AN INTRODUCTION TO STRUCTURES DESIGN FOR MODEL AIRCRAFT

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by

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INTRODUCTION

Some time back I gave a presentation at our MMM Club Annual Meeting "Symposium" discussing structural design techniques. At that time I had some little visual models of frames covered with tissue, an open tube, a closed tube, and a handout comparing different design solutions and their relative effectiveness.

This discussion is an attempt to verbalize that presentation relative to today's approaches for model aircraft, particularly higher technology approaches. It is appropriate to discuss the "why" of structural design with showing the various loading conditions and forces that our model airplanes have to endure. The load conditions experienced by models is not much different than real aircraft although we subject model aircraft to some unique loading conditions like popping the stabilizer (DT) during glide and "sometimes" under power. In addition, we crunch our ships into the ground more than we care to by DT or other circumstances and hope they survive.

But, first I would like to talk some fundamentals.

LOADS

We design aircraft to fly. For an aircraft to fly it must take advantage of aerodynamic forces and other loading conditions. For reference, loading conditions are described in the manner which they are applied. Generally, two classifications are used 1) Static Loads, and 2) Dynamic Loads. For explanation, each is further subdivided. Static Loads are comprised of continuous loads, slowly applied loads, and slowly applied repeated loads. Dynamic Loads are defined as impact or rapidly applied loads (shock) or repeated impact loads. If you think about it you can describe each of these in what you observe when flying your model.

We have heard of lift and drag, the two most common aerodynamic forces, but what are they? The force of moving air on a solid body is referred to as aerodynamic force. It has been discovered that certain body shapes in moving air produce unique air pressure distributions on the body. These pressure distributions result in certain forces which act on the body. If the body wants to be pushed a certain direction, say up, we call it lift, back, we call it drag. Airplanes use different shape configurations to produce desired resultant forces of lift and drag to produce and enhance flight. For example, we have an aerodynamic shape for wings called an airfoil.

An airfoil is a shape that tries to produce maximum lift force and minimum drag force. Fuselages usually have small cross sections and are shaped to reduce drag. The combined distribution of all these forces on the total airplane are called "loads."

An airfoil section, as stated, provides for certain lift and drag forces relative to the airspeed across it and its angle of attack. The magnitude of these forces is dependent upon the flying speed of the aircraft. The forces across the total wing span produces what we call a "loading condition."

For most conditions, wing loads are uniform and distributed equally across the span. If the lift is described as 1 pound per inch along a 10 inch span, then the total load is 1x10 = 10 pounds uniformly distributed, or a uniform load of 1 pound per inch. Either is acceptable. Loading conditions produce applied loads to the physical airplane. Another applied load is *shock*. Shock loads are the result of sudden conditions that act on the aircraft. Shock loads are expressed in terms of "g's," or "number of times gravity." If a structure supports a weight 1 pound subjected to 5 g's, it reacts a load of 5 pounds.

SHEARS, MOMENTS, AND COUPLES

To adequately describe a force you need to know its magnitude and direction. A simple force is sometimes described as a *shear*. Shear forces are singular forces acting in a direction and are sometimes said to be *shear loads*. The two nomenclatures are sometimes used interchangeably, but they could have unique definitions, depending on who's talking. Shear forces are typically applied at a single point or have a single line of action.

A *moment* is the result of applying loads such to cause bending. For lack of a better description a moment is the value of a force multiplied times a distance. A 150 pound man standing on the end of a 10 foot long diving board develops a moment at the root of the diving board of 10'x150#=1500 foot pounds. There is still a moment distribution in the total length of the diving board, but the greatest magnitude of the moment is at the root and the value drops off to zero at the end. If you look at formulas for calculating bending moments, you will see this is consistent for most moments in beams. You cannot have a moment on a free or unrestrained end. This is good for wing builders because it implies that the greatest strength is required at the root of the wing and theoretically the structural strength could be zero at the tip.

Another type of moment is described as a *couple*. It has its own usage and implies that two forces act to produce moment or twist. If shear forces act such that they are not in plane or in line with structural members or their joints, they also produce what we call couples. Couples are best understood if you think of them as the results of forces or shears that act such to want to bend or twist something. Prying loose a nailed down board is done with a couple by using a pry bar. The couple is on the foot of the bar causing a moment in the bar. If you have a "T" handle wrench and twist a socket head screw, you are applying a twist, or couple on the screw. In this example a couple is applied as opposing forces on each handle end. This is a torsional couple.

To simply summarize, shears are forces and moments want to bend things. Bending moments are referred to as just "moments", and torsional moments are called "torques." These above definitions of shears and moments are fundamental when describing loading conditions. We design structures to react these loading conditions.

STRESS, FORCE, STRENGTH, AND STIFFNESS

Many people confuse stress and force. *Force is force*, like weight, and *stress is force per unit area*. This is true whether talking tensile, compressive, or shear stresses and forces. Each of which will be discussed later.

The *strength* of a material is usually measured in its tensile or compressive strength. However, there are distinctions to be made. When we measure the strength of a material, many tests are run and many results are discovered.

If a material permanently deforms over a range of values, we usually call the least strong value the minimum "Yield Strength." Because there are many variables in the consistency of a material, we reduce the yield strength by a factor and call that the "Allowable Strength." In addition, there is defined an "Ultimate Strength" which is the ultimate strength of a material before it breaks (Note: like stretching a rubber band until it breaks). Again this value is subject to testing and perhaps a factor. If structural design is based upon the allowable strength, we can be generally assured that the structure will carry the forces or loads applied to it.

Another value we sometimes use is the "Modulus of Elasticity" or *modulus*. There are many "moduli." There is a different value for tension, shear, rigidity, tangent, and compression moduli but we mostly talk about tension. The simplest way do describe the modulus is to say that materials behave like springs, and the modulus is the spring rate. For example, if a spring has a rate of 1 pound per inch, it implies that if we pull on that spring with 2 pounds it would stretch 2 inches

The modulus is in written terms of stress values "pounds per square inch," but stress is proportional to strain (stretch) and is analogous to a spring rate. The *higher* the modulus, usually the *stiffer* the material. Keep this in mind when reading about some of the new structural materials being used in model airplane structures. We can combine stiffer or softer materials to create stiffer or more flexible design solutions in our models. For example, we tie our wings down with rubber bands to provide a soft method of mounting to prevent breakage of wings during crashes. In addition, we may find that making certain parts stiffer or softer may actually enhance the overall airplane performance.

The strength of a material is a characteristic of the material. If a material has a specified allowable strength, say 1 pound per square inch (psi), then it is suitable for a 1 psi application

Tensile strength is directly proportional to a structural member's cross sectional area. For example, if I hang a 1 pound weight on a 1 square inch uniform cross section bar, it develops a stress of 1 psi.. If the calculated loads develop a higher stress in a structural member, we can either substitute a stronger material or increase the area of the member until the stress is lowered to the material allowable.

Tensile stresses are easy to understand and deal with. However, with compressive and shear stresses, this is not so straight forward. Compressive stresses are those developed by pushing on a member and shear stresses by applying forces across a member (Note: In subjecting a beam to bending, the top of the beam is usually in compression and the lower part of the beam is in tension. This corresponds to the upper part of the beam being the inner or smaller curve as you bend it and the bottom the outer or larger curve as you bend it).

By this statement it would seem that compressive stresses act just like tensile stresses only in the opposite direction. Indeed they do, however, in compression the *allowable* stresses vary with *geometry*. If a short compact section like a post is pushed on it does develop a force/area computed stress. It also has a high *allowable* stress, perhaps much higher than its allowable tensile stress. But if the post is much longer, it has stability problems. Its computed force/area stress may be the same, but its *allowable* stress is usually reduced. You have to consider its length and geometrical cross section. This relationship is referred to as the slenderness of a member and is an additional factor used to determine the allowable compressive stress. The easiest way to understand this is to push a short piece of rope. As you try to push a longer and longer piece, there is a point where the rope just buckles. The same thing is true for most all structural compression members. We can generally say that it's easier to push a short rope than a longer one and for a given length, a fatter one can be pushed harder that a skinny one before it buckles. In our case, the airplane wing, typically the upper wing spars are our compression members. Their length, the rib spacing, and their cross section, usually square, are the parameters.

When dealing with compressive stresses in a panel, geometry again plays a role, only in this case the panel slenderness can be related to the thickness of the panel to its length. Imagine pushing a bed sheet. It wants to buckle very quickly. If you add a coat of paint to it gets stiffer and you can push on it harder before it buckles. If you change its geometry by curving it and push on it (like crushing a pop can), its buckling strength is increased even more. Change the material to one with a higher modulus and you have again increased its buckling strength for the same geometry. In like manner, its allowable stress is increased and the more load it can support.

DEMONSTRATION OF CONCEPT

To demonstrate, support your favorite wing by the wing tips using two piles of books or whatever so the center panel is off the ground. Slowly push down on the center of the wing until the top covering goes slack, you are now subjecting your wing to bending. Notice what is happening. The upper covering is under compression and since it does not have too much capacity to resist the compression forces, it buckles, or goes limp. Conversely, on the underside, the covering is being stretched. Covering develops its strength capability much better in tension and it shows this by getting taut.

Shear stresses do indeed calculate similar to tensile forces (force/area), but the allowable shear stress is usually lower than the pure tensile allowable stress for a given material. Pure shear force is similar to cutting across a material like a knife, it wants to shear off the material. When a skin is used to cover an open area we subject it to "panel" shear. Panels are usually thin relative to their length and width. In addition, panels are loaded such to stretch or push on the panel by applying forces to their edges. Wing and fuselage skins are examples. Panel shear can be demonstrated by holding your hand (panel), palm down, fingers together. With your other hand, grab your finger tips and push them back and forth. The friction between your fingers is analogous to the shear forces developed in the panel. Again, the shear stress is the relationship of that shear force to the thickness and length of the panel and there is an associated *allowable* shear stress for any given material.

There is another nifty thing that a skin panel does for the strength. Typical model airplane structures are considered frames with covering. When they distort from external forces, each of the different structural components pick up loads. If our wing was a true frame with no covering and were twisted, it would keep twisting until the structural strength resisted any further distortion. If the wing were "stiff" enough, no covering would be needed except to add to the aerodynamic shape. But, since wing structures are not infinitely stiff and do deform somewhat, the covering, if it is attached to the surrounding structural members, does indeed react loads. I mentioned before about skin tension, but there is another very beneficial load resisting case: Diagonal or field tension.

When we twist our favorite wing, we notice that wrinkles can form in the covering and they are diagonal across the wing. The covering is acting in tension in the direction of the wrinkles and are not resisting any compression loads across the wrinkles. We know this because the wrinkles show that the covering buckled, hence lost it's load carrying capability. We could use diagonal braces between the wings ribs, but since they add weight why not use the covering to do the same job?

Now we have developed a way to have the covering (skin) of our models add to the structural strength. If we want to have light structure we can utilize the frame/skin covering to be included as part of the design. The trick is to balance the strengths of each of the components to not unduly require one of them to be stronger than they are and subsequently fail.

As you can see, there is a definite trade off when using panels or additional ribs to resist shear and compression loads.

DESIGN EVOLUTION

Conventional design, years ago, was "stringer / truss / frame." This was used for both the fuselages and wings. In the wings, the frame was the wing rib and the spars were the stringers. In the fuselages, there were usually enough stringers and frames in the assembly that all of the structural loads were reacted in the stringer / truss / frame system. Torsional and bending loads were usually not a problem due to the large cross sections inherent to such designs. The coverings on the fuselages did add some torsional restraint, but I suspect that their biggest contribution was to keep the air out and reduce parasitic drag. Also, the truss designs, complexity of the structures, and the number of parts was at a maximum.

With the increase in performance of engines it was just a matter of time for airplanes to increase their speed and hence the forces on them. The evolution was to use as much of the structure as efficiently as one could. A first step was the *monocoque* structure. A pure monocoque structure is like a tube with no other members. However, this is not usually practical because of joints, stiffeners, and other things that are added so we use the term “semi” monocoque, A semi-monocoque structure is one where one considers the whole cross section as adding to the strength, including the stringers, frames, and skin. As mentioned, the skin had been used mostly to keep the air out of the fuselage and reduce parasitic drag, now it is needed to add strength. A discovery was that if the skin was made stiffer it indeed added to the effective strength. Paint and fabric did a great job reacting panel shear forces, but it left a bit to be desired. It wasn’t much later that sheeted fuselages replaced fabric coverings. The availability of better quality sheet material probably had something to do with it. Aluminum skin, especially if it had curvature, reacted compressive loads quite well and soon replaced fabrics. Your basic soda pop can will demonstrate that nicely. In addition, if the skin was continuous all around the section, it resisted twisting nicely too, at least up until the skin buckled and collapsed. Twisting a pop can shows that also.

For wings, bending due to the forces of the air and landings required something a bit more applicable. It didn’t take long to realize that a wing acted more like a big beam and therefore a big beam was added to the wing as main spar and a primary structural member. And, if we wanted all of our wing to act as a semi-monocoque structure, the covering had to react compressive forces realized from bending. The large wing surface area dealt with things like wing loading, and its cross section (airfoil) dealt with lift, provided you could keep the whole plane moving through the air. Fortunately, the wing had a reasonably large enough cross section and depth which added to the effective beam strength.

Early wing designs relied on holding it all together with external bracing, trusses, and struts. The aircraft industry eventually progressed to using the wing as a big free hanging beam with not very much external bracing. It was designed such to be an integrated homogeneous structure. However, our model airplane model wings lagged a bit behind. We had spars and tissue paper which worked quite well, except for those stalwarts who used sheeted wings, but they were *heavy*! Sheeting worked well for large wings, but think about it. The cross section of a 1/32” sheeted wing with a 3” chord is much more balsa per square inch than a 1/32” sheeted wing with a 10” chord. We were destined for improvement.

FORCES, OR LOADS, ON THE WING

Since the wing of an airplane carries the major portion of the forces, it seems natural that we talk mostly about its design. For example, in maintaining level flight the vertical force, lift, approximately equals the weight of the airplane. The wing also sees large dynamic loads when reacting the stabilizer popping at DT and when the plane hits the ground (at one time I calculated that the wing could see up to 20 g’s at the wing root when it hits the ground, depending on whether it had a wire skid and it landed on grass or concrete).

We use the term *airfoil* to describe the cross sectional shape of the wing. For any given airfoil, there is an associated lift and drag force for specific air velocities and angle of attack. Free flight models usually fly at very low angles of attack relative to their thrust center lines or at least their angles of attack are fixed relative to their motors thrust lines (except for excessive down thrust, etc.).

The various lift and drag values for an airfoil are influenced by many factors such as its general shape, its thickness to chord (width), and the relative curvature (camber) for the top and bottom surfaces. The values of the lift and drag forces most always have to be determined by wind tunnel testing. In any event, we model builders do not usually do this and are great copy cats on successful designs. Fortunately this has been a good approach for many years and there are some good experimenters out there to copy.

In airplane wings we talk about the *aerodynamic center*. Since an airplane flies at various angles of attack, the pressure distribution changes across the top and the bottom of the airfoil. As this distribution changes, the resultant force varies on the wing and tends to form a wing moment, or twist, about the cross section of the wing due to the shifting of the resultant force. There are also the associated lift and drag forces. It so happens that there is one point that the moment due to the lift and drag forces is constant for any given angle of attack. This point is called the *aerodynamic center*. What it describes is a location where the resultant forces on the wing can be replaced by a lift and a drag force and associated wing moment. Its approximate location is about 25% of the chord aft of the leading edge.

This really does not affect the typical model airplane builder because of the low speeds we fly at and the fact that the average guy out there building does not consider it a problem. However, as the speeds increase ala F1C, things happen. That little thing we ignored called wing moment just got to be something to contend with. It is not a very steady thing. Small twists in the wing change the magnitude of the wing moment. Reversal of pressures as the wing twists back and forth causes radical shifting in the wing moment too. Your wing acts like a torsion spring and wants to rotate back and forth. As this wiggle exaggerates itself, the wing structure could be in jeopardy. Hence, a "stiffer" wing is required to keep the dynamic effects of this wing moment small.

As our model airplanes started getting faster and the plan forms more efficient, the loading conditions changed too. Faster airplanes start generating all sorts of peculiar effects on them. For example, the faster airflow may generate more turbulence over the wing and hence the erratic air forces are greater. As the speed increases the lift and torsional forces increase with the square of the speed! For example, at 10 mph the forces are on the order of 10x10=100. At 15 mph the forces are on the order of 225, or 2.25 times! All of this for just a 50% increase in speed.

Now considering that lift and drag are proportional to the *square* of the speed, imagine how our conventional stringer frame wings are becoming obsolete, especially in our higher technical design environment. Conventional airframes are constantly needing "beefing up" from their original design, especially when we hang that new "Belchfire .15" on the front end. Steve McLellon's Satellite 450 has gone through numerous wing beef-ups in it's short lifetime.

The first evolutionary impact to model airplane structures was multiple-spar wings, and then to add shear webs between top and bottom spars in a wing. This made the main wing spar/beaming system more efficient and acting like a real flanged beam. This was a first good step because the primary rule of bending is that all plane sections remain plane, in other words, do not deform too much. The web aided in that. You may not know it but as your wing was up there flying on your airplane, all of the little parts were constantly warping around. If they warped enough to allow out of plane loads and stresses that were beyond their strength they failed. Ever seen a wing fold under power? Remember my comments on compression buckling? Your wing spars were like that. Spars, like beams can fail either from high bending stresses or collapse from high compressive stresses.

In addition, a typical wing with polyhedral has a tendency to twist because of the forces applied to the tips. Look at it this way. The wing is held down at the root. The tips are above the root and the wing drag forces are applied above the root. This causes a wing twist to be applied. As the speed of the wing increases the more it wants to twist until it either resists the forces and springs back or it just rips off. If it springs back repeatedly under flight it looks like flutter. As mentioned, stiffer wings resist twisting better, but stiffer wings also have higher structural frequencies. This can be envisioned by considering a tuning fork. The stiffer the tines on a tuning fork the higher the pitch or frequency. The same is true for structures. The stiffer the structure the higher the structural frequency.

In like manner, little vortices are generated on the wing at a certain aerodynamic frequency for a given airfoil, air densities, aircraft speed, and some other factors. If the two frequencies, structural and aerodynamic, are about the same value during flight all sorts of fun things happen. Ever watched an airplane shake itself apart? Scenes such as this are becoming more evident as thinner higher aspect ratio wings are being used on faster higher performance airplanes like F1C, F1B, AMA Gas, and some Catapult launched gliders. I have even witnessed the effect on a towline glider during zoom launching. It would seem then that we want to make higher performance airplanes structurally stiffer.

DEMONSTRATION OF TORSIONAL STIFFNESS AND TWISTING

To demonstrate torsional loads, stiffness, and twisting, get in your car and drive down the freeway. At about 55 mph, roll down the window and put your left arm straight out, hand straight and palm down. Raise your fingertips by bending your hand at the wrist. Slowly roll your arm forward and back so your hand is waving to people in the oncoming lane. Feel the torsional forces on your upper arm? Your inner wing panel is feeling them too. As the wind tries to push your hand back, you resist it with your muscles. As you roll your arm back and forth you are acting like your wing.

Drive back home and get out your favorite wing and try to recreate the effect. You can do this by holding your wing down on a table, at the center, and twisting the wing tip. Notice how the covering buckles? It forms wrinkles in the tissue. The direction of the wrinkles indicates where the covering is picking up tension load. Across the wrinkles is compression load, hence the wrinkles to indicate buckling, and therefore not resisting any compression load. The stiffer, torsionally, your wing is the less you will be able to twist it.

Now if you really want to get nervous, here's how to demonstrate your wings torsional stiffness or "springiness." As your wing is subjected to forward motion in its high speed climb, it wants to twist back similar to your hand out the car window. As its elastic limit is reached it "springs back," torsionally, and sort of pops! For your demonstration, hold the center of the wing down again and twist just as above, but instead of holding it, let go! Now twist it the other way and let go. If you can do this fast enough, you will demonstrate what your wing is doing in the climb, chattering back and forth. The softer, torsionally, it is the more pronounced the chatter as the airplanes speed increases. This is sometimes interpreted as *flutter* alone, however, flutter results from a combination of aerodynamic forces, torsional stiffness, and inertial properties of the wing.

FLUTTER

Flutter is a most peculiar phenomenon of aircraft. One could spend a long time understanding flutter. At the least, flutter is a dynamic effect. It is a combination of the resultant aerodynamic forces on a wing, its relative torsional stiffness, and its inertial properties (or mass distribution). OK, so I used some big words. A little simpler way of putting it is we know that the air forces are continually changing as a plane flies, therefore tending to shake and twist the wing. And, since we do not tend to make solid wings for weight considerations, wings are flexible. We want them to be more stiff. However, a wings mass distribution is a big consideration. Mass distribution effects can be demonstrated by using a broom. Hold the handle and see how easy it is to rotate the broom by twisting it. Now rotate the broom by swinging it like a baseball bat. It has larger rotational inertia as a bat.

Well, "things" have shown that if the center of mass of a wing is forward of the center of pressure the tendency to flutter, from an aerodynamic force standpoint, is apparently reduced. Also, as the rotational stiffness of the wing is increased the tendency to flutter is apparently reduced even further. What is really happening is the tendency to *flutter is not reduced but the speed at which flutter occurs is increased*. The faster our airplanes fly, the more tendency to flutter if we do not upgrade the wing structure.

This would imply that our *wings should be built "forward heavy" and infinitely stiff in torsion so build them that way.*

A simple statement to make, isn't it. But at least if you understand that in slower airplanes, conventional structure and doped coverings seem to satisfy all of the load carrying requirements. As the speed of our airplanes increase (along with higher aspect ratios) the need for more torsionally stiff structures dominates.

For our purpose, how do we increase the inertia and torsional stiffness of our wings? Well, put most of the structure up front.

APPLICATIONS: STRUCTURAL SYSTEMS

Lest you be totally frustrated with how you design and build your next airplane, I'll try to show some representative approaches and what they each buy for you.

There are some basic structural designs that all have their application for our use and I will try to explain each of their benefits and application. However, since this wants to be addressed to the lay person, some heavy technical stuff will be omitted in favor of showing guidelines for design. Where analysis results are shown do not worry about the details too much, but rather the implications.

Previously mentioned was the concept that all plane sections remain plane. Unless their is extreme distortion in the structure, which would cause catastrophic failure anyway, we can assume that all of our designs will follow this guideline. In addition, I hope to present what I would call a design guidelines for the conventional outdoor competition models flying under normal circumstances. Scale, indoor, solid models, etc. are their own thing and different parameters apply.

We strive for the lightest and strongest structures that will carry the loads. We can either use a strong structure with weak covering, or try to maximize the strength of the airplane by having all of the components work to take load. Again, strength to weight is the issue. For open designed structures of today, and I mean typical structures that have polyester or tissue wings, the best approach is to utilize design techniques that use the structure for most of the stiffness and let the coverings be a freebee for any additional benefit. This would allow us to use the lightest covering combinations available. For higher technical designs like F1C and peculiarly high aspect ratio designs, try to design a composite type structure using all of the new material resources and techniques we can.

The goal is we want our structures to have the following characteristics:

- Adequate strength
- Adequate bending capability
- Adequate torsional stiffness
- Light weight

STRUCTURAL SYSTEMS

There are some basic structural systems to consider in design and construction. They are:

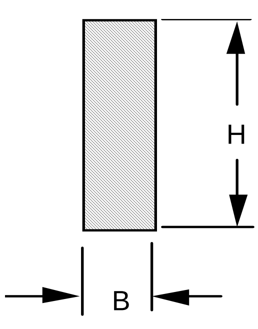
- Beams
- Frames and Trusses
- Cells, Closed and Open
- Composites

BEAMS

A beam is the basic structural member. It's primary use is to resist bending loads. Beams can be solid rectangles, trusses (diagonally braced frames), or any other shape which efficiently reacts bending loads. The two most familiar beams are solid rectangles and flanged shapes. Both are useful, but for equivalent bending strength, the solid rectangle is usually heavier. Flanged shapes need not have a web connecting the top and bottom flanges to be considered a beam (as in the case of trusses), but for a given application, the top and bottom flanges must be stable enough to allow their plane section to remain plane (not deform) when subjected to loading.

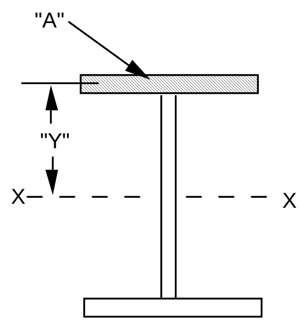
Beam bending strength is measured by comparison of it's "Moment of Inertia." Moment of inertia has no physical significance, but is a term which is used in many engineering calculations. To best understand it, it is a characteristic of a cross section (like that of a beam) which indicates the moments of areas, volumes, or masses relative to a reference axis or plane. For cross sectional areas, it represents the influence of area itself when applying uniformly varying forces over it, like a bending moment. It is calculated by summing moments about an axis and usually has a specific formula for regular symmetrical shapes.

For example, the formula for the moment of inertia for a rectangular section is $I=BH^3/12$, where B=width and H= height of the section. For other sections, cylinders, ovals, triangles, etc., there are either formulas or other analytical procedures.



SIMPLE BEAM

Similarly, the formula for computing moment of inertia for a flanged bead uses the effective area of the flanges ("A") times the square of the distance ("y") from the section center of area (X-X axis). It's not quite that simple, but this explanation suffices for our understanding.



FLANGED BEAM

For strength comparisons, I analyzed a typical model airplane wing main spar configuration for a 1/2" deep wing section. As a baseline, Case 1 is a solid rectangle 3/16" x 3/8". Case 2 is two 3/16" square spars (beam flanges), one top and one bottom. Case 3 is a top and bottom spar arrangement of similar area to case 2, but each spar is 1/16" x 9/16" laid flat. Case 4 was added with top and bottom spars same as Case 3 but using a 5/8" deep section.

All of these numbers are fine, but what does it show? For one thing, all of the sections used the same cross section area for the spars, or, each of the sections had the same weight. Another result is that you get a stronger beam using top and bottom flanges instead of single beam type spars. But, the most outstanding feature says that the spars, or flanges, should be *as far apart as possible!* Case 3 offers double the moment of inertia over case 2 just by reconfiguring the spar geometry to a flat top and bottom flange. This should come as no surprise if you have ever paid attention to steel buildings being erected. There is an additional feature we can use for model airplanes which I will discuss later when talking about torsion.

The following table compares the results:

CASE	CONFIGURATION	MOMENT OF INERTIA (in^4)	STRENGTH INCREASE
1	(1) 3/16" x 3/8"	.00082397	BASELINE
2	(2) 3/16" SPARS	.00203423	146.8 %
3	(2) 1/6" x 9/16"	.00337593	309.7 %
4	CASE 3 @ 5/8" H	.00508716	506.00 %

FRAMES AND TRUSSES:

A simple open *frame* is exactly that, simple. It is like a picture frame and only has sides.

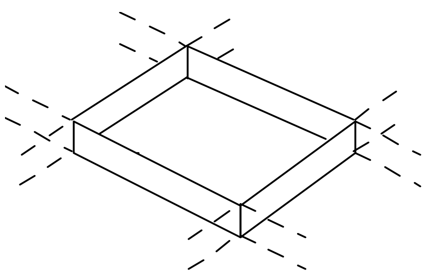


FIGURE 1
SIMPLE FRAME

A basic wing structure of ribs, main spar, with a leading and trailing edge is a simple open frame. It is just made sticks as far as structural analysis is concerned. If we bend or twist it, it offers very little resistance. As soon as we give it's members some cross section size, it then starts resisting the bending and twisting. We select member shapes and cross sections as we perceive their load carrying responsibility. It seems logical to use a deep spar as a beam to carry the wing bending loads and the leading and trailing edges to give the wing section shape and to attach the covering to. But, are we aware of their contribution to the wing structure? The main spar contribution to bending strength seems obvious, but the leading and trailing edges add strength also, even if minimally. They also add to the torsional strength of the wing as we shall discuss further on.

A frame is converted to a *truss* by adding diagonal members. The diagonal members greatly add to the strength of the structure by giving a more efficient load path to react diagonal forces. In addition, trusses attempt to develop efficiency by utilizing the outer frame members as primary load carrying members and eliminating bending or prying loads at the joints. In the case of a model airplane structure, the glue joint is not very good when pried upon. A diagonal member intersecting at a joint attempts to eliminate bending on that joint.

If we add covering to a frame we increase it's ability to resist forces. This converts our simple frame to a *closed frame*. We then are using the covering or skin as part of the load carrying system. There is a special term used for the covering across a frame called *shear panel*.

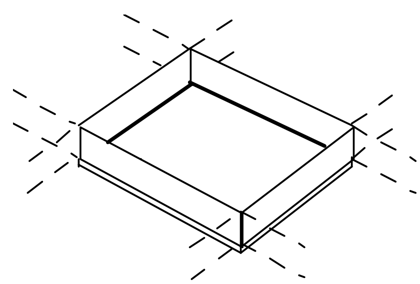


FIGURE 2
FRAME WITH PANEL

Simple flanged beams have the flanges connected by a web between them. This web is sometimes referred to as a shear panel. In the sense of a beam versus a truss, if the flanges are very far apart relative to the beam span, a truss configuration may be more desirable. If the flanges are closely spaced relative to their span, a web may react the shear and diagonal forces better but the tradeoff as to efficiency has to be considered. In some cases, say in a large shear panel, the weight of the panel may be more that an equivalent load carrying diagonal member. Aspect ratio is another consideration. A rather long and narrow frame would be more likely to benefit from a shear panel than a diagonal member.

CELLS

Cells are special application closed frames, like boxes. The theory in their structural ability is that all sides and edges react loads efficiently in shear. A pure cell would only require the thickness of its sides and their edge connections to be considered. For example, the smaller the cell, the thinner the sides need to be for a given loading condition. Cells also assume that they are loaded at their edges and not in the center of their sides. Cells can be either box or tube like. A simple open cell is a frame with only four walls, like four playing cards taped at their ends. With no top or bottom attached it has very little strength except in the plane direction of the sides. When a top and bottom are added, it's box strength is substantial. Try this with a shoe box. Take the cover off and twist it about. Now put the cover on, tape it around the edges and try to twist it. You will see that the torsional strength is greatly increased. The closing feature of taping the lid has added a *shear transfer mechanism*. In other words, shear loads are transferred to all of the sides to cause the box to act efficiently. It is conventionally described as a "Torque Box."

A torque box is a fundamental structural design system in all full sized aircraft. It is used in creating efficient light structure for wings. It expands on the monocoque design of fuselages and is adapted to wings because the wing is thin relative to it's chord. A conventional monocoque design still works for wings, but wing geometries and practical structural features lean to a torque box being a better approach. Keep in mind that the monocoque wing does act like a beam but the fact that we add ribs at intermediate points creates small consecutive cell sections when utilizing the covering. The structural efficiency comes when these consecutive stacked cells form a long torque box. However, each individual cell is subject to all of the structural considerations like buckling, etc., and that must not be overlooked.

Similarly, a tube is a cell. Because of it's geometry it does not need closed ends to resist forces. By it's definition it is closed on it's circumference but closing the ends really stiffens it. If the tube is not continuous along it's length, say it has a slot down it's length, it offers no more strength that a curved panel. As soon as it is continuous (no slot), it is a wonderfully efficient tension / compression / torsion member. It's primary use is to resist torsion and it is very efficient in that application. As a compression member, a tube is better when symmetrically loaded than most other shapes because of it's regular and symmetrical geometry.

To show this compare the formulas for relative torsional stiffness for a closed and an open tube. There is a value called the polar moment of inertia which defines the relative torsional stiffness of a section and is represented as "J."

For a *closed* tube the formula for "J" is:

$$J_c=\pi/2(R_o^4- R_i^4)$$

where

π=pi (3.1416),

R_i^4 = Inside radius of the tube,

R_o^4 = Outside radius of the tube.

For an *open* (slotted) tube "J" is:

$$J_o=\pi Dt^3/3$$

where

D=Average tube diameter,
t = tube thickness.

For a 1 inch inside diameter tube with 1/16 inch wall (like a P-30 fuselage),

$$J_c = 0.059082$$
$$J_o = 0.000264$$

Comparing the two relative torsional stiffnesses, the closed tube is $J_c / J_o = 224$ times as torsionally stiff ! It is not necessary to know the analytical details, but to understand the concept: *Closed cell sections are usually stiffer and more structurally efficient than open cell sections.*

In recent years there has been an enormous amount of print dealing with the new concept of a "D" box for model airplanes. Well, in reality, we have been using a concept of a "D" box or "Torque Box." We glued ribs in our wing making little cell boxes all along. Even older designs with ribs and stringers were closed tube by virtue of the covering system, although the whole wing section was considered and not just a portion like a "D" box. As times progressed the older design systems were not adequate for the newer planforms and higher loading conditions. It wasn't very long that stiffer closed cell sections came into being, only now described as the "D" box. This suits our wing structures quite nicely too.

Since we want most of the structural mass to be forward why not utilize the "D" box to do this? We can add most of our torsional and beaming structure up front this way. And, you can build in all of your wash in and wash out features as you construct it but be careful, when you close out the "D box with the aft vertical shear web, you are going to live with the result. Also, if you do not close out the "D" box with the aft shear web you just have an open cell. Jig your structures as you build them, because the wash in / wash out will be permanent!

See **Table A** for relative design configuration stiffnesses. Included are frames analogous to diagonal wing rib configurations.

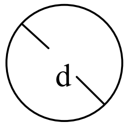
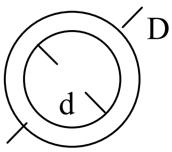
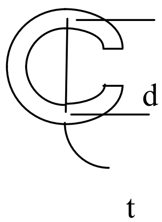
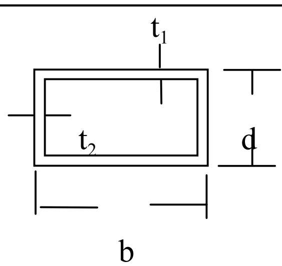
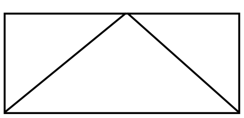
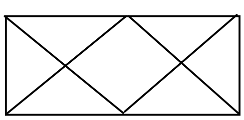
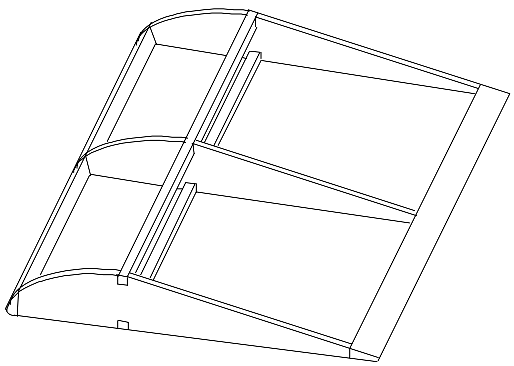
Section	**"K" = Torsional Resistance**	**"K"**	**"K"/Area (for similar comparison**
	$K = .0982\ d^4$	for d=1 Area=.7854 K=.0982	**.125**
	$\text{"K"} = .0982(D^4 - d^4)$	for D=1 d=.0875 (tw=.062) K=.0393	**.2086**
	$\text{"K"} = 1.0472\ t^3 d$	d=average dia for d=1 t=.062 K=.0023	**.0122**
	$\text{"K"} = \dfrac{2t_1t_2(b-t_2)^2(d-t_1)^2}{b\,t_2 + d\,t_1 - t_2^2 - t_1^2}$	For 1"x1" $t_1 = t_2 = .062$ t_1=same for top &bottom t_2=same for sides K=.049	**.2042**
 Vertical Diagonal Bracing	"K"=3.54 "I" where "I" = Inertia of Diagonal Brace	for 1/16" x 3/8" members I=.000275 in4 K=.0011	
	$I = bh^3/3$ where b=web thickness and	for 1/16" x 3/8" members I=.000275 in4	Approximately a 36% increase in torsional stiffnes for a 32% increase

TABLE A - COMPARISON CHART OF RELATIVE DESIGN STIFFNESS

TORSIONALLY RESISTANT OPEN STRUCTURES

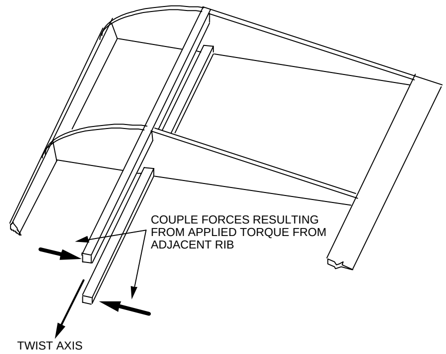
Use of the "D" box seems to be the way to go for all models, but it is not necessary for lower performance ones. There is another way to resist torsion in a wing. The old conventional spar / stringer, and even the multi spar system. For this discussion, let's not consider the covering acting as part of the load carrying system and look only at the bare structure.



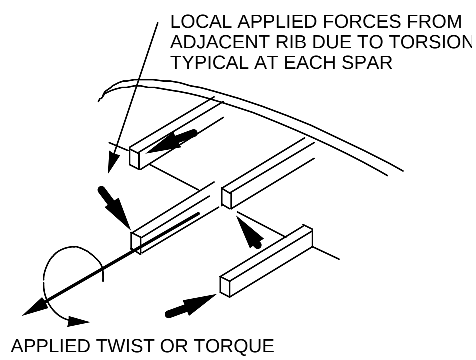
As a beam section, the multi spar system adds to the effective flanged areas of the beam and makes it a better moment carrying structure. But by adding those additional spars, spaced appropriately, we get an additional benefit, torsional resistance. A multi-spar system does not offer the same efficiency and strength as a closed cell system, but that kind of strength is not required for most models either.

Let's take a two spar system with top and bottom spars in a wing (not considering the leading and trailing edges).

Say there are wing ribs evenly spaced at 2 inches and there is no leading or trailing edge, yet. If we apply a torsional couple on the section by means of the wing rib, equivalently, two forces of equal and opposite direction (torque divided by 2) are each applied to the top and bottom spars, respectively. There is a force times distance moment acting on each of these spars. The top and bottom spars resist that couple like two 2 inch long diving boards, only one force acts left and one force acts right. The spar's resistance to the bending is directly proportional to it's moment of inertia in the direction of the force. For a given spar area it may suggest that a *flat, wider* spar is more efficient.



In the above case I used two spars. If I were to use four spars and space them such that they are in an equivalently spaced square pattern, each of the spars would resist a force of the torque divided by 4. The diving board analogy would still be considered, however, the force is 1/2 the value used when there were only two spars, the computed moment is reduced, and the relative twist is less. What this means is that for a spar of equivalent moment of inertial, a four spar system has more torsional resistance than a two spar system. The following picture is to illustrate:



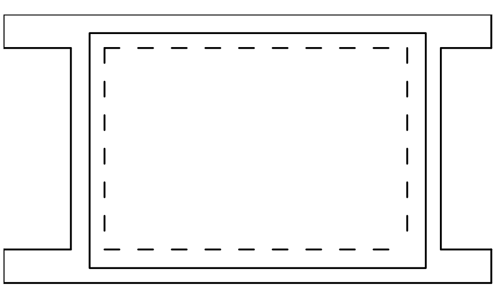
The actual forces applied to a multi spar system as a result of torsion is a function of the distance from the spar system's center of area. The value is a force times distance distribution with the spar farthest from the center of area seeing the lowest value and the spar closest to the center of area seeing the greatest. The direction of the force is perpendicular to the line connecting the center of area to the spar. Each force times distance value for each spar will be equal. For example, if one spar is two times as far from the center of area it will see a force of 1/2 the value of the closer spar. By this description we see that the leading and trailing edges contribute to the torsional stiffness too.

SHEAR WEBS AND DIFFERENTIAL BENDING

The concept of a shear web can be complicated if you get into the detail analysis. but just remember one single thing:

A shear web is a panel that covers a structural frame and resists loads in its plane. It reacts the shear loads resulting from the wing spars wanting to act like a beam. However, all of the edges must be continuously attached or glued to the surrounding structure and the panel must be of sufficient thickness to be of any value. By gluing it to the ribs it effectively makes the wing main beam a successive collection of "shorter" wing beams. If you remember, the magnitude of the bending moment in a wing falls off as you get to the wing tip so it seems apparent that the shear webs would only be required near the middle of the wing and not necessary near the tips.

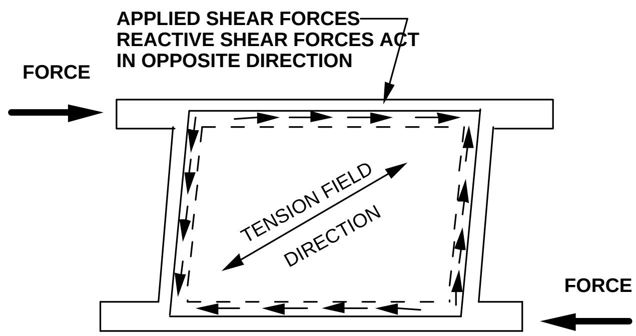
The picture below is a simple frame and shear panel arrangement.



FRAME WITH BASIC SHEAR PANEL

In model airplane wing design the first application of a shear web was to connect the top and bottom spars. This did two things, 1) It kept the top and bottom spars in plane to add to the effectiveness of their acting like a beam, and 2) It added a shear transfer mechanism to react bending loads completely utilizing the spars and ribs.

The following picture illustrates . The little "applied shear forces" are really the applied force acting across the length of the side. More correctly the terminology should be "shear flow" in terms of pounds per inch (Magnitude of the Force (lb) / length of side (in)). Shear stresses then are calculated using that term divided by the web thickness.

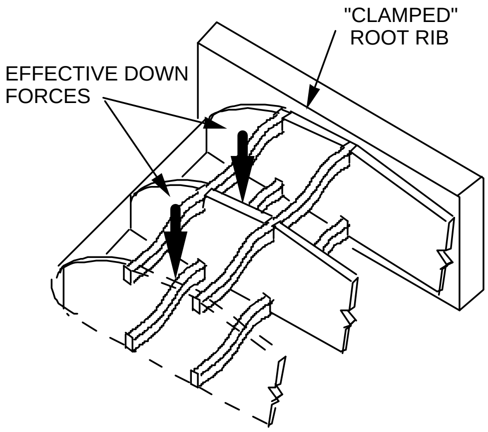


FRAME WITH SHEAR FORCES APPLIED SHOWING SHEAR FORCES ON PANEL AND TENSION FIELD REACTION

One question always comes up, Which way should the grain of the wood be, vertical or horizontal. I wish there were a straightforward answer but, it depends on the loading condition, the aspect ratio of the rib spacing vs. section depth (spar spacing), and thickness of the web.

For reference, usually the greatest shear strength of wood is across the grain rather than along the grain. Therefore if the web were of the optimal thickness, ignoring standard balsa sheet stock sizes, the grain wants to be across the member with the greatest shear flow. What did I just say?

I had hoped not to confuse you but the loading condition that dominates shear web grain direction is *differential bending*. Differential bending is best understood by using a picture.



If I were to apply a shock load to the wing like when hitting the ground an a Dethermalized (DT) landing, the wing would not want to bend uniformly. It distorts like little successive forces are applied to the beam at each wing rib. Partly because each wing rib acts like a clamp on the wing beam and partly because the wing "beam" structure is not uniform. The ribs interrupt it's continuity. The distortion pattern is "stepped" like in the above picture.

The shear force generated is reacted down the rib and wants to make the rectangular shear web a parallelogram. The distortion is resisted by the shear web not wanting to stretch beyond it's strength will allow. The force develops shear stresses in the web. If the shear web were homogeneous like aluminum it would develop a tension field, but since it has grain it has to resist these forces in it's own structure, i.e. along or across the grain.

Conveniently, to develop strength, all of the forces have to equalize, or balance, around the shear panel. I will make a lot of statements here but again, try not to get into the analytical details but grasp the concept.

Assuming that the shear panel will not break and is sized such to resist the shear forces, let's look at how it does. Well, lets say that I have a wing section that is 1 inch deep, my rib spacing is 2 inches, and I am using a 1/32 inch thick shear web.

If a vertical force, F_v, of 1 pound and acts down on one rib, a balancing force (resisting) of 1 pound must act up on the other rib. The resulting shear force on the vertical edge of the web is 1 pound across 1 inch. Coincidentally, the force along the top and bottom edges must be in balance and equal to 1 pound also (this is a show of faith). By the geometry, there are 2 inches of shear web to react the 1 pound force on the horizontal edges.

The shear stress (Force/Area) for each edge is computed as follows:

Vertical edges:

$$1 \text{ pound} / .032 \text{ in}^2 = 31.25 \text{ psi}$$

Top and bottom edges:

$$1 \text{ pound} / .064 \text{ in}^2 = 15.62 \text{ psi}$$

(Note: The area of the web reacting the shear force is it's thickness x it's length. For the vertical edges, 1/32 inch x 1 inches = .032 in^2, and in like manner 1/32 inch x 2 inch = .064 in^2 for the top and bottom.)

Now if my web material has a shear strength of 50 psi across the grain and 30 psi along the grain it would say that the grain should be horizontal. The grain direction should be that to resist the highest shear force. If the allowable shear stress was less that the computed shear stress, all one has to do is increase the panel thickness to reduce the shear stress, i.e. increase the shear area. Note: If the computed shear stresses were divided by 2 and their values were 15.62 and 7.81 psi respectively, and using the above material's lowest allowable shear stress of 30 psi minimum, it would not make any difference which direction the grain went.

COMPOSITES

When I talk about composites here I mean using two dissimilar materials to achieve a result. This needs to be clarified. In engineering circles, composites may imply carbon/graphite or glass/epoxy composite materials. In true definition, composites are "combinations" of materials used together. Since a carbon fiber system is extremely strong by itself, not much is needed, therefore, we typically only use what is required to reinforce conventional balsa structures. Most notably carbon is used in wing spars and on hand launch glider fuselages. I am not going to try to give you all of the engineering required to use composites but I will try to explain how they are beneficial when used.

Previously I discussed the term "modulus" when describing material characteristics. The modulus is a term to define the relative stiffness of a material and varies with material physical properties. For wood the value is all over the place and for homogeneous materials like metals it's value is relatively uniform.

When calculating moments of inertia and stresses in members, we can use a technique called "equivalent areas." Equivalent areas implies that a higher modulus material can be glued to a lower modulus material and their effective area for calculation purposes like calculating the moment of inertia, can be found through the ratio of their moduli (forgetting all local effects like glue, etc.). In other words, a material of modulus 10 is equal to 5 times the material cross section of material of modulus 2.

Aluminum has a tension modulus of about 10,000,000 psi and light weight balsa has a tension modulus of about 200,000 psi. This implies that aluminum is about 50 times as strong as balsa. In our application of using carbon fiber on model airplanes. the modulus of carbon fiber is about that of steel at 30,000,000 psi. What this means is carbon fiber is about 150 times as strong as balsa in tension! When used as a tension member a 1/8" wide x .005" thick (.000625 in^2) piece of carbon fiber is equal to .09375 in^2 of balsa (.000625 x 150). That is about a 5/16" square equivalent balsa member.

However, if I were to use just carbon fiber/epoxy alone as a structural material in building a model airplane, there may be a weight penalty. On the surface is would seem that composites are the way to go but composites weigh about 15-20 times that of balsa for equivalent volume. Hence, there is a tradeoff of a strength to weight issue for any specific structural application. If one has the time and money you could solve the problem, but leave that for the technical entrepreneurs.

Keep in mind that there is room for using fiber / epoxy composite systems exclusively in model aircraft, but there are things to consider. Even though weight is an issue, the biggest factor is cost. A good composite structure could cost about $1500 per pound, not including tooling and the autoclave to build it. But, as in everything, it really helps in specific applications. There is no doubt that fiber / epoxy systems can replace balsa / composite systems, but at this time the average builder is not up to it. In FAI there is a trend to buy "ready builts" and proceed from there and when it becomes cost effective the product will be there for the rest of us. The RC community already does this with pre-made parts. If you have a strong desire to build with composites, forget the politics, just buy the pre-made airplane and fly it better than the next guy.

CONCLUDING STATEMENTS

I hope that the discussion presented will help you understand what structural concepts will best serve your design needs and help you build better performing airplanes.

To understand what is the best structural design concept for a given model aircraft is to understand it's performance requirements. Does the airplane fly fast or slow, is the configuration short and stubby or long and thin, are you striving for optimum weight versus strength, are you trying to keep the design simple, is money no object? We could go on for a long time with these questions. For most of us these questions do not even pop up. We should strive to build what is easy, light, straight and true, and gives us the performance we want.

It takes some amount of experience to fully evaluate an airplane's desired performance and to determine the best structural concept to use. For people that do this for a living, some things seem intuitively obvious. For the rest of the crowd who fly model airplanes, reliance on those that are successful and seem to have the notoriety is a safe bet. Remember, imitation is the finest form of flattery.

However, if you want to try your hand at designing that special creation of yours I hope this article has been of some benefit. The concepts are easy to understand on the surface and apply ideally to practical use. The detail guts analysis typically is not needed because we are going to use standard materials and sizes available to us in the market place. Analysis may say we need only .04265" stock, but we are going to use 1/16" balsa because that's what we have in our balsa box. What will make a difference is using some of the techniques in this article and using that 1/16" sheet in the appropriate application.

Fundamentally:

- Build "forward heavy" wings keeping the spars as far apart as possible
- Where possible, build closed sections for those subjected to torsion
- Use diagonal bracing or shear webs where appropriate.

ABOUT THE AUTHOR

Rick Pangell, P.E., is a graduate of the University of Minnesota in Aeronautical and Aerospace Engineering (1968), a proud member of the Magnificent Mountain Men Free Flight Club of Colorado, a Registered Professional Engineer, and has been a structural design engineer for about 30 years in the aircraft and aerospace industry.

He is currently a Senior Group Engineer in the Advanced Special Programs area with the Lockheed Martin Astronautics Company in Denver, Colorado.

He has worked on all aspects of aircraft design from fighter aircraft to advanced spacecraft designs. His most recent acknowledged experience is spacecraft structures and mechanisms design on Mars Global Surveyor, launched in October 1996 and with advanced spacecraft designs.