The science of model flying: Structures

It will be helpful if you have read my article on forces.

When people ask me what my model is made from I usually reply, ‘Mostly air.’ Our models are hollow so their densities are low but the structure is the correct shape for flight and strong enough to withstand the forces that try to break it. Engineers talk about safety factor. This is how many times more than the expected maximum load a structure can withstand without breaking. Ancient buildings were often a hundred times stronger than needed. Modern buildings are at least two times and cars are three or more times stronger than they need to be. However an aircraft’s safety factor can be as low as 1.2 and perhaps 2.0 for a pressurised area. Any stronger and heavier and it wouldn’t fly.

There are two quotations that are relevant here. The first is from a now dead freeflight champion in the UK, John O’Donnell, or John O’Winall as he was affectionately known. He said, ‘Build it again, lighter.’ The other quote is from Bill Stout of US Trimotor and Ford fame, ‘Simplicate and add more lightness.’ We want our models to be just strong enough consistent with minimum weight.

In another field – Formula one motor racing - Colin Chapman, the head of Lotus Cars, was an advocate of Stout’s idea and said that the perfect racing car would fall to pieces just after it crossed the finish line. If it didn’t it was too strong and heavy to win. Mind you his cars sometimes fell to pieces during the race and people I knew who built Lotus kit cars were for ever mending them. I am sure that the versions now produced by Caterham in the UK are better.

Look into the fuselage of a 3D power model. There’s almost nothing there, just some filigree carbon fibre frames. Apart from air of course.

SMAE

The governing body for UK aeromodelling is now called the British Model Flying Association but used to be the Society of Model Aeronautical Engineering (SMAE). I much prefer the latter with its connection with engineering design as well as flying. Hey ho! Though it is changing a bit, the UK is poor in recognising the skills and creativity of engineers. When we call out a plumber, he or she is often called an engineer rather than the equally noble and more correct title of technician. UK governments usually comprise people educated in the classics or law, so have no notion of science or engineering, or even numbers in some cases.

Beams

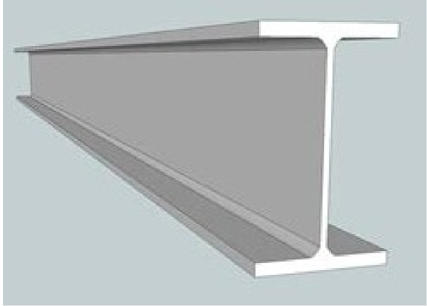
All our models include beams of one sort or another. What is a beam? The first ones were just tree trunks or stone slabs, crossing rivers or placed across the tops of doorways. These are inefficient, as they are heavy and wasteful of material and unless huge are not very strong.

That is because many materials are weaker when you bend or stretch them than when you compress them. In the case of doorways or windows, stone or brick is much better when formed into an arch. The weight of the structure above then imposes a compression force rather than a bending one, and stone is usually very strong in compression. As you will see we use similar techniques in airframe design.

Experiment Find a strip of balsa say 3 x 3 mm. Try to pull it apart by stretching. I'd suggest then pushing on each end but when it breaks the broken ends might embed themselves in your flesh. Snap it by bending. Which is easier? So balsa is stronger in tension.

Fabricated beams

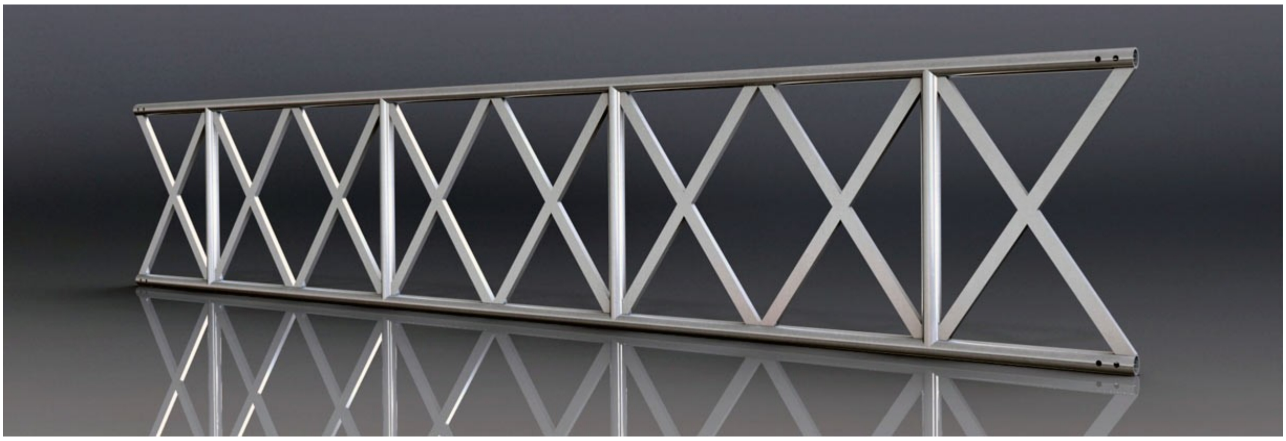
Imagine a solid rectangular beam. The central part adds very little to the strength but a lot to the weight. As you move out from the centre the material adds more strength because the resisting force has a greater moment. So let's remove the centre. We now have two flat strips. They each bend much more easily. Now fix a thin vertical piece between them. We have made an I-beam and example of which is shown in Picture 1. When we try to bend it, one strip is in tension and the other is in compression. The material is much stronger against these forces. You now have a beam that is lighter and yet much stronger. The material between the parts is called a web or shear web. Mostly it is there just to hold the strips in the correct position. The further apart the strips are the stronger is the beam. This creates a problem for thin wings. And of course we call the strips spars, or even sheeting as you will see later.



Picture 1

Modern scaffolding beams

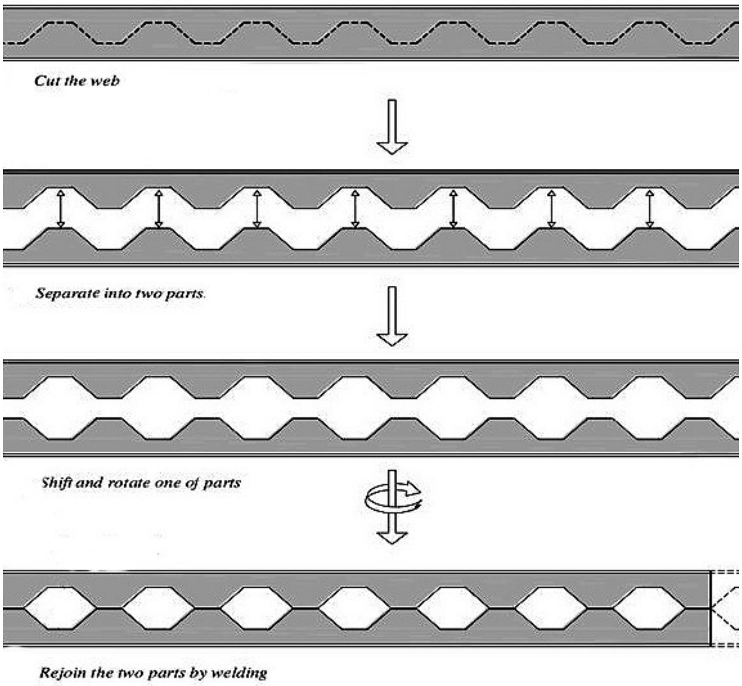
These appear very full of holes but in practice are very strong and light (Picture 2)



Picture 2
apolloscaffoldservices.co.uk

I beam

In Picture 3 we see how a metal beam can be made stronger with no increase in weight by having the web cut and rewelded.



Picture 3

My project

For a while now I have been planning a new project. I want to compare weights and bending strengths of beams built with the same dimensions and materials but with different layouts. I want to use 10 x 1 mm carbon fibre strips for the top and bottom strips and a variety of materials and styles for the web. No, I haven’t started it yet.

Sheeted wings

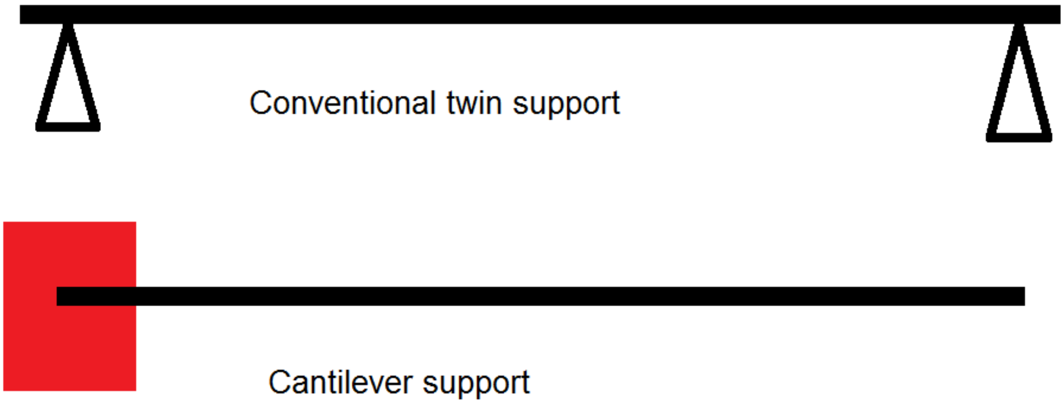
Seán Bannister, a leading glider designer and competition flyer of a few years back with his Algebra designs, was on a BFMA In The Air Tonight webinar in March 2022. It is still available on youtube https://itat.bmfa.uk/22-03-2022. He described himself as a pragmatic designer. He used all-sheeted wings and had a light-bulb moment when he realised that such a wing was inherently a beam so did not need spars. He either used shear webs or rohacell foam to fill the space between the sheets of his successful models. You can see his 1970’s three metre World Championship winning model in South Africa on the far left in Picture 4.

Picture 4

Cantilever beams

These are beams that are only supported at one end. Eh? In fact they are held up by two forces close together towards one end. They are beloved by those architects who like unconventional structures and open designs and of course are used in bascule type rising bridges. Most important, they are how our wings and tailplanes are held in position.

In Picture 5 you see a beam conventionally held up at both ends and a cantilever beam held up close to one end and embedded into some sort of solid support. If the beams are equally strong, the cantilever one can only carry a much smaller load depending on how far apart the support loads are and how strong the support material is.



Picture 5
Peter Scott

Consider a load near the end of the cantilever (Picture 6). The moment arm of the load is about ten times that of the supporting forces. They will have to exert forces on the beam that are ten times the load. What is worse the forces from the beam onto the support tend to push the support material apart. Remember they are equal and opposite to the blue forces. Many materials such as concrete or stone are weak in tension.

Picture 6
Peter Scott

Picture 6 is a good representation of a wing. Wings are cantilevered. What do we do to protect it from folding? The usual techniques are flexibility, a wide fuselage to reduce the support forces and very strong root spars and root structure.

Forces in structures

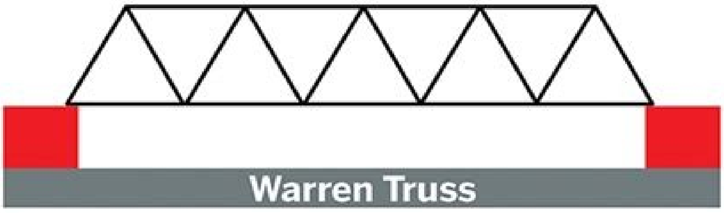
Forces on a fixed structure such a house or a bridge, must balance or the structure would move. For a large structure upward forces must act together to balance its weight. Such things are usually made of many components each of which carries part of the load. Some components are vertical, some at an angle and some horizontal. The last won’t carry weight but will tie together other components that do.

Even in pre-university physics students learn how to calculate the forces in each part of a structure.

Triangles

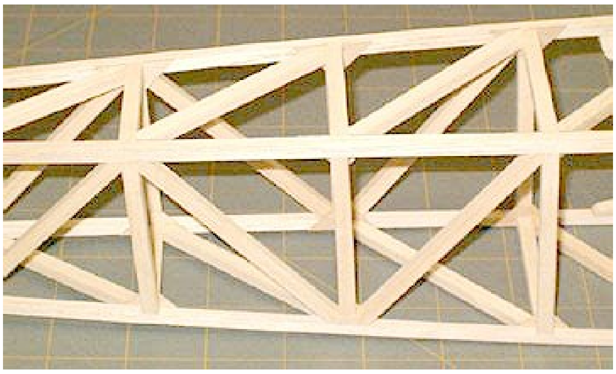
The ancient Egyptians were good at simple maths and geometry. One of their discoveries was the 3,4,5 triangle. If you draw or make a triangle with the sides in that ratio, say 15, 20, 25 cm, one of the angles will be an exact right angle. That is how the Egyptians were able to set out the pyramids so accurately and ground staff set out their playing field corners with a knotted rope, or perhaps used to. 7, 24, 25 is another right angled triangle.

For modellers there is a better reason for using a triangle because a triangle is rigid. For a set of sides of given length a triangle can only have one shape and cannot be deformed except for twisting. When we build our models we frequently include triangles to stiffen them. The cross braces add very little weight but great strength. An extreme example, beloved of free flight flyers, is the warren girder (warren truss in US) as seen in Picture 7. We see this everywhere especially in bridges, but it is widely used for the sides, tops and bottoms of box-type lightweight model fuselages.



Picture 7
From makezine.com

In picture 8 is a warren-based fuselage. It is very light and astonishingly strong, especially when covered. For an even lighter frame you can leave out the right angled struts. To save wing weight you could use warren cross braces between the spars instead of shear webs. The structure will not bend. It will only fail if the forces imposed on the component struts become greater than they can take or if the joints come apart.



Picture 8

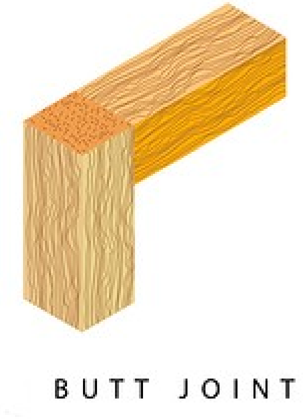
If you look carefully you can see triangular wood fillets in some of the right-angle joints. There will be another example later.

Joints

Talking of joints, one key to joint strength for a given glue is to maximise the surface area of the mating parts of the joint. Cutting accuracy is equally important as most glues have only a limited capacity to fill gaps with any strength. The aim is to make the joint stronger than the surrounding wood. Pictures 9 – 16 show a range useful to us.

There are many types of wood joint. (Haha, my English teacher would have struck out that sentence at the start of an essay and given me a D-.) I have here limited myself to joints commonly used in model aircraft. Some standard joints, like tenons, are not suitable for us either because balsa is weak and grainy or the cross-sections of the hardwood sections are too small. Corner joints are often strengthened with triangular fillets of glue or pieces of wood, especially corner butt joints.

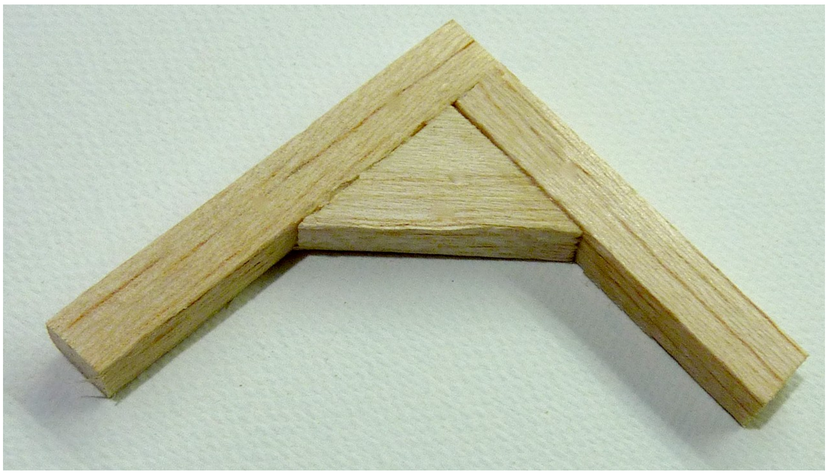
Butt



Minimal joint area

Picture 9
From blogudemy.com

Corner bracing



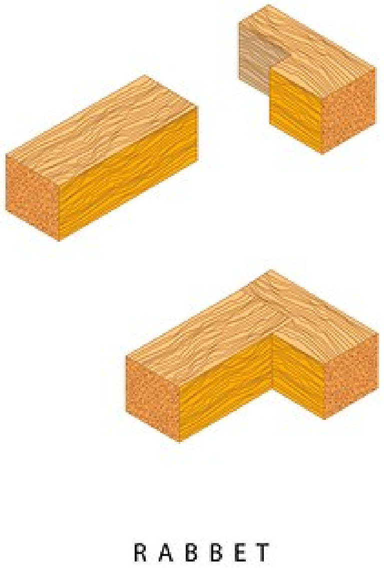
Picture 10

Mitred butt
Peter Scott

40% increase in area

Picture 11
From westerntimberframe.com

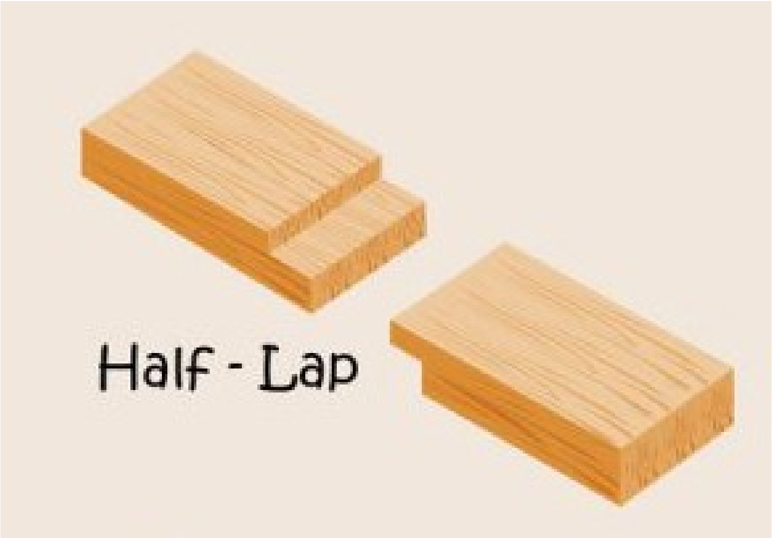
Rabbet (from ‘rebate’)



About the same but in two directions

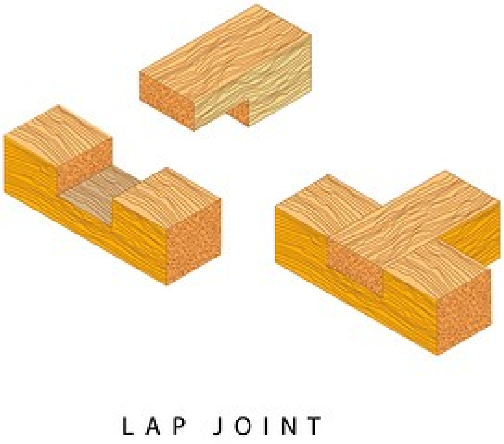
Picture 12
From blogudemy.com

Half or lap joint



Picture 13
From westerntimberframe.com

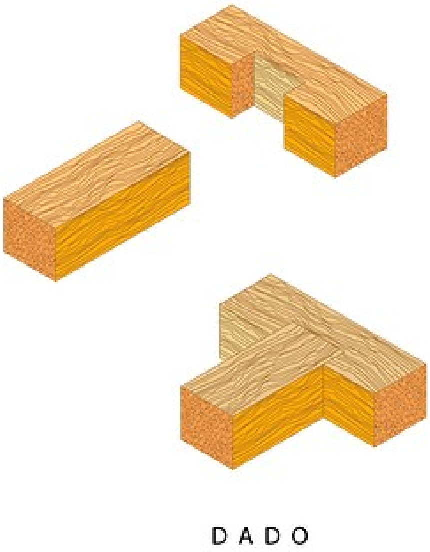
Scarf (below) is probably better for models



Double the area

Picture 14
From blogudemy.com

Dado

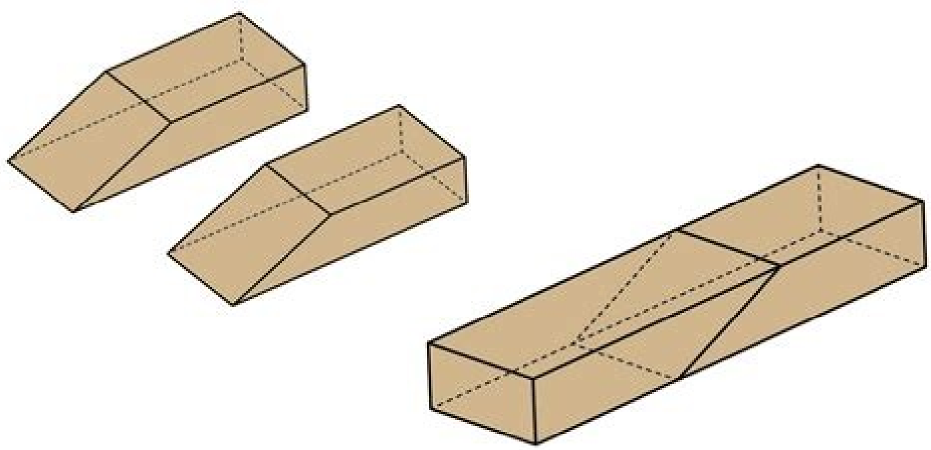


Double the area

Picture 15
From blogudemy.com

Pegged or pinned joints
Wood pegs are used in full size joinery but we also use them. I like to push in glued cocktail sticks or even bamboo kebab sticks to strengthen marginal joints.

Scarf joint
Modellers use a joint that is not used in joinery in the simple form that is shown here (Picture 16). This is the scarf joint and is strong if the correct glue is used. Joiners' version are often ornate and beautiful to see.



Picture 16
From pinterest.com

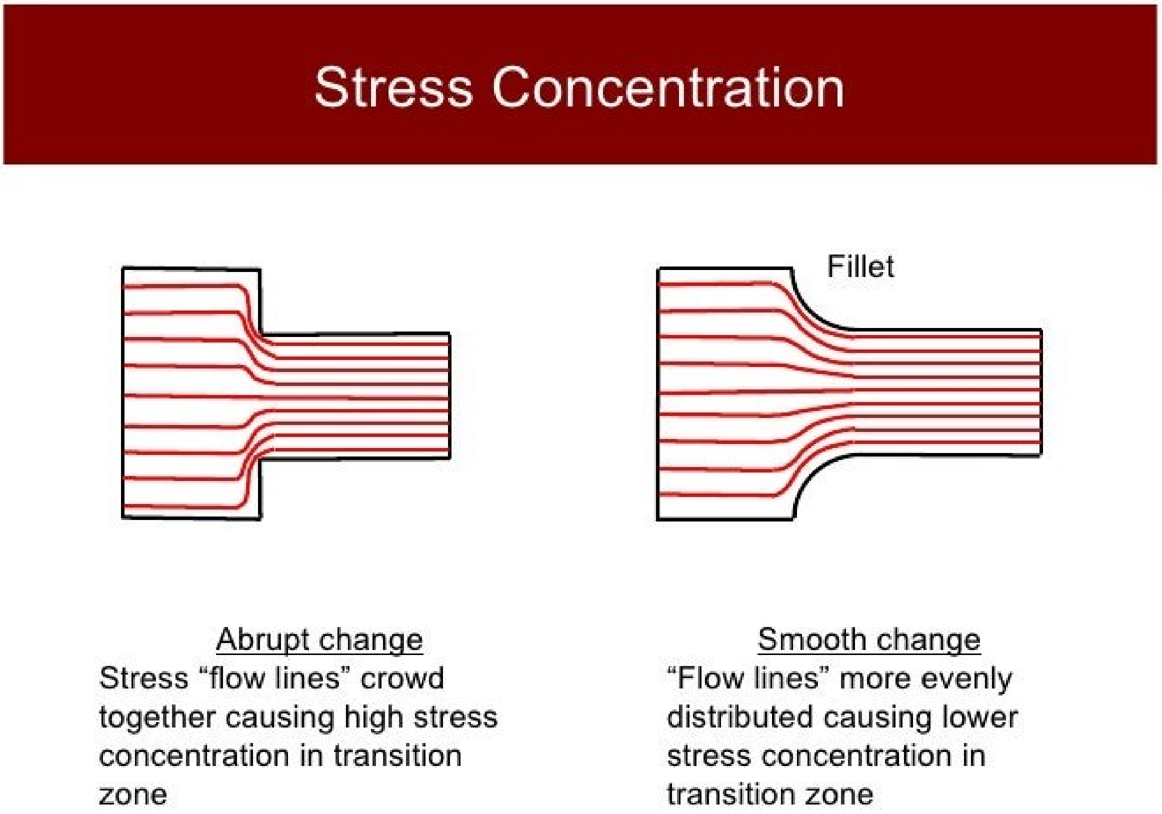
Stress and strain

Stress raisers, surface finish, round holes

Why do aircraft have round windows? To see out of! No, why are they not rectangular? Why do we avoid right-angled holes and internal corners in stressed metal parts? Why are we careful to polish metal surfaces and then not scratch them? Stress raisers, that's why.

Any sudden change in profile can increase the stress force. This will find surface faults and other weaknesses and cracks might start. In the early days of civil aircraft pressurised fuselages were often monocoque, that is a continuous sheet of aluminium. As de Havilland found with the Comet, cracks will inevitably form over time especially around stress-raising holes like windows or small surface faults. Unless barriers are in the way to stop them, the cracks will spread widely and the whole structure will explode as happened in the air to two Comets. Boeing fuselages were made from a series of rings. Not only did this reduce cost and make later increases in length easier, but also stopped cracks. This meant that Boeing's aircraft stayed in the air while DH's were grounded. The UK civil aircraft industry was set back many years. Metal fatigue was little understood until DH cycled a whole new Comet fuselage in a water pressure tank at Farnborough until it failed.

Picture 17 shows how this works with sharply tapered and curved pieces. Failure is most likely where the lines are closest together. As usual the lines are not real. They are a model or analogy just like magnetic lines or streamlines.



Stress Concentration

Abrupt change

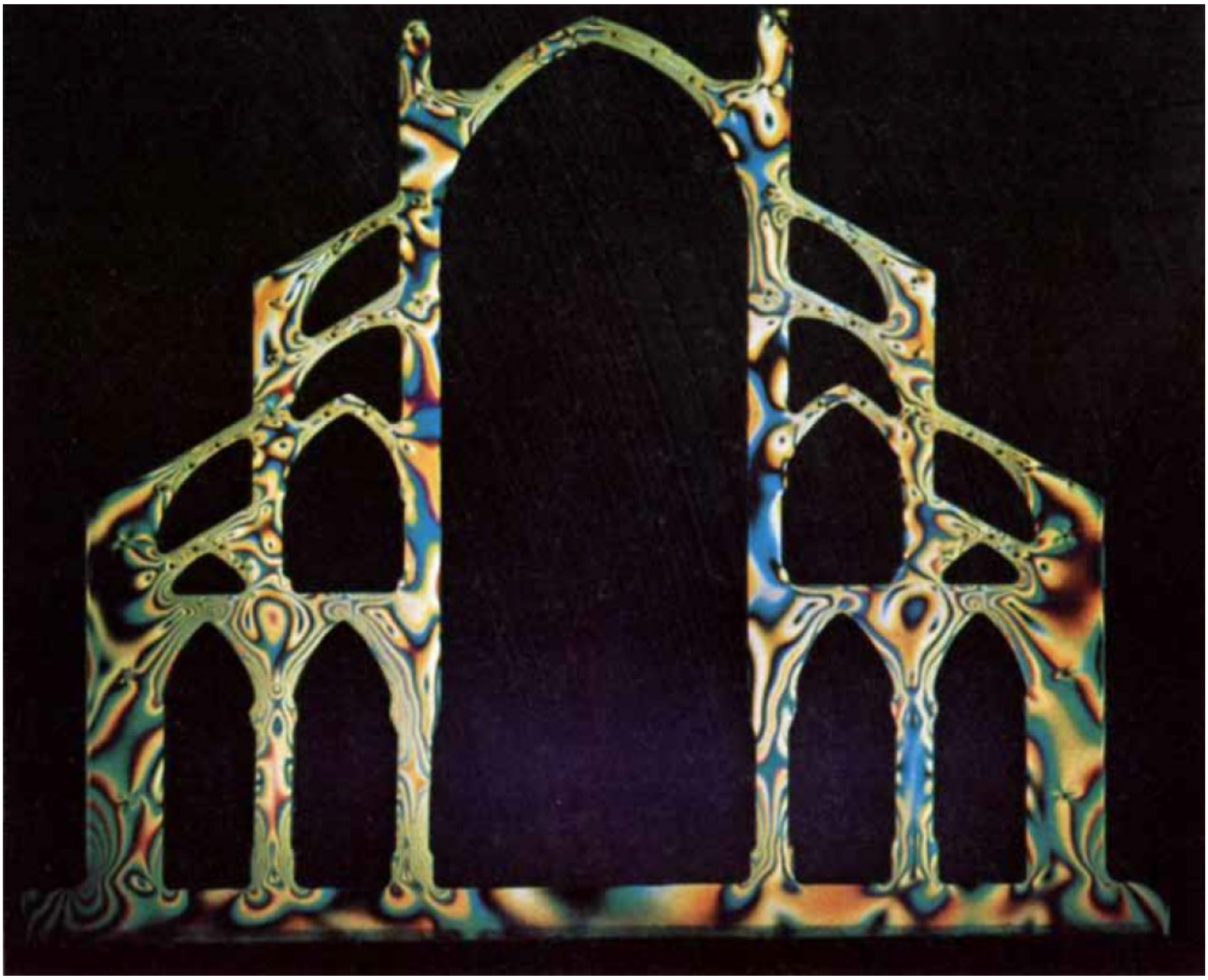
Stress “flow lines” crowd together causing high stress concentration in transition zone

Smooth change

“Flow lines” more evenly distributed causing lower stress concentration in transition zone

Picture 17
From slideshare.net

If the shape of a designed piece is cut out of perspex (plexiglass) exactly to scale and then forces are applied you can see the stresses. They polarise the light and the patterns can be seen with a polaroid sheet. In 1984 Scientific American ran an article on ancient European cathedrals to see how weight and wind forces were carried by the various components like pillars, vaulted ceilings and buttresses. They used the polaroid method and found, as they expected, that Chartres cathedral was an almost perfect design. If you get the chance to visit it, do so. On a trip to France I broke my usual travelling ABC banning rule for Chartres after reading the article. ABC? Another Bloody Cathedral! The openness and lightness of structure is remarkable. I was astonished to find the article recently using duckduckgo and list the link at the end as well as the image in Picture 18. Even without expertise in using the method you can see intuitively that the structure has a sideways force from the right as well as a downward weight force.



Picture 18
Scientific American

The magazine is still going strong and I highly recommend it for people who want to keep up to date in science. Articles are written in clear and simple language. It has a superb archive. It is however now achingly expensive.

Forces on the airframe.

Dynamic soaring really intrigues me, especially the numbers. Over 800 kph (500mph)! And we are told 80 g in the manoeuvres. Really? That would mean a force of 800 N on a 1 kg model. Can we really build model wings that withstand that? Now that is impressive! Coupled with that is the need for thin flying surfaces to reduce frontal drag. I have watched videos of people laying up such wings. One I saw involved endless layers of carbon and I ended wondering if it was all necessary. But when you envisage the forces on the wings, particularly when you remember that they are cantilevers, it all seems worth it.

Sources
https://static.scientificamerican.com/sciam/assets/File/scientificamerican1184-176.pdf
https://www.sciencedirect.com/topics/engineering/stress-raiser

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