The all-wood airplane tends to be heavy; compare weights of airplanes of this type with weights of various single-seaters of composite construction designed for similar power.

What Material Shall I Use?

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WHAT MATERIAL should you choose for your homebuilt aircraft? This question must be given serious consideration by anyone contemplating construction of their own airplane.

Airplanes have been built from many materials: Bamboo, spruce, pine, linwood and mahogany. Such materials have been used both as lumber and in the form of plywood. Various metals such as aluminum, magnesium, steel and stainless steel have been used in sheet, tube and wire form. Use has also been made of various composite materials such as fiberglas, plastics, molded plywood and micarta.

Which of these many possibilities is best for your airplane project?

Every constructor is interested in the following factors:

I. Cost of the material.

II. The labor involved in construction.

III. The performance of the material, which is to say its weight-to-strength characteristics.

IV. The economic life of the airplane, or the number of years it will remain a dependable flying machine and what type of protection will be needed to achieve this life expectancy.

Some men already have some experience in working with certain materials, so their problem is to know how best to utilize these existing skills as well as any related equipment that might be owned. Other men have no experience or equipment and have first to choose materials, then learn to work with them.

Of course, an airplane can be built almost entirely out of some particular material, before it is finished, one will have had to do some work with most of the different basic materials. The welded steel fittings in an all-wood plane, for example.

Some builders are limited by cost and have to choose such materials that the total investment does not exceed a certain figure. Each builder has to make his materials decisions on the basis of his own set of circumstances.

Any particular material has a certain strength for a given cross-sectional area. It is quite common for designers to use a one square inch cross-sectional area as a point of reference. Regardless of the material, it will obviously have an ability to support a certain amount of weight per square inch of cross-section area.

Each material also has a certain weight for a given cubic volume. We will refer to the weight in terms of cubic feet, again because this is common practice.

The less a material weighs per unit of volume, the stronger it will prove to be per square inch of cross-section-

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al area—and the better it will be for airplane construction. For example, nobody would think of building an airplane of lead, as everyone knows that a bar of it can be bent with the bare hands and that it is very heavy.

Thus, it is easy to say that we should use the very strongest of materials in an airplane. But this does not always prove to be the best answer, because very strong materials such as hardened steel are difficult to work and they are very apt to break in service from fatigue resulting from vibration. This brings the realization that toughness is a vital property in aircraft structural materials. Materials being what they are, we must compromise the strength-to-weight capabilities to achieve toughness and long life. So, we will now investigate materials which have been accepted by the aircraft industry and are thus obviously suitable for our purpose.

Of the many species of wood, northern Sitka spruce is the best from the standpoint of weight to strength . . . the northern grown tree is subject to long, cold winters and short summer growing seasons. Consequently the annual growth rings are closely spaced. Quarter-sawn lumber from these trees, carefully selected to be free of imperfections, is used for aircraft. This wood can be subjected to 6,000 lbs./psi maximum fiber stress in tension and about 4,000 lbs./psi in compression.

It is found only on the west coast of the United States in Oregon and Washington and in the coastal area of British Columbia.

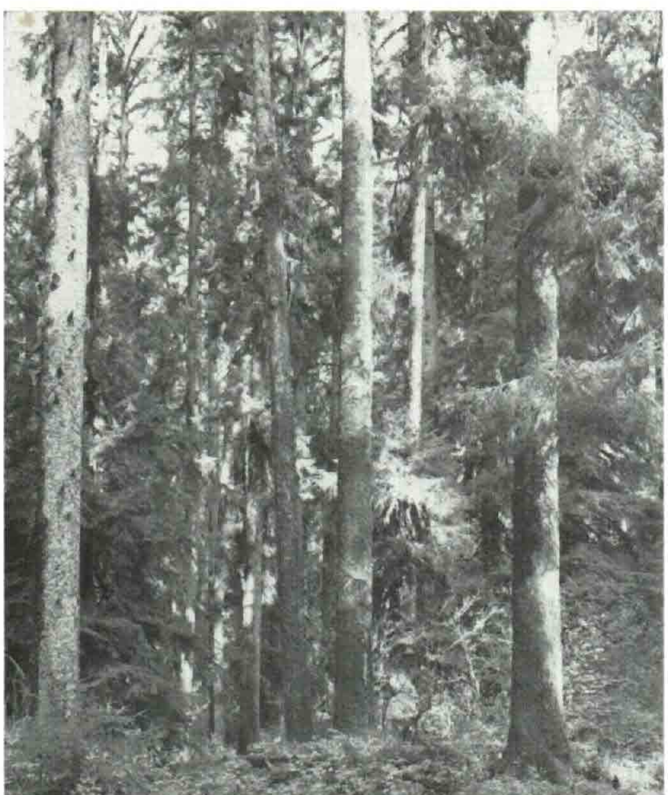
A dead tree that remains standing in the weather dries out and gradually develops a number of longitudinal cracks radiating out from the center of the trunk; they are often quite wide on the tree's outer surface. This demonstrates a principle of wood shrinkage; the major shrinkage in wood is normal, or perpendicular, to the annual growth rings.

Undue shrinkage and expansion is undesirable in aircraft, for it leads to fractured joints and warped components. We want material that is dimensionally stable. Mark "wheel spokes" on the end of a log; obviously if the log is sawn up so that each spoke line becomes the vertical centerline of a wing beam, most of the dimensional instability will be across the thickness of the beam, which is normally a small dimension, while the width of the beam remains acceptably stable. Sawing up a log in this manner is called "quarter sawing."

One way to saw up a log is to start on one side and slice board after board off of it, like slicing a loaf of bread lengthwise. The pieces sawn off near the beginning and end of the job will have "flat grain" and tend to change dimensions appreciably with changes in weather. In quarter sawing, the tree is first cut into four equal quarters lengthwise, then boards are cut out of each quarter segment as in an accompanying illustration. This procedure gets many more useful "edge grain" boards from a tree.

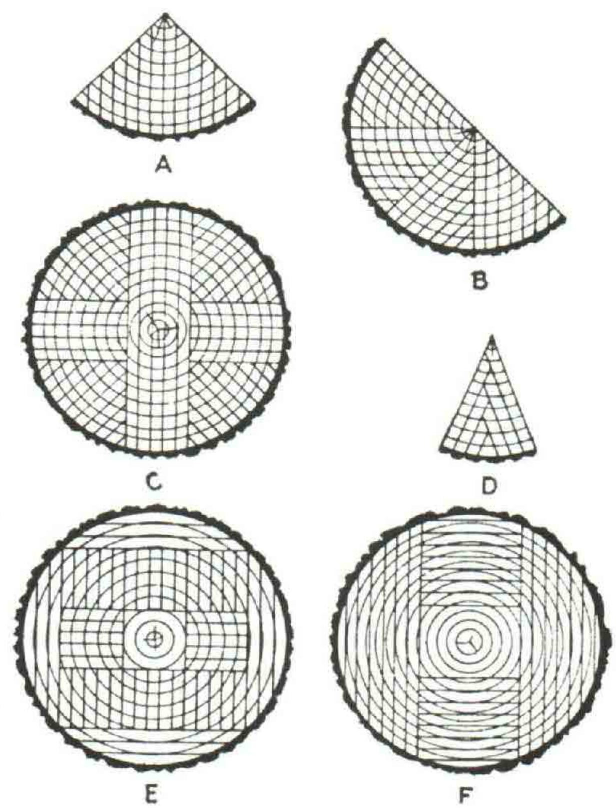
Of course, wood is never completely stable dimensionally. There is always some moisture in it, for the atmosphere itself is never totally devoid of moisture. Wood's moisture content changes with the weather, not only from season to season but from day to day. No known finish is completely impervious to moisture. Even when a finish seems to repel liquid water, water in the air in the form of vapor can get through. There is constant though small change in wood's dimensions. This is usually not a serious consequence in lumber or laminated wood where the grain runs the same way and the possibility of swelling and shrinking is taken into account while designing the structure.

However, in plywood there is a different situation. Here alternate



(American Forest Products Institute Photo)

Aircraft lumber in the raw. A stand of Sitka spruce trees growing in the rain forest of the Pacific Northwest.



(American Forest Products Institute Photo)

Illustrating how a log is quarter-sawed to obtain as much edge-grain lumber as possible.

plies running in different directions prevent the normal expansion and contraction of wood fibers. Ripples result when plywood applied while it is very dry is exposed to dampness in service, or when plywood applied in a period of humid weather encounters a dry spell. Under extreme conditions of alternate wetting and drying the tensions created at the glue lines may cause the plywood to gradually break itself up. Much depends on plywood thickness — thin stock will ripple, thick stock resists rippling and tends to break itself up.

Metals used in aircraft construction have maximum tensile strengths ranging from 65,000 lbs./psi for aluminum to 90,000 lbs./psi for steel. However, these ultimate strength figures cannot be used when designing structures because by the time we reach these levels and the material is about to break, they will have stretched from 15 to 22 percent of their original length and will not return to their original size when the load is removed. There is an "elastic limit" which must not be exceeded. Thus, we use what is called the "yield strength." This is the loading at which a material will just begin to make a permanent set.

Most small airplanes are designed to be 3½ times stronger than needed for level flight in smooth air. They will take rough air and maneuvering loads without harm as long as the 3½ G loading limit is not exceeded. Of course, this limit is sometimes made higher, such as in aircraft designed for aerobatic work, and it sometimes varies in a given aircraft with the load aboard. With a light passenger and gasoline load some planes are classed as aerobatic but with a full load aboard they may not be flown aerobatically. It all boils down to the ever-present conflict between the need for lightness in an airplane and the need for adequate strength.

Yield strength of aircraft 2024 T-3 aluminum is 45,000 lbs./psi. For 4130 normalized steel it is 70,000 lbs./psi. If these materials are worked into proper shapes for the job, they can be loaded in compression to about 75 percent of their tensile yield strength. It is the tendency to deform and buckle that determines strength in compression, while it is the resistance to being pulled apart that determines tensile strength.

At this point, refer to the accompanying chart which compares structural materials on all important factors. I originated this chart for my own use and it has never been published before. Remember that it is only an overall planning chart and may have small discrepancies in it that will probably not be detrimental to its purpose. It was constructed with slide rule calculations so a few errors may have crept in.

In the left-hand column are listed the basic recognized aircraft construction materials, plus fiberglas which is of interest to experimenters. The 45,000 lbs./psi figure for a fiberglas fabric lay-up was obtained from testing a lay-up I made for the purpose. Experience in laying up the material is very important in determining the strength achieved. The "mat" material composed of short fibers, such as is widely used in sports car bodies, wheel pants and boats is not suitable for load carrying structural applications. Uni-directional fiberglas filaments such as used in fishing rods and aircraft landing gears are two or three times stronger in uni-directional loading as is the mat layup.

In column No. 1, note the wide variation in weights per cubic foot.

In column No. 3 is to be found the first meaningful comparison. These numbers are the result of the ratio between the strength per square inch and the weight per cubic foot. The numbers mean nothing by themselves; they are significant only when compared to one another. Notice that fiberglas has a "one" in parentheses after 460. It is the strongest material for its weight on the chart—but there are problems that have to be solved before it can be used in an airplane's

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COMPARISON OF STRUCTURAL MATERIALS

	Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8
	Yield Strength Per Sq. In.	Weight Per Cu. Ft.	Strength to Wt. Ratio Col. 1 / Col. 2	Cost Per Cu. Ft.	Strength To Dollar Ratio Col. 1 / Col. 4	Labor To Construct	Economic Life	Performance
Wood — Northern Spruce	6,000	45 lbs.	153 (3)	Lumber @ $1.25 per Bd. Ft. $15.00	400 (1)	Moderate	(3)	85% (3)
				Plywood @ 90c 1 Sq. Ft. .090 in. $132.00	45 (6)			
Aluminum 2024 T-3	45,000	192 lbs.	235 (2)	Sheet @ $1.25 per pound $240.00	187 (4)	Moderate	(1)	95% (2)
Steel S.A.E. 4130	70,000	480 lbs.	145 (4)	Tube @ $2.00 per pound $960.00	73 (5)	High	(2)	100% (1)
				Sheet @ 50c per pound $240.00	375 (2)			
Fabric Lay-Up. Fiberglas	45,000?	95 lbs.	460 (1)?	Cu. ft. cloth @ $1.25 per yd. and .013 thick costs $125.00.		Highest	(?)	Should be best 200%?
Mat, Random Fiber	10,000	95 lbs.	105 (5)	At $8.00 per gal. for Resin, 4 gals. required per cu. ft. Cost $32.00. Total cost $157.00.	296 (3)			Undesirable

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structure. The rewards for finding solutions to these problems would be high, because it is about twice as strong per pound as aluminum — which in turn is the strongest material per pound of the recognized aircraft materials. You cannot, for example, weld a fitting into the end of a streamlined fiberglas strut as can be done with steel. And threads on the end of a fiberglas rod will strip off long before that will happen on a steel rod.

Wood is the next best material in this column, while steel is the heaviest material for its strength.

Column No. 4, cost per cubic foot, is interesting to all designers. These prices are retail catalog prices. Through group purchasing it is possible to realize substantial savings — that is one reason why it pays to join and support an EAA chapter!

Note the difference between the cost per cubic foot for lumber at $15.00 and the cost per cubic foot for plywood at $132.00. Lumber is a natural product, plywood is a manufactured article—and you pay for the manufacturing! These costs include fungus proofing and sealing the surface. It is appropriate to figure on lumber at a rate of .33 per lb. and on plywood at a rate of $2.90 per lb. It can be seen that the cost per pound for lumber is lowest while the cost for plywood is the highest in column No. 4.

Note also that the $2.00 per lb. price of steel tubing is much higher than the price of 50c per lb. for steel sheet. That's because it is easier to produce sheet in volume by rolling than it is to manufacture individual lengths of tubing by piercing billets of steel with a mandrel. However, these prices become more meaningful in terms of actual design work when we go on to column No. 5. Here is shown the strength-to-dollar ratio; this column holds the answers to your budgeting problems.

It can be seen here that lumber is the lowest priced source of strength, if low cost is the main consideration. However, a check with column No. 3 shows that it is somewhat heavier than aluminum structures and slightly lighter than steel tube structures.

If an airplane could be made entirely of sheet steel it would be the next least expensive material strengthwise. Since there would be practical objections to a sheet steel airplane, this figure just means that whatever part of an airplane might be made of sheet steel would be fairly inexpensive for the strength involved. Fiberglas ranks third, but column No. 6 shows that it requires more labor to make anything from it. Aluminum is fourth on the expense list, but if you are interested in minimum structural weight and do not want to stand the cost of hangar storage, you would prefer it.

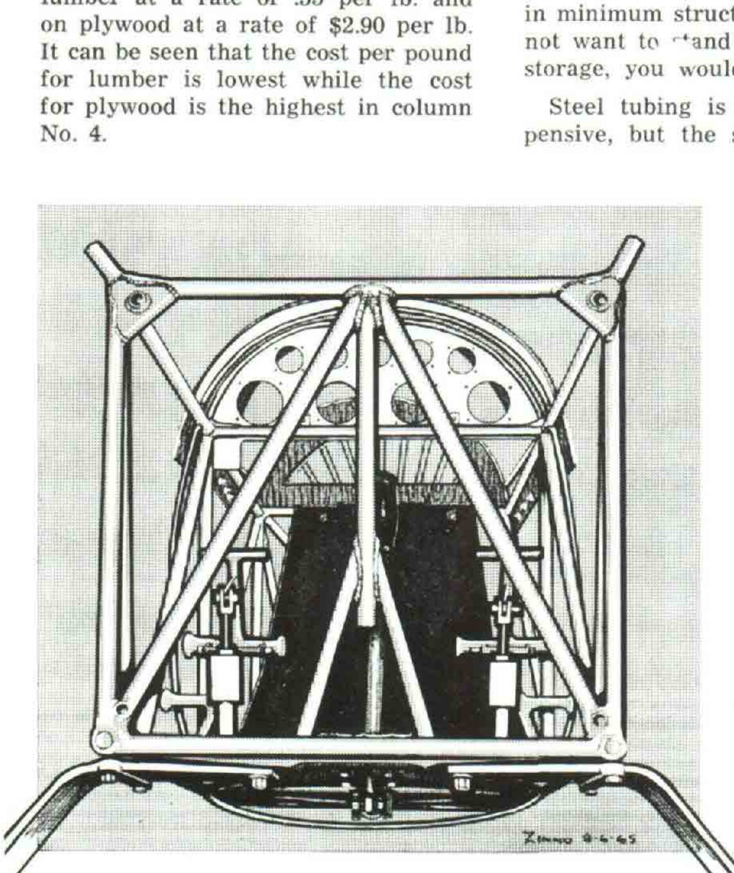
Steel tubing is the next most expensive, but the surprise in column No. 5 is that plywood is the most expensive material of all. Not only that, but finished cost is apt to be even higher than indicated because of the need to apply fabric, fiberglas, plastic or other finish to it for weather protection. Note that the aluminum structure is closed in and serviceable as soon as it is completed.

In considering external surfaces the following cost figures are interesting:

.090 in. plywood	$ .90 sq. ft.
Fabric covering over any structure	1.00 sq. ft.
.025 in. 2024 T-3 aluminum	.45 sq. ft.
.020 in. 2024 T-3 aluminum	.35 sq. ft.
.016 in. 2024 T-3 aluminum	.28 sq. ft.

On a plywood covered airplane the usual practice is to cover the plywood with fabric, so the total cost comes to $1.90 per sq. ft., compared to 45c per sq. ft. for .025 in. aluminum skin.

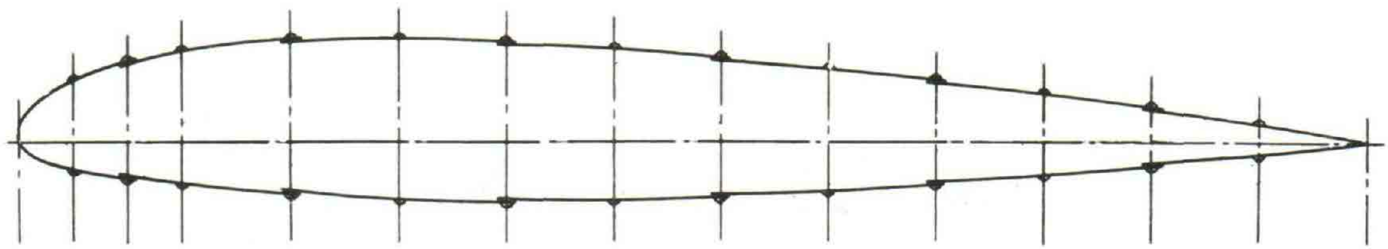
Wooden airplanes built in the past have often suffered in performance because they have often been overbuilt and there has been a tendency to take short cuts in design and construction that could have been helped by a little more thought and labor. For example, in one popular wooden airplane the wing tips have dihedral and there are as a result two joints. This means that there are four overlapping splices in the two wing spars, each two feet long. Since the material in these spars weighs 1¼ lbs. per ft., this construction is 9 lbs. heavier than a spar of laminated construction



Steel tube construction is expensive, partly because of the high material cost, partly because of the labor involved in fitting and welding the tubes, and also because supplemental fairing and then a fabric or metal skin are needed.

Fine finish possible with fabric covering adds to performance.

The all-aluminum airplane is light in weight and stands exposure to weather best of all.



Rivet heads and metal joints in aluminum construction add to drag. To eliminate this, extra care is needed in construction in order to avoid increases in time and cost.

with the dihedral angles steamed into laminations.

Another example of where weight could be saved is in the 1 in. by 4 in. wing spars of an aerobatic biplane. These weighed one pound per foot of length. Metal spars were investigated and it was found that they could be twice as strong as wooden spars for the same weight. Part of this increase in strength is due to the better strength-to-weight characteristics of aluminum, and some of it is due to the I-beam section incorporated into the aluminum spars as a matter of course as compared to the rectangular cross section of the wooden spars.

In other words, the wooden spars could be improved by making top and bottom strips of spruce with a balsa central section, as the middle third of a solid wood spar does little work and can be replaced with very light material so long as solid blocking is used at points of high stress such as at attachment fittings. Of course, in actual practice a balsa-cored spar would have its shortcomings due to glue problems, fitting design, etc. but the point is made clear that some wooden aircraft construction is in fact overweight.

The geodetic type of construction uses mostly lumber and relatively little plywood and from this standpoint holds promise of being the least expensive type of construction in addition to offering fairly good performance.

To recapitulate what has been covered in this article, the amount of labor involved in building with lumber is moderate. In sheet aluminum it is also moderate, chiefly because fabric covering is not needed over it. In steel tube construction the amount of labor is great, as there is need first for the frame, then for suitable fairing strips and finally a fabric or metal skin.

The labor involved in fiberglas construction is almost so high as to rule it out unless an answer can be found to this problem; it is high because each cubic inch of material must be built up by hand laminating the mat and resin. It has proved worthwhile for compound curved surfaces that would be difficult to make any other way or would call for extensive and costly tooling.

Aluminum requires the least in the way of protective coatings and lasts longer with the least amount of maintenance, since there is no fabric to replace. Steel structures pose the problem of rust protection. Wooden airplanes must be designed with a thorough knowledge of the cause and prevention of wood rot, their life is short if they are left out of doors, and their surfaces must receive regular maintenance if they are to give acceptably long service life.

Laminated fiberglas is still a question mark. We still have little service experience to go by. There is the problem of safe and durable fittings and fastenings, and the problem of gradual warping or distortion of the material under the influence of weather and gravity. If the surface is protected with paint or some other abrasive resistant coating, weather resistance might be very good.

From the standpoint of performance, steel tubing is superior because the fabric skin when skillfully applied is smoother than many sheet metal jobs with all their rivets and seams. On the other hand, it is true that with proper care a sheet metal surface can be as smooth as a fabric one—it is a question then of the amount of labor. Wood takes third place in performance, not because it lacks a smooth skin, but because of the weight penalty that is basic to the choice of materials as in column 3.

The typical amateur-built airplane with steel tube fuselage, solid spar wings and fabric covering is often derided as being "old fashioned." Actually, as a study of this article will reveal, this choice of materials represents a scientifically sound solution to the builder's problems of cost, weight, etc. The all-metal homebuilt airplane has its place when lightness and durability are sought, and the wooden airplane can be the solution to the needs of the man who has had no steel or aluminum working experience. The main thing is to make a wise choice for your circumstances.