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THE DESIGN OF AIRPLANE WING RIBS

By J. A. NEWLIN and GEO. W. TRAYER

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AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Symbol	Unit	Symbol
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of one kilogram	kg	weight of one pound	lb.
Power	P	kg/m/s		horsepower	hp
Speed		{km/hr	k. p. h.	mi./hr.	m. p. h.
		{m/s	m. p. s.	ft./sec.	f. p. s.

2. GENERAL SYMBOLS, ETC.

W, Weight, $=mg$

g, Standard acceleration of gravity $=9.80665$ m/s$^2=32.1740$ ft./sec.^{2}

m, Mass, $=\frac{W}{g}$

ρ, Density (mass per unit volume).

Standard density of dry air, 0.12497 (kg-m^{-4} s^2) at 15° C and 760 mm$=0.002378$ (lb.-ft.$^{-4}$ sec.^{2}).

Specific weight of "standard" air, 1.2255 kg/m$^3=0.07651$ lb./ft.^{3}

mk^2, Moment of inertia (indicate axis of the radius of gyration, k, by proper subscript).

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord length.

b/c, Aspect ratio.

f, Distance from C. G. to elevator hinge.

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed.

q, Dynamic (or impact) pressure $=\frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L=\frac{L}{qS}$

D, Drag, absolute coefficient $C_D=\frac{D}{qS}$

C, Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

R, Resultant force. (Note that these coefficients are twice as large as the old coefficients L_C, D_C.)

i_w, Angle of setting of wings (relative to thrust line).

i_t, Angle of stabilizer setting with reference to thrust line.

γ, Dihedral angle.

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension.

e. g., for a model airfoil 3 in. chord, 100 mi./hr. normal pressure, 0° C: 255,000 and at 15° C., 230,000;

or for a model of 10 cm chord 40 m/s, corresponding numbers are 299,000 and 270,000.

C_p, Center of pressure coefficient (ratio of distance of C. P. from leading edge to chord length).

β, Angle of stabilizer setting with reference to lower wing, $=(i_t-i_w)$.

α, Angle of attack.

ϵ, Angle of downwash.

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Forest Products Laboratory

100510—30——1

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THE DESIGN OF AIRPLANE WING RIBS

By J. A. Newlin[1] and George W. Trayer[2]

SUMMARY

The purpose of the investigation reported here was to obtain information for use in the design of truss and plywood forms, particularly with reference to wing ribs. Tests were made on many designs of wing ribs, comparing different types in various sizes. Many tests were also made on parallel-chord specimens of truss and plywood forms in place of the actual ribs and on parts of wing ribs, such as truss diagonals and sections of cap strips.

It was found that for ribs of any size or proportions, when they were designed to obtain a well-balanced construction and were carefully manufactured, distinct types are of various efficiencies; the efficiency is based on the strength per unit of weight. With ideal construction the truss comes first; second, a lightened and reinforced plywood type; third, a full plywood web type with stiffeners; fourth, a plywood web with lightening holes and no reinforcing; and fifth, a full web with no stiffeners. If a type falls out of this order, the probable reason is either that it is poorly designed or that it was designed with some special consideration for manufacturing details and is therefore not so strong for its weight as it can be made.

Each type has its place in airplane design because manufacturing difficulties set up practical limits for the various types. For example, shallow trusses can not be manufactured and assembled without great difficulty. Neither can a reinforced plywood truss be substituted for a full plywood type when to obtain maximum efficiency an excessively thin plywood must be used.

In all types of ribs the heavier are the stronger per unit of weight. Reductions in the weight of wing ribs are accompanied even in efficient designs by a much greater proportional reduction in strength.

Obtaining maximum efficiency in truss designs would require all diagonals to be of cruciform cross section and all members to be proportioned according to their individual stresses.

Members with thin, outstanding flanges and with little torsional rigidity, especially ⊔ *sections, fail by twisting, at times carrying only 50 per cent of the calculated compression load. Slight modifications in cross section without change in area increase the torsional rigidity sufficiently to overcome this twisting.*

In resistance to both end loads and bending, ⊔ *and* ⊤ *sections built up of wood and plywood in combination are inefficient as compared with sections having the grain of the wood all parallel to the axis of the piece.*

Compression diagonals are more suitable in the panels adjacent to the spars than tension diagonals, since tension diagonals have been found more difficult to hold at the joint than compression diagonals.

Bending stresses in plywood types can be calculated with a fair degree of accuracy provided that the plywood is of sufficient thickness or is so braced as to prevent buckling and the rib is so braced as to prevent bending of the caps out of the plane of the rib. Form factor must be taken into account, and in calculating the moment of inertia only that part of the plywood having grain parallel to the axis of the rib should be included.

No tests were made from which the required vertical rigidity of the webs can be determined absolutely, but approximately it may be said that any unit of length, including its proportional part of the stiffeners, should be able to carry, as a pin-end column, two-thirds of the load that will come upon this unit of length when the rib is loaded to failure.

Plywood webs with a balsa core proved very satisfactory from a construction standpoint and in full webs were found to be strong per unit of weight in comparison with other plywoods. When lightening holes were added, however, the strength dropped very rapidly because of the ease with which the face plies tore the balsa core apart around the holes at the least tendency to buckle. Even shrinkage and swelling stresses may cause rupture of the balsa core at the edges of the lightening holes.

In general, vertical face grain in plywood webs gives consistently greater strength when a full web is used, but longitudinal face grain is better when a web with lightening holes and stiffeners is used.

Webs of single-ply spruce, in comparison with three-ply poplar plywood webs of the same total thickness, proved stronger than the plywood when lightening holes were present and somewhat weaker when no holes were present.

Two-piece cap strips in most designs are preferable to single-piece cap strips.

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[2] Senior engineer, Forest Products Laboratory, U. S. Department of Agriculture; maintained at Madison, Wis., in cooperation with the University of Wisconsin.

Wide diagonals and web members are subject to large indeterminate secondary stresses, which often start failures. A similar concentration of stress occurs around lightening holes, causing buckling.

The coefficient of fixity for diagonal members under compression appears to be about one and one-half in a plane at right angles to the plane of the rib.

Maximum efficiency appears to be obtained with a ratio of spar spacing to height of about six, except for full plywood types without stiffeners, for which the ratio appears to be about eleven.

Double compression members with a spacer block at the center were found to be about one-half as strong as the same members brought together and glued throughout their length when the length is such as to throw both in the Euler column class.

Small stiffeners glued near the edges of lightening holes were found very effective in reducing buckling; the small resulting percentage of increase in weight will often be accompanied by several times that percentage increase in strength. Reinforcing around lightening holes to avoid buckling should be equally satisfactory in metal construction.

The appendix of this report contains other comments on various designs and a description of characteristic failures.

INTRODUCTION

In aircraft construction the ordinary methods of calculation, suitable for most engineering structures, are either inapplicable or are too inaccurate to be applied to an unavoidably complex structure in which the factor of safety must necessarily be extremely low. Wing ribs, for example, with their rigid connections and often redundant members can scarcely be considered amenable to accurate calculation. The first necessity in designing such structures is a knowledge of certain principles, of broad application, that govern the distribution of stresses, principles that will assist in the selection of the most effective type of rib for a given airfoil and chord length and that will help in the design of members and details.

Realizing the need for such information, substantiated by experiment, the Bureau of Aeronautics, Navy Department, financed an investigation made by the Forest Products Laboratory, Madison, Wis. The following report is a description and analysis of the tests made in connection with this investigation.

PURPOSE

This investigation was made to determine general principles of broad application that govern wing-rib design and apply also to other truss and plywood forms used in aircraft construction. The results are intended to assist in determining the most effective type of rib for a given airfoil and chord length, to help in the design of members and details of any new rib, and to aid designers in formulating rules regarding the effect of various factors on the design and the strength of different parts. A knowledge of the facts set forth will not entirely eliminate the necessity of making tests or take the place of testing, but it should be of considerable value in planning designs for new ribs.

SOURCE OF MATERIAL

Many tests have been made at the Forest Products Laboratory on wing ribs and parts of airplanes during and since the World War. Part of these were made simply to determine the strength of a particular rib while others were made primarily to improve the design of a given rib. Considerable general information that is of value in determining factors of design resulted from these studies. The ribs or parts tested were sometimes built at the laboratory according to plans furnished by the company that designed the plane and sometimes they were built by the company and submitted for test.

Extensive tests were made on ribs of the BS–1 airfoil, station 3, near the fuselage, both of 48-inch and of 96-inch chord lengths. (Fig. 1.) This airfoil section was recommended by the Bureau of Aeronautics, Navy Department, as a somewhat typical section of a deep wing. Tests were also made on rectangular or parallel-chord sections of truss and plywood forms representing the portion of a rib that is between the spars.

The BS–1 test ribs and the parallel-chord sections were made at the laboratory from stock suitable for airplanes. Slightly greater care was probably exercised in the construction of these test specimens than is ordinarily met with in the production of airplane parts.

DESCRIPTION OF TEST SPECIMENS

The test material for this particular investigation consisted of wing ribs and of parallel-chord rib sections. The wing ribs had either a 48-inch or a 96-inch chord length and had the airfoil section of the BS–1 lower wing, station 3. The rib sections were 44 inches from center to center of spar blocks and were rectangular or parallel chorded. Both the ribs and the parallel-chord specimens were of various designs—plywood, truss, and a combination of plywood and truss. Detailed drawings of all these are included in the figures accompanying this report.

In the original design, ribs of the BS–1 wing had full plywood webs with vertical angle blocks for bracing. The plywood was three thirty-seconds inch thick with mahogany faces and poplar core. In the first variation lightening holes were made in similar ribs, then a three forty-eighths inch full plywood web was substituted for the three thirty-seconds inch web, and finally a three forty-eighths inch web with lightening holes was used in place of the three thirty-seconds inch web. Warren, Pratt, and Howe trusses were also designed with diagonals of various sizes and cap strips of various shapes and sizes.

The ribs with 96-inch chords were also of the BS–1 station 3 airfoil section, but were double the size planned for the BS–1 plane. In other respects these ribs were substantially duplicates of the ribs of normal size, and the tests on them merely repeated the earlier tests.

Parallel-chord specimens were 44 inches in length between centers of blocks. The depths were 3⅞, 7¾, 11⅝, and 15½ inches. The end blocks, which were 4 inches wide, represented the spars. Specimens were tested in which thickness of plywood web and

The loading apparatus (fig. 3), which was used in connection with a universal testing machine, consists of a lever system to distribute the pressure and a set of stirrups to hold the specimens in place. The lever system was so designed that pressures at the stirrups were proportional to the areas of the corresponding zones in the loading diagrams. The downward force of the movable head is transmitted to the spar sections or blocks and draws the specimen against the stirrups, producing the effect of an upward lift. The entire lift is applied to the lower chord.

In low-speed loading a 48-inch rib was held by eight stirrups spaced equally along the chord. If this same

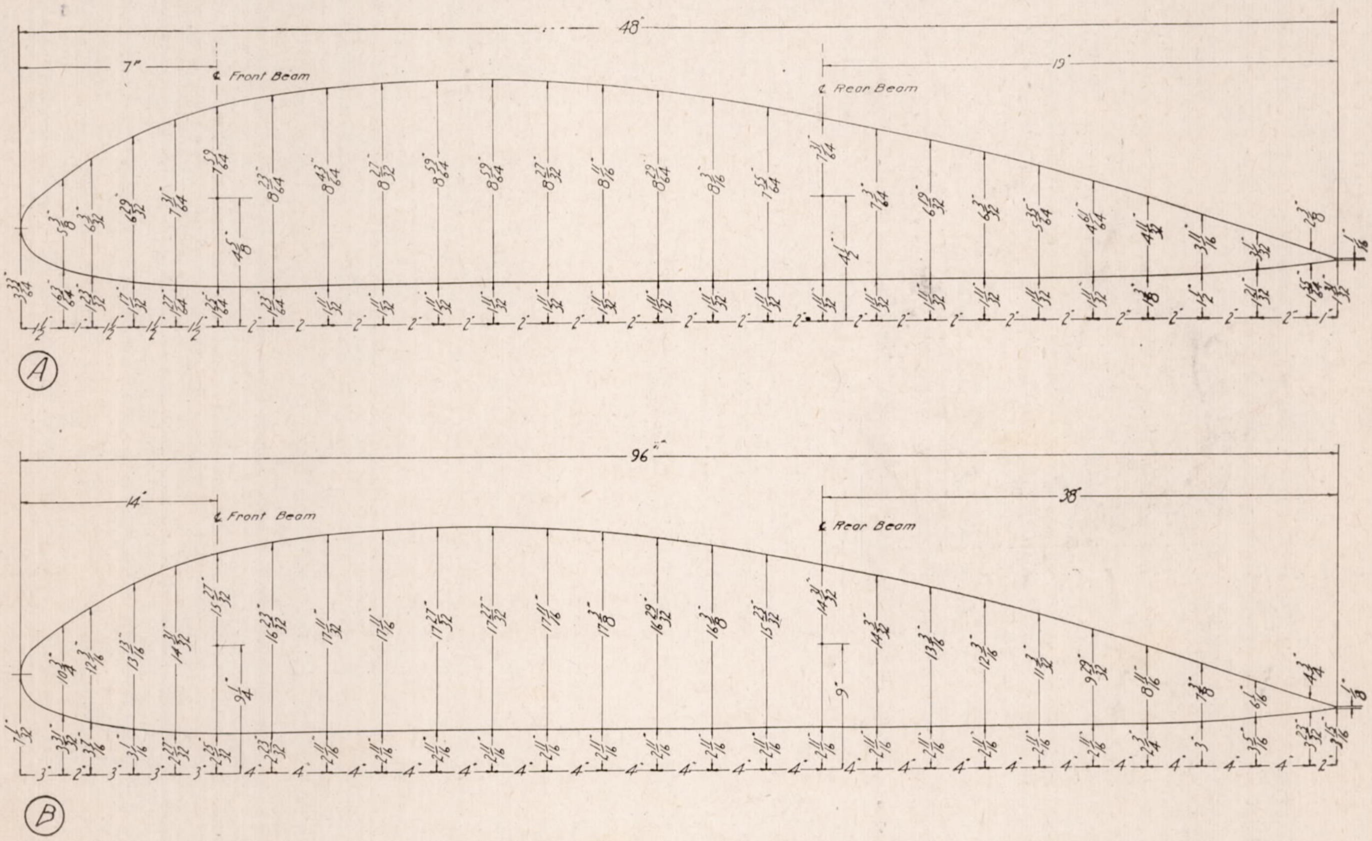

FIGURE 1.—Airfoil section of the BS–1 lower wing at station 3

A—Dimensions as called for in the original design.
B—The original dimensions doubled.

direction of face grain were varied and in which different bracing and forms of lightening holes were used. Trusses of various designs were also tested in the different depths. Diagonal truss members of cruciform cross section and of rectangular cross section were compared.

METHOD OF TEST

The lift or pressure on the wing ribs was distributed according to the diagrams given in Figure 2. These distributions were recommended for wing rib tests by the Bureau of Aeronautics, Navy Department. The lift on the parallel-chord specimens was practically a uniform load.

spacing were used for high-speed loading the division nearest the leading edge would receive part positive and part negative pressure. To avoid using the resultant of these two pressures in this division, two stirrups instead of one were used, one to apply the negative and one the positive pressure. The downward force producing the negative pressure was applied through a wire attached to the upper cap strip of the nose and extending around a pulley on the lower timber and then to the upper part of the lever system.

The 96-inch ribs were held by 16 stirrups spaced equally along the chord. With this spacing the division nearest the leading edge receives only negative pressure and the stirrup applying this pressure is placed on the upper cap strip. A wire extends from this stirrup, around a pulley that is fastened to the timber attached to the movable head, and up to the evener system, the same as for the 48-inch rib.

The parallel-chord specimens were held in place by eight stirrups spaced equally along the chord. Equal pressure was applied to each stirrup. The lever system was symmetrical and corresponding levers had arms of equal length. The specimens were braced against the frame of the testing machine to prevent lateral buckling. Strips of wood were centered under each load point to prevent local crushing.

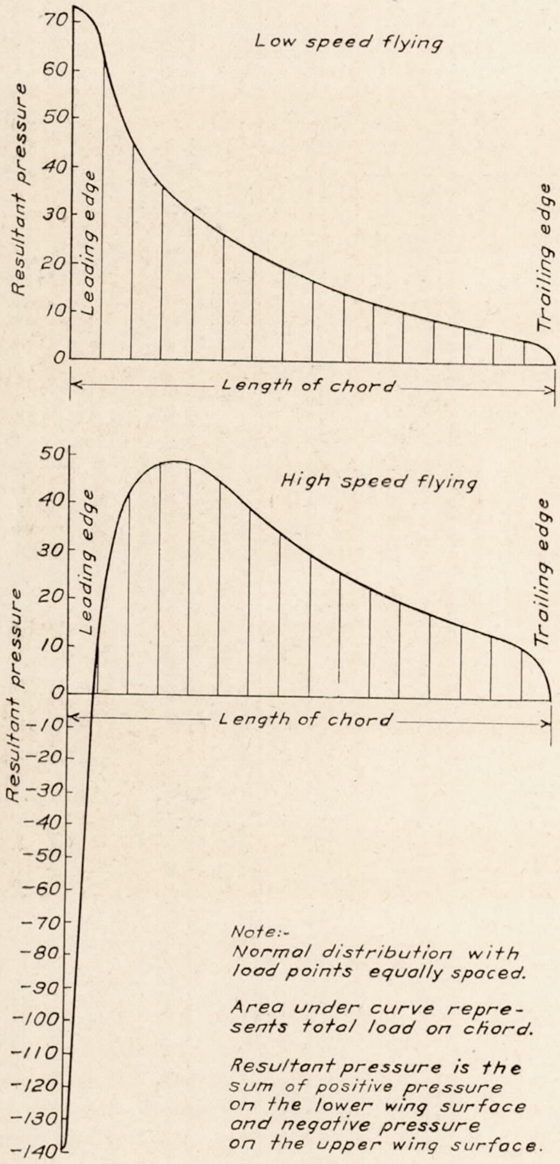

FIGURE 2.—The distribution of pressure on the wing ribs for low-speed and for high-speed flying

ANALYSIS

In addition to the data included in this discussion, considerable information obtained from strength tests in general and from development studies made previously on ribs for particular planes was used in arriving at the conclusions and principles of design embodied in this report. While all past tests have been considered in arriving at the conclusions, only the tests of the BS-1 ribs and the parallel-chord specimens are definitely referred to and the data therefrom included in the tables.

A wing rib with its rigid connections, redundant members, and nonuniformity of section is a complex structure. Simple assumptions to make an analysis possible by the ordinary methods of calculation often lead to mere approximations for a structure in which the factor of safety must necessarily be extremely low. Wing-rib design is still dependent upon the results of strength tests on complete ribs, and to some extent will continue to be so. Stresses are largely indeterminate because the ribs have rigid connections; the ribs act as a truss or a girder with cantilever arms and are of nonuniform section. The stresses are further complicated by the nature of the load distribution.

From a study of test failures and from a knowledge of the stress that a member is capable of sustaining, we are able to estimate the secondary stresses at different points in the structure and to redesign so as to redistribute the stresses. Furthermore, we are able to develop principles of design that will distribute the failures and afford a more nearly perfect balance among the strengths of the different parts.

RELATIVE EFFICIENCY OF VARIOUS TYPES

In this investigation the relation of strength to weight of rib was taken as a criterion of the value of the rib; it is necessary, however, to keep in mind the fact that this relation is a suitable criterion only as far as the rib is within reasonable limits of both strength and weight. High strength per unit of weight has but little value when the strength is in excess of that required for service.

Results showing strength-weight relations for different types of ribs are plotted from data obtained from the tests of parallel-chord specimens. The data for each type, such as simple truss, reinforced-plywood truss, plywood web with bracing, and plywood web without bracing, are plotted separately. (Figs. 4, 5, 6, and 7.) In each of these figures a curve showing the ideal efficiency is drawn through the maximum value of strength-weight ratio obtained from the tests. A definite relation of strength to weight for the various types is evident from the figures. It is also evident that the various types are not of equal efficiency from the standpoint of strength per unit of weight.

In any size or proportions of wing ribs the ideal truss comes first in efficiency. This is to be expected, for the material in a truss can be placed more nearly to the greatest advantage. Next to the truss in order of efficiency is the plywood-web type with lightening holes and bracing. This type if properly designed can be made to approach a truss in form, for excess material can be cut out at points of low stress and reinforcing added at points of high stress. Third in order of efficiency is the plywood-web type having full web and reinforcing. The web in this type is so thin that stiffeners are required at the highly stressed points. Fourth is the plywood-web type with full web and no reinforcing. Here we undoubtedly have excess material in portions of the web.

The curves of Figures 4, 5, 6, and 7 represent the ideal ribs of various weights for each type and are identical except for a constant factor. The ideal curve for all types is represented by the equation

$$P = KW^{\frac{4}{3}},$$

where P = Breaking load in pounds.

K = Constant factor dependent upon type of construction.

W = Weight of rib in ounces.

These curves were obtained by a study of the ribs of the various types that approached most closely to a balanced construction; that is, those that appeared to have no excess strength in any part and no evident opportunity for redesign to obtain greater load with the same weight.

The constant K in the equation represents the relative efficiency of different types of ribs when each is of ideal construction. The greater the value of K, the more efficient the type of rib. For each chord and airfoil section there will be a different value of K, but the ideal ribs of any type for a given airfoil will have their K's in the same relation as the K's following, which are for parallel-chord specimens. K is 60 for the parallel-chord truss type, 48 for the reinforced-plywood truss, 43 for a full webbed rib with stiffeners, and 40 for a rib with a full web and without stiffeners. The ideal lightened rib with no bracing would fall between 40 and 43. Usually, however, the rib to be lightened is made of heavier plywood and has numerous holes introduced to reduce the weight and the load-weight ratio is below that which could be obtained by the use of full plywood of ideal thickness.

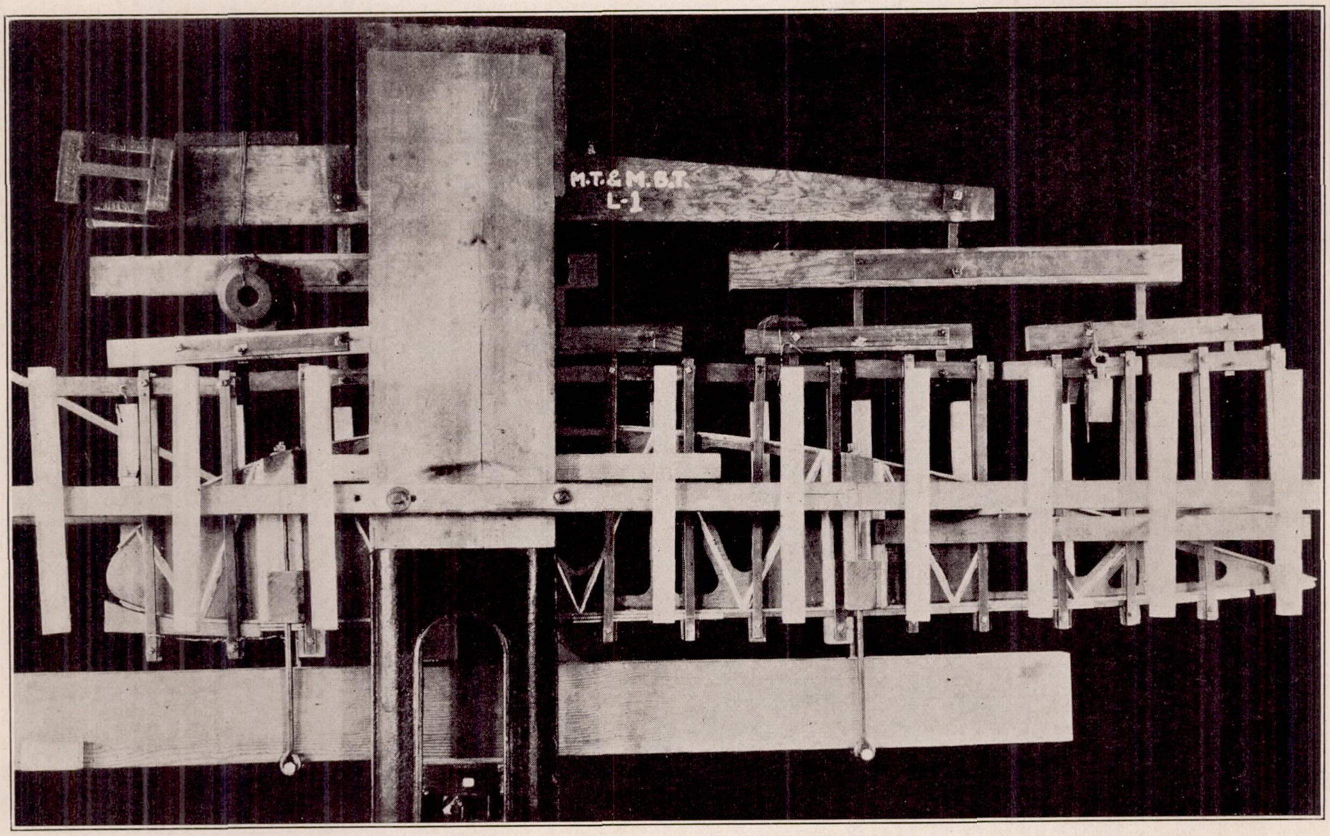

FIGURE 3.—A wing rib in the testing machine. The large timber below the rib is rigidly attached to the movable head of the testing machine and the evener system is supported on vertical standards that rest on the weighing platform

It is evident from the nature of the curves that the heavy and excessively heavy ribs have the best strength-weight ratios, and that a given increase in weight is accompanied by a greater increase in strength. Thus, in most instances heavy ribs spaced far apart, with well-balanced design, will sustain the same load on the wing with less weight than lighter ribs with closer spacing. However, considerations such as obtaining a smooth-surfaced airfoil without too much

100510—30——2

flapping of the covering often necessitate choosing the lighter rib with close spacing rather than the more efficient heavy rib.

In Figures 4, 5, 6, and 7 the ideal curves pass through points of maximum strength-weight ratios. It is more difficult to build efficient shallow ribs as the design approaches a truss because diagonals and bracing must then be made in sizes smaller than those small ribs, because the number of parts and joints in a small truss is as great as in a large one of the same design. In building large ribs with plywood webs it is harder to approach the ideal than in the smaller ones because of the difficulties encountered in the warping of large sheets of plywood and the greater tendency of the plywood to buckle. Other types have their advantages in certain sizes, each type that can be manufactured and assembled without great difficulty and the members must be properly proportioned for the stress that is to come upon them. Therefore great care and refinement is necessary in the design and construction of small trusses, and the less efficient plywood types will often be preferable to the truss.

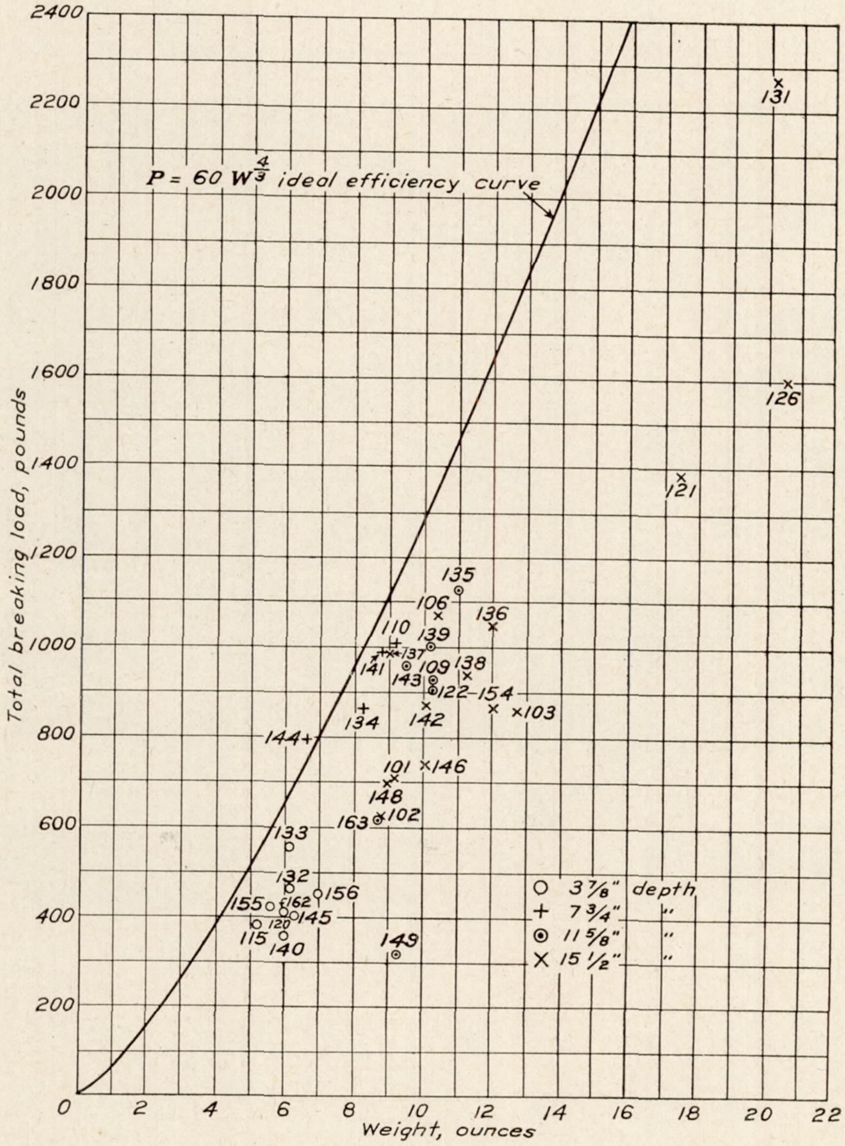

FIGURE 4.—Relation between breaking load and weight of rib for parallel-chord rib sections of the truss type

NOTE.—Each point is the average of three tests. Point numbers are design numbers.

The truss is relatively easier to construct in large ribs and approaches more closely to the ideal than in appearing to have its particular place in airplane design.

In the experimental work a large number of the ribs and specimens were not of well-balanced design, since the testing was usually for the purpose of developing the ideal rib and thus required experimenting with all kinds of designs, and any given size or type was discontinued when the ideal was apparently reached. Many of the ribs and other specimens were designed with various special considerations for determining the effect of certain factors on particular points of design. Furthermore, manufacturing conditions and limits of service controlled the designs to some extent. Production facilities, of course, will always be one of the chief factors in the selection of the type of rib.

A consideration of these factors will lead to a more nearly perfect balance among the strengths of the different parts of a rib.

The computed stresses in a truss, assuming the joints to be pin connected, are direct tension and direct compression along the member when the loads are applied at the panel points. In trusses with

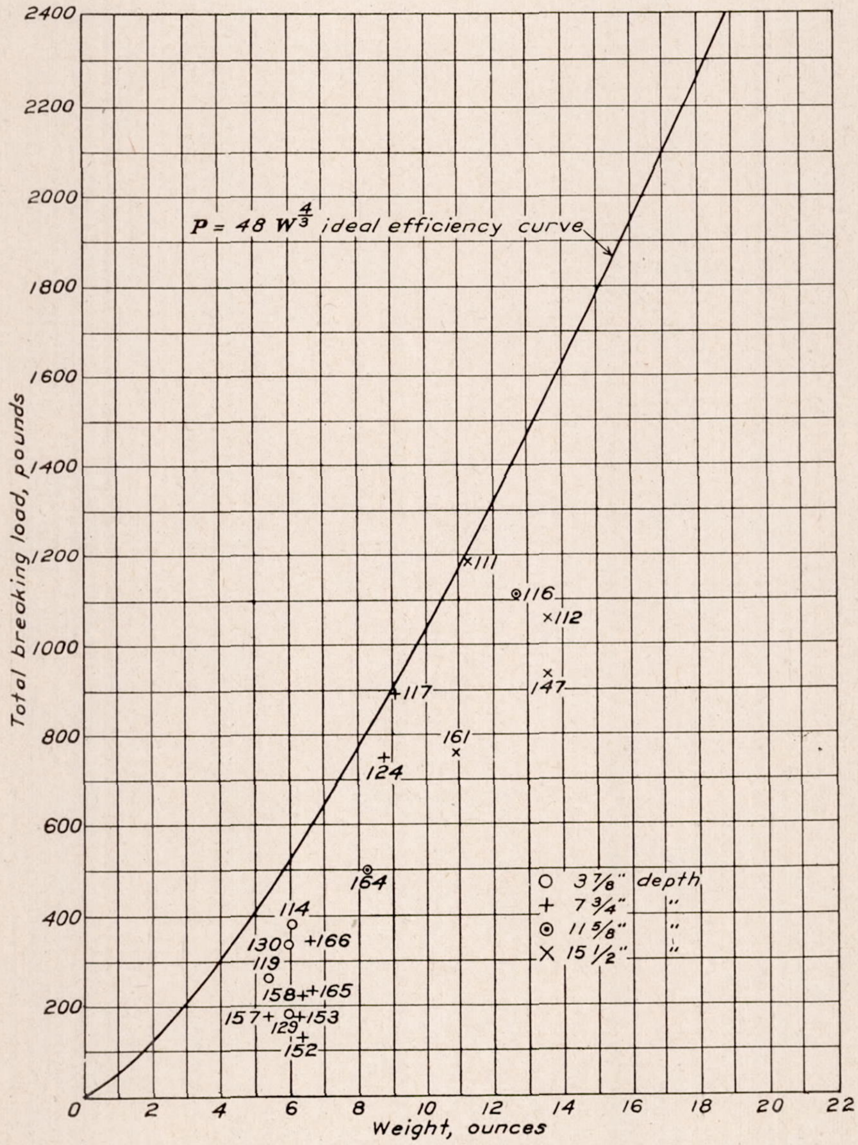

FIGURE 5.—Relation between breaking load and weight of rib for parallel-chord rib sections of the reinforced plywood truss type

NOTE.—Each point is the average of three tests. Point numbers are design numbers.

FACTORS AFFECTING DESIGN

After manufacturing conditions, service limitations, and production facilities have been considered in the selection of a type, the next necessity in designing a rib is a knowledge of certain principles of broad application that govern the distribution of stresses. Following is a discussion of certain principles of design developed from a study of test failures and a knowledge of the stress that a member is capable of sustaining.

rigid connections between members, such as those encountered in airplane design, stresses are introduced through chord deflections, and members that are mutually supported transfer their stresses to one another. The support one member gives to another may range from a condition of perfect fixity to one where the induced stresses are greater than the direct stresses. Wide diagonal or post members increase the fixity of the cap strip and as the cap strip deflects secondary stresses are introduced into the compression and the tension members. The secondary stresses act to deflect the diagonal and to increase the stresses in it. In a pin-connected truss, on the other hand, one may say that there is neither fixity nor secondary stresses. With rigid connections bending is thrown into the diagonals and the posts as the cap strips deflect and the length of effective column is made greater. Such a condition amounts to a negative fixity and is similar to an eccentric load with a pin connection. The column in this case is resisting chord deflection. When the end connections are such that the diagonals and the posts increase the bending in the chord—that is, throw additional stress into the chord—there is positive fixity in the diagonals and the posts. With such a condition, the diagonals and the posts amount to columns with partially fixed ends.

The effect of secondary stresses varies not only with the type of rib, but in a given type varies also with the details of the fastenings and the proportions of the members. Ribs with full plywood webs are relatively free from secondary stresses of a nature corresponding to those that occur in the joints of a truss. These and other plywood types are inefficient in taking the large compression in the lower chord unless the cap strip is wide beyond practical limits. If the cap strip is made wide and thin in order to obtain lateral rigidity, it may buckle as a thin outstanding flange. The strength of plywood ribs in service depends largely on the efficiency of the lateral support furnished by the connection to the wing covering.

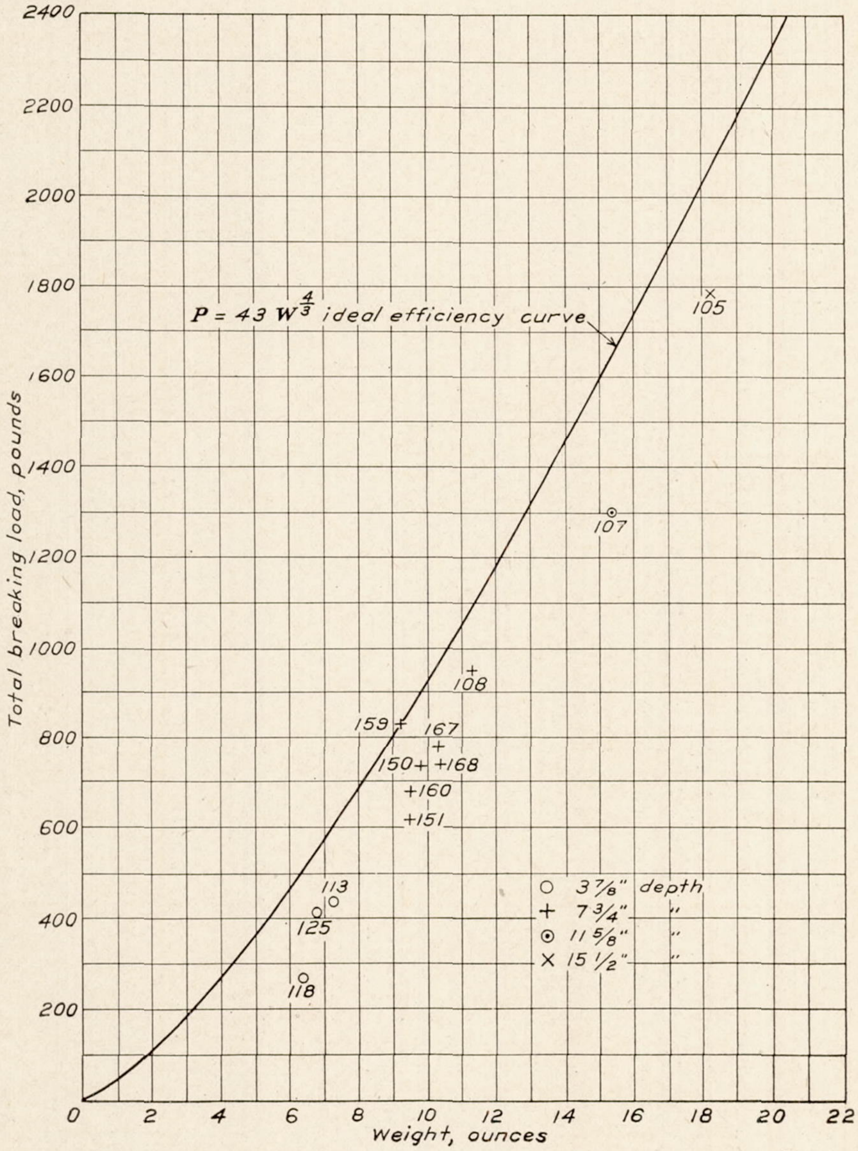

FIGURE 6.—Relation between breaking load and weight of rib for parallel-chord rib sections with full plywood webs

NOTE.—Each point is the average of three tests. Point numbers are design numbers.

The lateral buckling in ribs with plywood webs is either a buckling of the cap strip caused by the column load along its length or a buckling starting in the plywood web and drawing the cap strip to the side with the web. With ribs that buckle in the web, stiffeners placed to resist the web buckling add considerable strength, but with ribs that buckle in the cap strip such stiffeners do not materially increase the strength.

In rigidly connected truss types the design must be based not only upon the primary stresses; full consideration must also be given the large secondary stresses that occur even in the best construction. In poor construction the secondary stresses may be the primary cause of failure. If a member is made less rigid in the plane of the rib and near the end fastening, by such means as a joint in the diagonal or a reduction in the cross section of the member, the secondary stresses may be reduced.

Wide members, of course, are subject to much larger moments and secondary stresses than narrow ones, and two narrow tension members will often be much better than a single wide one of the same cross-sectional area.

In the design of glued joints, such as those at the intersection of truss members, a stress of one-fourth of that used for shear in the wood parallel to the grain should be used in calculating the required glue area. This rule is predicated on the assumption that the members are so proportioned as to avoid excessive secondary stresses. Using such a stress value does not mean we have a factor of safety of four, because it includes a factor of two to take care of the cross-

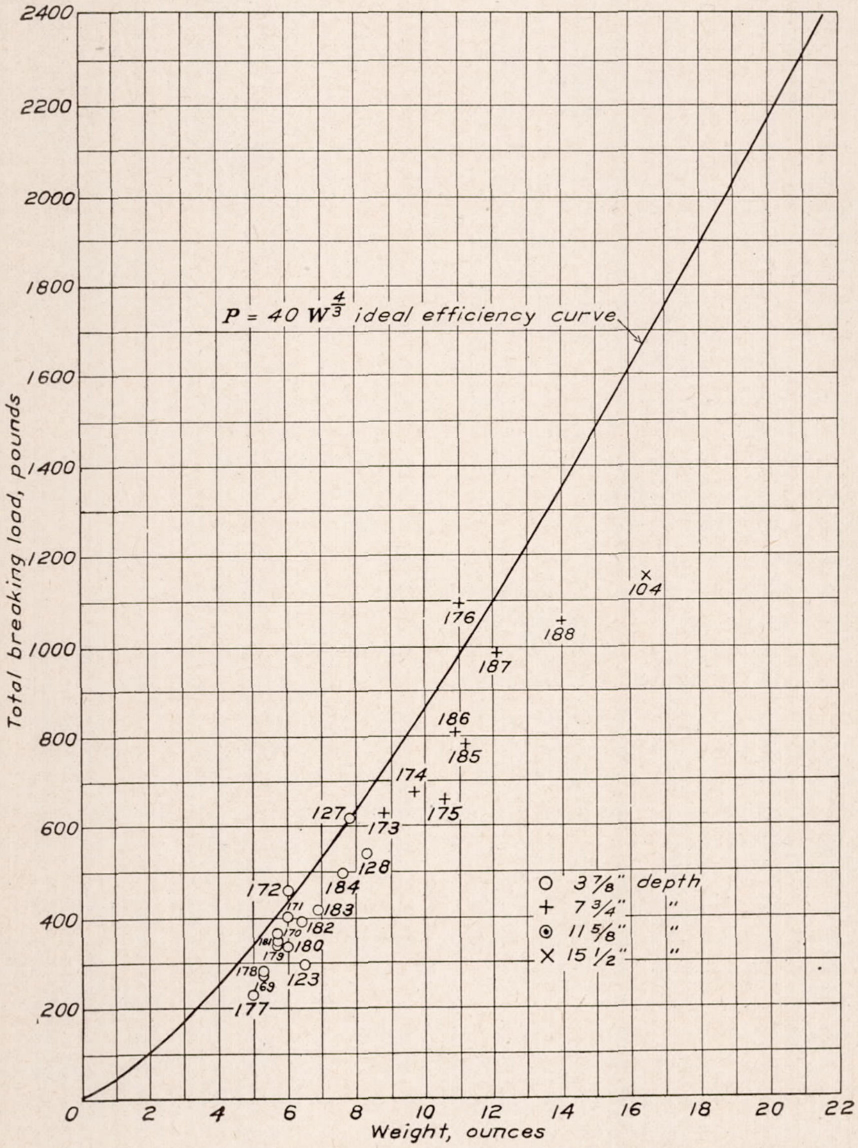

FIGURE 7.—Relation between breaking load and weight of rib for parallel-chord rib sections having full plywood webs without bracing

NOTE.—Each point is the average of three tests. Point numbers are design numbers.

banded shear strength, and an additional factor of two to take care of secondary stresses. In good construction, we find, the secondary stresses in these joints will equal the primary stresses.

The fastenings at the intersections of ribs and spars are vital points in design. Strips or angle blocks used in all four corners of each spar intersection contribute greatly to the strength of a rib. All these joints are likely to be cross-banded (the grain of one piece at right angles to the grain of the other) and to have high secondary stresses either from the load or from shrinking and swelling.

Nailing is sometimes resorted to under the supposition that it will increase the strength of a glued joint. Tests have demonstrated that the nails do not come into action until the glue has given way and that the reduction in strength caused by each nail is equivalent to that caused by a bored hole the diameter and the length of the nail. In light cap strips, this reduction will amount to as much as 20 or 25 per cent.

Data on the strength of ribs having either compression diagonals or tension diagonals adjacent to the spars are given in Table I. The ribs were of similar design so that differences in strength are due chiefly to differences in the types of the diagonals. In comparing these two types it is necessary to make use of high-speed loading, because with low-speed loading failure occurred in the web of the nose section in many of the ribs, and such failure gives no indication of the relative strength of the two diagonals. The lack of correct indication accounts for the ribs with tension diagonals appearing stronger in low-speed loading in some cases. The data show that compression diagonals in the panels near the spars are somewhat stronger than tension diagonals. Further, tension diagonals are harder to hold at the joints because when stressed they pull away from the other members, while a compression diagonal pushes more firmly against the members to which it is attached. Again, much greater glue area must be provided than a tension member would furnish if made only large enough to withstand the tensile stress. In designs of reinforced plywood trusses, tension diagonals can often be used to advantage because of the large area available for gluing. In truss design the matter of proper fastening at the joints is a problem that should always receive special attention from the designer. A perusal of the appendix will disclose the fact that very often the first source of weakness in a great many of the designs was in the joints.

Table I.—COMPARISON OF TENSION DIAGONALS AND COMPRESSION DIAGONALS OF BS-1 WING RIBS UNDER HIGH-SPEED [1] LOADING

Type of truss	Rib length	Design [2] No.	Type of stress	Net lift load, P	Weight of rib, W	$\frac{P}{W}$
	Inches			*Pounds*	*Ounces*	
Pratt	48	3	Tension	578	6.7	86
Do	48	3	do	515	6.7	77
Do	48	3	do	647	6.8	95
Average				580	6.7	86
Howe	48	4	Compression	618	6.4	97
Do	48	4	do	791	6.6	120
Do	48	4	do	748	6.3	119
Average				719	6.4	112
Pratt	96	3-A	Tension	654	24.2	27
Do	96	3-A	do	783	25.0	31
Do	96	3-A	do	790	24.6	32
Average				742	24.6	30
Howe	96	4-A	Compression	821	23.7	35
Do	96	4-A	do	902	23.8	38
Do	96	4-A	do	900	23.9	38
Average				874	23.8	37

[1] In low-speed loading the failures were not at the ends of the diagonals.
[2] The designs are described in the appendix.

In the design of trusses a large moment of inertia is sought so that members may be light and still have high column strength, especially in the plane at right angles to the plane of the rib. Data on the strength of trusses of similar designs afforded an opportunity to compare sections with diagonals of various cross sections. Double compression members with a spacer at the center were found to be about one-half as strong as the same members brought together and glued throughout their length when the length was such as to throw both in the Euler column class. Two such members unattached would theoretically be one-fourth as strong as when glued throughout their length. This difference is accounted for by the resistance to shear offered by the glued joints at the ends and at the spacer block.

The increase in moment of inertia occasioned by the spread of the members can not be taken as a measure of the increase in strength. Although compression members of U and of cruciform cross section are stronger than those of rectangular form as long as they are designed to avoid twisting and excessive secondary stresses, their increase in strength is far below their increase in moment of inertia. For example, the three types of diagonals used in the ribs listed in Table II have the same cross-sectional area, while the moments of inertia for the rectangle, cross without fillets, and cross with fillets, are as 1, 2, and 2.6. Yet because of the increase in secondary moments and twisting of the diagonals in design No. 101, in spite of an increase of 100 per cent in moment of inertia, it still was only 18 per cent stronger than No. 102. The wide members in design No. 106 included still larger secondary stresses, but the fillets prevented twisting and the larger moment of inertia increased the load to cause failure over that of No. 102 by approximately 70 per cent only, instead of the 160 per cent indicated by the increase in the moment of inertia.

TABLE II.—COMPARISON OF RECTANGULAR DIAGONALS AND CRUCIFORM DIAGONALS IN PARALLEL-CHORD WARREN TRUSS[1] RIB SECTIONS, 44 INCHES LONG BY 15½ INCHES DEEP

Cross section of diagonal	Fillets	Design[2] No.	Rib No.	Net lift load, P
				Pounds
Square		102	4	658
Do		102	5	558
Do		102	6	683
Average				633
Cruciform	None[3]	101	1	758
Do	do.[3]	101	2	733
Average				746
Cruciform	⅛ inch	106	16	983
Do	do	106	17	1,033
Do	do	106	18	1,218
Average				1,081

[1] In all 3 of these designs the diagonals were of the same cross-sectional area and for all these ribs failure was in the diagonals.
[2] The designs are described in the appendix.
[3] In this design the diagonals failed by twisting. Design No. 106 gave much higher loads because the moment of inertia was increased and the fillets prevented twisting.

Practical considerations often lead to the manufacture of ribs not of ideal construction. A truss with all its diagonals and posts rectangular in cross section and of the same size, for example, has only one-half the advantage of the ideal truss over the ideal full plywood web without bracing, and has no advantage over the ideal reinforced plywood truss in which the reinforcement is proportional to the stresses.

From results on strength tests of truss sections, it appears that the coefficient to be applied to the Euler column formula for the strength of compression web members in a plane at right angles to the plane of the rib is about one and one-half.

PLYWOOD TYPES

The laboratory tests of various plywood types brought out a number of factors that affect design. With plywood of a sufficient thickness, or so braced as to prevent buckling, and with proper bracing to prevent bending of the caps out of the plane of the specimen, bending stresses can be calculated by the usual $S=F_u \frac{Mc}{I}$ formula. In calculating the moment of inertia (I), however, only that part of the plywood with grain parallel to the axis of the specimen can be used. The form factor for the specimens in all heights tested was very low, reducing the modulus of rupture to practically the compressive stress parallel to the grain. Now, if the web can buckle easily in a plane at right angles to the plane of the specimen, failure by buckling will occur before the stress in the extreme compression fiber has reached the ultimate compressive stress parallel to the grain. Three methods can be employed to increase the vertical stiffness of the rib, one of which is to put the face grain vertical. With three equal plies, doing this is at the expense of the moment of inertia to resist bending, but the resistance to buckling is usually of greater importance. Another method is to glue small stiffeners on the web, and a third method is to separate the face plies well by some light core stock such as balsa.

No tests have been made and no criterion has been set up at the Forest Products Laboratory by which the degree of rigidity required in plywood webs can be determined absolutely. Approximately, however, it may be said that any unit in the length of the rib, including its proportional part of the stiffeners, should be able to carry, as a pin-end column, two-thirds of the load that will come upon this unit of length when the rib is loaded to failure.

A comparison was made between rib sections built up with balsa-core plywood and corresponding sections having three-ply poplar plywood with stiffeners. Table III gives data for this comparison. It is evident from the table that balsa-core plywood without stiffeners is about equal in strength per unit of weight to three-ply poplar with stiffeners. With lightening holes in the rib, however, the ease with which the balsa-core tears apart offsets the advantages gained by separation of the face plies.

A comparison was also made of rib sections having plywood webs with balsa cores of various thicknesses. Data for this comparison are in Table IV. These data show how the strength increases with the core thickness, because of the separation of the face plies, which gives greater column strength to resist buckling in a plane at right angles to the plane of the rib. The increase in strength is greater than the corresponding increase in weight.

TABLE III.—COMPARISON OF BALSA-CORE PLYWOOD WEBS AND THREE-PLY POPLAR WEBS IN PARALLEL-CHORD RIB SECTIONS 44 INCHES LONG

3⅞-inch depth

Design[1] No.	Plywood webs: Thickness of plies	Plywood webs: Species of wood	Plywood webs: Bracing	Net lift load, P	Weight of rib, W	$\frac{P}{W}$
	Inch			*Pounds*	*Ounces*	
113	1/50+1/50+1/50	Yellow poplar	Truss	460	7.2	64
113	1/50+1/50+1/50	do	do	433	7.3	59
113	1/50+1/50+1/50	do	do	440	7.3	60
Average				444	7.3	61
127	1/40+1/20+1/40	Yellow poplar	None	558	8.0	70
127	1/40+1/20+1/40	do	do	724	7.7	94
127	1/40+1/20+1/40	do	do	568	7.8	73
Average				617	7.8	79
171	1/48+1/8 +1/48	Mahogany+balsa+mahogany.	None	366	5.9	62
171	1/48+1/8 +1/48	do	do	423	5.9	72
171	1/48+1/8 +1/48	do	do	413	6.2	67
Average				401	6.0	67
172	1/48+5/32+1/48	Mahogany+balsa+mahogany.	None	449	5.9	76
172	1/48+5/32+1/48	do	do	455	6.1	75
172	1/48+5/32+1/48	do	do	478	6.0	78
Average				461	6.0	76
184	1/48+3/16+1/48	Mahogany+balsa+mahogany.	None	450	7.7	59
184	1/48+3/16+1/48	do	do	525	7.5	70
184	1/48+3/16+1/48	do	do	500	7.5	66
Average				492	7.6	65

7¾-inch depth

Design[1] No.	Plywood webs: Thickness of plies	Plywood webs: Species of wood	Plywood webs: Bracing	Net left load, P	Weight of rib, W	$\frac{P}{W}$
	Inch			*Pounds*	*Ounces*	
108	1/50+1/50+1/50	Yellow poplar	Truss	903	11.3	80
108	1/50+1/50+1/50	do	do	1,063	11.2	95
108	1/50+1/50+1/50	do	do	893	11.3	79
Average				953	11.3	85
117[2]	1/50+1/50+1/50	Yellow poplar	Truss	844	9.2	92
117[2]	1/50+1/50+1/50	do	do	900	9.0	100
117[2]	1/50+1/50+1/50	do	do	928	9.0	101
Average				891	9.1	98
159	1/50+1/50+1/50	Yellow poplar	Vertical	846	9.1	93
159	1/50+1/50+1/50	do	do	893	9.6	93
159	1/50+1/50+1/50	do	do	758	9.0	84
Average				832	9.2	90
187	1/48+1/8 +1/48	Mahogany+balsa+mahogany.	None	935	12.6	74
187	1/48+1/8 +1/48	do	do	966	12.3	78
187	1/48+1/8 +1/48	do	do	1,058	11.5	92
Average				986	12.1	81
176	1/48+5/32+1/48	Mahogany+balsa+mahogany.	None	1,143	11.2	102
176	1/48+5/32+1/48	do	do	905	10.9	83
176	1/48+5/32+1/48	do	do	1,234	11.0	112
Average				1,094	11.0	99
188	1/48+3/16+1/48	Mahogany+balsa+mahogany.	None	995	13.9	72
188	1/48+3/16+1/48	do	do	1,021	14.1	72
188	1/48+3/16+1/48	do	do	1,153	14.1	82
Average				1,056	14.0	75

[1] The designs are described in the appendix.

[2] The web of this design has lightening holes.

TABLE IV.—EFFECT OF THE THICKNESS OF THE CORE ON THE STRENGTH OF 44-INCH PARALLEL-CHORD RIB SECTIONS USING BALSA-CORE PLYWOOD WITH 1/48-INCH MAHOGANY FACE PLIES

3⅞-inch depth

Design[1] No.	Thickness of core	Face grain	Net lift load, P	Weight of rib, W	$\frac{P}{W}$
	Inch		*Pounds*	*Ounces*	
169	1/16	Longitudinal	258	5.3	49
169	1/16	do	258	5.4	47
169	1/16	do	298	5.1	58
Average			271	5.3	51
181	1/16	Longitudinal	320	5.8	56
181	1/16	do	393	5.4	72
181	1/16	do	325	5.8	56
Average			346	5.7	61
170	3/32	Longitudinal	366	5.3	69
170	3/32	do	408	5.9	69
170	3/32	do	323	5.8	56
Average			366	5.7	65
182	3/32	Longitudinal	468	6.1	77
182	3/32	do	383	6.7	57
182	3/32	do	323	6.4	50
Average			391	6.4	61
171	1/8	Longitudinal	366	5.9	62
171	1/8	do	423	5.9	72
171	1/8	do	413	6.2	67
Average			401	6.0	67
183	1/8	Longitudinal	445	6.7	66
183	1/8	do	421	6.7	63
183	1/8	do	375	7.2	52
Average			414	6.9	60
172	5/32	Longitudinal	449	5.9	76
172	5/32	do	455	6.1	75
172	5/32	do	478	6.1	78
Average			461	6.0	76
184	3/16	Longitudinal	450	7.7	59
184	3/16	do	525	7.5	70
184	3/16	do	500	7.5	66
Average			492	7.6	65
177	1/16	45°	148	5.0	30
177	1/16	45°	291	4.8	61
177	1/16	45°	242	5.1	47
Average			227	5.0	46
178	3/32	45°	294	5.6	52
178	3/32	45°	246	5.1	48
178	3/32	45°	300	5.1	59
Average			280	5.3	53
179	1/8	45°	300	5.8	52
179	1/8	45°	343	5.6	61
179	1/8	45°	358	5.8	62
Average			334	5.7	58
180	5/32	45°	320	5.9	54
180	5/32	45°	351	6.1	57
180	5/32	45°	335	5.9	57
Average			335	6.0	56

7¾-inch depth

Design[1] No.	Thickness of core	Face grain	Net lift load, P	Weight of rib, W	$\frac{P}{W}$
	Inch		*Pounds*	*Ounces*	
173	1/16	Longitudinal	630	9.0	70
173	1/16	do	655	9.0	73
173	1/16	do	606	8.3	73
Average			630	8.8	72
185	1/16	Longitudinal	868	10.9	80
185	1/16	do	648	11.8	55
185	1/16	do	834	10.9	76
Average			783	11.2	70
174	3/32	Longitudinal	580	9.4	62
174	3/32	do	794	9.6	83
174	3/32	do	650	10.1	64
Average			675	9.7	70
186	3/32	Longitudinal	1,054	11.0	96
186	3/32	do	708	10.7	66
186	3/32	do	658	11.0	60
Average			807	10.9	74
175	1/8	Longitudinal	750	11.0	68
175	1/8	do	678	9.9	68
175	1/8	do	559	11.0	51
Average			662	10.6	62
187	1/8	Longitudinal	935	12.6	74
187	1/8	do	966	12.3	78
187	1/8	do	1,058	11.5	92
Average			986	12.1	81
176	5/32	Longitudinal	1,143	11.2	102
176	5/32	do	905	10.9	83
176	5/32	do	1,234	11.0	112
Average			1,094	11.0	99
188	3/16	Longitudinal	995	13.9	72
188	3/16	do	1,021	14.1	72
188	3/16	do	1,153	14.1	82
Average			1,056	14.0	75

[1] The designs are described in the appendix.

In connection with the use of balsa as a core stock, it was found that when lightening holes are added the strength drops very rapidly, because of the ease with which the face plies pull away and tear the balsa core apart around the holes at the least tendency to buckle. Shrinking and swelling at times cause a separation of the balsa core at the raw edges between the cap strips, and the Forest Products Laboratory, therefore, recommends nailing through the cap strips, although, as previously stated, it is not usual to recommend nails in cap strips.

Results of tests on rib sections having vertical or longitudinal face grain show that, for normal core thicknesses, greater strength can be obtained with vertical face grain providing the webs are not lightened. (Table V.) When lightened plywood with stiffeners was used the best results were obtained with longitudinal face grain. Grain at an angle of 45° to the chord will not give so great strength per unit of weight as either the longitudinal or the vertical face grain; in all cases the grain of the core was at right angles to the grain of the faces.

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TABLE V.—COMPARISON OF LONGITUDINAL AND VERTICAL FACE GRAIN ON WEBS OF PARALLEL-CHORD RIB SECTIONS, 44 INCHES LONG BY 7¾ INCHES DEEP

Full webs with bracing						
Design[1] No.	Plywood web			Net lift load, P	Weight of rib, W	$\frac{P}{W}$
	Thickness	Species of wood	Face grain			
	Inch			*Pounds*	*Ounces*	
151	3/50	Yellow poplar	Longitudinal	638	9.6	66
151	3/50	do	do	585	9.6	61
151	3/50	do	do	628	9.4	67
Average				617	9.5	65
150	3/50	Yellow poplar	Vertical	700	9.6	73
150	3/50	do	do	800	10.1	79
150	3/50	do	do	713	9.8	73
Average				738	9.8	75
160	3/50	Yellow poplar	Longitudinal	635	9.7	65
160	3/50	do	do	588	9.8	60
160	3/50	do	do	813	9.1	89
Average				679	9.5	71
159	3/50	Yellow poplar	Vertical	846	9.1	93
159	3/50	do	do	893	9.6	93
159	3/50	do	do	758	9.0	84
Average				832	9.2	90
168	3/40	Mahogany	Longitudinal	608	10.2	59
168	3/40	do	do	858	10.5	81
168	3/40	do	do	758	10.4	73
Average				741	10.4	71
167	3/40	Mahogany	Vertical	808	9.9	81
167	3/40	do	do	776	10.2	76
167	3/40	do	do	756	10.9	69
Average				780	10.3	75

Webs with lightening holes						
Design[1] No.	Plywood web			Net lift load, P	Weight of rib, W	$\frac{P}{W}$
	Thickness	Species of wood	Face grain			
	Inch			*Pounds*	*Ounces*	
153	3/50	Yellow poplar	Longitudinal	178	5.8	31
153	3/50	do	do	208	6.2	33
153	3/50	do	do	135	7.0	19
Average				174	6.3	28
152	3/50	Yellow poplar	Vertical	148	6.2	24
152	3/50	do	do	135	6.6	20
152	3/50	do	do	103	6.4	16
Average				129	6.4	20
158	3/50	Yellow poplar	Longitudinal	220	6.7	33
158	3/50	do	do	218	6.4	34
158	3/50	do	do	230	6.1	38
Average				223	6.4	35
157	3/50	Yellow poplar	Vertical	183	5.1	36
157	3/50	do	do	175	5.4	32
157	3/50	do	do	177	5.8	31
Average				178	5.4	33
166	3/40	Mahogany	Longitudinal	330	6.7	49
166	3/40	do	do	362	6.6	55
166	3/40	do	do	344	6.4	54
Average				345	6.6	53
165	3/40	Mahogany	Vertical	203	6.6	31
165	3/40	do	do	241	6.6	36
165	3/40	do	do	261	7.0	38
Average				235	6.7	35

[1] The designs are described in the appendix.

The comparison of single-ply spruce with three-ply poplar of the same total thickness, for web material, was limited to one depth of section and two designs, one with lightening holes and stiffeners and one without. (Table VI.) Designs can of course be made in which so little material is left between lightening holes that longitudinal shear will occur in the spruce at low loads, but in this investigation it was attempted to have enough material so that there would be little likelihood of failure caused by shear. The single-ply spruce proved much stronger than the three-ply poplar when lightening holes and stiffeners were used in both and somewhat weaker when the web was not lightened.

Each design of both parallel-chord specimens and regular wing-rib sections is discussed in the appendix.

TABLE VI.—COMPARISON OF SINGLE-PLY SPRUCE WEBS AND THREE-PLY POPLAR WEBS OF EQUAL THICKNESS IN PARALLEL-CHORD RIB SECTIONS 44 INCHES LONG BY 3⅞ INCHES DEEP

Web			Full web			Lightened web		
Number of plies	Thickness of plies	Species of wood	Net lift load, P	Weight of rib, W	$\frac{P}{W}$	Net lift load, P	Weight of rib, W	$\frac{P}{W}$
	Inch		*Pounds*	*Ounces*		*Pounds*	*Ounces*	
1	1/10	Spruce	558	7.9	71	345	6.1	57
1	1/10	do	568	8.3	68	330	5.7	58
1	1/10	do	498	8.8	57	334	6.2	54
Average			541	8.3	65	336	6.0	56
3	1/40+1/20+1/40	Yellow poplar	558	8.0	70	173	5.7	30
3	1/40+1/20+1/40	do	724	7.7	94	203	6.1	33
3	1/40+1/20+1/40	do	568	7.8	73	163	6.1	27
Average			617	7.8	79	180	6.0	30

CONCLUSIONS

1. Wing ribs, with their rigid connections and redundant members, are not amenable to accurate calculation.

2. The first necessity in designing such a structure is a knowledge of certain principles upon which the selection of a type for a given airfoil section is based.

3. Following the selection of a type, the calculation of approximate strength values must be guided by principles of broad application that govern the distribution of stresses and control the design of members and details.

4. Wing-rib design is still dependent upon the results of strength tests on complete ribs, and to some extent will continue to be so.

5. On a strength-weight basis, various types are of various efficiencies, with the truss type heading the list for all sizes and proportions.

6. Although a truss may be the most efficient type, it can not always be selected as the most suitable type. Manufacturing difficulties will make a place for the various other types.

7. Poor design or design with some special consideration for manufacturing details in any type will often reduce the efficiency of that type below the efficiency of a poorer type.

8. When selecting a type and when considering various designs in that type, the Forest Products Laboratory recommends careful consideration of the elements of design discussed in the analysis and in the appendix.

APPENDIX

Extensive tests for the study reported here were made on ribs of the BS–1 airfoil section (the results appear in Table VII) and on parallel-chord specimens. Different types were compared in various sizes and often many designs were tried within a given type. Following are comments on the various designs and descriptions of the failures.

The ribs tested are illustrated in the figures that are assembled at the end of the appendix. The index for the figures appears on page 54.

TABLE VII.—SUMMARY OF STRENGTH TESTS ON RIBS AT STATION 3 OF THE BS–1 AIRFOIL

CHORD LENGTH 48 INCHES

	Rib No.	Net lift load		Weight [2]	Moisture content	Type of failure	
		First test	Final test			First test	Final test
Design No. 1 [1]		*Pounds*	*Pounds*	*Ounces*	*Per cent*		
Low-speed loading	1	1,054	2,287	12.2	8.7	Nose crushed	Nose broke off.
	2	1,281	2,569	12.2	8.9	do	Do.
	3	1,245	2,657	12.1	8.3	do	Tail broke off.
	4	Cull.					
Average			2,504	12.2			
High-speed loading	5	1,127	1,568	11.9		Nose broke off	Tail broke off.
	6	1,020	1,878	12.2	9.4	Tail broke off	Do.
	7	1,345	1,983	12.2		do	Web in tail buckled and broke.
	8		1,422	12.1			Do.
Average			1,713	12.1			
Design No. 2							
Low-speed loading	55		1,221	8.7			Web buckled at lightening hole.
	56		1,428	8.8	9.5		Do.
	57		1,206	8.9	10.5		Do.
Average			1,285	8.8			
High-speed loading	58		598	8.9			Do.
	59		611	8.8	9.8		Do.
	60		742	8.8	10.7		Do.
Average			650	8.8			
Design No. 3							
Low-speed loading	1		1,059	6.7	11.2		Diagonal pulled web away at front spar.
	2		988	6.7			Do.
	3		1,042	6.7			Do.
Average			1,030	6.7			
High-speed loading	4		578	6.7			Diagonal pulled web away at rear spar.
	5		515	6.7	8.7		Do.
	6		647	6.8	9.1		Do.
Average			580	6.7			
Design No. 4							
Low-speed loading	7		799	6.3	9.6		Nose crushed.
	8		744	6.3			Do.
	9		857	6.2			Do.
Average							
High-speed loading	10		618	6.4	10.2		Diagonal pushed web and cap away at rear spar.
	11		791	6.6			Do.
	12		748	6.3	9.2		Do.
Average			719	6.4			
Design No. 5							
Low-speed loading	13		1,268	7.1	9.7		Nose crushed.
	14		1,166	7.2			Do.
	15		1,344	7.5			Do.
Average							
High-speed loading	16		937	7.6	10.0		Lower chord broke.
	17		943	7.2	9.4		
	18		977	7.1			Diagonal broke.
Average			952	7.3			

[1] The designs are described in the appendix.

[2] The weights given do not include reinforcement.

TABLE VII.—SUMMARY OF STRENGTH TESTS ON RIBS AT STATION 3 OF THE BS-1 AIRFOIL—*Continued*

CHORD LENGTH 48 INCHES—Continued

	Rib No.	Net lift load		Weight	Moisture content	Type of failure	
		First test	Final test			First test	Final test
Design No. 6		*Pounds*	*Pounds*	*Ounces*	*Per cent*		
Low-speed loading	19	716	1,822	8.4	8.3	Nose crushed	Rib sheared at rear spar.
	20	556	1,957	8.5	8.8	do	Web in tail buckled.
	21	541	2,267	8.5		do	Web buckled near front spar.
Average			2,015	8.5			
High-speed loading	22		908	8.4			Web in tail buckled.
	23		1,243	8.5	9.0		Do.
	24		1,308	8.5	8.8		Do.
Average			1,153	8.5			
Design No. 7							
Low-speed loading	25		683	6.8	9.0		Web buckled at lightening hole.
	26		658	7.2	8.7		Do.
	27		738	7.1			Do.
Average			693	7.0			
High-speed loading	28		435	7.6			Do.
	29		356	7.2	9.1		Do.
	30		316	6.8	8.9		Do.
Average			369	7.2			
Design No. 8							
Low-speed loading	31		761	7.0	8.1		Lower chord broke.
	32		781	6.9			Do.
	33		751	7.1	8.3		Do.
Average			764	7.0			
High-speed loading	34		510	7.0	9.7		Do.
	35		522	6.9			Do.
	36		504	6.9	10.6		Do.
Average			512	6.9			
Design No. 9							
Low-speed loading	37		486	5.7	8.5		Lower chord buckled.
	38		568	5.7			Do.
	39		676	5.6	8.0		Do.
Average			577	5.7			
High-speed loading	40		391	5.6			Tail section buckled.
	41		432	5.6	10.2		Do.
	42		484	5.7	10.1		Do.
Average			436	5.6			
Design No. 10							
Low-speed loading	43		1,751	7.6	8.9		Chord broke near front spar.
	44		1,696	7.7	9.1		Do.
	45		1,383	7.6			Nose broke off.
Average			1,610	7.6			
High-speed loading	46		908	7.7			Chord broke near rear spar.
	47		1,032	7.8	9.8		Do.
	48		839	7.7	9.1		Do.
Average			926	7.7			
Design No. 11							
Low-speed loading	49	1,037	1,559	7.2		Diagonal broke	Lower chord broke.
	50	802	1,502	7.3		do	Nose failed.
	51		1,502	7.2	13.3		Chord broke in tail.
Average			1,521	7.2			
High-speed loading	52	481	755	7.2	12.4	Diagonal broke	Lower chord broke.
	53		809	7.3			Do.
	54	890	904	7.3		Diagonal broke	Do.
Average			823	7.3			

CHORD LENGTH 96 INCHES

	Rib No.	First test	Final test	Weight	Moisture content	First test	Final test
Design No. 1-A							
Low-speed loading	19	3,266	4,166	52.1	12.5	Nose crushed	Tail broke off.
	20		4,300	53.6			Do.
	21		4,441	50.5	11.7		Do.
Average			4,302	52.1			
High-speed loading	22		1,822	52.7	11.1		Do.
	23		2,050	51.9	11.0		Do.
	24		1,730	52.6	11.8		Do.
Average			1,867	52.4			

TABLE VII.—SUMMARY OF STRENGTH TESTS ON RIBS AT STATION 3 OF THE BS-1 AIRFOIL—Continued

CHORD LENGTH 96 INCHES—Continued

	Rib No.	Net lift load		Weight	Moisture content	Type of failure	
		First test	Final test			First test	Final test
Design No. 2-A [3]		*Pounds*	*Pounds*	*Ounces*	*Per cent*		
Low-speed loading	25	2, 616		39. 2		Web buckled at lightening hole	
	26		3, 691	44. 6	12. 5		Web buckled at lightening hole.
	27		4, 291	46. 2			Do.
Average							
High-speed loading	28		1, 260	40. 3	10. 5		Do.
	29		1, 161	39. 6	11. 7		Do.
	30		1, 122	39. 8			Do.
Average			1, 181	39. 9			
Design No. 3-A							
Low-speed loading	1		1, 331	24. 6	7. 2		Web of cap broke in nose.
	2		1, 238	24. 9	7. 1		Do.
	3		1, 276	24. 2			Diagonal pulled web away at front spar.
Average			1, 282	24. 6			
High-speed loading	4		654	24. 2			Diagonal pulled web away at rear spar.
	5		783	25. 0	8. 5		Do.
	6		790	24. 6	8. 7		Do.
Average			742	24. 6			
Design No. 4-A							
Low-speed loading	7		1, 491	24. 1	6. 8		Nose crushed.
	8		1, 621	24. 2	7. 0		Do.
	9		1, 421	23. 8			Do.
Average							
High-speed loading	10		820	23. 7	7. 3		Diagonal pushed web and cap away at rear spar.
	11		902	23. 8	8. 0		Do.
	12		900	23. 9			Do.
Average			874	23. 8			
Design No. 5-A [4]							
Low-speed loading	13		2, 916	32. 5			Lower chord broke.
	14		2, 741	33. 5	12. 7		Do.
	15		3, 216	33. 3			Nose broke.
Average			2, 958	33. 1			
High-speed loading	16		1, 131	33. 4	9. 9		Lower chord broke.
	17		1, 266	33. 1	10. 2		Do.
	18		1, 227	32. 3			Do.
Average			1, 208	32. 9			
Design No. 8-A							
Low-speed loading	37	2, 029	2, 219	37. 4		Lower chord buckled	Lower chord broke at joint.
	38	2, 021	2, 446	37. 4		Lower chord buckled and diagonal broke.	Do.
	39		2, 146	37. 2			Chords and diagonal broke in tail.
Average			2, 270	37. 3			
High-speed loading	40	900	1, 074	37. 6		Diagonal in tail broke	Lower chord broke.
	41	1, 076	1, 176	38. 0		do	Do.
	42		1, 227	37. 0			Do.
Average			1, 159	37. 5			
Design No. 9-A [5]							
Low-speed loading	31		1, 091	30. 7			Lower chord broke.
	32		1, 316	30. 6			Do.
	33		1, 516	30. 2	12. 9		Do.
Average			1, 308	30. 5			
High-speed loading	34	555		30. 5		Lower chord broke in tail	
	35		1, 142		12. 2		Lower chord broke in tail.
	36		1, 038		12. 7		Do.
Average							
Design No. 10-A							
Low-speed loading	55	2, 704	3, 004	38. 0	13. 4	Diagonal adjacent to front spar broke	Lower chord broke.
	56	2, 804	3, 104	37. 6	13. 8	do	Do.
	57	2, 504	3, 229	37. 6		do	Do.
Average		2, 671		37. 7			
High-speed loading	58	1, 314	1, 038	37. 7		Diagonal adjacent to rear spar broke	Do.
	59	1, 314	1, 658	37. 6		do	Do.
	60	1, 503	1, 842	37. 7	14. 2	do	Do.
Average		1, 377		37. 7			

[3] Small stiffeners near the edges of the lightening holes were clamped on rib 26 and glued on rib 27.
[4] Rib 15 was reinforced before test.
[5] Ribs 35 and 36 were reinforced before test.

TABLE VII.—SUMMARY OF STRENGTH TESTS ON RIBS AT STATION 3 OF THE BS-1 AIRFOIL—Continued

CHORD LENGTH 96 INCHES—Continued

	Rib No.	Net lift load		Weight	Moisture content	Type of failure	
		First test	Final test			First test	Final test
Design No. 11-A		*Pounds*	*Pounds*	*Ounces*	*Per cent*		
Low-speed loading	43	2,004	2,724	34.6	11.1	Diagonal adjacent to front spar broke	Tail broke off.
	44	2,384	3,064	34.2		do	Lower chord broke.
	45		3,336	34.5			Do.
Average			3,041	34.4			
High-speed loading	46	1,071	1,386	34.4		Diagonal adjacent to rear spar broke	Chords broke.
	47	923	1,452	34.0	13.3	do	Do.
	48		1,486	34.4	13.6		Do.
Average			1,441	34.3			
Design No. 12-A							
Low-speed loading	61	604	1,279	18.8		Diagonal failed	Chord broke.
	62	579	1,279	18.6		do	Do.
	63	479	1,383	18.9		do	Do.
Average		554	1,314	18.8			
High-speed loading	64	382	871	18.5		do	Do.
	65	348	658	18.4		do	Do.
	66	417	727	18.7		do	Do.
Average		382	752	18.5			
Design No. 13-A [6]							
Low-speed loading	67	509		23.5		Web buckled	
	68		2,304	36.3			Web buckled.
	69		1,879	26.7			Web buckled, breaking bracing
Average							
High-speed loading	70	331		23.5		Web buckled	
	71		1,383	37.0			Web buckled.
	72		1,124	26.8			Do.
Average							
Design No. 14-A							
Low-speed loading	73	879	1,079	16.0		Diagonal broke	Lower chord broke.
	74		929	16.0			Do.
	75		954	16.5			Do.
Average			987	16.2			
High-speed loading	76	486	469	16.0		Diagonal adjacent to rear spar broke	Do.
	77	417	538	16.1		do	Another diagonal broke.
	78	417	538	16.1		do	Lower chord broke.
Average		440	515	16.1			

[6] Ribs 67 and 70 had full plywood webs with no bracing. Ribs 68 and 71 had full plywood webs with 12.8 ounces and 13.5 ounces bracing, respectively. Ribs 69 and 72 had lightening holes with decrease in weight of 9.6 ounces and 10.2 ounces, respectively.

BS-1 AIRFOIL SECTION

PLYWOOD TYPES

Design No. 1; 48-inch chord.—The original full plywood type with stiffeners and a web thickness of three thirty-seconds inch has been designated design No. 1. The plywood of this design is slightly heavy, causing a reduction in efficiency of about 10 or 15 per cent below the ideal for this type. In a preliminary test the nose section of the design broke off. The condition revealed by this test, however, was not considered satisfactory, since normally the intermediate nose sections would receive their share of the load and transmit the moments to the rest of the rib by torsion in the spar. Thus, in contrast with the load upon the rest of the rib, only about one-half the load applied to the nose in test comes upon it in service. The rib was therefore reinforced in the nose and the results of the tests reported are for ribs thus reinforced.

Design No. 1-A; 96-inch chord.—It was found in the tests of the 48-inch rib that the web is slightly heavy as compared with the reinforcement and caps. In going to the 96-inch rib, therefore, an attempt was made to compensate for this lack of balance, which resulted in a rib that rates well in efficiency. Failure occurred through buckling and breaking of the tail section of this design, No. 1-A.

Design No. 2; 48-inch chord.—By cutting lightening holes in design No. 1 its weight can be reduced materially and perhaps it will still carry all the load that is needed. In design No. 2, however, the lightening is excessive and consequently it resulted in a reduction of strength far in excess of the reduction in weight. (Table VIII). The ribs failed in test by buckling and breaking of the web at the lightening holes. The design is 25 or 30 per cent low in efficiency for its type.

TABLE VIII.—STRENGTH OF WING RIBS, HAVING DIFFERENT DESIGNS OF PLYWOOD WEBS, OF THE SIZE REQUIRED AT STATION 3 OF THE BS–1 AIRFOIL

Design[1] No.	Web				Low-speed loading				High-speed loading			
	Thickness of web	Species of wood		Type of web	Net lift load, P	Weight of rib, W	$\frac{P}{W}$	Moisture content	Net lift load, P	Weight of rib, W	$\frac{P}{W}$	Moisture content
		Core	Faces									
	Inch				*Pounds*	*Ounces*		*Per cent*	*Pounds*	*Ounces*		*Per cent*
1	3/32	Poplar	Mahogany	Full web	2,287	12.2	188	8.7	1,568	11.9	132	----------
1	3/32	do	do	do	2,569	12.2	210	8.9	1,878	12.2	154	9.4
1	3/32	do	do	do	2,657	12.1	219	8.3	1,983	12.2	162	----------
1	3/32	do	do	do	Cull.	----------	----------	----------	1,422	12.2	116	----------
Average					2,504	12.2	206	----------	1,713	12.1	141	----------
2	3/32	Mahogany	Mahogany	With lightening holes	1,221	8.7	140	----------	598	8.9	67	----------
2	3/32	do	do	do	1,428	8.8	162	9.5	611	8.8	69	9.8
2	3/32	do	do	do	1,206	8.9	136	10.5	742	8.8	84	10.7
Average					1,285	8.8	146	----------	650	8.8	73	----------
6	3/48	Mahogany	Mahogany	Full web	1,822	8.4	217	8.3	908	8.4	107	----------
6	3/48	do	do	do	1,957	8.5	230	8.8	1,243	8.5	146	9.0
6	3/48	do	do	do	2,267	8.5	266	----------	1,308	8.5	154	8.8
Average					2,015	8.5	238	----------	1,153	8.5	136	----------
7	3/48	Mahogany	Mahogany	With lightening holes	683	6.8	100	9.0	435	7.6	57	----------
7	3/48	do	do	do	658	7.2	91	8.7	356	7.2	49	9.1
7	3/48	do	do	do	738	7.1	104	----------	316	6.8	46	8.9
Average					693	7.0	98	----------	369	7.2	51	----------

[1] The designs are described in the appendix.

Design No. 2–A; 96-inch chord.—The design made by cutting lightening holes in design No. 1–A has been designated No. 2–A. The usual failure of buckling at the lightening holes resulted in a load considerably lower than that which the reduction in weight alone would justify. With small stiffeners clamped near the edges of the lightening holes, which increased the weight about 13 per cent, the load was increased about 40 per cent. With stiffeners glued and nailed on, the load was increased to approximately that carried by the full plywood No. 1–A and the ribs weighed approximately 15 per cent less. This last variation in No. 2–A gives a rib that comes very closely to an optimum load-weight curve for the type.

Design No. 6; 48-inch chord.—Design No. 6 is an attempt to lighten the original design by using thinner plywood. A web 3/48 inch in thickness was substituted for the 3/32-inch web. In low-speed loading, the nose section failed by local crushing under the load block. The rib was repaired by renewing the cap strip at this point and gluing a piece of plywood on each side of the web in the nose section. While the loads causing crushing of the original nose section were less than half those expected for the ideal of this type, those obtained after the repairs were made were even greater than would be expected of the ideal rib in which the nose had the same web and cap as the rest of the rib. These facts show that a rib of uniform strength can not be obtained by using a web of uniform thickness.

Design No. 7; 48-inch chord.—Design No. 7 is merely No. 6 with lightening holes. As pointed out in the discussion of No. 2, the lightening is excessive. Further, when extremely thin plywood is lightened, the reduction in strength is always far in excess of the reduction in weight. (Table VIII.) With the combination in this design of excessive lightening and thin plywood, the resulting efficiency was approximately but half of that expected of the ideal for the type. The ribs failed by buckling and breaking of the webs at the lightening holes.

Design No. 13–A; 96-inch chord.—For a preliminary test a rib with a full plywood web 3/55 inch thick was used. As the test progressed and buckling of the plywood occurred at different parts of the rib, reinforcement was clamped to the web. This process was followed until the plan of reinforcement shown in the sketch of design No. 13–A was reached. In this preliminary test, the reinforcing members were rectangular and all of one size. For final tests the ribs were made up as shown in the sketch except that a solid web instead of one with lightening holes was used. In tests of these ribs, failure occurred by buckling of the webs to such an extent as to cause failure in the stiffeners. The ribs, however, rated well in efficiency. As an additional development, lightening holes as shown in the sketch were added in this design; the holes really throw it into the reinforced plywood truss class. Such lightening gives a lighter rib but one more efficient than the reinforced full plywood rib, a fact that was also demonstrated in the tests of the parallel-chorded specimens.

TRUSS TYPES

Design No. 3; 48-inch chord.—Design No. 3 is of the Pratt truss type, which has tension diagonals adjacent to the spars. These diagonals pulled away at the joint, shearing off the web of the lower chord at the spar and separating it and the cap. Because of the difficulty in securing tension diagonals, the design is decidedly inefficient, falling far below the ideal for the truss type of construction.

Design 3–A; 96-inch chord.—The failure of the larger rib of design No. 3–A was identical with that of No. 3 in the 48-inch length. The web that sheared off was twice as deep, although of the same thickness as the one in the shorter rib, and failure might be expected to occur at double the load. Because of the nature of the union of the diagonal and the web, however, the failure would necessarily be a progressive one, which would account for the fact that an average increase of only 25 per cent was obtained.

Design No. 4; 48-inch chord.—The Howe truss with comparatively short panels, represented in design No. 4, has compression diagonals. In low-speed loading the ribs failed in the nose section by crushing under the load block. Such concentration of load, however, would not occur in actual practice where intermediate nose sections or other reinforcement is used. Therefore no comparison can be made in this loading with ribs of design No. 3. A comparison in high-speed loading, however, shows clearly the superiority of No. 4 over No. 3, although No. 4 is still considerably lower in efficiency than the ideal truss type. Failure occurred in some ribs of No. 4 by buckling of the diagonal inside the rear spar and in others by shearing of the web of the upper chord at this spar.

Design No. 4–A; 96-inch chord.—In the larger design, No. 4–A, the failures in high-speed loading were similar to those in the shorter length. Again, this rib might be expected to carry twice the load as that which produced failure in the 48-inch rib. An increase of but 22 per cent was obtained, however, since the shearing of the upper web was of the same progressive type as that in the lower web of the Pratt truss; in the Howe truss the shear was transmitted by a compression member and in the Pratt truss by a tension member.

Design No. 5; 48-inch chord.—Design No. 5 differs from No. 4 principally in that the chords are channel sections instead of T sections and that it has two panels between spars instead of three. The low-speed tests were not indicative of the efficiency of this rib because, as noted under previous designs, lack of nose reinforcement permitted failure at loads considerably lower than those which the remainder of the rib would sustain. High-speed tests, however, showed this design to be superior to Nos. 3 and 4 and well balanced as to chords and diagonals. It is still slightly below the ideal truss, but about the maximum that should be expected with square diagonals.

Design No. 5–A; 96-inch chord.—Design No. 5 had shown a good balance between chords and diagonals, but in making the corresponding 96-inch rib the thickness of the channeled chords was left the same for double depth and the diagonals were increased in a 9 to 5 ratio in both dimensions. Except for one test in which abnormal deflection was observed in one diagonal and the diagonal reinforced, the result was failure in the chords in both low-speed and high-speed loading at more than double the load in the low-speed loading and at about a 30 per cent increase in the high-speed. The depth of the channeled section was increased from ¾ inch to 1½ inches with the same thickness of 3/32 inch, thus giving an outstanding flange with a ratio of unsupported width to thickness of 12 to 1 as against 5⅔ to 1 for design No. 5. This gave a preliminary failure by buckling of the outstanding flanges, which was followed by twisting and buckling sidewise of the entire cap.

Design No. 8; 48-inch chord.—The long-panel Howe truss, with combination spruce and plywood channeled chords, of design No. 8 is decidedly weak in the chord members. Even in the low-speed loading the lower chord failed between spars before the unreinforced nose section gave way. This design is poor and the type offers little possibility of approaching the ideal truss in efficiency. The plywood made a section too weak to resist bending under the loads applied, which resulted in failure of the lower cap. Further, this cap does not offer the resistance to twisting and buckling that the spruce cap of design No. 5 offers. From the standpoint of the strength of the cap, No. 8 can not be made the equal of No. 5. There is probably an advantage, however, in the fastening of the ends of the web members to the cap, since the shrinkage and swelling caused by changes in moisture content will not materially stress the glued joint.

Design No. 8–A; 96-inch chord.—Since design No. 8 is decidedly weak in the chord members, in constructing the larger type the thickness of the webs of the chords was increased by 60 per cent and the depth in a 7 to 3 ratio. The diagonals were increased in an 8 to 5 ratio, which left them still stronger in proportion than the chords in No. 8. From the changes in the chord it might be expected that the load to cause failure would be several times that required for the shorter rib. By changing the ratio of unsupported depth to width of the channel webs from 9 to 15, as we have done, however, a greater tendency to twist and buckle is introduced, which accounts for the fact that the ribs failed at approximately two and one-half times as much load as the shorter ribs. Design No. 8–A will not carry the load that No. 5–A will carry because U sections with plywood webs will not resist twisting and sidewise buckling so well as a U section of spruce. When the final test values given in Table VII were obtained, a small strip was placed between the chord and the loading blocks in the weak panel. It is estimated that this increased the load by about 10 per cent. Even then the chords were still weak.

Design No. 10; 48-inch chord.—Design No. 10 is similar to No. 8 except that the section between spars is divided into four panels instead of two and the diagonals are made correspondingly lighter. Although considerably better than No. 8, yet it is questionable if this type can be made to approach closely to the ideal. The ratio of the width to the thickness of the outstanding flanges of the U cap section is too great.

Design No. 10–A; 96-inch chord.—It was found that in the short rib of design No. 10, for both low-speed and high-speed loading, the chords failed repeatedly. Accordingly, in No. 10–A an attempt was made to bring about a closer balance by a greater increase in the chords than in the diagonals. Failures in the rib then occurred in the diagonals at approximately one and one-half times the load sustained by the shorter ribs.

After the first failure of a diagonal, it was reinforced and further failure was thus thrown into the chord. Failure loads were then approximately double those obtained in the shorter rib. The load that the increase in the size of the chords might indicate is about two and one-third times the load for the smaller ribs. The load obtained, however, was only about double. Wrinkling and twisting of the thin channel sections accounts for the reduction, as previously explained.

Design No. 11; 48-inch chord.—In design No. 11 we have a Warren truss with cap strips similar to those of Nos. 8 and 10. The rectangular diagonals are decidedly weak as compared with the chords. In low-speed loading the diagonal adjacent to the front spar failed at a comparatively low load, and in high-speed loading the diagonal adjacent to the rear spar failed. Retests were run after reinforcing these diagonals and failure then occurred in the chords at considerably higher loads. The loads thus obtained however, were insufficient to place this design near the ideal load-weight curve. Again attention is called to the unsupported depth of the web of the flanges, as pointed out under the discussion of designs No. 8 and 10.

Design No. 11–A; 96-inch chord.—It was pointed out under the discussion of design No. 11 that the diagonals are weak in comparison with the chords. The increase in the size of the diagonals for the 96-inch design should almost double their capacity to carry load. In low-speed loading failures occurred at loads slightly less than double those that caused failure in the smaller size. Yet the design is still unbalanced, with a decided weakness in the diagonals. By reinforcing the weak diagonals, failure was thrown into the chords with a 25 per cent increase in load. With proper balance No. 11–A should be expected to approach more closely the ideal truss, and yet, with plywood sides and square diagonals all of the same cross section, it can not possibly come to the ideal truss.

Design No. 12–A; 96-inch chord.—In design No. 12–A an attempt was made to obtain a rib weighing about half as much as the 96-inch No. 11–A ribs just discussed. The balance between the chords and the diagonals of the No. 12–A rib is poor, failures occurring in the diagonals in all cases at a relatively low load. As a diagonal failed, in each specimen, it was reinforced and a retest was made until failure was thrown into the chord. These tests showed that, by increasing the size of the weak diagonals, the strength of the No. 12–A rib can be doubled with only a 10 or 15 per cent increase in total weight of rib. The buckling of the thin plywood webs of the chords, however, will prevent this design from reaching the ideal strength-weight curve. Another possibility for increasing the efficiency of the original design is to increase the size of the diagonals somewhat and lighten the chord. The result would be a lighter rib, one that would not carry so much load as the one developed by the first mentioned method of improvement, and yet one that can approach as near to optimum efficiency. Such improvement was attempted in the next design, No. 14–A.

Design No. 14–A; 96-inch chord.—With chords lighter and diagonals heavier than those of design No. 12–A, the individual members varying in size according to the stresses imposed upon them, a rib is formed that is one-sixth lighter and yet carries one and two-thirds times as much total load. The design, No. 14–A, is but slightly below the ideal. By the use of cruciform diagonal members and parallel-grained sides for the U caps, the ideal could have been readily reached.

REINFORCED PLYWOOD TRUSSES

Design No. 9; 48-inch chord.—Design No. 9, although simple in construction, appeared to give no promise of a high degree of efficiency on account of its nonsymmetrical construction. In low-speed loading the web and the cap strip of the lower chord in the panel adjacent to the front spar buckled and broke and in high-speed loading similar failures occurred in the tail section.

Design No. 9–A; 96-inch chord.—Failures in the larger size, design No. 9–A, were identical with those in the 48-inch ribs, which were a buckling and breaking of the chord in the long panels at a relatively small load. Some attempt was made to develop this design by reinforcing the rib at points of failure, but the success was relatively slight. The comments on No. 9 apply also to No. 9–A.

PARALLEL-CHORD SPECIMENS

TRUSS TYPE

15½-inch Depth

Design No. 101.—The Warren truss of design No. 101 has diagonals of cruciform cross section without fillets. The greatest weakness of this design is a lack of glue area between the cap strip and the spar block. When reinforced at the restricted glue areas the diagonals failed by twisting. This type of failure is readily over-

100510—30——4

come by means of fillets or through a slight decrease in the width of the outstanding flanges and an increase in their thickness.

Design No. 103.—Except for fillets in the crosses, design No. 103 was similar to No. 101. One specimen failed because of poor material and the other two showed that portions of the cap strip were too light to furnish sufficient glue area to hold the diagonals.

Design No. 106.—The flanges on the cap strips of design No. 106 are thicker and of better material than those of No. 103. The specimens are well balanced in strength between the cap strips and the diagonals adjacent to the spar block. Although the specimens are about 20 per cent below the ideal strength for their weight, their efficiency is about the maximum that should be expected of what appears to be excessive depth, a ratio of spar spacing to depth of about 3.

Designs No. 121, 126, and 131.—In design No. 121 all the members are larger in cross-sectional area than those in No. 106, and all are in the same ratio. This change gives an unbalanced construction and the increase in strength is about directly proportional to the increase in weight and not to its four-thirds power, as in the ideal design. Failure of designs Nos. 121, 126, and 131 occurred in the glued joints. Design No. 126 was improved at places where No. 121 had failed, but it still showed weakness, primarily because of poor gluing. In No. 131, the cap strip is the same size as in No. 126, better gluing was obtained, and the center diagnals and posts were made somewhat lighter. The lower cap strip at the union of the tension and the compression diagonal nearest the spar block seemed to be weak, but otherwise the design appears to be well balanced.

Design No. 136.—The failure in design No. 136, which has heavier cap strips than No. 106, occurred in the diagonals adjacent to the spar blocks. The center diagonals and posts are smaller than those in No. 106.

Design No. 137.—In design No. 137 both the cap strips and the center diagonals are lighter than those in No. 106. Failures were well distributed throughout the different diagonals, indicating a good balance. This design showed weakness at the junction of the cap strips with the spar blocks, and clamps were applied to prevent failure at these joints.

Design No. 138.—A slightly wider cap strip than that in design No. 137 is used in No. 138 and the flanges are placed at the spar blocks to provide large glue areas. The failures, however, were the same as those in the unclamped specimens of No. 137. The increase in the size of cap strip gives no material increase in strength.

Design No. 142.—The cap strip of design No. 142 is lighter than that of No. 138 and heavier than that of No. 137. No failures occurred in the cap strips themselves.

Design No. 146.—Made the same as design No. 137, No. 146 also developed weakness at the joints between the upper cap strip and the spar blocks.

Design No. 148.—The cap strip of design No. 148 is relatively shallow and additional glue area for the tension members was obtained by widening the ends. This widening seemed to increase the secondary stresses.

Intermediate conclusions.—All the pertinent information combines to indicate that design No. 106 is the best balanced parallel-chord truss of 15½ inches in depth and having diagonals of cruciform cross section. Design No. 131, although a much heavier truss, is a close second.

Designs No. 102 and 154.—Designs No. 102 and 154 have rectangular diagonals. The diagonals adjacent to the spar blocks failed and greater efficiency could have been obtained by increasing the size of these members. This, however, was not done in trusses 15½ inches deep.

11⅝-inch Depth

Design No. 109.—In design No. 109 the union between the upper cap strip and the spar blocks appears to be weak.

Design No. 122.—In design No. 122 also the joint between the upper cap strip and the spar blocks is weak. When this joint was clamped after the first failure, an increase in strength of from 10 to 20 per cent was obtained.

Design No. 135.—The specimens of design No. 135 failed at the joint between the upper cap strip and the spar block.

Design No. 139.—Design No. 139 is the same as No. 135 except that the cap strip is smaller in the middle part of the rib and is flared at the spar blocks. The distribution of failures was more general than for No. 135, approaching a balance.

Design No. 143.—The lack of strength at the joint between the upper cap strip and the spar block and insufficient depth in the flange of the cap strip at its joints with tension members cause design No. 143 to fall below the ideal.

Design No. 163.—Design No. 163 has rectangular diagonals and a U-shaped cap strip with plywood flanges. Failure occurred in the diagonals adjacent to the spar blocks in all specimens.

Design No. 149.—The diagonals in design No. 149, which is the Martin truss type, proved to be abnormally weak in comparison with the flange. After the initial work no further tests were made, since there appeared to be no chance of this type of truss equaling the efficiency of the other trusses, such as the Warren and the Howe.

7¾-inch Depth

Design No. 110.—Design No. 110 appears to be out of balance. The union between the upper cap strip and the spar blocks is not strong enough. One specimen failed through the tension diagonal pulling away from the cap strip, indicating that the cap strip may be strong enough, but that the joint is too weak.

Design No. 134.—In design No. 134 the cruciform diagonals are not filleted, the tension diagonals are thin flat members, and the center diagonals and the posts are reduced in size in comparison with those in No. 110. The outstanding flanges on the diagonals adjacent to the spar blocks buckled. It appears that these specimens would have been slightly stronger had the diagonals been filleted.

Design No. 141.—The tension members of design No. 141 are reduced in comparison with those of No. 134, fillets have been added to the diagonals adjacent to the spars, and their width is decreased slightly. The weight of the cap strip is somewhat less than that of No. 134. The flanges of the cap strip have proved somewhat thin although this design approaches closely to the ideal as given by the curve. (Fig. 4.)

Design No. 144.—Design No. 144 has the highest efficiency of any of the trusses tested and is slightly above the ideal curve.

3⅞-inch Depth

Design No. 115.—The lower cap strip in the specimens of design No. 115 buckled laterally.

Design No. 120.—The diagonals of design No. 120 are reduced in size and the cap strips are slightly increased in comparison with No. 115. The specimens failed through direct compression in the diagonals at the reduced section near the joint. The efficiency was about the same as that for No. 115.

Design No. 132.—The diagonals of design No. 132 are larger than those of No. 120, but they have no fillets and the flanges of the cap strip are thinner. The specimens, which failed by buckling in the cap strip, gave an efficiency about the same as that of No. 115.

Design No. 133.—The diagonals and the posts of design No. 123 are smaller than those of No. 115 and the flanges of the cap strip are a little more rigid. All specimens of this design failed by lateral buckling in the lower cap strip. This set shows the highest efficiency of any of the designs in this height.

Design No. 140.—A slight reduction in the diagonals adjacent to the spar blocks of design No. 140 and a slight increase in the stiffness of the cap strips over those of No. 133 resulted in failure in the diagonals at a lower load than that obtained for No. 133.

Design No. 145.—Fillets have been added to the diagonals adjacent to the spar blocks; in other respects design No. 145 is the same as No. 140. The efficiency is increased over No. 140, but does not equal that of No. 133. The diagonals adjacent to the spar blocks failed in compression.

Design No. 155.—Design No. 155 appears to be fairly well balanced, but the quality of the material in the actual ribs is not quite up to that used in No. 133 ribs.

Design No. 156.—Design No. 156 has rectangular compression members that failed in compression at the ends where the section was reduced for the spline.

Design No. 162.—The splines in design No. 162 were reduced in thickness as compared with those of No. 156, and the diagonals adjacent to the spar blocks were also reduced in cross-sectional area. This design gave an increase in efficiency over No. 156 and was close to the average of those with diagonals of cruciform cross sections.

Intermediate conclusions.—In shallow specimens with short compression members there is but slight advantage of cruciform over rectangular diagonals and obtaining maximum efficiency is not practical for trusses having a ratio of 11 or more for spar spacing to height.

REINFORCED PLYWOOD TRUSS

15½-inch Depth

Designs No. 111, 112, 147, and 161.—This group of designs is an attempt to develop a balanced type of reinforced plywood truss. In design No. 111 lightening holes are cut in the web between the stiffeners, leaving only a narrow strip at the stiffener supports with a somewhat wider margin at the cap strips as a flange. Failure occurred in the stiffeners. The reinforcement appears to be somewhat light to give a well-balanced design; this is true especially of the stiffeners adjacent to the spar blocks. Design No. 147 is practically the same as No. 111, except that more of the plywood web is cut away and the stiffeners are still lighter. The diagonal reinforcements are too light to balance the specimen, and failure occurred in the diagonals. Design No. 112 has oval-shaped lightening holes with stiffeners; the specimens failed by buckling of the web around the lightening holes. In design No. 161 the plywood web is cut away except for flanges left at the cap strips and spar blocks, a condition that resulted in a specimen lighter than No. 111. Better results can probably be obtained with diagonals not quite so wide in the plane of the rib, reinforced by a thin full-length strip instead of spacer blocks separating the two diagonal members. This strip should be about two and one-half times as wide in the plane of the rib as the diagonal. Such a design would approach the truss with cruciform section members.

11⅝-inch Depth

Design No. 116.—The cap strips in design No. 116 are a little too light to obtain the greatest efficiency. If more plywood were cut away, it would improve this design.

Design No. 164.—The glue area at the end of the diagonals adjacent to the spar block in design No. 164 is insufficient. The diagonals would have nearly double the strength if each one were filled for its entire length with a thin strip in place of the spacer block.

7¾-inch Depth

Design No. 117.—The specimens of design No. 117 all failed in shear near the joint where the tension and main compression diagonals meet. More plywood at this joint, no doubt, would improve the design.

Design No. 124.—Design No. 124 is not quite the equal of No. 117. Further, the material in the cap strips of the specimens made to this design apparently was not so good as that of No. 117 specimens. Additional lightening of the plywood web along the stiffeners would improve both designs.

Designs No. 152, 153, 157, 158, 165, and 166.—Plywood webs with rectangular holes rounded at the corners and vertical stiffeners, but no diagonals, are the characteristics of designs No. 152 and 153 and the group Nos. 157, 158, 165, and 166. The plywood webs buckled and failed around the lightening holes because of shearing stresses. The specimens with vertical face grain gave the highest values, but all the results show these designs to be grossly inefficient.

3⅞-inch Depth

Designs No. 114 and 119.—Designs No. 114 and 119 give values somewhat below the ideal. In service they would no doubt give higher values because of the lateral support provided by the wing covering, a support that can not be obtained in the test of one rib. Somewhat wider cap strips and a reduction in the width of plywood along the diagonals would also result in higher values for these designs.

Designs No. 129 and 130.—Because of the small amount of lightening in the region of large shear stress as compared with the general lightening of the rib, failure occurred in both the first and the second panel of designs No. 129 and 130. The general design is poor and should be expected to fall below the ideal curve. (Fig. 5.) The plywood web buckled more readily than single-ply spruce. Rectangular openings at points of high shear stresses should be avoided.

FULL WEB WITH BRACING

15½-inch Depth

Design No. 105.—A wider cap strip would undoubtedly improve design No. 105, which failed by lateral buckling.

11⅝-inch Depth

Design No. 107.—Failure occurred in the cap strips of the specimens of design No. 107. The stiffeners appear to be heavier than necessary.

7¾-inch Depth

Design No. 160.—The cap strip and the web of design No. 160 failed through the wrinkling or buckling of the plywood web immediately over the lower cap strip. This buckling was caused by compression in the depth of the section.

Design No. 159.—Design No. 159 is characterized by single-piece unnailed cap strips, and the face grain of the web is vertical. Failure occurred by lateral buckling at about 45° to the chord. This design is the most efficient of this type.

Design No. 150.—Design No. 150 has a 2-piece nailed cap strip. The nails reduce the strength of the cap strip about one-sixth; and since three-fourths of the bending stress is in the cap strip, omission of the nails would increase the strength of this design to equal that of No. 159.

Design No. 151.—The plywood web of design No. 151 buckled just above the lower cap strip. Here again a 2-piece nailed cap strip was used; by omitting the nails, the strength can probably be increased to that of a single-piece cap strip of the same size.

Design No. 167.—Design No. 167 has vertical face grain and thicker plywood than the other designs of its depth, which have already been described. Failures occurred through lateral buckling. There appears, however, to be a balance in strength between the cap strip and the web.

Design No. 168.—Design No. 168, in which the failures were similar to those of design No. 167, has longitudinal face grain.

Design No. 108.—The specimens built to design No. 108 failed through buckling in the cap strip. If the diagonals were reduced in size and the nails omitted from the cap strip, the strength-weight ratio would be increased.

3⅞-inch Depth

Design No. 118.—Specimens of any braced design with the ratio of spar spacing to depth of design No. 118 (about 11 to 1) are not very efficient. This design would be better if the plywood web had vertical face grain and if the nails were omitted from the cap strip. The weight can be reduced with no reduction in strength by cutting down the size of the vertical stiffeners. It is estimated that a 10 per cent reduction in weight and a 20 per cent increase in strength can be obtained by means of these changes.

Design No. 125.—In the tests of specimens of design No. 125 stiffeners were clamped to the web. The strength of the rib can be increased by omitting nails from the cap strip, using vertical instead of longitudinal face grain, and using a greater number of stiffeners that are smaller in size.

Design No. 113.—Design No. 113 almost reaches the ideal. The bracing or stiffeners, however, are heavier than necessary. By using vertical face grain and omitting the nails from the cap strip and stiffeners, an increase in strength of about 15 per cent and also a reduction in weight of about 15 per cent can be obtained.

FULL WEB WITHOUT STIFFENERS

15½-inch Depth

Design No. 104.—A wider cap strip would improve design No. 104. When stiffeners were added to the specimens of this design the increase in strength was greater than the increase in weight.

11⅝-inch Depth

No tests were made on full-web ribs, without stiffeners, of 11⅝ inches depth.

7¾-inch Depth

Design No. 176.—Design No. 176 is well balanced as to the thickness of the balsa core and the longitudinal-grain mahogany faces. There is also a good balance between the strength of the plywood web and the cap strips. This design is the equal of any of the designs tested that have a plywood web with stiffeners.

Design No. 188.—The balsa core in design No. 188 is thicker than that in No. 176 and the proportions are not so well balanced. The quality of material in the cap strips of the specimens is probably not up to that of No. 176, or perhaps the same lateral bracing was not obtained during test.

Design No. 187.—During test the specimens of design No. 187 were not braced laterally so well as those of No. 176.

Design No. 186.—During test the specimens of design No. 186, too, were not so well braced laterally as they would be in service. One exceptionally low value caused by poor bracing pulled the average down. A slightly thicker core would increase the strength.

Design No. 185.—Design No. 185 failed through lateral buckling. The plywood web is too thin for the rib to obtain a high efficiency.

Design No. 173.—The plywood web of the specimens of design No. 173 buckled laterally, and the balsa core is a little too thin to obtain the maximum efficiency.

Designs No. 174 and 175.—Some of the specimens of designs No. 174 and 175 were not braced laterally so well as others, permitting them to buckle laterally at lower loads than they would have held had they failed in some other manner. A thicker core would also have increased the strength.

3⅞-inch Depth

Design No. 123.—Failure of the specimens of design No. 123 occurred by lateral buckling in the cap strip. Vertical face grain and the omission of nails in the cap strip would improve the design.

Design No. 127.—In design No. 127 a good balance between the thickness of the plywood web and the size of the cap strip is obtained. If vertical face grain were used, the web could be thinner.

Design No. 128.—Design No. 128, which has a web of single-ply spruce, failed through buckling of the web and the cap strip. In the specimens the stiffness of the single-ply spruce in the vertical direction is not so great as that of three-ply poplar because the bending is entirely across the grain.

Designs No. 169, 170, 171, and 172.—The specimens of this group of designs failed through lateral buckling. Design No. 172, which has a core thickness of five thirty-seconds inch, is the most efficient. The designs in this group form a series in which the core thickness is varied from one-sixteenth to five thirty-seconds inch. The increase in the thickness of the balsa core is accompanied by an increase in strength somewhat more pronounced than the increase in weight, up to a thickness of five thirty-seconds inch, which is the maximum tested in the 3⅞-inch depth of specimen. The difference in strength-weight ratios in specimens with core thicknesses from three thirty-seconds inch to five thirty-seconds inch is not nearly so pronounced as that in thicknesses from one-sixteenth inch to three thirty-seconds inch.

Designs No. 177, 178, 179, and 180.—The designs of this group also have various thicknesses of balsa core, but the grain both of the face plies and of the core of all of them is at 45° to the chord. The relation of strength to thickness of core appears to be the same in this set as in the preceding group (designs Nos. 169 to 172, inclusive), but the efficiency of the web with 45° grain is lower.

Designs No. 181, 182, 183, and 184.—The designs of this group have wider cap strips than those in designs No. 169 to 172, inclusive, but, like the other designs, they have various thicknesses of balsa core. With wider cap strips the increase in strength in the various core thicknesses is practically what would be expected from the corresponding increase in weight.

Intermediate conclusions.—Considering primarily the strength-weight ratio, it appears that the best thickness of balsa core is about one-eighth inch in full-web parallel-chord specimens, without stiffeners, of the dimensions 3⅞ by 44 inches.

Forest Products Laboratory,
Forest Service, United States
Department of Agriculture,
Madison, Wis., *January 8, 1930.*

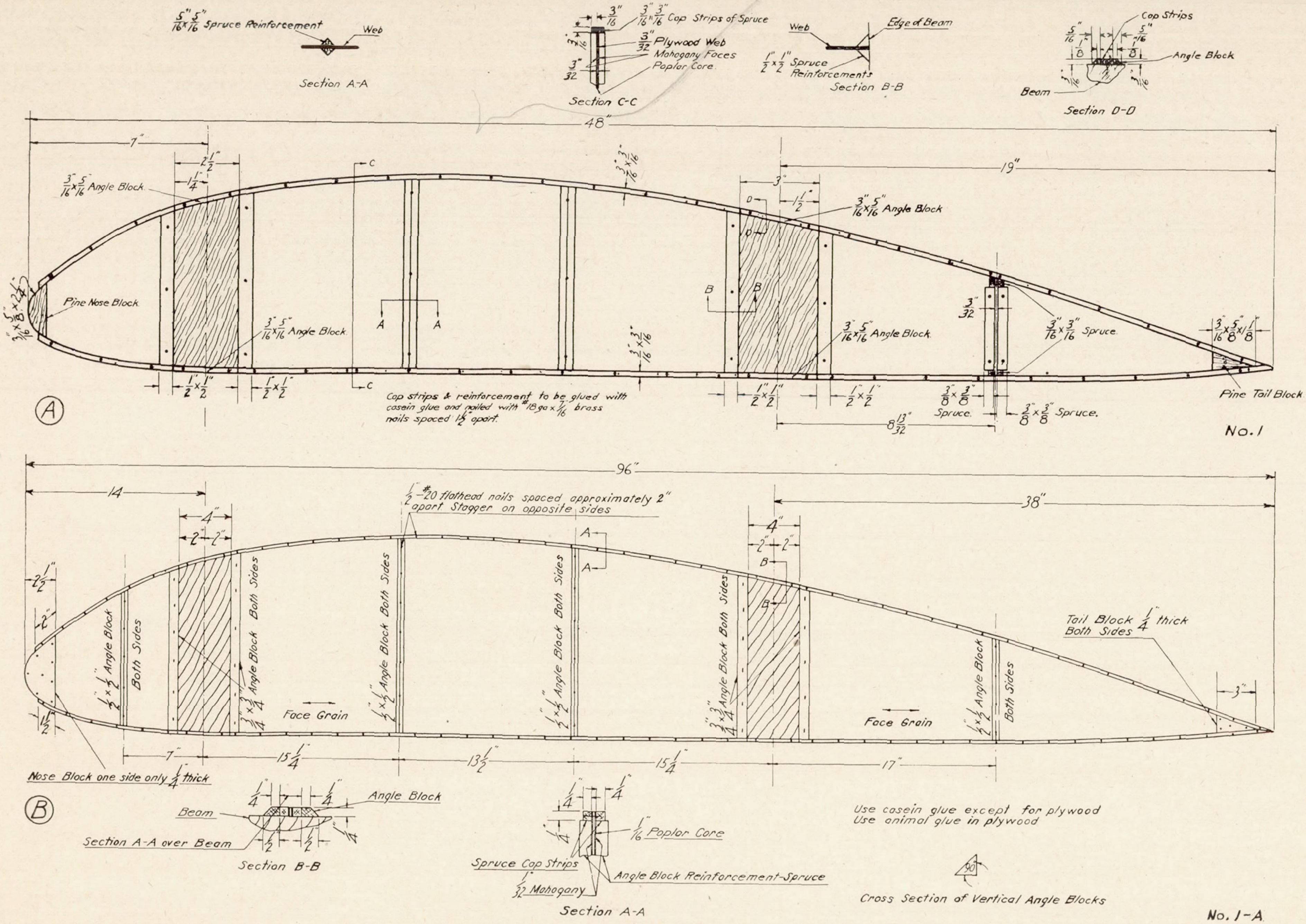


FIGURE 8.—Designs No. 1 and 1-A of wing ribs at station 3 of the BS-1 airfoil (A, normal dimensions; B, doubled dimensions). These designs are the full plywood web type with relatively thick plywood

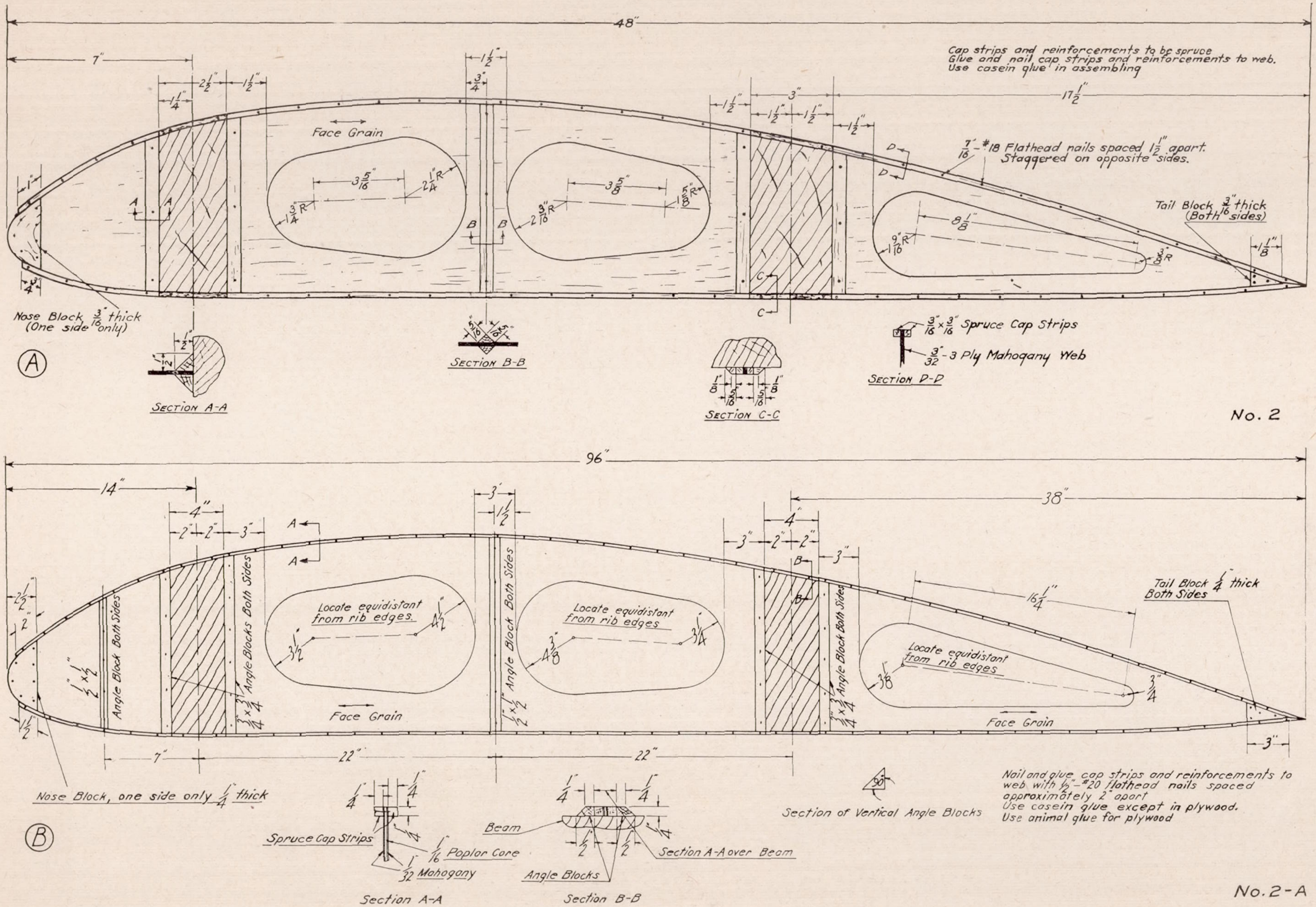


FIGURE 9.—Designs No. 2 and 2-A of wing ribs at station 3 of the BS-1 airfoil (A, normal dimensions; B, doubled dimensions). These designs are the lightened plywood web type with relatively thick plywood

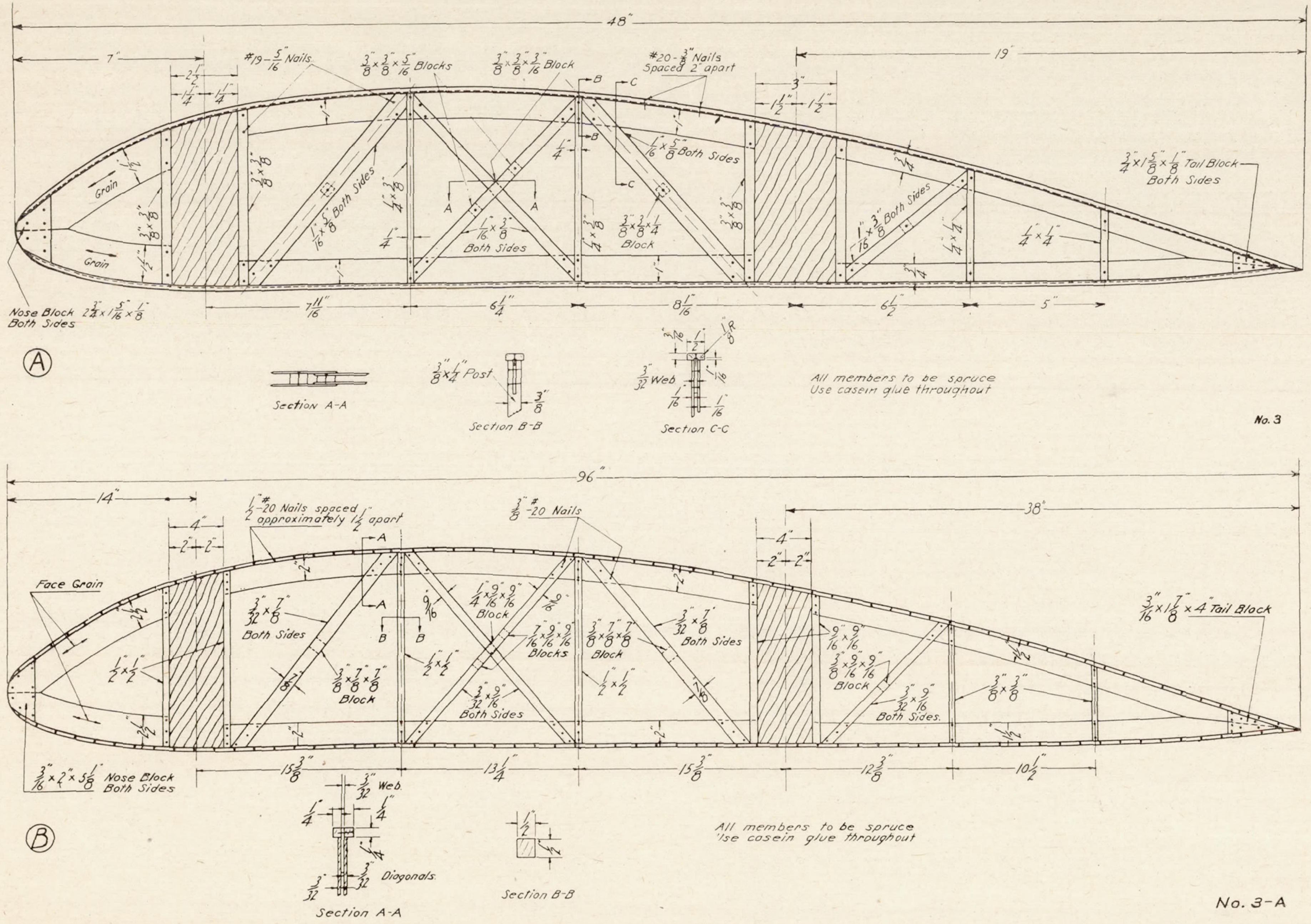


FIGURE 10.—Designs No. 3 and 3-A of wing ribs at station 3 of the BS-I airfoil (A, normal dimensions; B, doubled dimensions). This is the Pratt truss design, which has tension diagonals adjacent to the spars

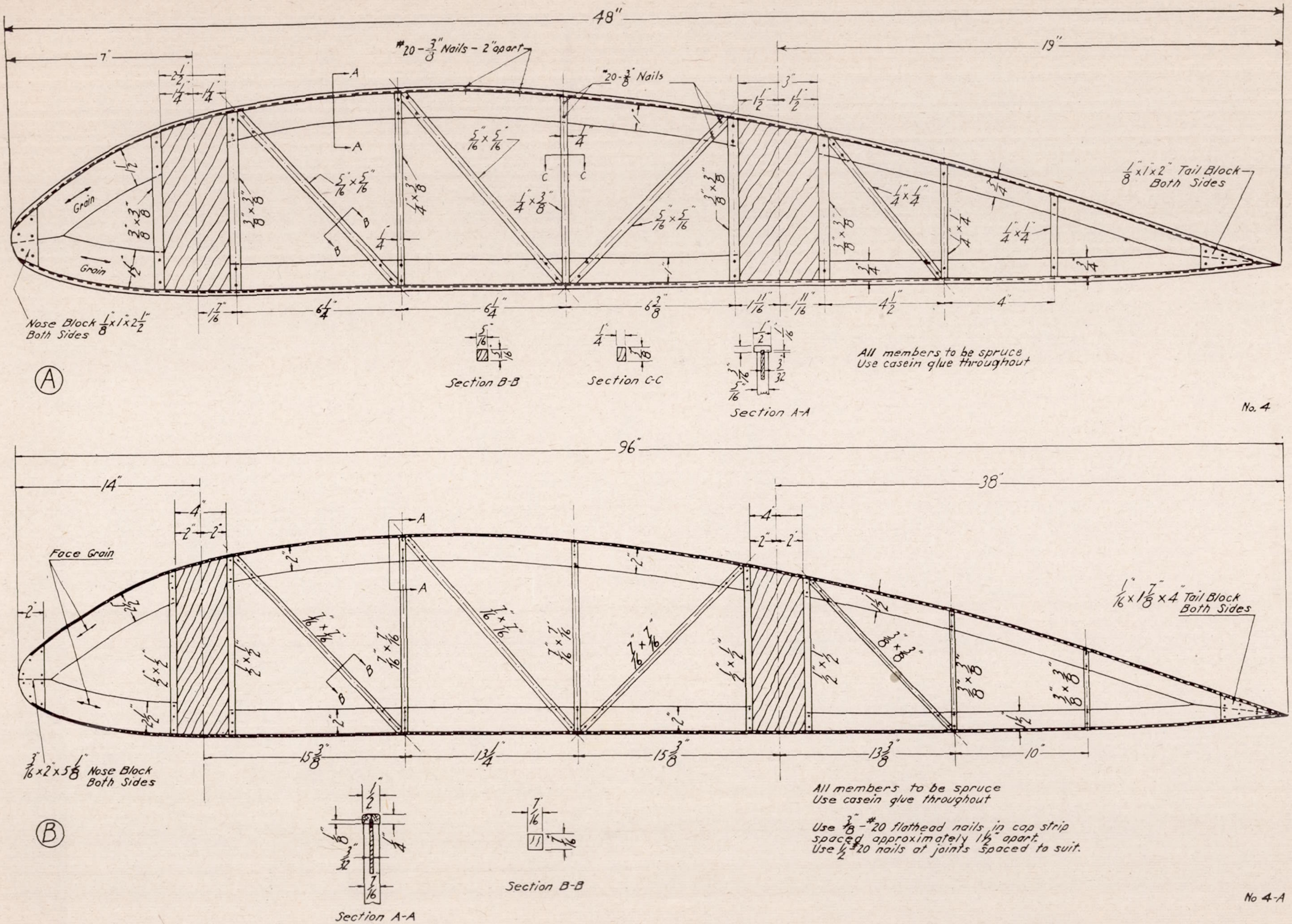


FIGURE 11.—Designs No. 4 and 4–A of wing ribs at station 3 of the BS–1 airfoil (A, normal dimensions; B, doubled dimensions). This is the Howe truss design, which has compression diagonals adjacent to the spars

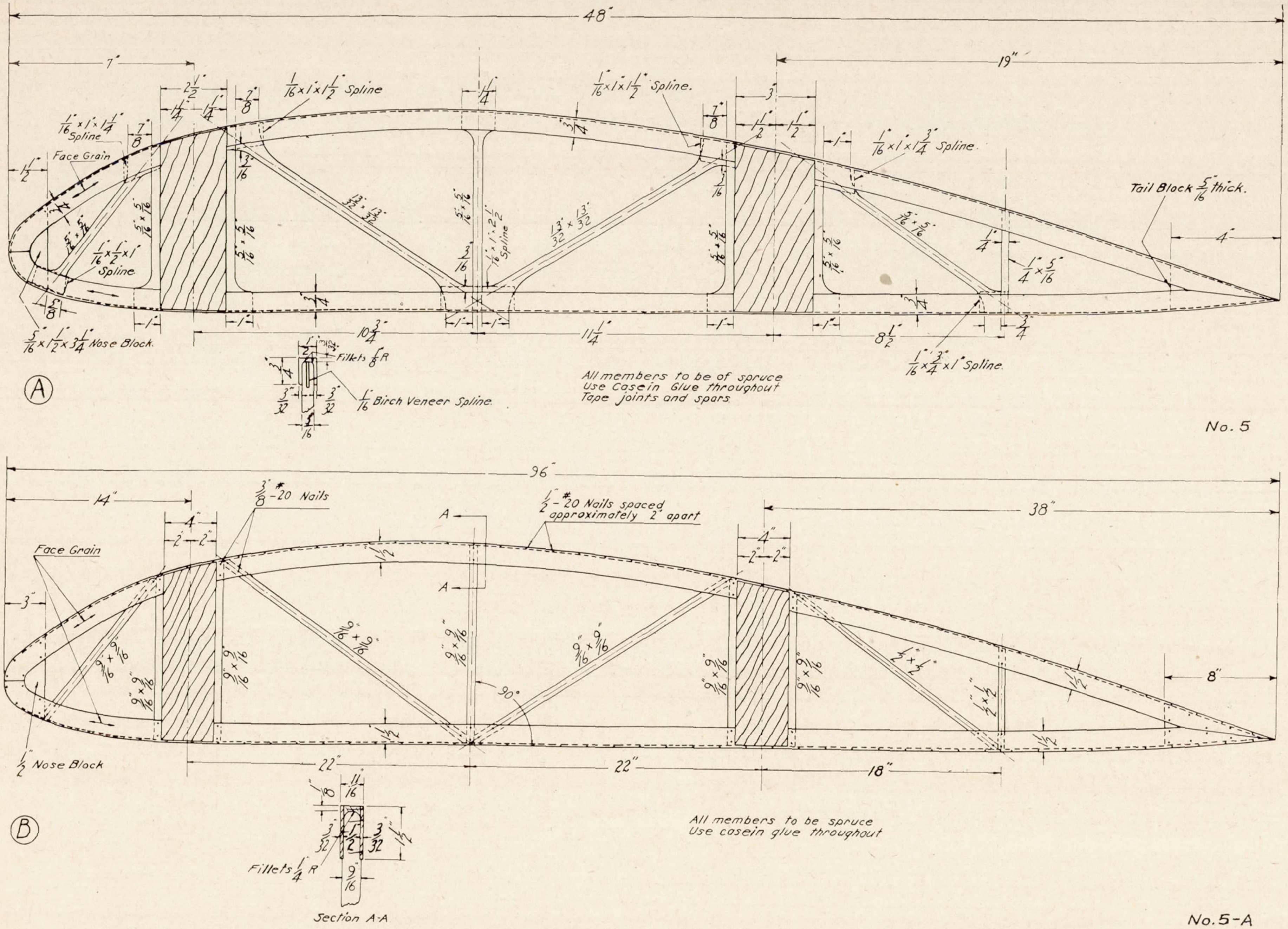


FIGURE 12.—Designs No. 5 and 5-A of wing ribs at station 3 of the BS-1 airfoil (A, normal dimensions; B, doubled dimensions). These are long-panel Howe truss designs. The channeled chords are of spruce

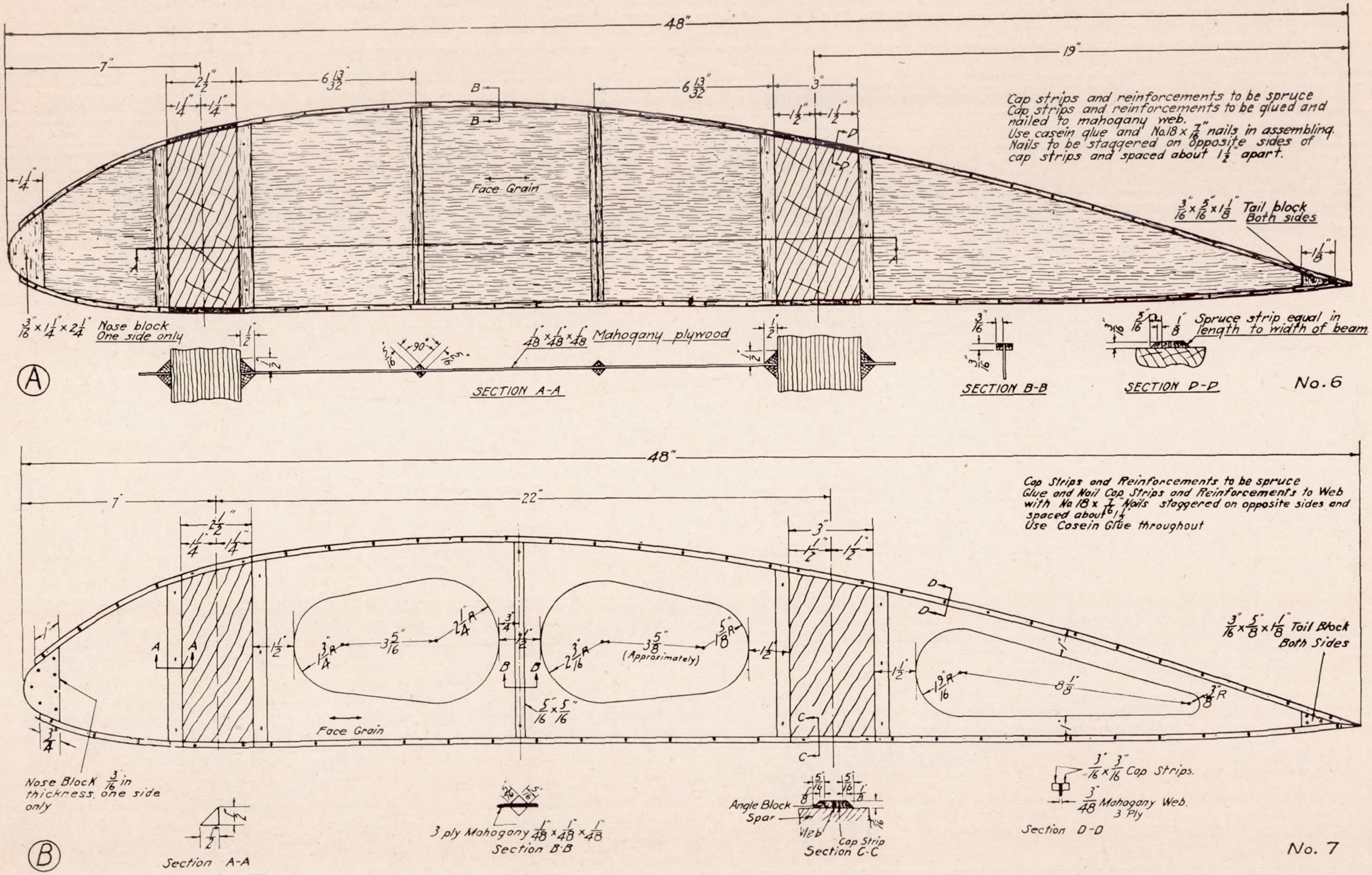


FIGURE 13.—Designs No. 6 and 7 of wing ribs at station 3 of the BS-1 airfoil

A—The full plywood web type with relatively thin plywood.
B—The lightened plywood web type with thin plywood.

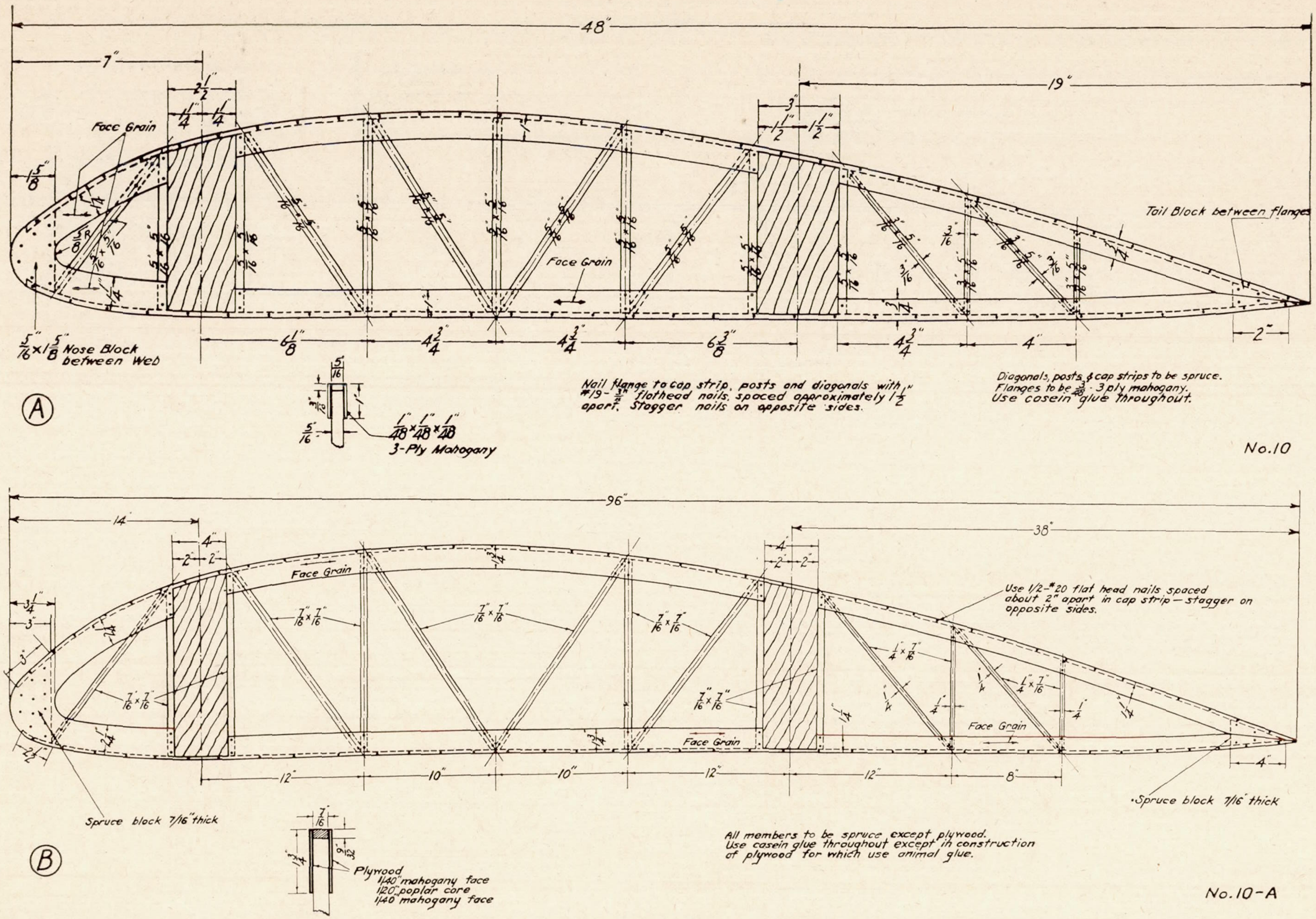
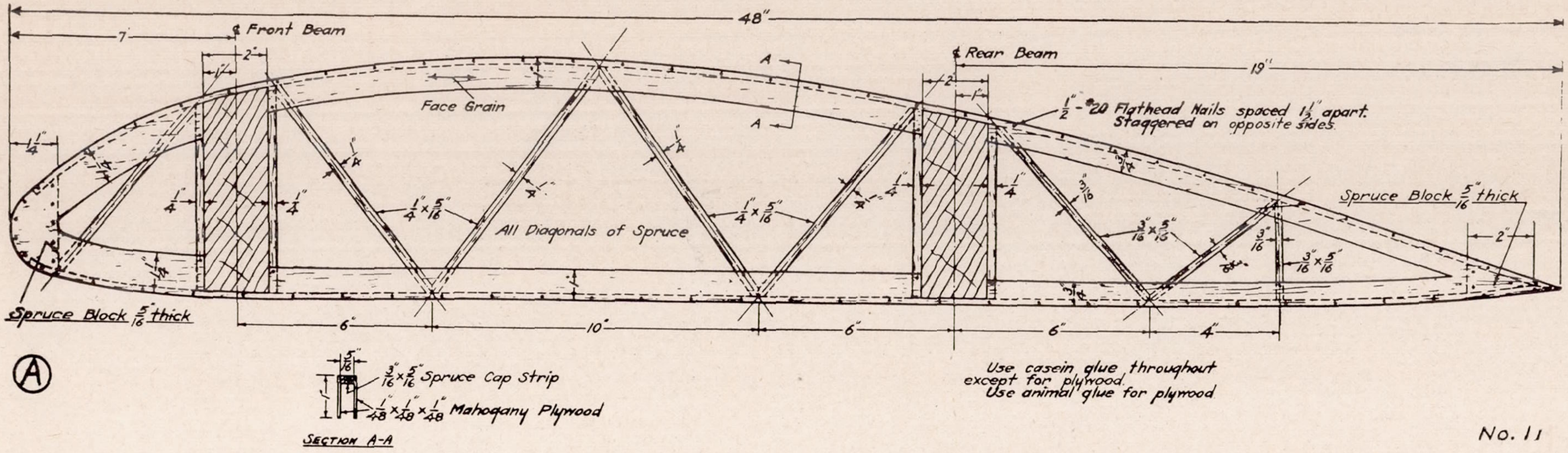


FIGURE 16.—Designs No. 10 and 10–A of wing ribs at station 3 of the BS–1 airfoil (A, normal dimensions; B, doubled dimensions). These are short-panel Howe truss designs. The chords are a combination of spruce and plywood



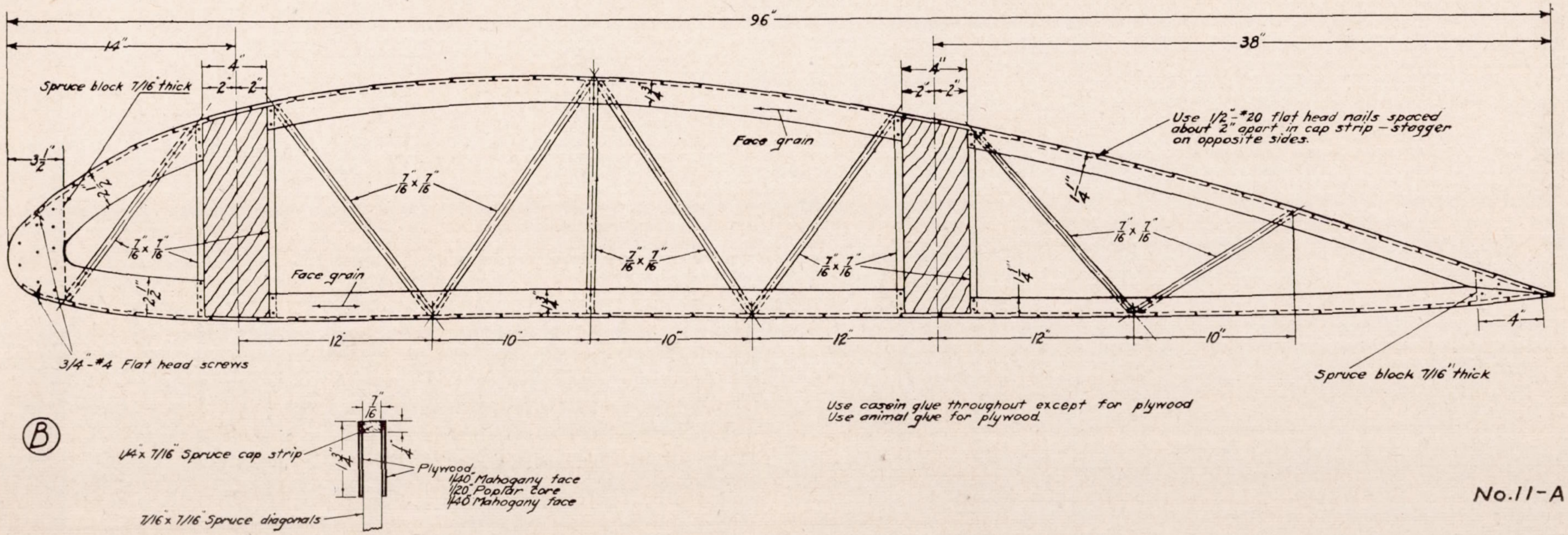


FIGURE 17.—Designs No. 11 and 11-A of wing ribs at station 3 of the BS-1 airfoil (A, normal dimensions; B, doubled dimensions). These are Warren truss designs. The chords are a combination of spruce and plywood

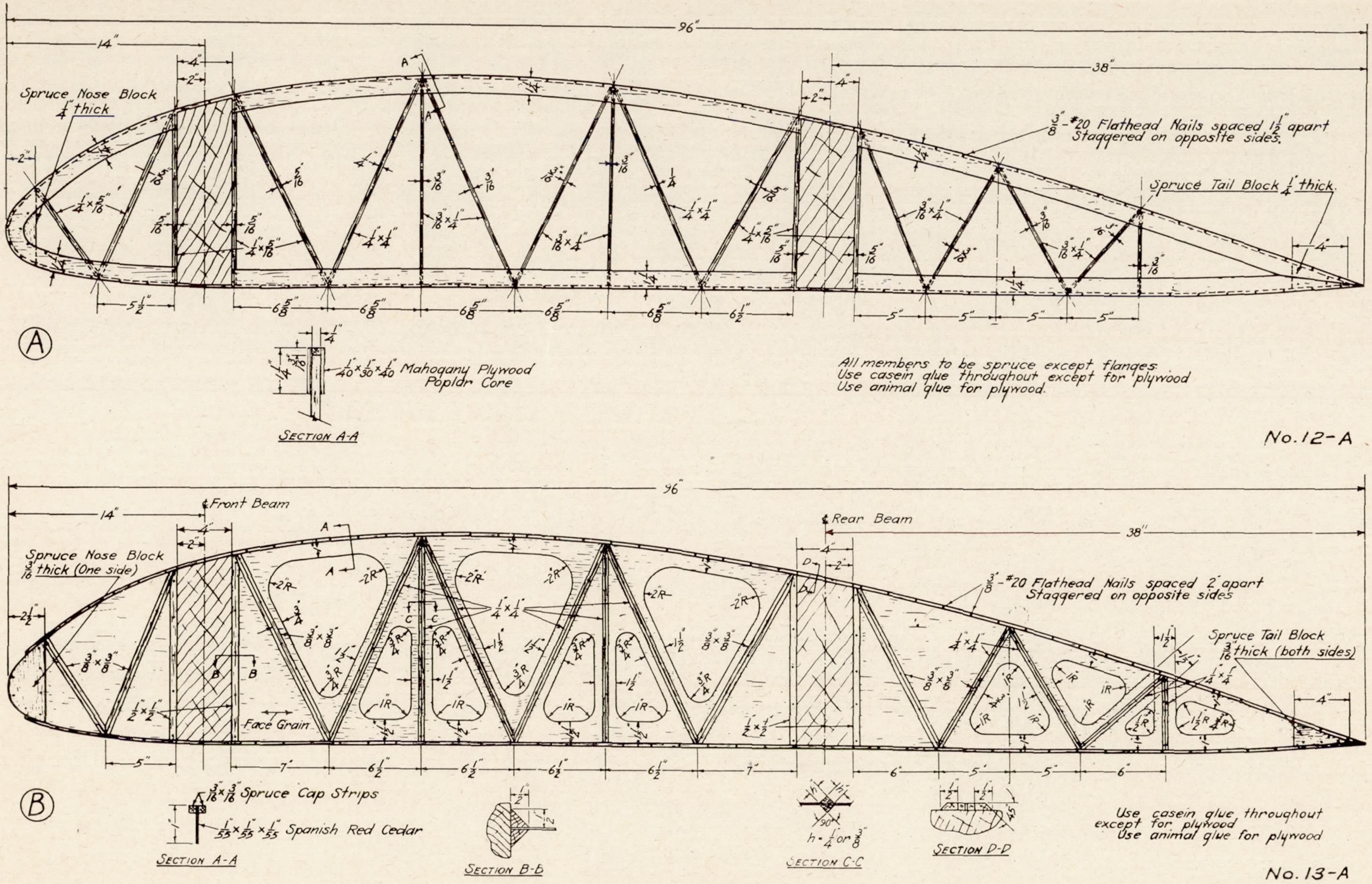


FIGURE 18.—Designs No. 12-A and 13-A of wing ribs at station 3 of the BS-1 airfoil; all dimensions are doubled

A—A lightweight, short-panel truss design.
B—A reinforced-plywood truss design with thin plywood.

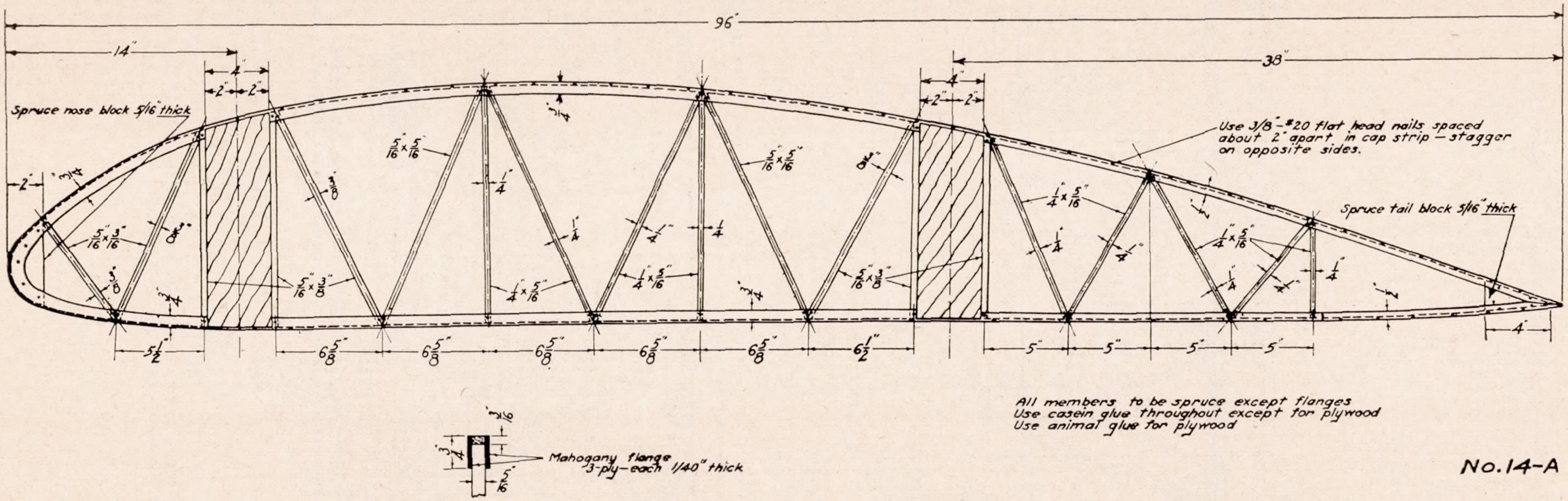


FIGURE 19.—Design No. 14-A of wing ribs at station 3 of the BS-1 airfoil; all dimensions are doubled. The design is of the lightweight, short-panel truss type. The chords are a combination of spruce and plywood

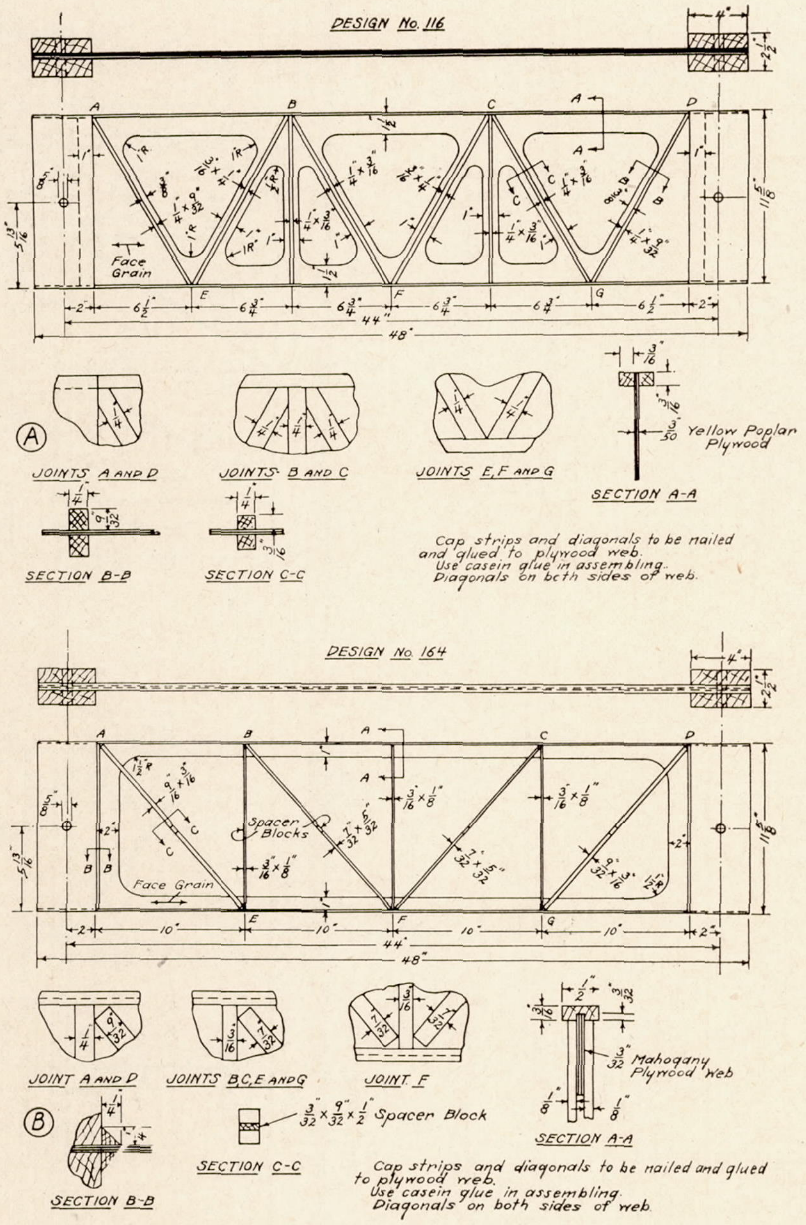


FIGURE 26.—Designs No. 116 and 164 of rib sections 11⅝ inches deep. No. 116 is of the reinforced-plywood truss type. No. 164 represents an extreme lightening of the plywood web and double truss members with spacer blocks at their centers

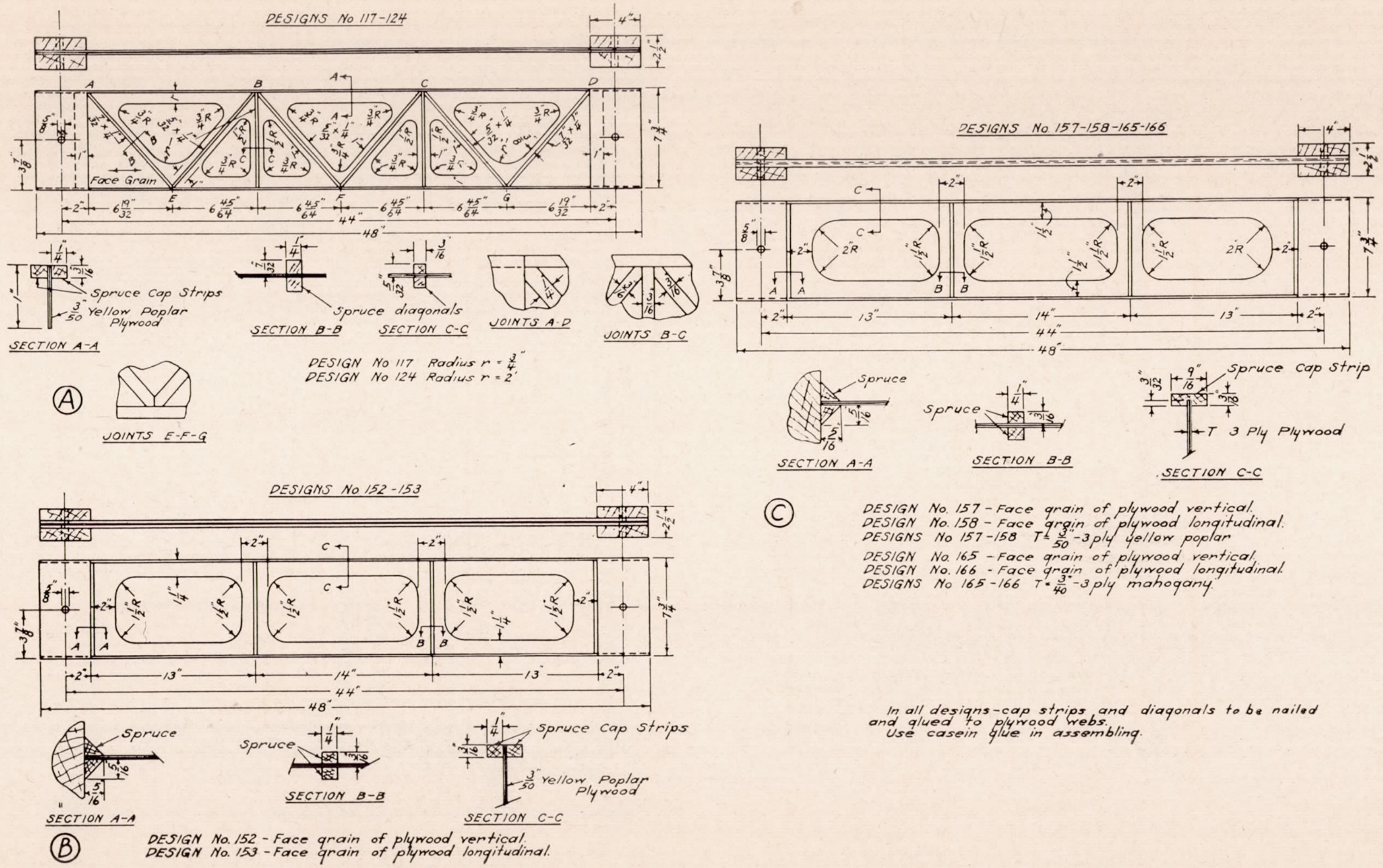


FIGURE 27.—Designs No. 117, 124, 152, 153, 157, 158, 165, and 166 of parallel-chord rib sections 7¾ inches deep. These designs are of the reinforced-plywood truss type

SECTION B-B

FIGURE 29.—Designs No. 105, 107, 108, 150, 151, 159, 160, 167, and 168 of parallel-chord rib sections. Nos. 105, 107, and 108 are 15½, 11⅝, and 7¾ inches deep, respectively. All the other designs are 7¾ inches deep. The designs show various forms of bracing for full plywood webs

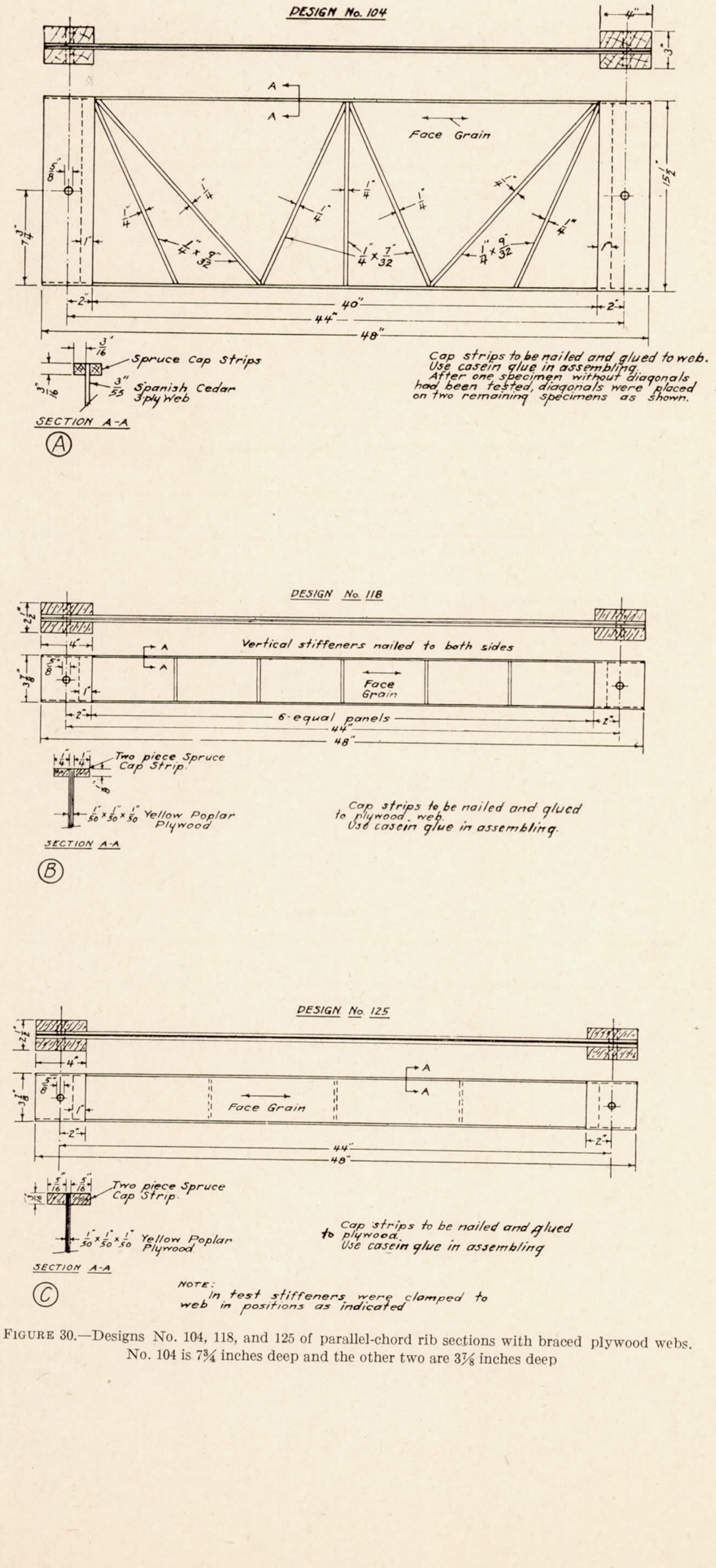


FIGURE 30.—Designs No. 104, 118, and 125 of parallel-chord rib sections with braced plywood webs. No. 104 is 7¾ inches deep and the other two are 3⅞ inches deep

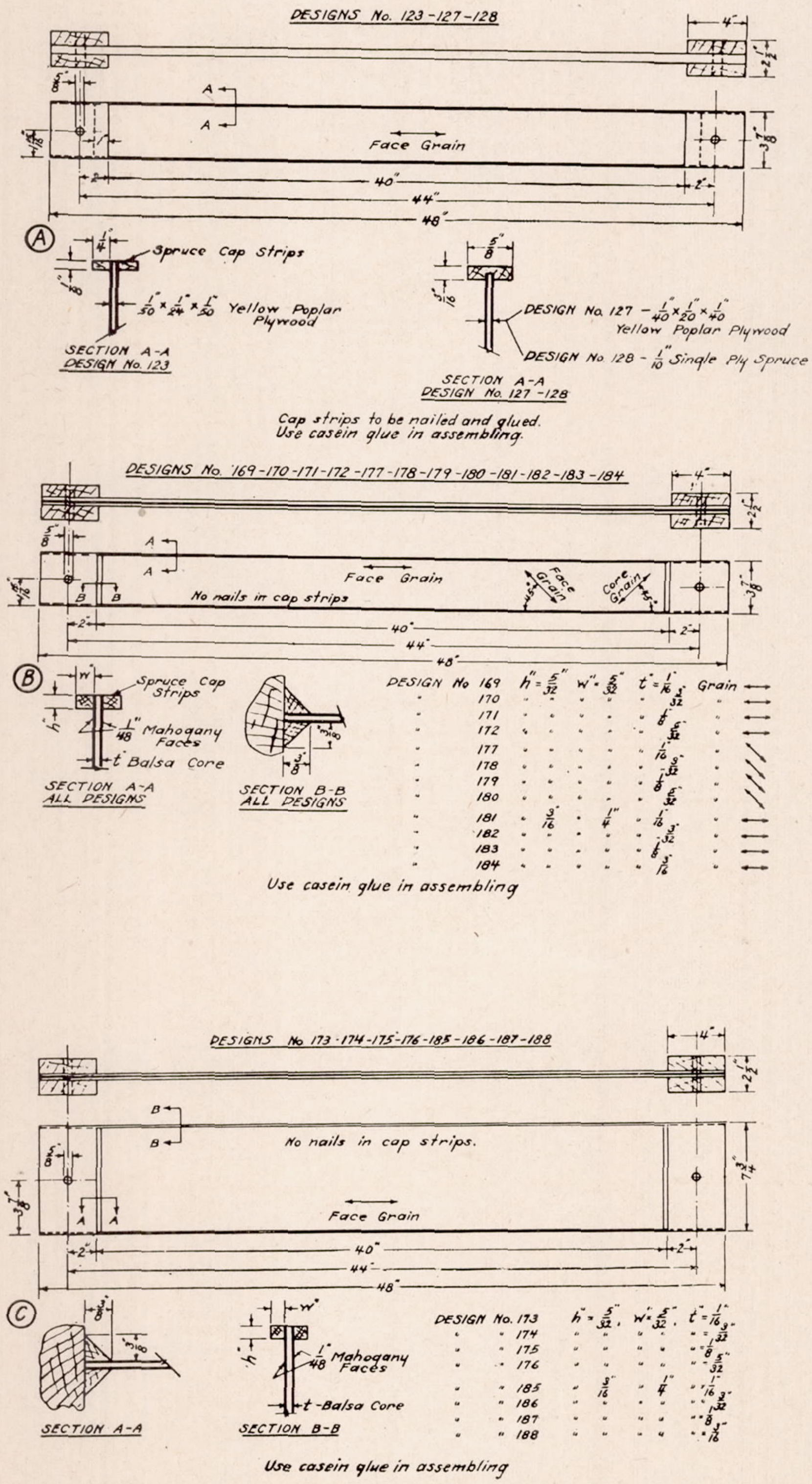
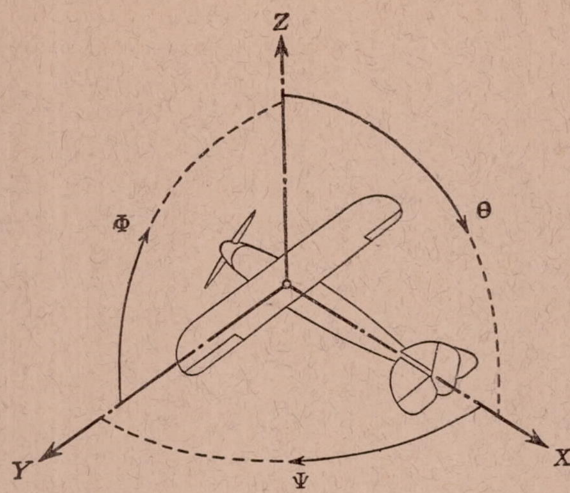


FIGURE 31.—Designs No. 123, 127, 128, 169, 170, 171, 172, 177, 178, 179, 180, 181, 182, 183, 184, 173, 174, 175, 176, 185, 186, 187, and 188 of parallel-chord rib sections 3⅞ and 7¾ inches deep. All designs are of the full plywood web type

INDEX OF WING RIB DRAWINGS

U. S. GOVERNMENT PRINTING OFFICE: 1930



Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	rolling	L	$Y \longrightarrow Z$	roll	Φ	u	p
Lateral	Y	Y	pitching	M	$Z \longrightarrow X$	pitch	Θ	v	q
Normal	Z	Z	yawing	N	$X \longrightarrow Y$	yaw	Ψ	w	r

Absolute coefficients of moment

$$C_L = \frac{L}{qbS} \qquad C_M = \frac{M}{qcS} \qquad C_N = \frac{N}{qfS}$$

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter.
p_e, Effective pitch.
p_g, Mean geometric pitch.
p_s, Standard pitch.
p_v, Zero thrust.
p_a, Zero torque.
p/D, Pitch ratio.
V', Inflow velocity.
V_s, Slip stream velocity.

T, Thrust.
Q, Torque.
P, Power.
(If "coefficients" are introduced all units used must be consistent.)
η, Efficiency $= T\ V/P$.
n, Revolutions per sec., r. p. s.
N, Revolutions per minute, r. p. m.
Φ, Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi rn}\right)$

5. NUMERICAL RELATIONS

1 hp = 76.04 kg/m/s = 550 lb./ft./sec.
1 kg/m/s = 0.01315 hp
1 mi./hr. = 0.44704 m/s
1 m/s = 2.23693 mi./hr.

1 lb. = 0.4535924277 kg
1 kg = 2.2046224 lb.
1 mi. = 1609.35 m = 5280 ft.
1 m = 3.2808333 ft.