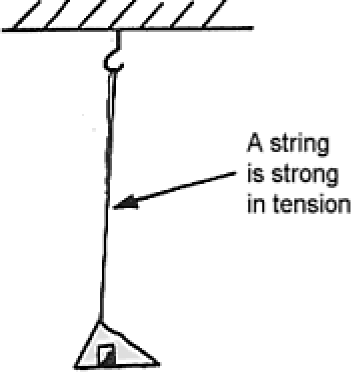
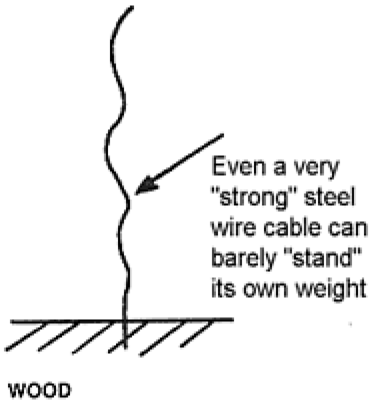




WOOD, ALUMINUM, STEEL AND COMPOSITES

... and the Properties of each.

By Chris Heintz

[This article is part 1of a series, where aeronautical engineer Chris Heintz discusses light aircraft design and construction.]

Aircraft structures are basically *unidirectional.* This means that one dimension, the length, is much larger than the others - width or height. For example, the span of the wing and tail spars is much longer than their width and depth; the ribs have a much larger chord length than height and/or width; a whole wing has a span that is larger than its chords or thickness; and the fuselage is much longer than it is wide or high. Even a propeller has a diameter much larger than its blade width and thickness, etc.... For this simple reason, a designer chooses to use unidirectional material when designing for an efficient strength to weight structure.

Unidirectional materials are basically composed of thin, relatively flexible, long fibers which are very strong in tension (like a thread, a rope, a stranded steel wire cable, etc.)

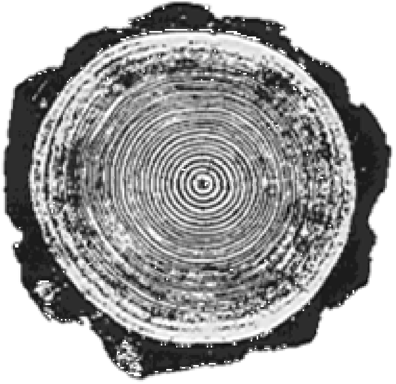
An aircraft structure is also very close to a *symmetrical structure.* That means the up and down loads are almost equal to each other. The tail loads may be down or up depending on the pilot raising or dipping the nose of the aircraft by pulling or pushing the pitch control; the rudder may be deflected to the right as well as to the left (side loads on the fuselage). The gusts hitting the wing may be positive or negative, giving the up or down loads which the occupant experiences by being pushed down in the seat ... or hanging in the belt.

Because of these factors, the designer has to use a structural material that can withstand both tension and compression. Unidirectional fibers may be excellent in tension, but due to their small cross section, they have very little inertia (we will explain inertia another time) and cannot take much compression. They will escape the load by bucking away. As in the illustration, you cannot load a string, or wire, or chain in compression.

In order to make thin fibers strong in compression, they are "glued together" with some kind of an "embedding". In this way we can take advantage of their tension strength and are no longer penalized by their individual compression weakness because, as a whole, they become compression resistant as they help each other to not buckle away. The embedding is usually a lighter, softer "resin" holding the fibers together and enabling them to take the required compression loads. This is a very good structural material.

WOOD

Historically, wood has been used as the first unidirectional structural raw material. Nature, in her wisdom, has provided a beautiful unidirectional material by making certain trees



grow in certain conditions: They have to be tall and straight and their wood must be strong and light. The cross section of a tree trunk shows the "annual rings" (a ring per year so that we can "count" the tree's age). The dark bands (late wood) contain many fibers, whereas the light bands (early wood) contain much more "resin". Thus the wider the dark bands, the stronger and heavier the wood. If the dark bands are very narrow and the light bands quite wide, the wood is light but not very strong. To get the most efficient strength to weight ratio for wood we need a definite numbers of bands per inch (see ANC No. 18,1951). In fact, what we want is a good balance of "early" and "late" wood, or in other words, very special growing conditions, i.e., the geographic altitude where the tree's growth varies with the latitude and local climatic conditions. Although this is a very interesting subject we will not go further into such details except to mention that it is nature who supplies us with a very efficient material from its plant kingdom. Remember that contrary to the strictly mineral world hopelessly subject to gravity pulling everything down, the plant has a force within itself which makes it grow against gravity, upwards. If we could use those life forces in our machines we could lift off without the help of an engine... Aviation still has a lot to discover....

Another subject we will not deal with this month is the testing of wood. There are a few simple tests (humidity, dynamics, resilience) but it seems that nobody knows them anymore.

Some of our aircraft structures are two-dimensional (length and width are large with respect to thickness). Plywood is often used for such structures. Several thin boards (foils) are glued together so that the fibers of the various layers cross over at different angles (usually 90 degrees today years back you could get them at 30 and 45 degrees as well). Plywood makes excellent "shear webs" if the designer knows how to use plywood efficiently. (We will learn the basis of stress analysis sometime later.)

To close this discussion on wood, let us plainly state the fact that our present day bureaucratic civilization uses so much paper that we are depleting the planet of trees without replanting them correctly. Today good aircraft wood is very hard to come by. Instead of using one good board for our spars, we have to use laminations because large pieces of wood are practically unavailable, and we no longer can trust the wood quality; we have to use many laminations so that the "average" has a reasonable chance to give us the required strength without too much penalty from a weight standpoint. From an availability point of view, we simply need a substitute for what nature has supplied us with until now.

ALUMINUM ALLOYS

So, since wood may not be as available as it was before, we look at another material which is *strong, light and easily available* at a *reasonable price* (there's no point in discussing Titanium - it's simply too expensive). *Aluminum alloys* are certainly one answer. We will discuss the properties of those alloys which are used in light plane construction in more detail later. For the time being we will look at aluminum as a construction material.

Extruded Aluminum Alloys: Due to the manufacturing process for aluminum we get a unidirectional material quite a bit stronger in the lengthwise direction than across. And even better, it is not only strong in tension but also in compression. Comparing extrusions to wood, the tension and compression characteristics are practically the same for aluminum alloys so that the linear stress analysis applies. Wood, on the other hand, has a tensile strength about twice as great as its compression strength; accordingly, special stress analysis methods must be used and a good understanding of wood under stress is essential if stress concentrations are to be avoided!

Aluminum alloys, in thin sheets (.016 to .125 of an inch) provide an excellent two dimensional material used extensively as shear webs - with or without stiffeners - and also as tension/compression members when suitably formed (bent).

It is worthwhile to remember that aluminum is an artificial metal. There is no aluminum ore in nature. Aluminum is manufactured by applying electric power to bauxite (aluminum oxide) to obtain the metal, which is then mixed with various strength-giving additives. (In a later article, we will see which additives are used, and why and how we can increase aluminum's strength by cold work hardening or by tempering.) All the commonly used aluminum alloys are available from the shelf of dealers. When requested with the purchase, you can obtain a "mill test report" that guarantees the chemical and physical properties as tested to accepted specifications. (MIL standards, QQA250 XYZ).

As a rule of thumb, aluminum is three times heavier, but also three times stronger than wood. Steel is again three times heavier and stronger than aluminum.

STEEL

The next material to be considered for aircraft structure will thus be steel, which has the same weight-to-strength ratio of wood or aluminum.

Apart from mild steel which is used for brackets needing little strength, we are mainly using a chrome-molybdenum alloy called AISI 413ON or 4140. (AISI .1025 is no longer available.)

The common raw materials available are tubes and sheet metal. Steel, due to its high density, is not used as shear webs like aluminum sheets or plywood. Where we would need, say a .100" plywood, a .032 inch aluminum sheet would be required, but only a .010 steel sheet would be required, which is just too thin to handle with any hope of a nice finish. That is why a steel fuselage uses tubes also as diagonals to carry the shear in compression or tension and the whole structure is then covered with fabric (light weight) to give it the required aerodynamic shape or desired look. It must be noted that this method involves two techniques: steel work and fabric covering.

The advantage of 4130N steel structure is that it can readily be welded together. This applies especially in North America where the welder does not have to be "approved" as he has to be in Europe and Australia. This difference in regulations, historically, has to do with the "pioneer spirit" and explains why welded steel fuselages are so common here and practically nowhere else.

We will be discussing tubes and welded steel structures in more detail later and go now to "artificial wood" or composite structures.

COMPOSITE MATERIALS

The designer of composite aircraft simply uses fibers in the desired direction exactly where and in the amount required. The *fibers* are embedded in *resin* to hold them in place and provide the required support against buckling. Instead of plywood or sheet metal which allows single curvature only, the composite designer uses cloth where the fibers are laid in two directions .(the woven thread and weft) also embedded in resin. This has the advantage of freedom of shape in double curvature as required by optimum aerodynamic shapes and for very appealing look (importance of esthetics).

Today's fibers (glass, nylon, Kevlar, carbon, whiskers or single crystal fibers of various chemical composition) are very strong, thus the structure becomes very light. The drawback is very little stiffness. The structure needs stiffening which is achieved either by the usual discreet stiffeners, -or more elegantly with a *sandwich* structure: two layers of thin uni- or bi-directional fibers are held apart by a lightweight core (foam or "honeycomb"). This allows the designer to achieve the required inertia or stiffness.

From an engineering standpoint, this method is very attractive and supported by many authorities because it allows new developments which are required in case of war. (The U.S. having no titanium or chromium needs to develop practical alternatives.) But this method also has its drawbacks for homebuilding: A mold is needed, and very strict quality control is a must for the right amount of fibers and resin and for good adhesion between both to prevent too "dry" or "wet" a structure. Also the curing of the resin is quite sensitive to temperature, humidity and pressure. Finally, the resins are active chemicals which will not only produce the well known allergies but also the chemicals that attack our body (especially the eyes and lungs) and they have the unfortunate property of being cumulatively damaging and the result (in particular deterioration of the eye) shows up only years after initial contact.

Another disadvantage of the resins is their limited shelf life, i.e., if the resin is not used within the specified time lapse after manufacturing, the results may be unsatisfactory and unsafe.

Finally unless the molds are very well designed, manufactured and maintained, the outside of the structure needs an often underestimated amount of "elbow grease" to provide the desired finish. Also a lot of care must be exercised as sanding down too much will result in a weaker structure. Historically, composites had their peak a couple of years ago. Today it is known (and proven by all those homebuilder "workshops") that only specialists can come up with a reliable and perfect structure and even the specialists take a chance on their own health.

LET'S SUMMARIZE

- Nature provides a raw material beautifully suited to aircraft structures. Unfortunately we are exploiting nature and today it is hard to find supplies of wood and plywood of the required sizes and quality.
- Aluminum alloys in extruded and laminated form are an attractive alternative especially as they are easy to supply with guaranteed properties.
- Steel tubing continues to be very popular in North America as welding does not seem to create any problems as feared in other parts of the world. A tubular structure is fabric covered.
- Composites can be looked at as "artificial wood" from a structural standpoint. Like everything artificial, it can be better than the natural product but the manufacturer needs to incorporate in the manufacturing process the wisdom provided by nature and/or the quality provided by other raw material's manufacturers (aluminum, chrome moly steel). This is in addition to an expensive mold, and the hazards to our own health (and our family's health when building in the basement).

In our next column, we will look closely at the various metal alloys suitable for light plane construction.

Introduction to this article, as first published in EAA Light Plane World (now EAA Experimenter), December 1995:

"This month we are happy to present the first in a series of articles on aircraft construction by Chris Heintz. We are very pleased to welcome Chris as a contributor to our magazine, and we're certain that our readers will benefit greatly from his wisdom.

"Chris will be writing articles to appear in LIGHT PLANE WORLD four to six times each year. In case you're not familiar with Chris, we'd like to tell you a little about him.

"Chris Heintz (EAA 78029) was born on November 1, 1938 in the city of Strasbourg on the German I French border. His formal education includes a degree in Aeronautical Engineering from ETH (Eigenoessische Technische Hochschule) in Zurich, Switzerland in 1961.

"Besides working on the Concorde, Chris was chief designer at Avions Robin in southern France. (The DR250 which Eric Mueller flew to Oshkosh '85 from Switzerland was one of his production aircraft as was the HR200 displayed in the Aerospatiale booth.)

"Immigrating to Canada, Chris worked for DeHavilland of Canada in the design of the STOL Dash-7 airliner. For the past 12 years he has devoted his time and talents to designing homebuilt aircraft, His complete line of aircraft, called the Zenair series, includes the CH1OO (Mono-Zenith), and 150 (Acro), the CH180 (Super Acro), the CH200 and CH250 (Zenith), the CH300 (Tri-Zenith) and the CH600 (Zodiac).

"In the ultralight field, Chris has designed a line of unique machines using the "Princeton Sailwing" concept for 5-minute foldability. In addition, Chris has designed a full line of aluminum floats from 500 lbs. buoyancy to 1950 lbs. by 200 lb. steps to cover every need for the ultralight and homebuilt owner."

This article is presented as part of a series, where aeronautical engineer Chris Heintz discusses the technical aspects of his light aircraft designs in laymen terms.

This article is the first in his series on light aircraft design and construction published in EAA Light Plane World magazine (December 1985). © 1985, Chris Heintz.

LIGHT AIRCRAFT RAW MATERIALS

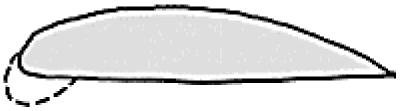
By Chris Heintz

[This article is part 2 of a series, where aeronautical engineer Chris Heintz discusses light aircraft design and construction.]

In this month's column, in contrast to our last column in the December '85 issue of LIGHT PLANE WORLD, we will discuss the **structural standpoints** *of the raw materials of which our aircraft are built. This viewpoint is quite different from the supply possibilities, and also the ease and safety of use (our own health as well as the aircraft's structural integrity).*

One important word of caution, before we begin, to the "would-be designer" - the technical data presented here are typical values *which are very adequate to compare materials, but are not the* guaranteed values *which must be used in structural analysis. (See ANC-18 for wood, and MIL-HDBK-5 and other handbooks for metals, the manufacturer's specifications for fibers, resins and their proven combinations). Special tests are required for new combinations and special "unconventional" applications.*

Original NACA 2300 Wing Profile With CM = .008



Modified Profile With cm = .18

Designing a new aircraft, or redesigning (modifying) an existing design, should be done by the amateur builder only with the help of a reputable light aircraft designer. The following situations are to be avoided: 1) too heavy a structure and, 2) not a strong enough airframe. Anyone who has been around amateur builders and designers long enough has seen them tapping on their wings or fuselage and saying, "That's strong enough", but is it really?

At low speed and high load factors, say a 75 degree bank and a speed just over 2.5 times the stall speed, the aerodynamic load is inclined some 20 to 30 degrees forward. Will this wing which may even have been "sand bag tested" in the "normal" load condition stand it? Or will the wing, which has been improved from a NACA 23012 profile by adding the "STOL" nose cuff to improve its original abrupt stall characteristics (because not correctly twisted), stand up to the new torsional loads due to a four-fold increase in the twisting moment coefficient (cm from -.008 to -18)?

Such loads are usually associated with an increase in cruise speed, say from 130 mph to 150 mph, by increasing the original design horsepower from 100 bhp to 150 bhp. This will further increase the torsion load on the wing by a factor of $(150/130)^2$. Will your "new" wing stand those loads? If you are not sure, you better ask somebody who *re*ally knows.

We will discuss the above formulas within the course of this series, but for this month's column, we will stick strictly to a comparison of materials. The values themselves should not be used as design data.

The focus of our article this month is our Table which gives **typical values** for a variety of raw materials.

Column 1 lists the standard materials which are easily available at a reasonable cost. As this column is not intended to be an "academic lecture," we will not discuss "fantastic" materials because we cannot afford them anyway. We want to acquire a simple, good understanding of practical solutions and practical materials.

Some of the materials that fall along the borderline between practical and impractical are:

- **Magnesium:** An expensive material. Castings are the only readily available forms. Special precaution must be taken when machining magnesium because this metal burns when hot.
- **Titanium:** A very expensive material. Very tough and difficult to machine.
- **Carbon Fibers:** Still very expensive materials.
- **Kevlar Fibers:** Very expensive and also critical to work with because it is hard to "soak" in the resin. When this technique is mastered, the resulting structure is very strong, but it also lacks in stiffness.

The values given in our Table are for fiberglass with polyester resins, which is very easy to use compared to the more critical (viscous) epoxy fiberglass. Epoxy fiberglass provides a somewhat stiffer and stronger result. ("Prepreg," epoxy pre-impregnated cloth, is still very expensive, has a limited shelf life and needs pressure as well as an oven to cure).

Aluminum Alloy 7075 - "T-whatever", has been left out intentionally as it is a very strong but also very brittle alloy. It is comparable to glass. Unless we state a "life" for a specified part made of 7075, it is unsafe to use this alloy in most light aircraft. (We are not an airline with an on-going maintenance schedule - we want to fly our planes year after year without having to worry about fatigue of our aircraft structure, something we'll talk about later.)

Columns 2 through 6:

Columns 2 through 6 list the relevant material properties in metric units. The multiplying factor on the bottom line will transform the figures into North American Units.

Column 2, the *density* (d), is the weight divided by the volume.

Column 3, the *yield stress* (fy), is the stress (load per area) at which there will be a permanent deformation after unloading (the material has yielded, given way ...).

Materials		**d**	**fy**	**fu**	**e**	**E/10^3**	**E/d**	**Root^2 of N/d**	**Root^3 of E/d**	**fu/d**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Wood	Spruce	.45	-	3.5/11	-	1.4	2200	70	22.0	(15)
	Poplar	.43	-	30/12	-	1.0	2200	70	22.0	(15)
	Oregon Pine	.56	-	4.0/13	-	1.5	2200	70	22.0	(15)
Fiberglass	Matte	2.2	-	15	-	1.5	700	17	5.0	7
(70% Glass)	Woven	2.2	-	35	-	2.0	900	20	6.0	16
	Unidirectional	2.2	-	60	-	3.5	1500	27	7.0	27
Alum. Alloy	5052-H34	2.7	16	24	4	7.1	2600	30	7.0	11
	8086-H34	2.7	22	31	5	7.1	2600	30	7.0	11
	6061 -T6	2.7	24	26	9	7.1	2600	30	7.0	11
	6351 -T6	2.7	25	28	9	7.1	2600	30	7.0	11
	6063-T6	2.7	17	21	9	7.1	2600	30	7.0	11
	2024-T3	2.8	25	41	12	7.2	2600	30	7.0	14
Steel AISI	1026	7.8	25	38	15	21.0	2700	18	3.5	5
	4130 N (4140)	7.8	42	63	10	21.0	2700	18	3.5	7
Lead		11.3	-	-	-	-	-	-	-	-
Magnesium Alloy		1.8	20	30	-	4.5	2500	37	9.0	16
Titanium		4.5	50	80	-	11.0	2400	23	5.0	18
Units for above		kg/dm^3	kg/mm^2	kg/mm^2	%	kg/mm^2	km	kg$^{-1/2}$m^2	kg$^{2/3}$m$^{1/3}$	km
to obtain:		lbs/cu^3	KSI	KSI	%	KSI				
multiply by:		.0357	1420	1420	-	1420				

Note to Table: The units used are the usual Metric S.I. (or MKFS) international technical system where kg f = kg force (not mass as in the Metric MKS, used in physics.) The usual North American units and the conversion factors are also supplied in the bottom lines.

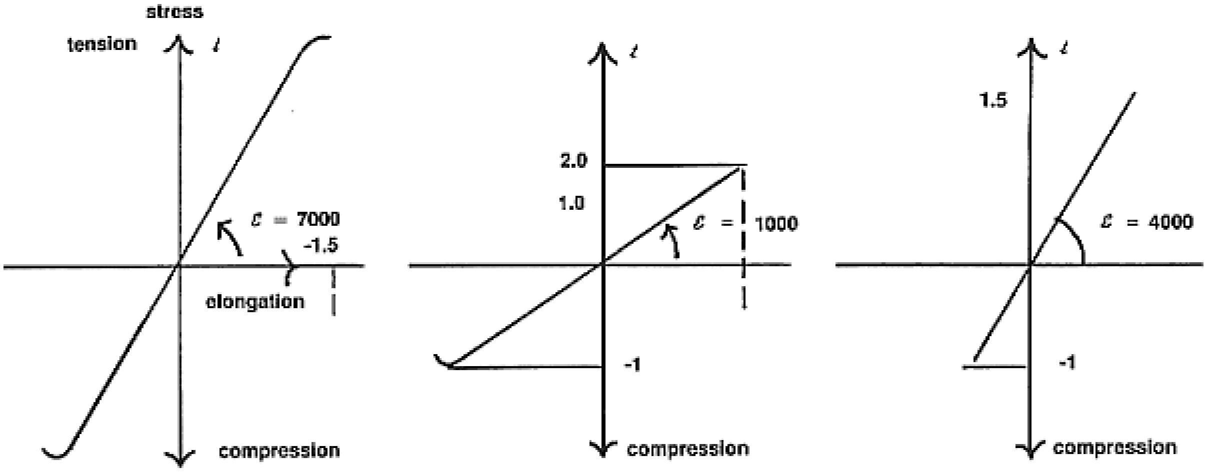
Column 4, the *ultimate stress* (fu), is the stress (load per area) at which it cannot carry a further load increase. It is the maximum load before failure.

Column 5, the *elongation at ultimate stress* (e), in percentage gives an indication of the 'Toughness" of the material.

Column 6 lists the *Yongs Modular or Modulus of Elasticity* (E), which is the steepness of the stress/strain diagram as shown in Figure 1.

Important Note: For wood, the tension is much greater (2 to 3 times) than the compression. Both values are given in the Table. For fiberglass, the same applies, but the yield is so dependent on the manufacturing process that we cannot even give 'lypical values'.

Figure 1



Typical Metal - Aluminum
Tension and compression are practicly symmetrical.

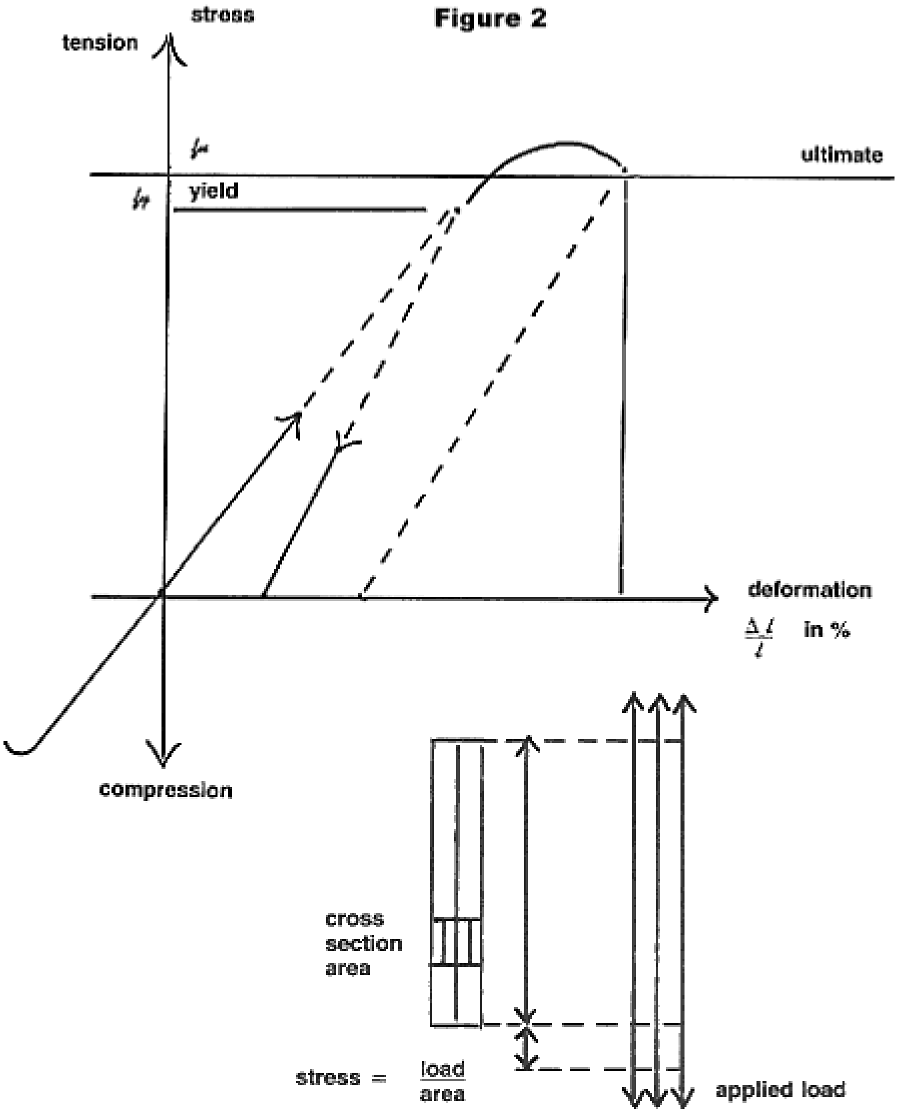
Wood

Composite

Both wood and fiberglass need special analysis procedures to predict the strength of a specific structural member. This analysis is quite different from classic strength of material formulas. Today we have to warn the "I wood' be designer" that his off-the-shelf computer program may be okay for metal, but not for wood and composites, even with the so-called "averaging" factors. We will not discuss further here, but the serious student may want a comprehensive textbook for engineers - not technicians who do not have enough mathematical background. *(STRENGTH OF MATERIALS* by Timoshenko, is a recommended sourcebook - Timoshenko, *STRENGTH OF MATERIALS,* Part 1, 1955, "Elementary Theory and Problems", $24.95; Part 11, 1956, "Advanced Theory and Problems", $31.50. Available from Krueger Publishing Company, P.O. Box 9542, Melbourne, FL 32902-9542.)

You see, math formulas and computers are tools like, say, a planer. if you know how to set them, where and how to use them, you can do very well with them. But if you play the sorcerer's apprentice, it becomes dangerous for the tool, the operator and the material.

Figure 2



Columns 7 to 10: Columns 7 to 10 are values which allow the comparison of materials from a weight standpoint (the above referenced text by Timoshenko will also show you why we use those "funny" looking values).

Column 7 gives the *stiffness of a sandwich construction.* The higher the value, the stiffer the construction. From the Table, we see that metals are high wood comes close, but fiberglass is low: which means fiberglass will be heavier for the same stiffness.

Column 8 shows the *column buckling resistance* for the same geometric shapes. This time, wood is better than the light alloys, coming before steel and fiberglass. (Surprisingly, the usual welded steel tube fuselage is not very weight efficient.)

Column 9 gives the *plate buckling stiffness,* which is also a shear strength measure. Here again, wood (plywood) is in a very good position before aluminum and fiberglass, with steel not very good.

Column 10 provides a crude way of measuring the *strength to weight ratio* of materials because it does not take into account the various ways the material is used in "light structures". According to this primitive way of looking, unidirectional fibers are very good, followed by high strength (2024) aluminum and wood, then the more common aluminum alloys and finally steel.

From just this simple table, we find there is not one material that provides an overwhelming solution to all the factors that must be considered in designing a light aircraft. Each material has some advantage somewhere. The designer's choice (no preconceived idea) will make a good aircraft structure ... if the choice is good!

This article is presented as part of a series, where aeronautical engineer Chris Heintz discusses the technical aspects of his light aircraft designs in laymen terms.