventional wing and case I of the joined wing are plotted along the semispans in Fig. 10 (joined-wing case II deflections were similar to case I). In these graphs, the deflections of the leading edge of the lower wings were plotted, but the upper skin deflections were almost identical. The conventional wing displays the parabolic deflection typical of a free-ended cantilever wing. The joined-wing deflection, though, reveals the influence of the tip joint in decreasing the deflection near the tip. Again, the 75% of the semispan position is critical, since the maximum deflection occurs at that location. Note that it coincides too with the maximum effective load location.

One definite advantage of the joined wing can be seen by comparing the maximum vertical deflections. The conventional wing deflects over twice as much as the joined wing. Another point to be noted from the deflection curves is the difference in the leading- and trailing-edge deflections of the joined wing. (This will be more noticeable in Fig. 12.) This reflects a twist in the truss structure caused by a combination of tension and compression in each wing. This feature may need to be tested further to identify its effect.

The fore-aft displacements of the tips are graphed in Fig. 11 for the two configurations. Unless noted otherwise, the leading- and trailing-edge displacements and the upper and lower skin displacements are also represented by the lines plotted. Notice the joined wing shows a very large deflection

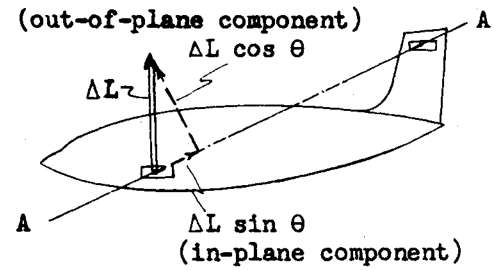

Fig. 8 In-plane and out-of-plane lift components.

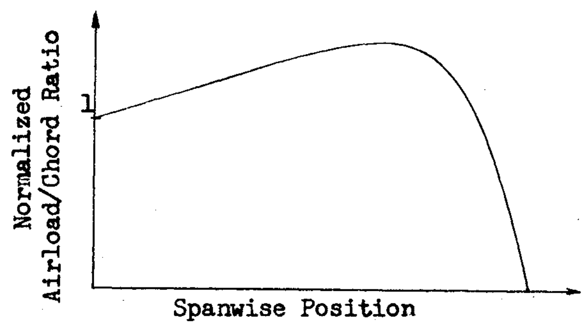

Fig. 9 Effective applied load.

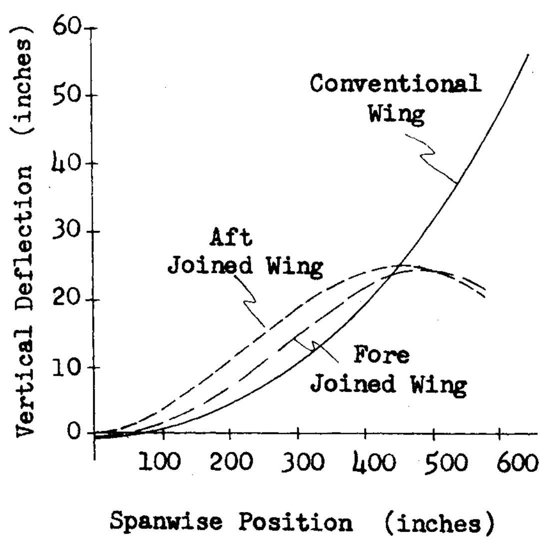

Fig. 10 Vertical deflections.

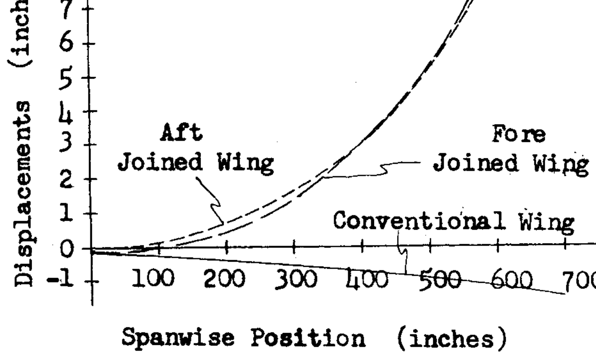

Fig. 11 Fore-aft displacements.

(8-9 in.) forward due to the airload, while the conventional wing displaces backward only a little more than 1 in. This is one feature of the truss-like joined wing that needs to be considered when designing the optimum shape. If not handled properly, this large displacement could cause some aerodynamic problems.

The final displacement graphs are given in Fig. 12. These are the tip displacements in the spanwise direction. A definite twist in the joined wing is again very evident. This reaffirms the need for more study on the effect of the truss shape of the wing as an aeroelastic structure.

Weight Comparison

Perhaps the most valuable results obtained are the wing weight comparisons given in Table 1. Since each configuration has been optimized for the same allowable stress level, the weights found can be used to indicate the lighter structure for the same strength. Practically speaking, the lighter structure is more desirable because it would permit more useful load to be carried. It should be noted that all wing weights are full-span wing weights, unless otherwise indicated. The weight of the tip joint is not included in the comparisons of Table 1 because the tip joint design was not fully optimized. The calculated total weights of the tip joint structures (left plus right wings) required to meet the given stress criteria were 150 lb for case I and 132 lb for case II.

Comparing the three box weights, it can be seen that the joined-wing case I is heavier (274 lb) than the conventional wing, while case II is lighter (155 lb). But the box weights are not the only parts that should be compared.

To obtain an estimate of the total wing group weight, only the box weight, the horizontal tail weight, and the leading-edge and fixed-trailing-edge airfoil weights will be included. (These weights will be full-span weights.) Thus, for this analysis, the weight of the control surfaces, joint inefficiencies, manufacturing tolerances, fairings, fuselage attachments, etc., will be assumed equal for all cases; therefore they will be disregarded in the comparisons. The reason for omitting these is that no acceptable means of determining (or guessing) these weights for the joined wing was found.

The weights of the leading and fixed trailing edges are calculated by assuming they are completely minimum gage thickness. To do this, the perimeter of the airfoil not taken up by the structural box and between 0 and 75% chord is estimated. (The control surfaces are located aft of 75% chord.) To calculate the total material areas outside the boxes, this perimeter was integrated over the span dimension: for the conventional wing this gives

$$2\int_0^{b/2} 0.527\,c\,dy$$

and for the joined wing,

$$2\left[\int_0^{b_j/2} 0.244\,c_j\,dy\right]\frac{1}{\cos\Gamma}$$

where b is the semispan dimension of the conventional wing; b_j is the semispan dimension of the joined wing; c is the chord dimension of the conventional wing; c_j is the chord dimension of the joined wing; and Γ is the dihedral angle of the wing. These areas are multiplied by the thickness and the specific weight density (0.1 lb/in.^{3}) to obtain the weight. These results are 1683, 945, and 529 lb for the conventional wing, and case I and case II of the joined wing, respectively.

To estimate the tail weight for the conventional wing, Vought Corporation's records of weight breakdowns were consulted.[4] These specifications for the Boeing 727 wing indicated that the wing weight is 18,698 lb, the horizontal stabilizer is 1943 lb, and thus the total wing weight is 20,640 lb. (These figures include the weights of fairings, fillets, control surfaces, etc.) This means that the horizontal stabilizer is 9.4% of the total wing group weight. Assuming that this percentage is the same for the weight of the box plus fixed airfoil weights (without fairings, fillets, etc.), the horizontal tail weight was calculated to be 1230 lb. [That is, $(10{,}156+1683)\times 0.094 = 1230$.] See Table 1. The tail weight is an estimate, therefore, of the tail box weight and the extra airfoil weight. The weight of the control surfaces, fairings, etc. are not included.

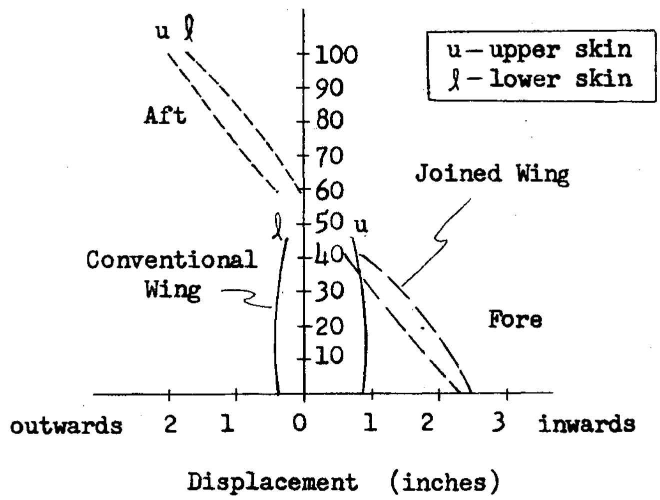

Fig. 12 Spanwise displacements of wings at tips.

Table 1 Overall weight comparison[a]

	Conventional wing	Joined wing case I	Joined wing case II
Minimum gage thickness, in.	0.125	0.125	0.070
Box weight, lb	10,156	10,554	9714
Edge airfoil weight, lb	1683	945	529
Horizontal tail weight, lb	1230	0	0
Total, lb	13,069	11,499	10,243
Percentage of conventional wing plus tail weight	100	88.0	78.4
Weight difference from conventional wing, lb	0	1570	2826

[a] Weights of joint inefficiencies, manufacturing tolerances, fairings, fuselage attachments, control surfaces, etc., are neglected in this weight comparison.

In Table 1, these weights are totaled to give an overall weight comparison. Case I of the joined wing was found to be 88.0% of the weight of the conventional wing. Case II was even lighter, at 78.4%. This means weight savings of 1570 lb for case I and 2826 lb for case II. It should be understood that these weights are estimated. It is the author's belief that if all weights could be included, the joined wing would be even lighter.

Conclusions and Recommendations

The joined wing with its truss-like structure was found to be a more efficient structure than a conventional wing such as the Boeing 727 wing. It was found to have a definite weight advantage, especially in the case where a smaller minimum gage thickness was employed. The smaller minimum thickness is reasonable, since the chord dimensions are smaller on the joined wing.

Deflection results also indicated that the joined wing was advantageous. Because of the joint at the tip, deflections were held down to less than 50% of the conventional wing deflections. As noted earlier, the evidence of a twist in the wing when loaded should be studied further to find its significance.

The thickness distribution provided very valuable information. It has shown that Dr. Wolkovitch's theory about the chord taper was not entirely correct. Equally important is the influence of the taper ratio on the thickness distribution. Further work will need to be done to determine the optimum taper for this type of wing configuration.

Finally, the author would like to stress the importance of building a structural model and performing structural tests to check the validity of the linear analysis used in this study. To encourage building a small-scale fiberglass model, a 10% scale joined wing was also optimized. The results of this optimization can be obtained from the author.

References

[1] Wolkovitch, J., "Principles of the Joined Wing," EEC Rept. 80-1, Engel Engineering Co., 28603 Trailriders Dr., Rancho Palos Verdes, Calif., 1981.

[2] Wolkovitch, J., "Application of the Joined Wing to Cruise Missiles," ONR-CR212-266-1, N81-25068, Contract N00014-79-C-0953, Aeronautical Consultant Associates, Rancho Palos Verdes, Calif., 1980.

[3] Jordan, B.M. Jr, Personal Communication, Vought Corporation, Dallas, Tex., 1979.

[4] *Specifications for Boeing 727-100,* Vought Rept. 63-025, Vought Corporation, Dallas, Tex., 1963, pp. 9-18.

[5] SAP V-User's Manual, Information Center Publication, Univ. of California at Berkeley, 1975.

[6] Fairchild, M.P., Structural Weight Comparison of a Joined Wing and a Conventional Wing, M.S. Thesis, Dept. of Engineering, Unvi. of Texas, Arlington, Tex., 1980.