COMPOSITE MATERIALS SUMMARY [Sketch]

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Complete course name: UWashingtonX: AA432x Composite Materials Overview for Engineers by Dr. Kuen Y. Lin, et. al.

Link

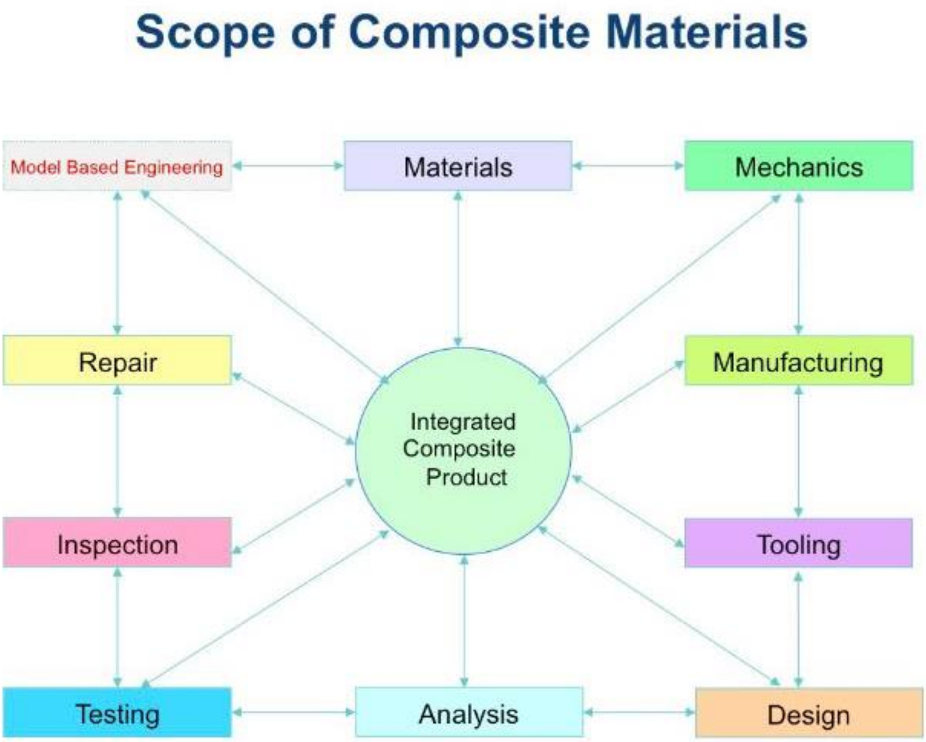
Composite material: it's basically a material made by 2 or + materials, visually identifiable on a macroscopic scale. For example Aluminium Alloy is not a composite because we can't detect the different materials visually (without using sophisticated electronics). When combined we get the best properties of each. Examples of composite materials:

- Reinforced concrete = cement + rocks (great in compression) + steel (great in traction)
- Fiber reinforced polymers (why fibers and not other things too?)
- Shape memory polymers reinforced with fibers
- Wood = cellulose fibers + lignin
- Bones = hydroxyapatite (hard and brittle) + collagen

People have been making composites for many thousands of years. One early example is mud bricks. Mud can be dried out into a brick shape to give a building material. It is strong if you try to squash it (it has good compressive strength) but it breaks quite easily if you try to bend it (it has poor tensile strength). Straw seems very strong if you try to stretch it, but you can crumple it up easily. By mixing mud and straw together it is possible to make bricks that are resistant to both squeezing and tearing and make excellent building blocks


Figure 1 Houses made with mud bricks in Siwa Oasis, Egypt

TOW is a term used mostly for carbon, meaning an untwisted bundle of continuous filaments. On the other hand, YARN is used mostly for fiberglass, usually meaning a twisted bundle of filaments, not necessarily continuous. Filaments come in various qualities, and form tows and yarns of various sizes. Individual filaments of the same material groups have usually the same density. With carbon fiber tow we usually have the "K" number, or the thousands of filaments per tow. 1K means 1,000 filaments / tow, 3K 3,000, 6K 6,000, 12K 12,000, etc.



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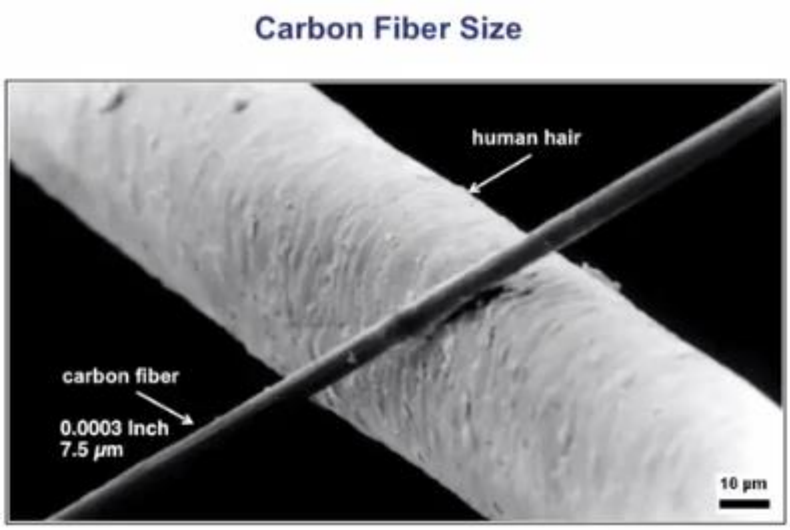


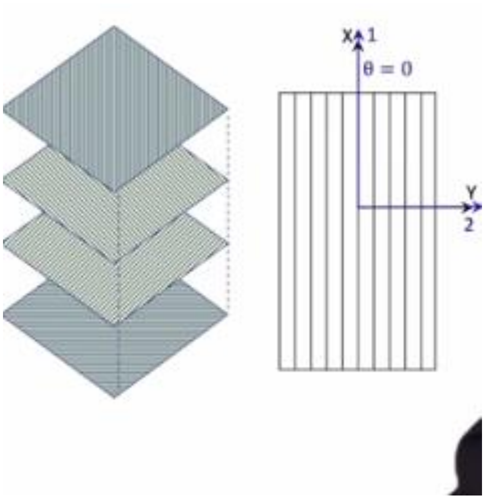
The smaller the fiber size the bigger the strength because there is a less amount of defects inside the materials. The smaller diameter leads to a more homogeneous microstructure inside the fiber and reduced defects.

In the metal we see a visible dent due to the plastic deformation. On the CFRP, on the other hand, the energy is going to be absorbed through internal delamination. Each layer will delaminate. Delamination is the separation of layers. Thus in a composite part, if you don't see any damage, it is NOT safe to assume the part is structurally intact.

What is a high performance structure?

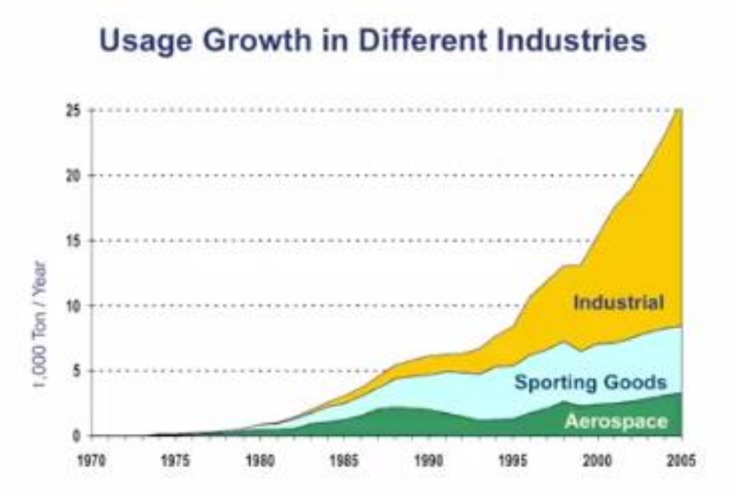
From a design and manufacturing perspective, thermosets are better because if a material is designed to a specification and it has minute tolerances then thermosets will not deform with temperature as it has stronger bonds, as they are thermally set. Also as manufacturing involves various treatments and process which differ in temperature, using thermoplastics can become a cumbersome job as it would change shape during different manufacturing stages.

Fiber direction



Generally what we do is according to the application to determine the quantity (%) of fibers to use in each direction.

With composite materials we can obtain larger pieces than with metals because crack doesn't propagate as easily because fibers arrest them >> quicker assembly, fewer parts, more efficient production reducing flow times.



Because metals are isotropic, using aluminum assembly pieces of the same area throughout an entire structure will lead to underuse of the loading properties. Therefore, if we are only to use aluminum, my proposal would be to use assembly pieces of different areas so that the structure as a whole resembles the qualities of an anisotropic composite, where each part of the structure is tailored based on the structural needs.

With composites we can tailor their properties to the application.

III. Tailored Properties

Composite:

Properties CAN be tailored

- Properties can be tailored by combining different percentages of 0º, 45º, -45º, and 90º plies

Optimal use of material

- Material properties can be tailored per loading requirements to meet design allowables while reducing overall weight

Metal:

Properties CANNOT be tailored

- Properties are represented in fixed values that cannot be tailored

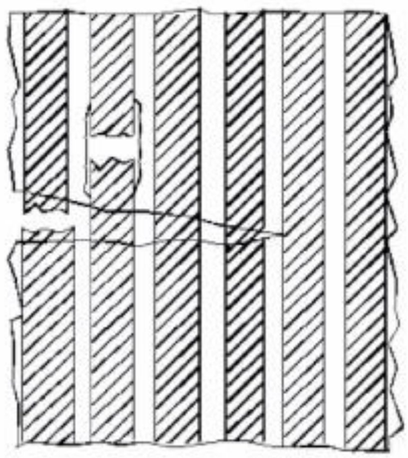
Material CANNOT be optimized

- Structural performance can only be improved through changes in geometry, such as in thickness, which adds weight

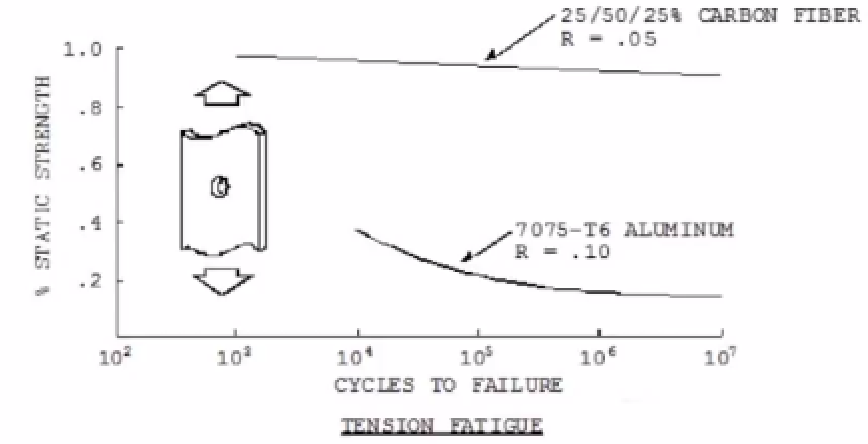
Notation used in industry: CFRP 60/30/10 : 60% of ply used at 0ºθ 30% of ply at +-45º and 10º at 90º. A 25/50/25 layup would have the same properties in every direction and it behaves like an isotropic material, so it’s called quasi-isotropic. It’s called quasi and not just isotropic because in the direction of the thickness it has different properties, so it’s only isotropic in any direction of one plane.

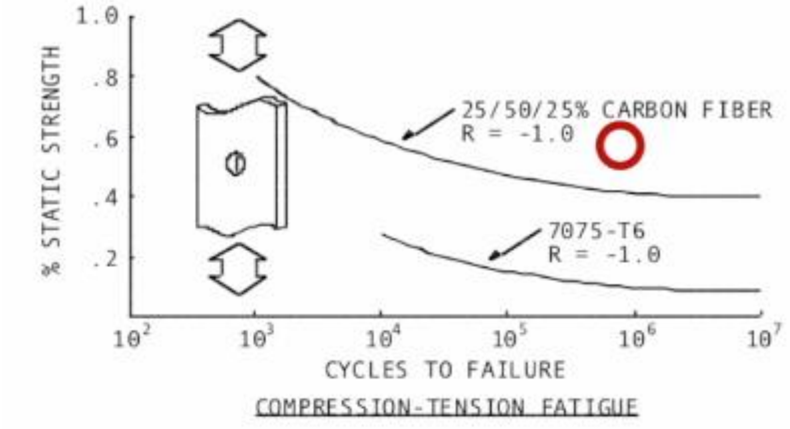
A non-tailored (or partially-tailored) structure may be more mechanically robust than the "ideal" solutions offered by a structural solver. For example, the computer will only output an ideal structure for the input forces. It cannot account for unknown and unaccounted forces that are likely to arise during the use of the proposed design. Because of this, some of those unknown forces can be accounted for by not perfectly tailoring the design. In turn, the partially tailored design may be robust enough to handle unknown and unaccounted for forces.

Some phenomena can occur when curing the composites which are warping and twisting. This happens when the composite is not balanced, that is, the layers are not layed up in a symmetrical manner.



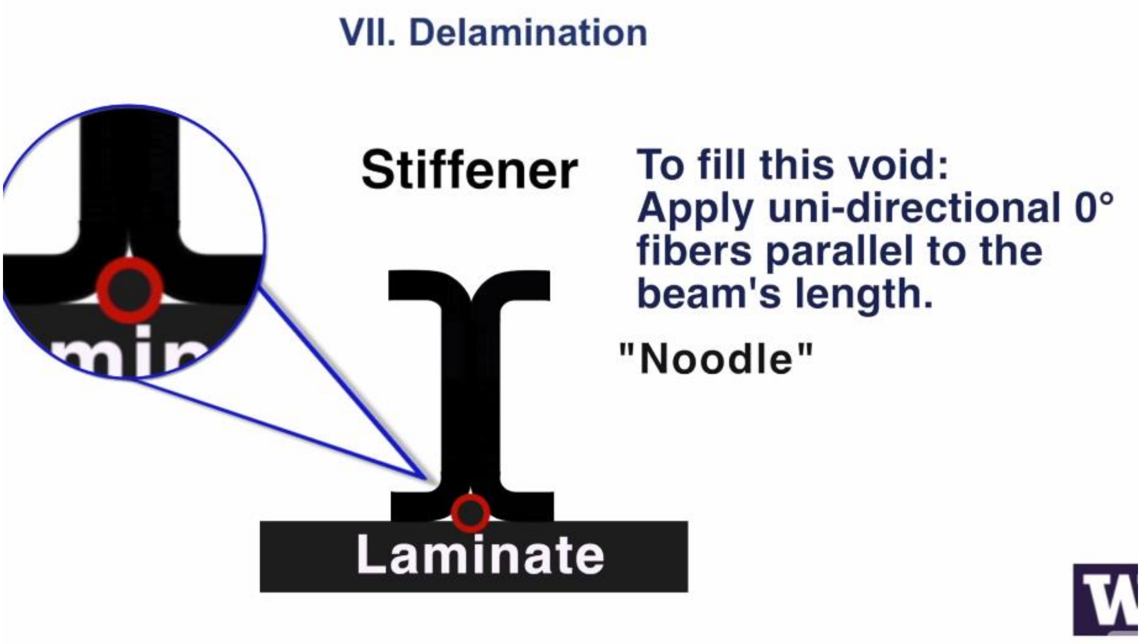
Why composites behave much better in fatigue than metals.





Composites are better at handling traction than compression, and thus handle better fatigue with R>0 where max and min are both traction.

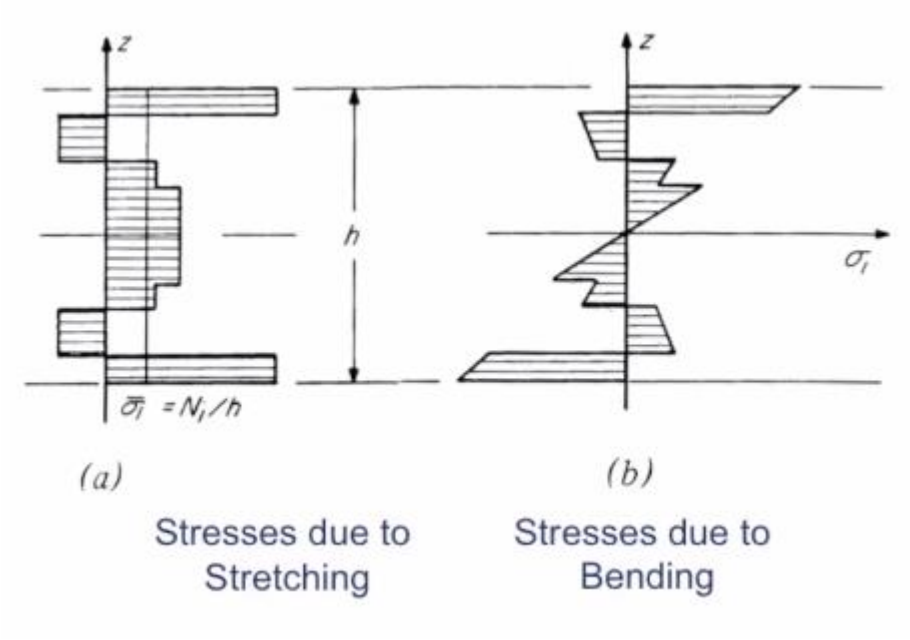
Corrosion: plastics don't corrode except UV light



These are find in aircraft wings.

Discontinuous stresses

In composites if we apply a load, the stress will vary between each ply.

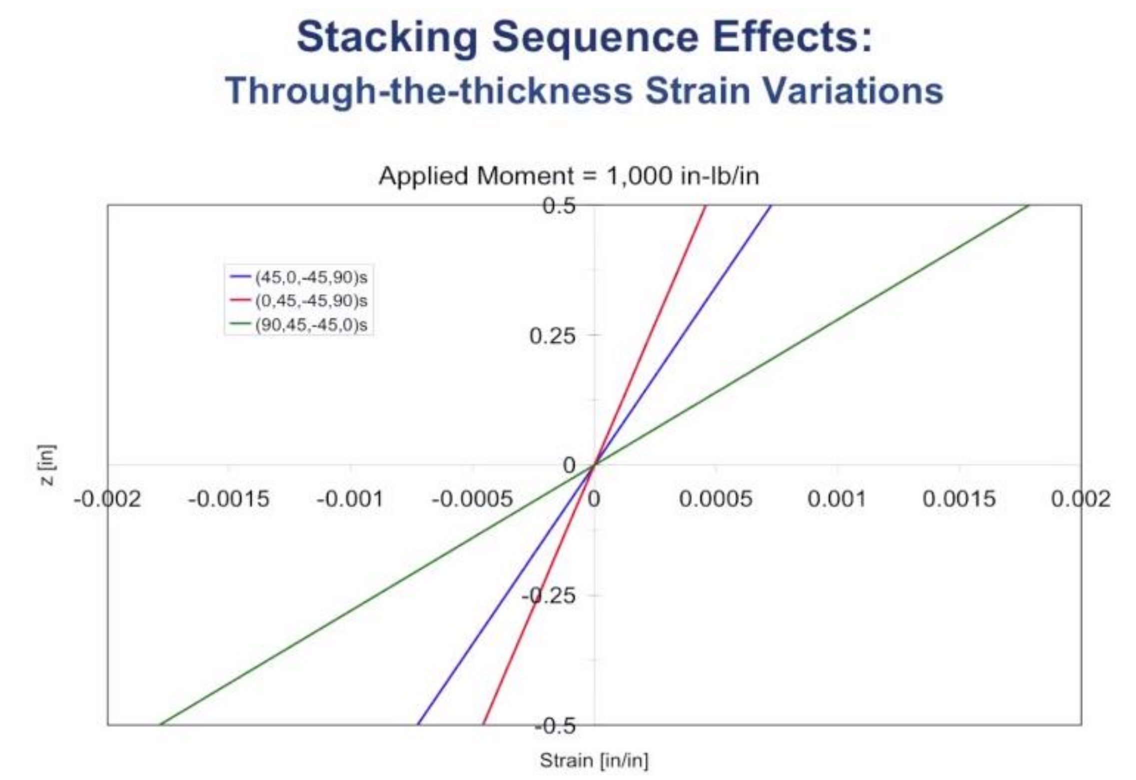


So what they do is, instead of using stress as a criteria for design, they use strain.

$[0]_8$ means an eight-lamina composite with all laminae having fibers in the same direction (0°). $[0/90]_{2s}$ (where the subscript "s" means "symmetric") means an eight-lamina composite with the stacking order 0, 90, 0, 90, 90, 0, 90, 0°, where the first four laminae and the remaining four laminae are mirror images and the mirror plane is the center plane of the composite. $[0/45/90/-45]_s$ means an eight-lamina composite with the stacking order 0, 45, 90, –45, –45, 90, 45, 0°, where the first four laminae and the remaining four laminae are mirror images. $[0/45/90/-45]_{2s}$ means a 16-lamina composite with the stacking order 0, 45, 90, –45, 0, 45, 90, –45, –45, 90, 45, 0, –45, 90, 45, 0°, where the first eight laminae and the remaining eight laminae are mirror images. $[0/45/90/-45]_{2s}$ means a 16-lamina composite with the stacking order 0, 45, 90, –45, 0, 45, 90, –45, –45, 90, 45, 0, –45, 90, 45, 0°, where the first eight laminae and the remaining eight laminae are mirror images. $[0/45/90/-45]_{3s}$ means a 24-lamina composite with the stacking order 0, 45, 90, –45, 0, 45, 90, –45, 0, 45, 90, –45, –45, 90, 45, 0, –45, 90, 45, 0, –45, 90, 45, 0°, where the first 12 laminae and the remaining 12 laminae are mirror images.

The direction perpendicular to the laminae is known as the through-thickness direction. The interface between two adjacent laminae is known as the interlaminar interface.

A symmetric laminate has the ply orientations mirror imaged about its mid-plane.



If you want to design a composite against bending you have to specify the stacking order.

Fracture behavior

In a sharp crack the stress becomes infinity. The materials fracture toughness decreases with cold temperature. The materials resistance to cracking decreases.

In composites with fibers there's no single crack but a zone of damage and multiple failure nodes near the stress concentration.

The Mar-Lin model as a way to predict the resistance of composites to fracture.

Composites (Mar-Lin)

$$\sigma_N^\infty = \frac{H_c}{(2L)^m Y}$$

σ_N^∞ = Residual Strength

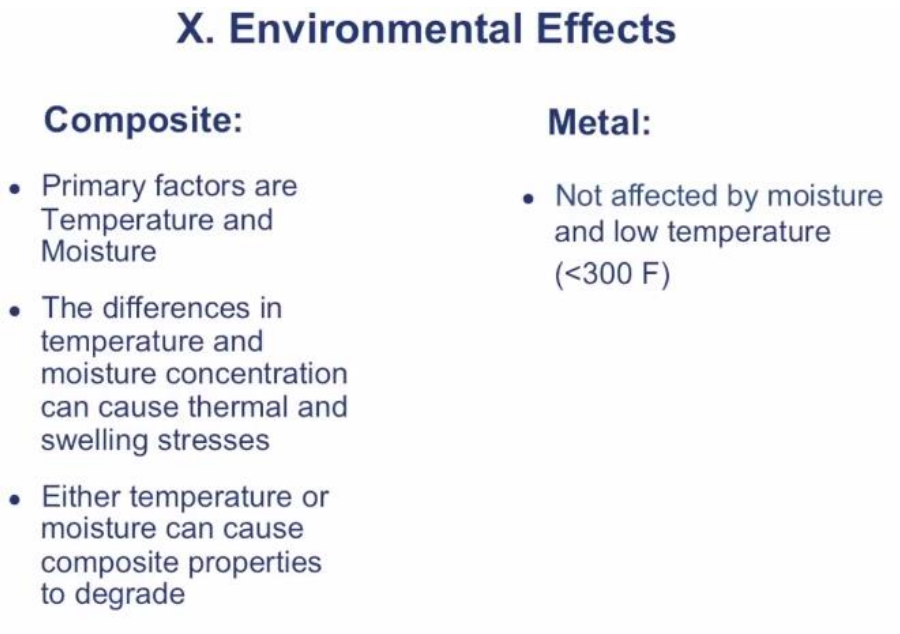
m = Order of Stress Singularity

H_c = Composite Fracture Toughness

L = Half Notch Length

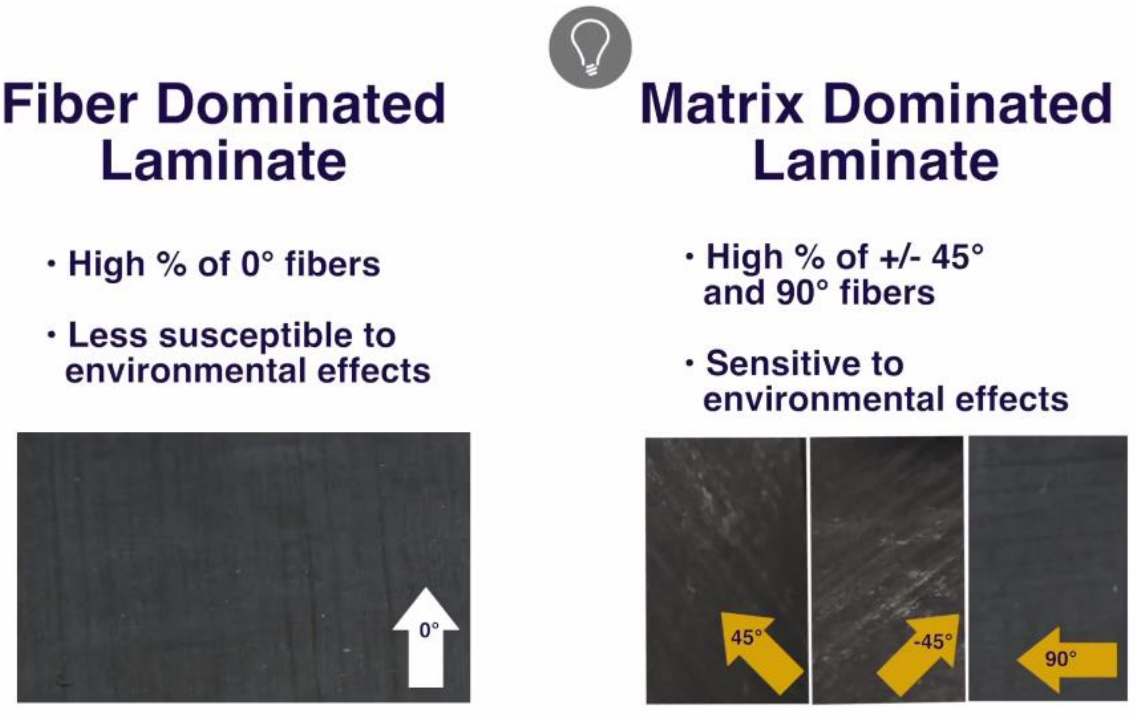
Y = Geometry Factor

Today in high performance structure design they have to account for the so-called tolerance design. Basically they assume that all structures will have defects to start with. And that defect is going to propagate with fatigue loading until it reaches critical size and then the structure breaks. From the design point of view you want to predict how the crack is going to propagate before it gets to critical size. However for composites this whole damage tolerance design philosophy is not applicable in the same ways as it is for metals because the damage is not sharp cracked but multiple delaminations. There are no cracks only damage zones. If a composite is impacted it delaminates.



When the material is exposed to high temperature for long periods of time the materials properties degrade. Another effect is that each ply has different fiber orientations so they expand and contract in different directions. As a result a residual stress will develop, and that could cause curvature: warpage or bending curvature.

Although typically this is more distinct in carbon/polymers because the coefficient of thermal expansion mismatch between carbon and polymers is much greater compared to other material combinations. If you have the same matrix and fiber (such as carbon/carbon or ceramic/ceramic), then there would be no mismatch in coefficient of thermal expansion and thus it wouldn't warp.



In this video, we compare the repairability of metals versus composites. Metal repair is straightforward. It is easy to detect the damage by inspection, and typically we patch the affected area. In composites, on the other hand, it is difficult to detect and assess damage, and it is more difficult to repair damaged areas. Damage can consist of delamination (internal), fiber fracture, or interface de-bonding. In addition, repairs are time-consuming, require highly skilled technicians, and can be impacted by the environment.

Part counts

In metals they typically use lots of small parts. One of the reasons is that in large parts they can't predict crack propagation.

Co-bond is when you have to already cured parts and you want to cure those two parts together (into one). So in composites you can co-cure or co-bond a structure reducing the number of parts.

Comparison between metals and composites

While composites would be the more appropriate material to use, they might prove to be too costly in labor costs and tooling costs; whereas injection molded plastic or cast metal would allow for cost savings while not being as well suited for the design requirements (weight, strength, etc.).

1. Production costs: It typically costs more in time and materials to use composites compared to metals
2. Production speed: Composite processes are typically slower
3. Ease of automation: Automation is easier with metal parts than with composites
4. 'Recyclability' and environmental impact: Composites are harder to recycle; and manufacturing processes produce more waste that is not reusable
5. Mass production versus one-off construction: It may be easier and cheaper to construct certain intricate shapes using composites; but metals seem to always win in mass production scenarios

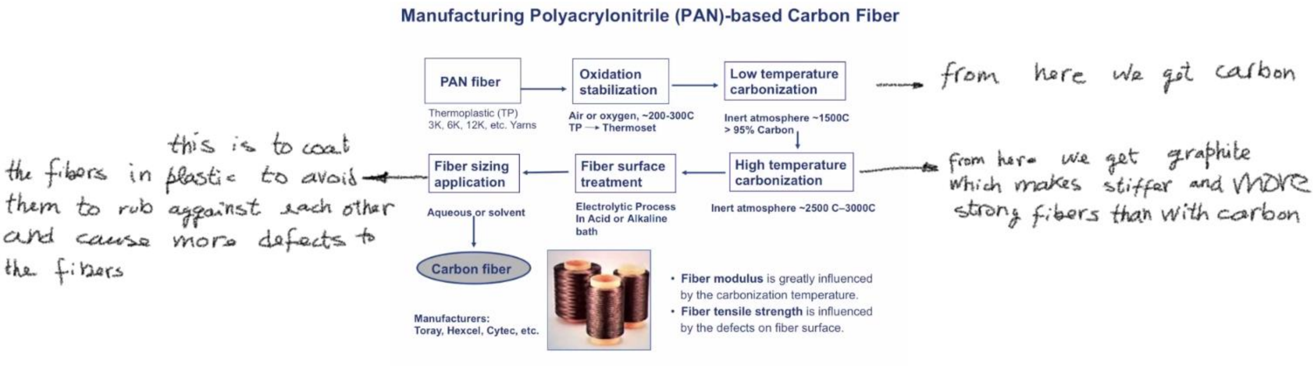
Composite materials

Ceramic fibers in ceramic matrix: because they have fibers they are more resistant to crack propagation than regular ceramics.

Fiber Forms - Basic Terminology

Fiber	A general term for a material which has a long axis that is many times greater than its radius.
Filament	A single fiber. This is the unit formed by a single hole in the spinning process.
Strand	A general and somewhat imprecise term. Usually refers to a bundle or group of untwisted filaments.
Tow	An untwisted bundle of continuous filaments, usually with a specific count, e.g., 12,000 filaments.
Yarn	A twisted bundle of continuous filaments; hence a twisted tow. Often used for weaving.
Roving	A number of yarns or tows collected into a parallel bundle without twisting.
Weaves	A planar material, made by interlacing yarns or tows in various specific patterns.
Braiding	The interlacing of yarns or tows into a tubular shape instead of a flat fabric.

So, in summary, modulus is affected by the carbonization temperature. The tensile strengths of carbon fibers is affected by the amount at defects on the fiber surface.



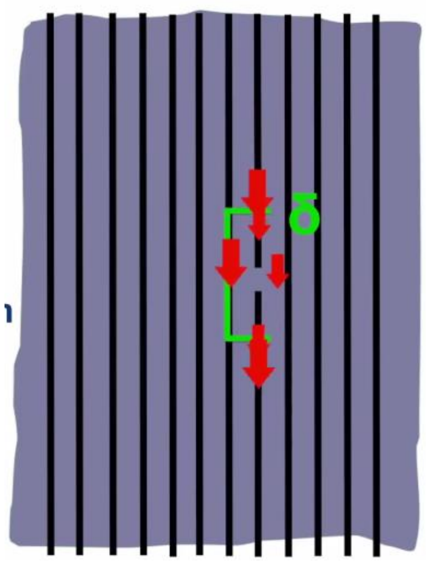
PROF. KUEN Y. LIN: You may have heard people call this carbon fibers, and some people call it graphite fibers. The terminology is kind of mixed, but actually there's a difference between carbon and graphite.

The carbon fibers-- they are manufactured at a low temperature, and they are not as pure. They are 93 to 95 percent carbon.

The graphite fibers-- they are manufactured at a higher temperature, and they are 99 percent carbon element. So they are very pure.

Shear Stress Transfer

So when you add epoxy, epoxy doesn't contribute to the tensile stress directly. However, indirectly it will contribute to the stress of composite. This is called shear stress transfer. Suppose we have many fibers. Say this is the weakest fiber. When this fiber fails, there's no stress carried by the fiber. So if you looked at the fiber stress distribution, the stress is zero. And if there's no matrix material when this fiber's broken, that fiber becomes useless because it doesn't carry loads anymore.



However, add the matrix material, these fibers will recover the stress from zero to the same stress level carried by other unbroken fibers. So basically, within a short distance, delta, the fibers will be able to fully recover the stress.

δ is the distance required to fully recover the stress back to the broken fiber. For carbon fiber it is 10 times the fiber diameter.

So you need the matrix to bind the fibers, protect the fibers from the surface abrasion and also to provide shear stress transfer around a broken fiber.

Matrix material requirements:

1. The elongation (strain to failure) of the matrix should be greater than the fiber’s. Otherwise, if a fiber's broken, then the matrix also breaks. Then the shear transfer mechanism will not take place.
2. It has to form a strong joint with the fiber
3. Low surface tension. When we make composite, the matrix is a liquid. And the liquid has to flow around to wet the fibers. Otherwise, you will create imperfections between the fiber and the matrix.
4. If you look at the woven fabric the epoxy has to flow to fit these very tiny holes in the fabric. And if the viscosity is very high, then you will end up with voids. And that is going to affect the stress of composite.
5. Cure temperature. In theory, you want to make composite as low temperature as possible. Unfortunately to get the best mechanical properties of epoxy, it has to be cured at a very high temperature. A typical cure temperature for epoxy for high performance structure is 175ºC.
6. Chemically stable during chemical reactions you want to have the matrix material to be chemically stable.

Polymeric Matrix materials

1. Thermosets
    a. Epoxies: offer the best mechanical properties
    b. Polyester, vinyl esters and phenolics can be cured at lower temps than epoxies and in shorter times but they’re not good enough for high performance applications. They’re good for consumer goods.
    c. Polyimides >> for high temperatures. When epoxy is heated to above 200ºC it’s properties drop significantly. Polyimides can be used at those temperatures.
2. Thermoplastics
    a. Nylons (such as nylon 6, nylon 66) TP polyester (such as PET and PBT) PC and polyacetals
    b. Polyamide-imide (PAI), polyether-ether-keton (PEEK) (<< this one is the most common thermoplastic used, has greater resistance to impact

Using thermoplastic matrixes we can reshape the piece. We just need to heat it, bend it the way we want, then the molecules will freeze in their new positions, secondary bonds are restored. It can be done as many times as desired. With a thermoset we cannot do it.

Figure 2 – A thermoplastic composite being heated and molded to a new shape.

Thermoplastic vs. Thermoset Polymers

Advantages of thermoplastics

- Higher impact strength
- Better fracture resistant
- Higher strain-to-failure
- Unlimited storage (shelf) life at room temperature
- Shorter fabrication time (but higher processing temperature- 700°F)
- Post-formability
- Ease of repair by welding, solvent bonding, etc.
- Ease of handling (no tackiness)
- Can be recycled

Advantages of thermoset

- Higher thermal stability
- Higher chemical resistance
- Less creep
- Less stress relaxation
- Lower curing temperature (350°F or less)
- Limited shelf life
- Cannot be recycled (melted)

The thermosets have limited shelf life. They have to be stored in a freezer. For example the epoxy is going through chemical reactions. A typical thermoset has three stages. A stage, that's a liquid state. B stage is a prepreg, which has a small amount of chemical reactions happening. You need that to hold the fibers in place. But you don't want chemical reactions to continue, because once it's completed, you won't be able to use the materials for the application. You want to stop the chemical reactions. That's why you store the materials in a freezer. If you store a prepreg in a freezer for a long time, say a year or two, it has to be requalified because there will be a large amount of chemical reactions completed. And the materials' properties are not going to be as good.

Metal Matrix

1. Aluminium
2. Titanium

Generally used with boron fibers, ceramic fibers, SiC.

Metal matrix composites are very expensive

Glass transition temperature

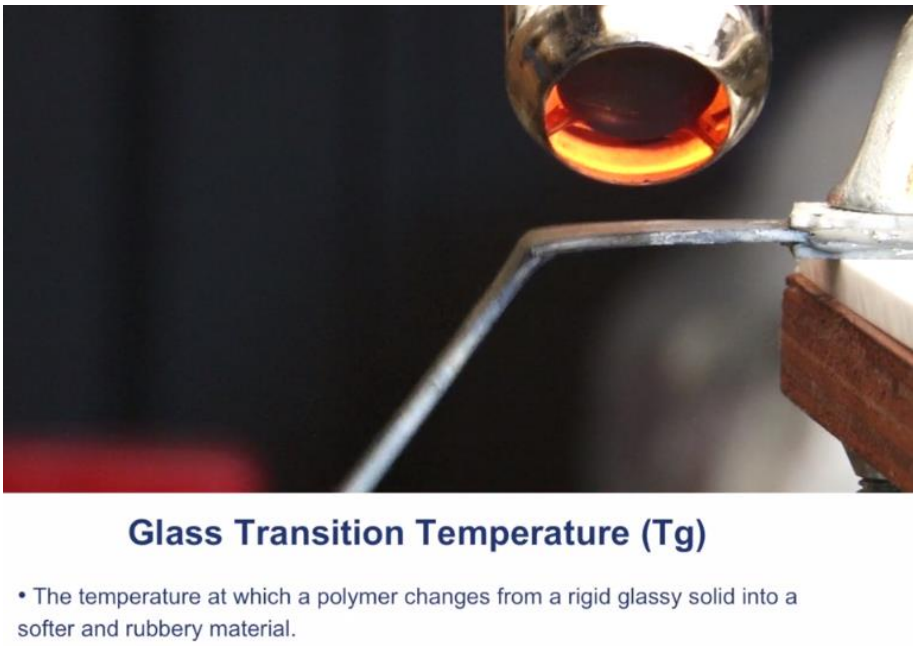


Figure 3 – Heating a bar of a thermoset to the Tg

Why is this important? When the material's usage is close to the Tg you know that the material becomes useless.

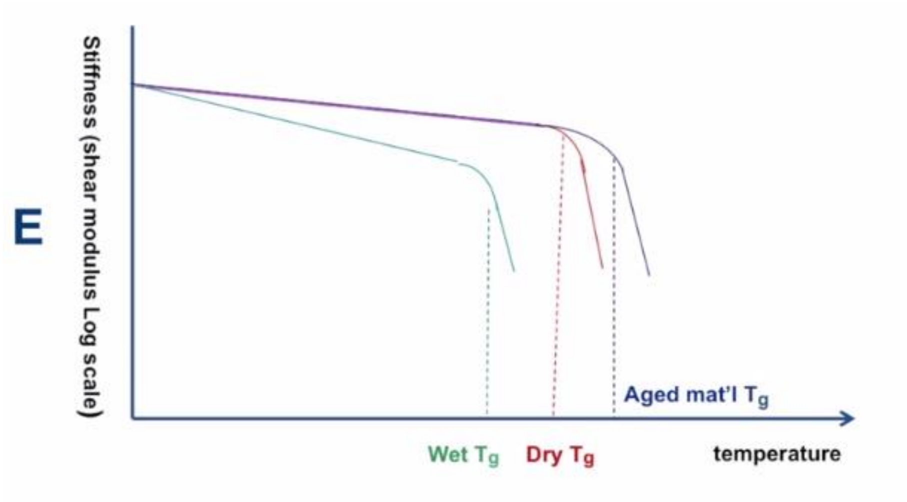


Figure 4 – Stiffness vs temperature for a thermoset and plastic?

Wet is when the polymer is saturated with water. If you look at shirts made today, a lot of them are made of polyester. And when you get wrinkles you want to iron it. So to iron a shirt the best effect would be what? To use steam. And make it wet, so the wet Tg is lower than the dry Tg and you can get the wrinkles out easier.

The maximum temperature for usage should be Tg - 50ºC

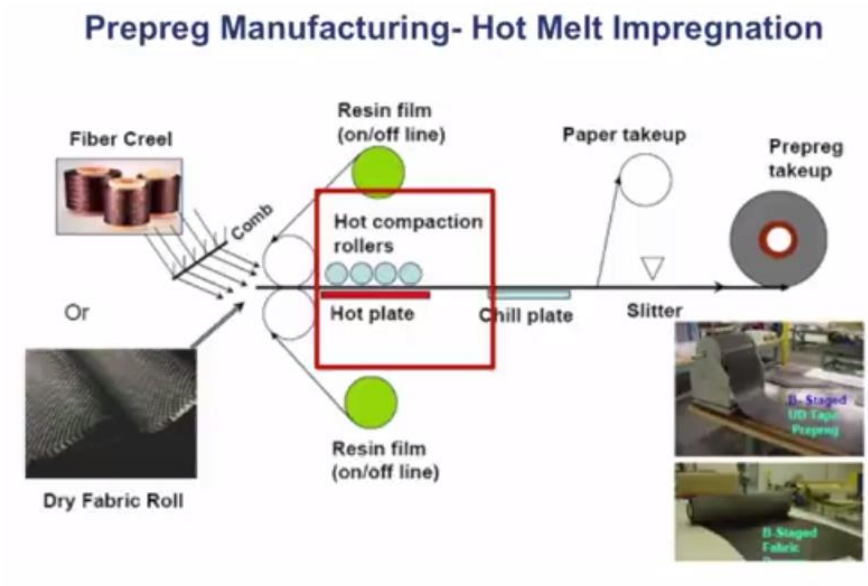


Figure 5 - Manufacturing of Prepreg

Effects of Moisture and UV Radiation

Ultraviolet (UV) radiation

- UV radiation breaks the covalent bonds in organic polymers. Sometimes a prolonged exposure of epoxy laminates to UV radiation results in a slight increase in strength, attributed to postcuring of the resin, followed by a gradual loss of strength due to laminate surface degradation.
- Kevlar fiber being an organic fiber undergoes degradation when exposed to visible as well as UV radiation, which shows up as a discoloration and loss in mechanical properties.

So to make sure neither moisture nor UV radiation get in the surfaces have to be painted. If there are micro cracks, the surface has to be repaired.

Galvanic Corrosion because of differences in electrical properties of Aluminum and CFRP. That's why they use titanium fasteners.

Composite Manufacturing

There are at least a dozen popular methods to make composites, depending on the applications, depending on what kind of precisions you need, and depending on how strict the requirements on the quality are.

1. Manual/hand layup
    a. Types
        i. prepreg
        ii. wet layup
    b. very flexible
    c. low capital investment
    d. labor intensive
    e. industrial safety issues with repetitive trauma
    f. used mostly on complex geometry where it's difficult to use machine layup
2. Bag molding
3. Automated Fiber (tow) placement
    a. the ply pattern is preprogrammed into the machine
    b. the head of the machine is loaded with a roll of prepreg tape (75mm is typical)
    c. the machine lays the tape onto the mold in the pattern that has been programmed
    d. all cutting and trimming is done automatically
4. Resin Transfer Molding (RTM)
5. Vacuum Assisted Resin Transfer Molding (VARTM)
6. Film unwinding
7. Pultrusion

Hand Layup

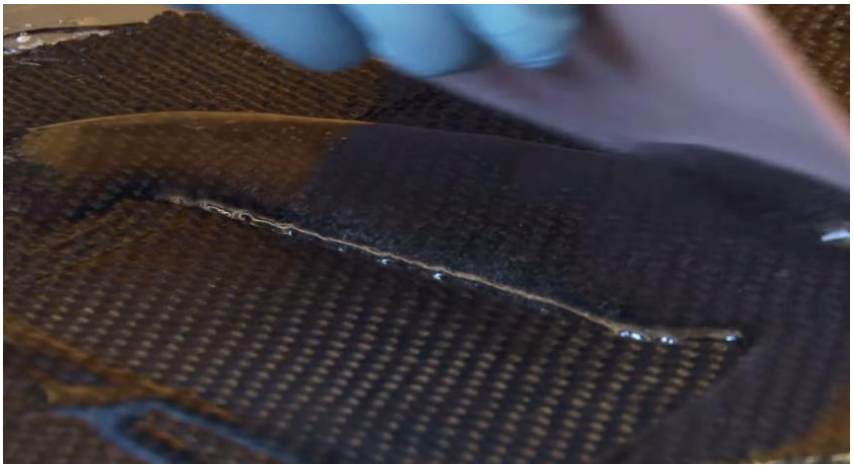


Figure 6 – Wet layup. Recipe: 1 use a dry fabric; 2 add the liquid resin; 3 apply heat and wait for it to harden.

Figure 7 – Removing the prepreg from the freezer. After this let it sit for about 2-3h at room temp.

Then you open the plastic bag and take the prepreg out. Then you cut the prepreg in certain size and certain fiber orientations, depending on the design.

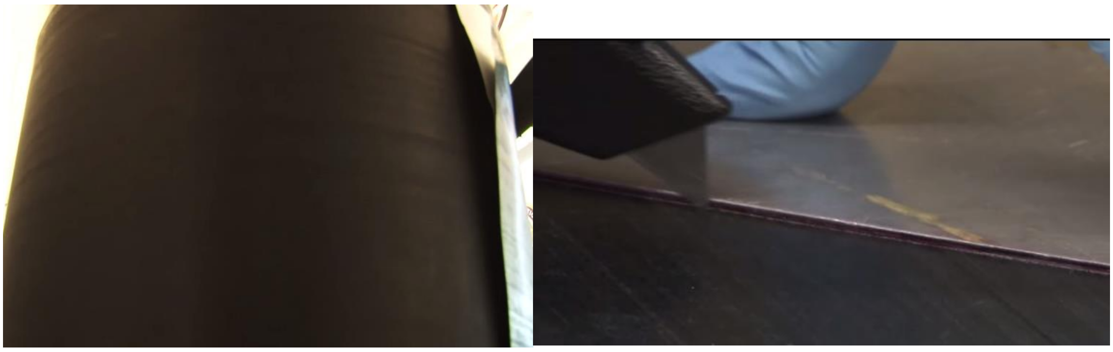


Figure 8 - Taking the prepreg out of the bag and cutting it

And then start laying up ply-by-ply. And if you make a honeycomb sandwich structure you need to put a piece of adhesive.

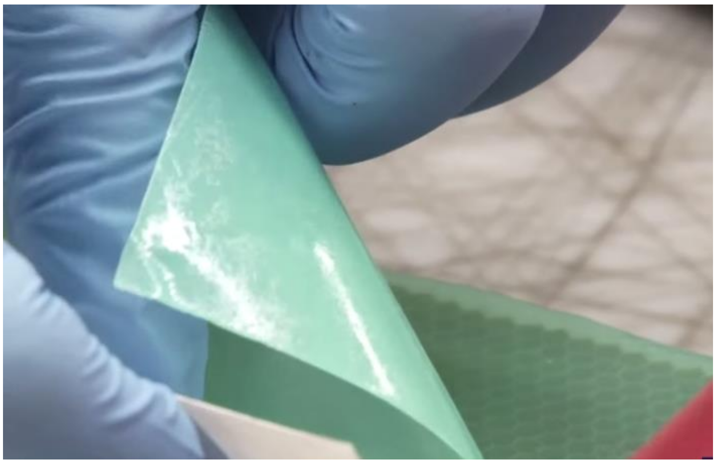


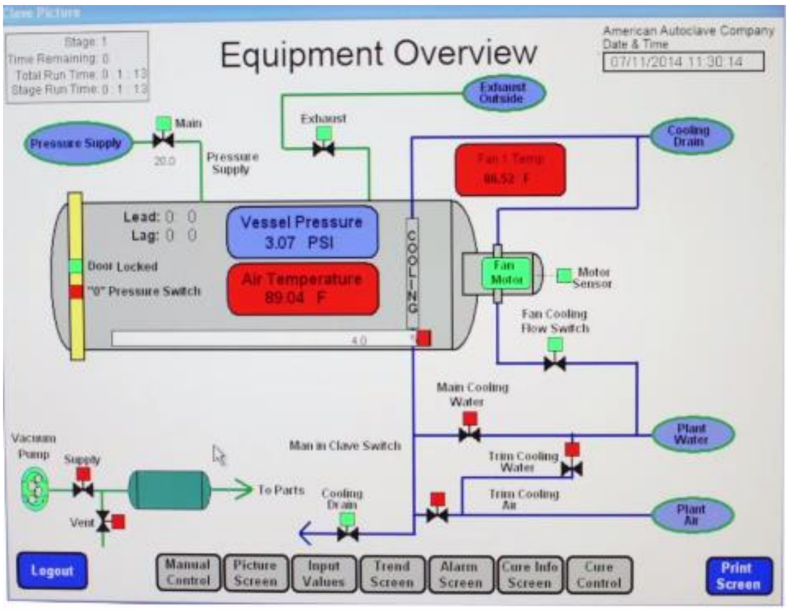
Figure 9 - Putting a piece of adhesive in a honeycomb structure

And if you want to have a bonding surface for a laminate you have to add the peel ply, et cetera. And then all is place in an arrangement. It's called bag molding.

Figure 10 - bag molding

And then the whole thing is placed into autoclave.

Then they apply temperature pressure.



After a certain time the chemical process is completed. And then you take the part out. And you trim the part, inspect the part, and assemble the parts.

Figure 11 – Inspection

Figure 12 – Assembling the parts.

The hand layup is a very flexible, very low capital investment. It's label intensive. There could be some industrial safety issues involved. The applications of hand layup is mostly on the secondary structure with complex geometry.

Bag molding

The layup parts are put against a tool (that has the opposite shape of the part we want). They are separated by a release film to separate the part from the tool when the curing is done.

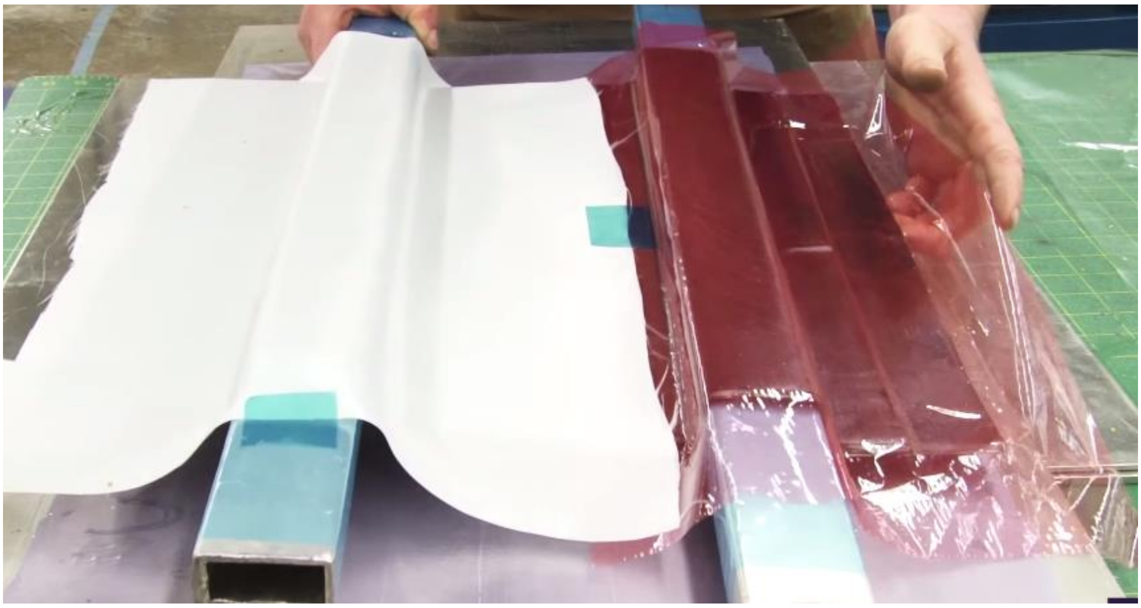


Figure 13- A peel ply and the tool

Figure 14 - Bleeder cloth, typically dry glass fibers, to absorb excess epoxy flowing out

So the whole thing is wrapped with a vacuum bag. And you apply vacuum. And vacuum is critical because you need to use vacuum to get rid of the air bubbles or other volatiles. Then you place the part to the autoclave. Then you apply heat and pressure through this curing cycle.

Automated Fiber Placement

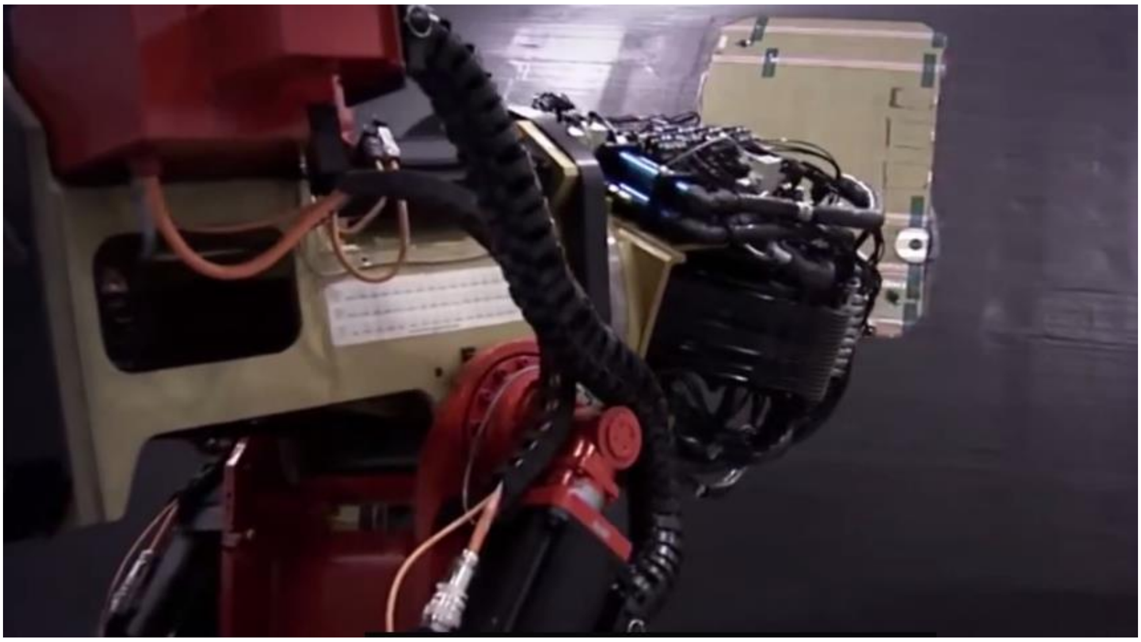
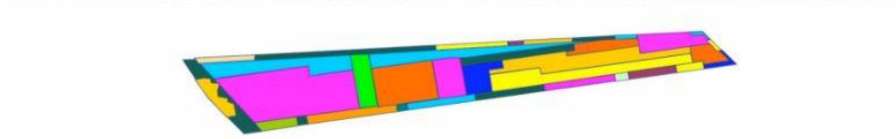


Figure 15 - machine applying prepreg

Figure 16 - machine applying prepreg

This automation is prefect for large parts with varying thickness and orientation of the composites like the wings of airplanes.



<u>Resin Transfer Mold</u>

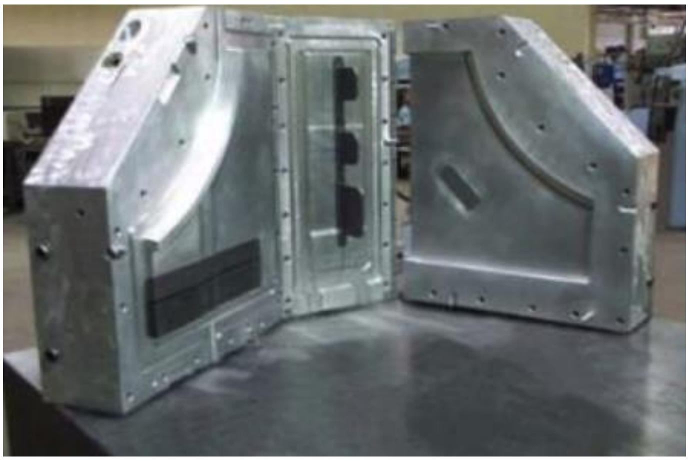


Figure 17 - Molds where the flat mat or preform is put in the RTM manufacturing process.

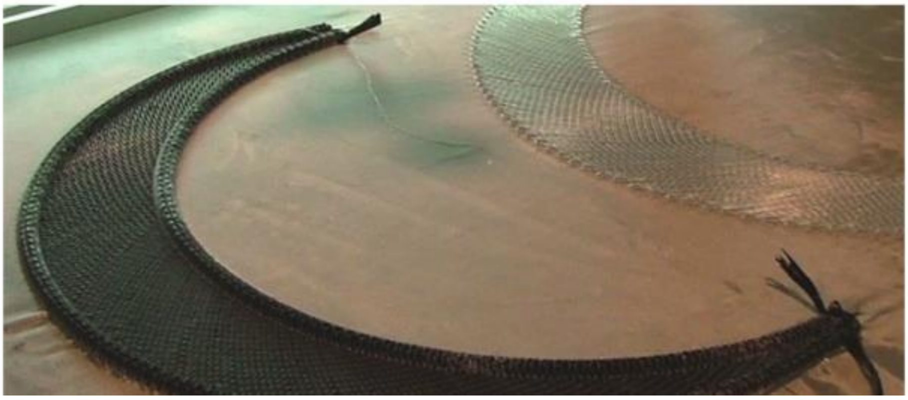
Using Flat Mat

- Place layers of mat, woven roving, or cloth in bottom half of mold.
- Close mold and inject liquid resin (polyester or vinyl ester resins are commonly used for the RTM process) at pressures in the range of 10 – 100 psi. Resin spreads throughout the mold, displacing entrapped air and impregnating fibers.
- Curing is performed at room or elevated temperatures.
- Cured part is pulled from mold and trimmed.

Because the liquid resin is at high pressure, and the mold is very rigid, we get very precise part, very good tolerances. Typically this process is used to make precise, small part with a good precision.

Using Preforms

•Instead of using flat reinforcing layers, such as a continuous strand mat, the starting material in an RTM process can be a preform that already has the shape of the desired product.



Advantages of Preforms

- Good moldability with complicated shapes (particularly with deep draws).
  Elimination of the trimming operation, which is often the most labor-intensive step in an RTM process.

This process allows us to make very precise small parts efficiently with cost savings.

<u>Vacuum Assisted Resin Transfer Molding (VARTM)</u>

VARTM

A process in which dry preforms are laid on the tool, vacuum sealed, and the resin is drawn flowing into the preforms using a vacuum pump.

Process

- A dry fabric or preform is laid on a one-sided tooling surface.
- The preform is sealed with a vacuum bag and the air is evacuated by a vacuum pump.
- Liquid resin from an external reservoir is drawn into the component by vacuum.
- The liquid resin is infused into the preform.
- A highly permeability resin distribution medium (RDM) placed on the top of the preform spreads the resin quickly over the lateral extent of the part.
- The resin flows through the thickness of the part.

The RTM requires two modes. And if you look at this VARTM here you use one mode instead of two. So you save 50% in cost to make mold. Then you place pre-form. This could be dried fibers and could be stitched to certain shape.

And then, typical, you place another highly permeable materials which has a tiny hole.

And that's called RDM. It's a resin distribution medium. And the purpose of that is to help resin distributions more uniformly. And the whole thing is wrapped up with a vacuum bag. And you've got bucket of resin here. Then you apply vacuum. Then the resin is going to go through from the top, diffuse down through the RDM.

Without RDM the resin distribution could be less uniform. The whole thing in placed inside an oven. Then you heat it up. And then chemical reactions happen. And then after that the part is fully cured. So you see that compared to RTM this is much affordable process because you only use one mold. The other side is a plastic back. The advantage of this method is low-cost manufacturing. What's the disadvantages? That automated process you get the best quality control of the parts besides prepreg offers the best mechanical properties. This starts with a pre-form. So the properties will not be as good.

Curing

Curing is transformation of uncured, which is in A-stage, that's a liquid stage, or partially cured, that's a B-stage, such as a prepreg. So a transformation of uncured or partially cured polymers or polymer composites into composite parts which is in the C-stage, that's a solid state. So curing of a composite requires three factors. One is temperature. The other one is pressure and time. You need a temperature to initiate and sustain the chemical reactions, and you need to pressure to consolidate fibers into the matrix, so you will get the maximum volume fractions and the minimum amount of voids. And time is also required to continue chemical reaction process. So the amount of time required to proper cure na laminate it's called cure cycle, because a cure cycle determines the production rate of a part. It is desirable to achieve the proper cure within the shortest time, that's the shortest cure cycle.

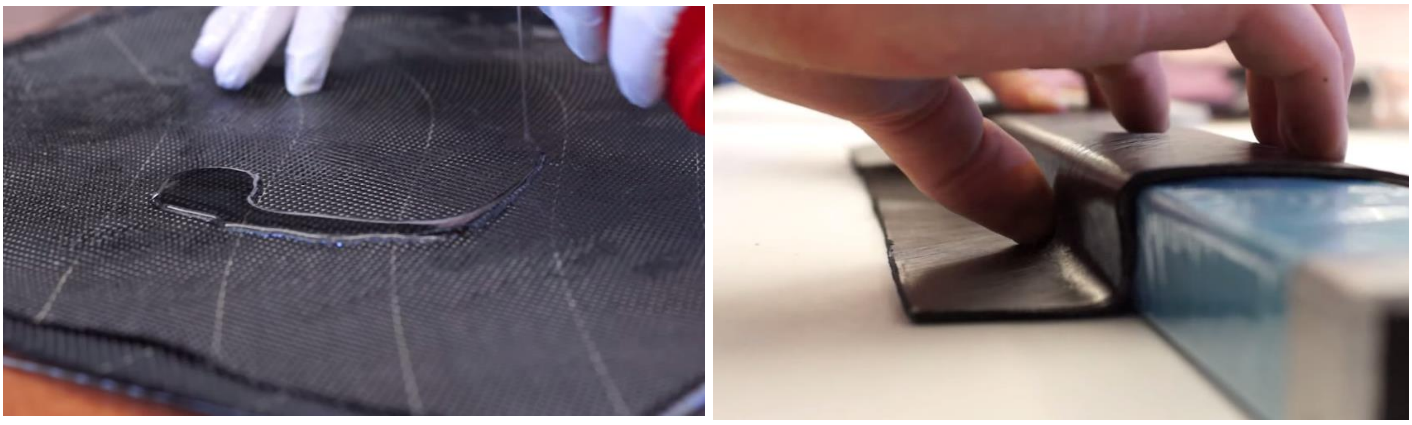
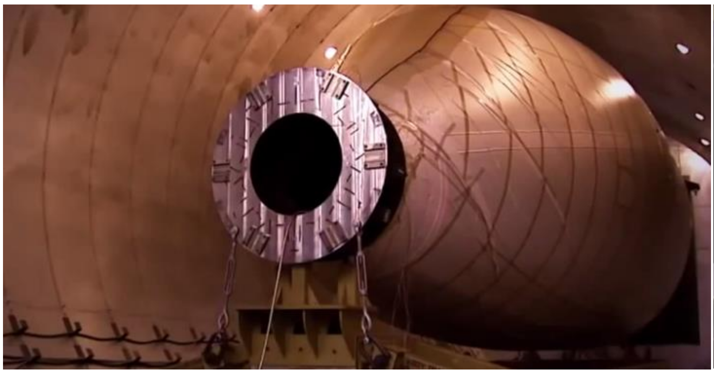


Figure 18 - Left: Liquid (A) stage, Right: prepreg (B stage).

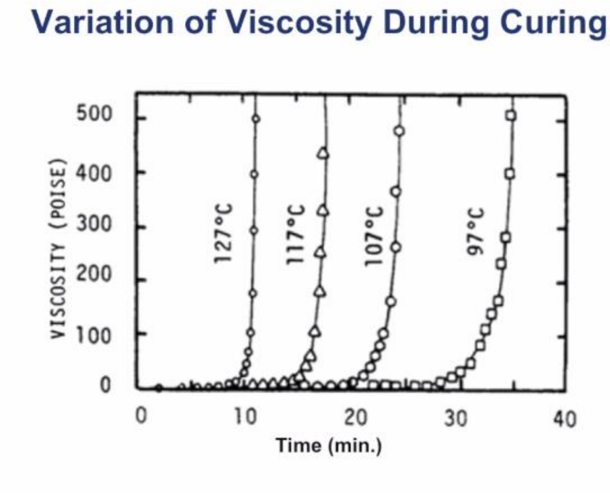
Figure 19 – The temperature and pressure inside the chambers where the resin is hardened are controlled.

Figure 20 - Resin going through chemical reaction and increasing its viscosity.

Fluid viscosity: measure of the resistance of the fluid to flow under shear stress.



Gel time is the time at which viscosity increases sharply and a lot of cross linking started.



Variation of viscosity during isothermal curing of an epoxy resin

A proper flow of resins through fiber network is critical in producing void-free parts.

If the resin flow is not good, which has a very high viscosity, then it doesn't get to the fibers.

Figure 21 – Applying resin to the fiber cloth.

In that case, there will be a lot of voids produced because the resin couldn't flow to wet the fiber. When the chemical reaction is completed, the thermoset polymers will have a reduction in volume. This is a result of rearrangement of polymers into a more compact mass. Typical shrinkage for polyester and vinyl ester resin is 5% to 12%. And that's pretty significant.

However, epoxy is pretty stable. And the amount of shrinkage is around 1% to 5%. Voids always happen in composite manufacture. I don't believe you can get rid of voids 100%. But a manufacturing engineer's job is to minimize voids. So typical causes of voids is air bubbles and volatiles getting trapped in the resin during chemical reactions.

Figure 22 - Fiber with voids

The Air bubbles occupy spaces. In composite manufacturing vacuum pressure is very important to get rid of air bubbles and volatiles. And this is not just to provide pressure. It has a function so to get rid of voids.

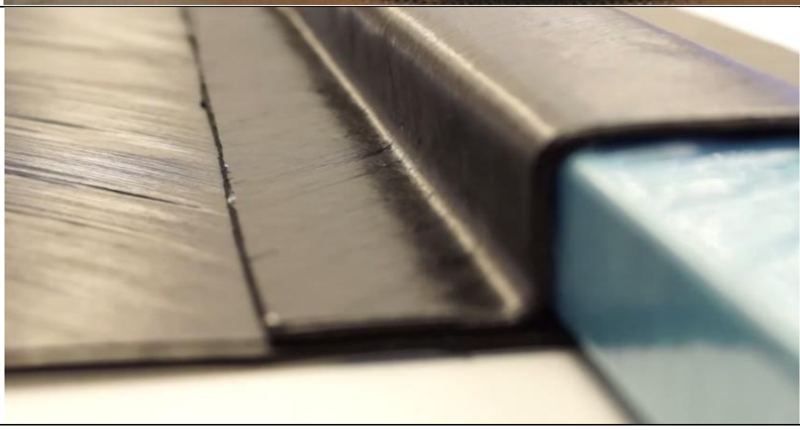
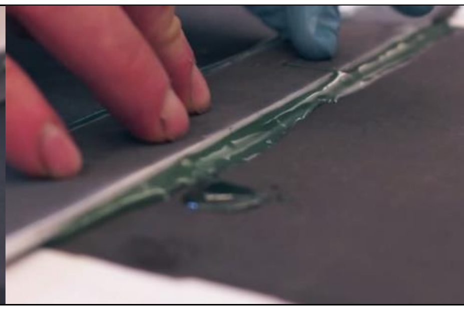
Common causes

- Inability of the resin to displace air from the fiber surface as fibers are coated with resin (most common).
- Air bubbles and volatiles entrapped in the resin.
- Air entrapped between various layers during the lamination process.
- For polyesters: dissolved solvents, moisture, and chemical contaminants in the resin and the styrene monomer that volatilize during curing.

Figure 23 - common causes of voids

Figure 24 - applying vacuum to get rid of air bubbles and volatiles

Terminology

Prepreg tape	
Prepreg woven fabric (that is 0-90)	
Preform – they have no resin, no matrix, just the dry fibers in a certain shape.	
Co-cured – process in which two materials are cured together at the same time.	
co-bond – process in which one uncured material is bonded to a cured material and then cured to it.	
Secondary bonding – bounding 2 fully cured parts together using adhesive	 

Microstructure

If you look at the quality of the parts, if the fibers are uniformly dispersed, that's a good quality. In this case, the dark area is an epoxy. Then when you've got too much epoxy there, it's called resin rich area. In the case of resin rich, the resin epoxy is very weak material, and you could initiate micro-cracking in the resin rich area. On the other hand, in some areas if the resin is not enough, for example, if the viscosity is too high it doesn't get to the fibers, so there's no resin there. And that's called resin starved, or resin poor. The fibers must be surrounded by the matrix material, otherwise the shear transfer mechanism will not function. And if a fiber is broken, that fiber will not recover strength, because there's no resins surrounding the fibers.

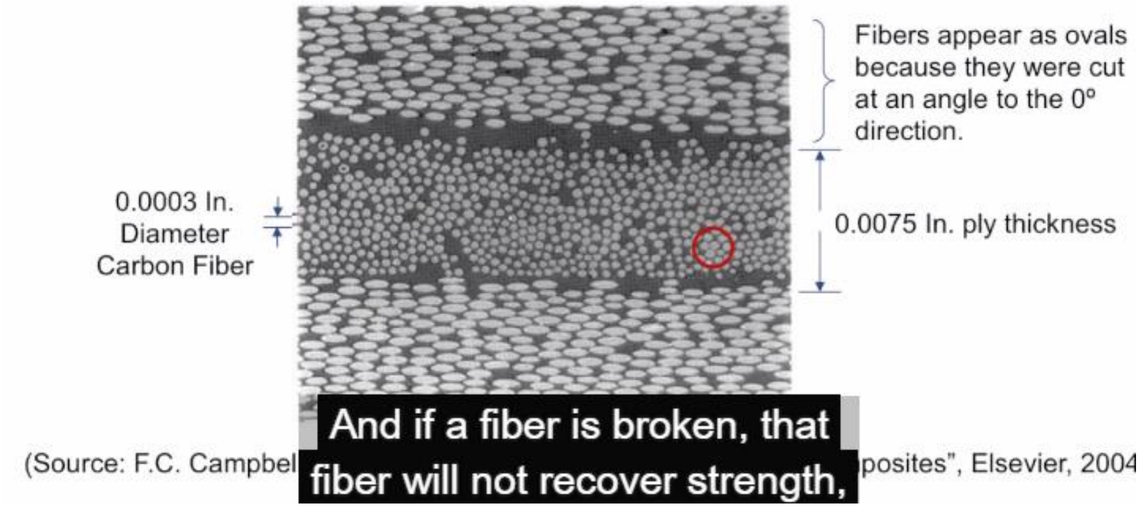


Figure 25 – Resin Starved Area

Toughened vs untoughened epoxy

Figure 26 – Delamination caused by impact on a composite with polymeric matrix

Thermoset polymers don't have that good impact resistance. Therefore when a composite with a polymeric matrix is impacted they could be delaminated. And that's typical of thermoset. So if you want to improve the toughness of the material, use some thermoplastic particles. See, the thermoplastic has much better impact resistance than thermoset. So use some of the thermoplastic particles or interlayer, embed it into thermoset polymers such as epoxy, and that's called toughened matrix.

Toughened matrix is great because it has more resistance to impact, but in terms of manufacturing, this cost is going to be higher.

Figure 27 - Thermoset resin with thermoplastic particles to make it more resistant to impact when cured.

However, toughened epoxy has a higher viscosity, may not be well suited for resin infusion manufacturing methods.

Thermoplastic Composites

The thermoplastic prepregs, they're not sticky, and they are not very flexible, just like a piece of metal. So what you do, is you take this thermoplastic, which is composite, and you heat it up at high temperature is above 320ºC. And then you apply pressure and you get this shape you want through the mold you design.

Figure 28 – Heating a composite with thermoplastic matrix to shape it.

There's no chemical reactions. So it could be shaped and formed by the applications of heat these are the common methods to make thermoplastic [? matches ?] composite.

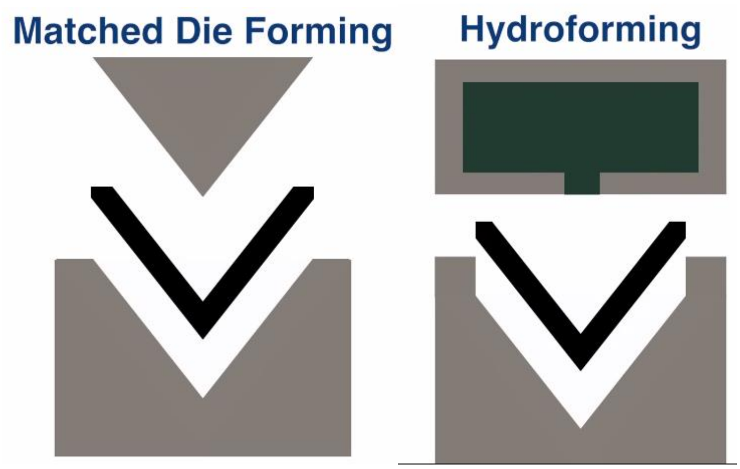
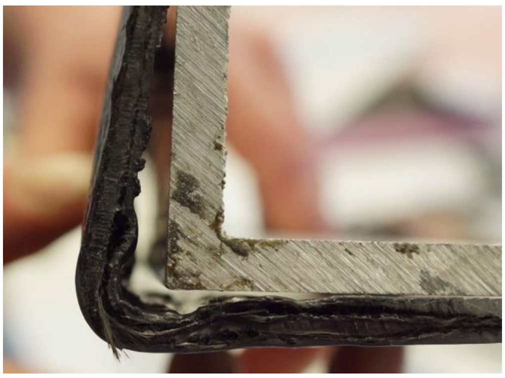
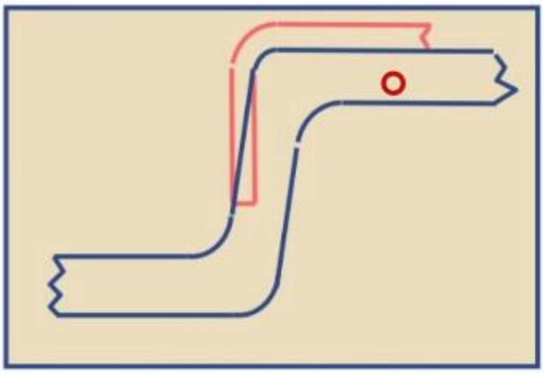


Figure 29 – Two methods of forming composites with thermoplastic matrix

Tooling considerations

When heating up the composite inside the tool, we have to consider that the coefficient of thermal expansion of the metal is higher than that of CF composite.

Also, there's springback, which is when the composite cools down and deforms due to residual stress. So for example if we want to have a composite part with a 90º angle we can't make a tool with a 90º angle. The tool has to be more than 90º so that after the springback the composite is forms the desired 90º angle.

Lamina and Laminate

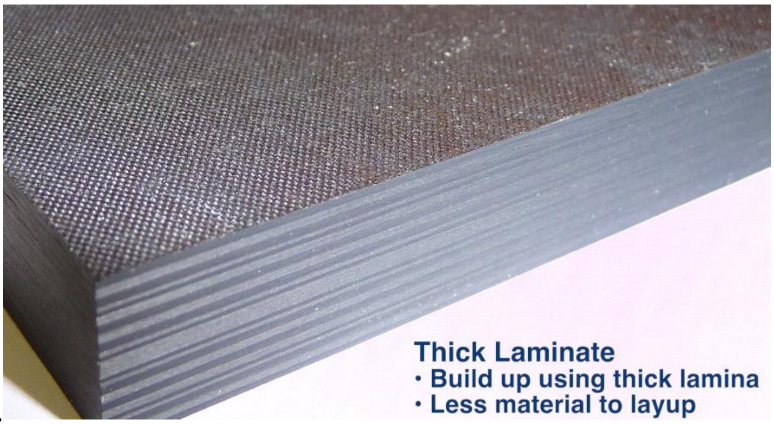
Lamina = ply

Laminate = several plies on top of each other

Use thick or thin plies?

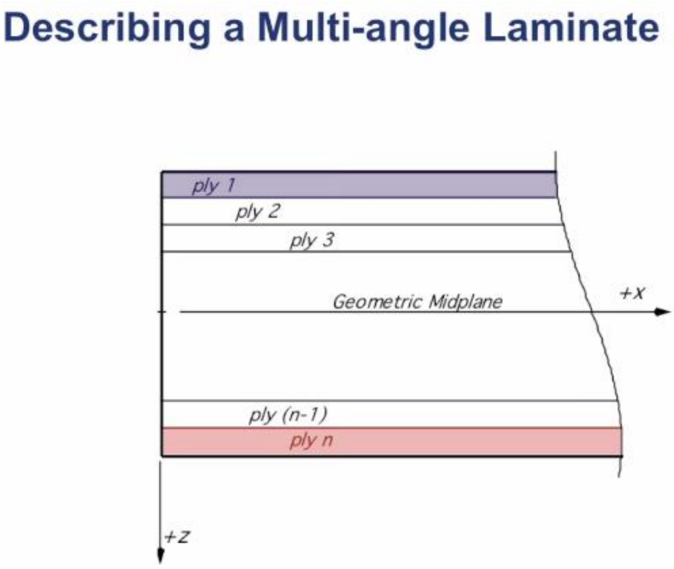
1. Depends on the thickness of the laminate you want to make.

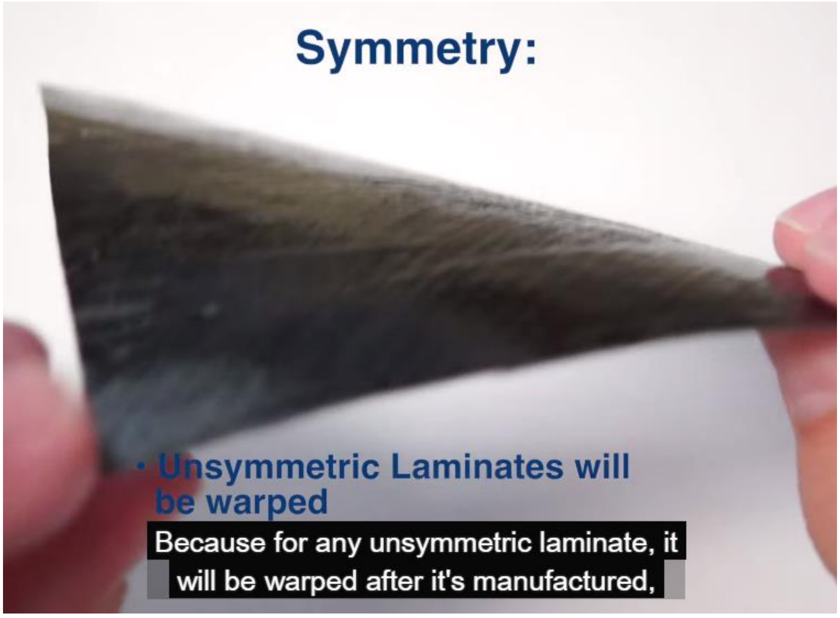
If you want to make a thick laminate it makes sense to use a thicker ply because it doesn't have to layer many times.

So the manufacturing costs go down. 

a. If you have a thick laminate, then you'll be better off using thin plies because then you have more freedom to tailor the material properties by changing the fiber angles.

2. If you've designed a sandwich structure which only use 6 or 8 plies on the face sheet, if you use very thick plies, it has a very limited freedom, flexibility to tailor the structure.





Balanced laminate:

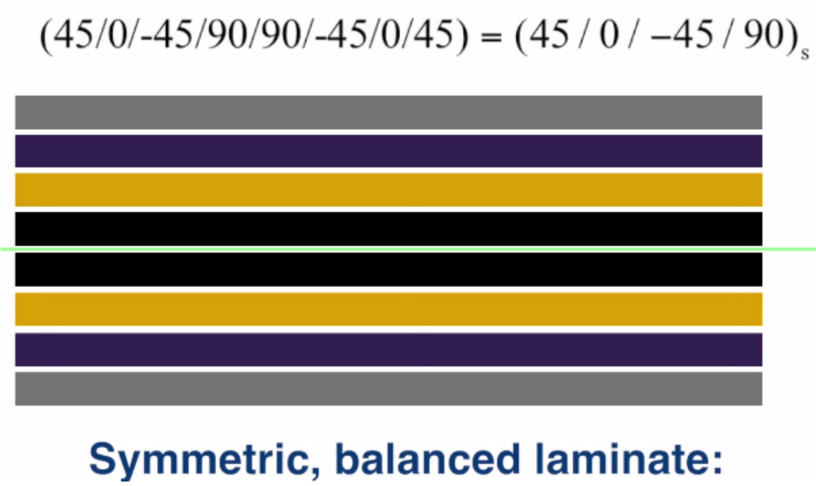
- A 45° ply must have a corresponding -45 ply to be considered balanced.

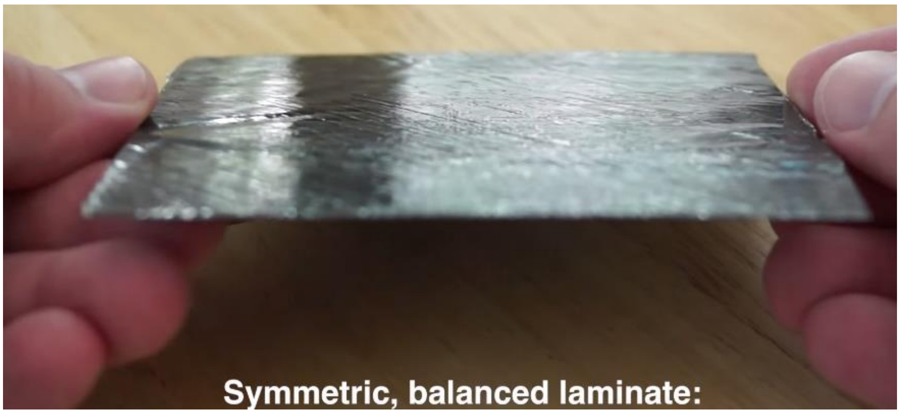
Notation for a Laminate

- Describing the "Stacking Sequence"

$$(0/45/90/90/45/0) = (0\,/\,45\,/\,90)_s$$

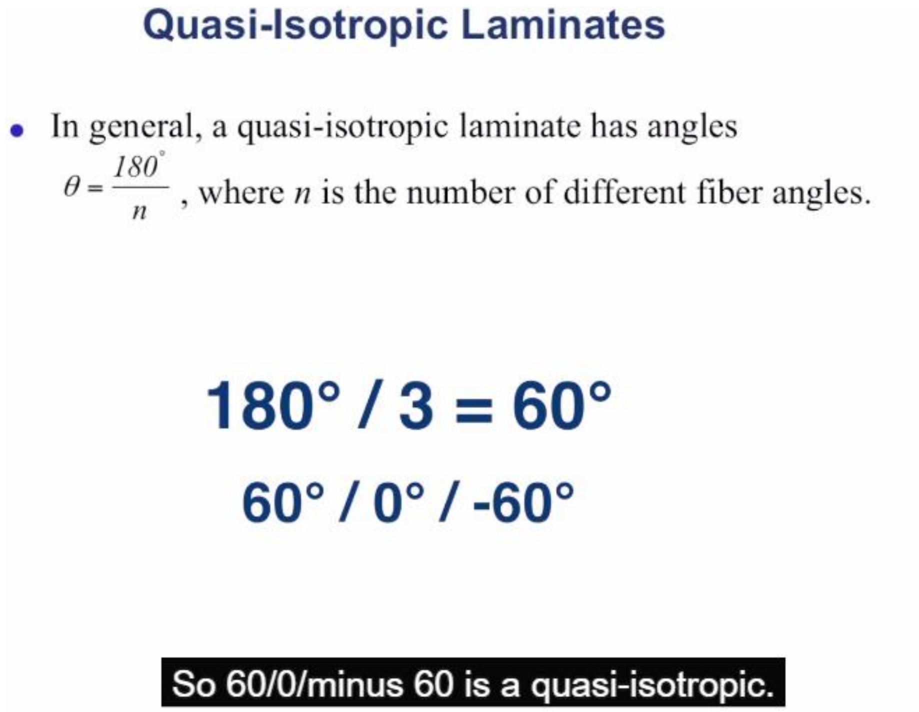
This is a symmetric but unbalanced laminate. This one will not be warped because it's symmetric, but when you apply tensile stress there will be a shear strain





If you apply tensile tress you will have no shear deformation.

While not often encountered, we show the notation for describing unbalanced or non-symmetrical laminates. Unsymmetric laminates tend to warp after curing due to internal stresses. Different unsymmetric stacking sequences will result in varying warpage.



Types of damage

Damage is categorized by its visibility to a trained observer

1. Non visible Impact Damage (NVID)
2. Barely Visible Impact Damage (BVID)
3. Visible Impact Damage (VID)

CAI, compression after impact, you take a composite part then impact it, then you test the materials under compression, and that determines the compressive strength after impact.

CAI is a good indication, a good parameter for damaged tolerance design. It's a damage resistance of the material. So if you look at CAI for untoughened resin, untoughened epoxy versus CAI for toughened epoxy, they're quite different. The CAI for toughened epoxy is much higher than the CAI for untoughened epoxy.

Detection methods of damage

Summary of NDI Methods

METHOD OF INSPECTION	TYPE OF DEFECT							
	DISBOND	DELAMINATION	DENT	CRACK	HOLE	WATER INGESTION	OVERHEAT AND BURNS	LIGHTNING STRIKE
VISUAL	X (1)	X (1)	X	X	X		X	X
X-RAY	X (1)	X (1)		X (1)		X		
ULTRASONIC TTU	X	X						
ULTRASONIC PULSE ECHO		X				X		
ULTRASONIC BONDTESTER	X	X						
TAP TEST	X (2)	X (2)						
INFRARED THERMOGRAPHY	X (3)	X (3)				X		
DYE PENETRANT				X(4)				
EDDY CURRENT				X(4)				
SHEAROGRAPHY	X (3)	X (3)						

NOTE:
(1) FOR DEFECTS THAT OPEN TO THE SURFACE
(2) FOR THIN STRUCTURE (3 PLIES OR LESS)
(3) THE PROCEDURES FOR THIS TYPE OF INSPECTION ARE BEING DEVELOPED
(4) THIS PROCEDURE IS NOT RECOMMEDED

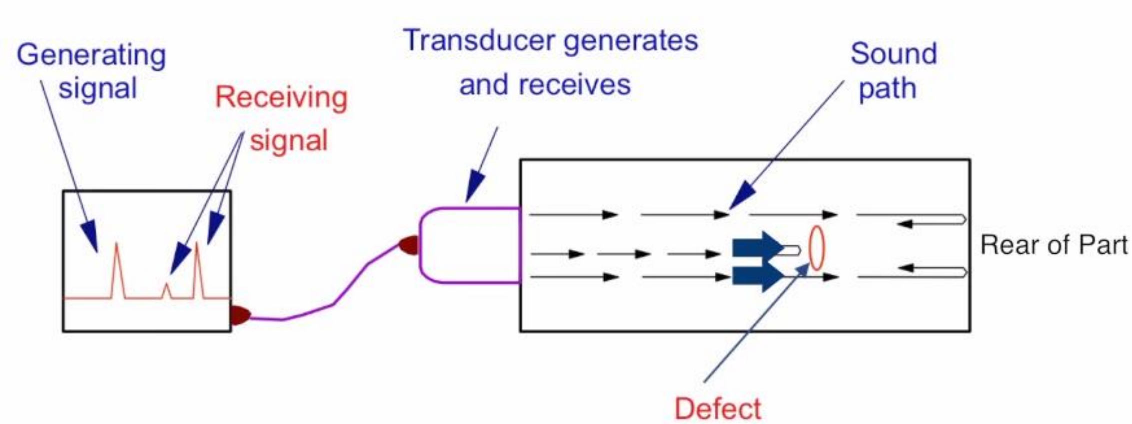
Manual inspection is the fastest and typically cheapest method of inspection. However, it relies on operator expertise and is not as sensitive compared to other techniques.

1. visual inspection. And you just look at the composite structure to see if they are damages or not. And visual inspection could be aided with flashlight and mirrors, and could help determine if there's a damage or not. So typically, a technician walk around the aircraft to look for damage.

2. Tap test. You tap structures and listen to the sound. Based on the frequency of the sound you can tell if that part is damaged or not. Also, there are different tap hammers developed. So different companies have different types of tap

hammer to detect damage in composites.

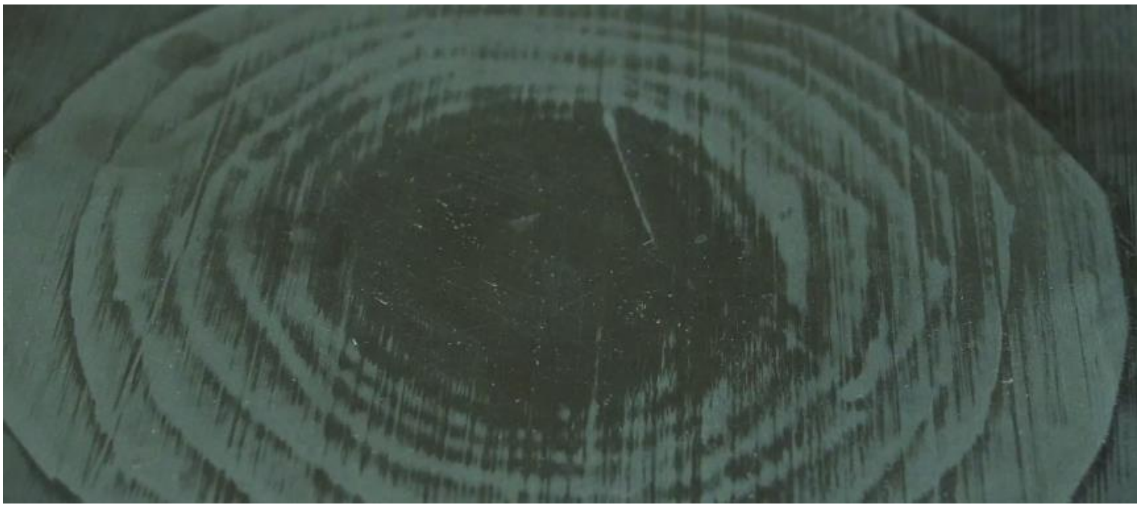
Ultrasonics. Ultrasonic is very effective in detecting delaminations, impact damage, disbonds, foreign object, or water ingressions. However, it needs a free surface for sounds to reflect it from and typically use couplings such as water for inspection.



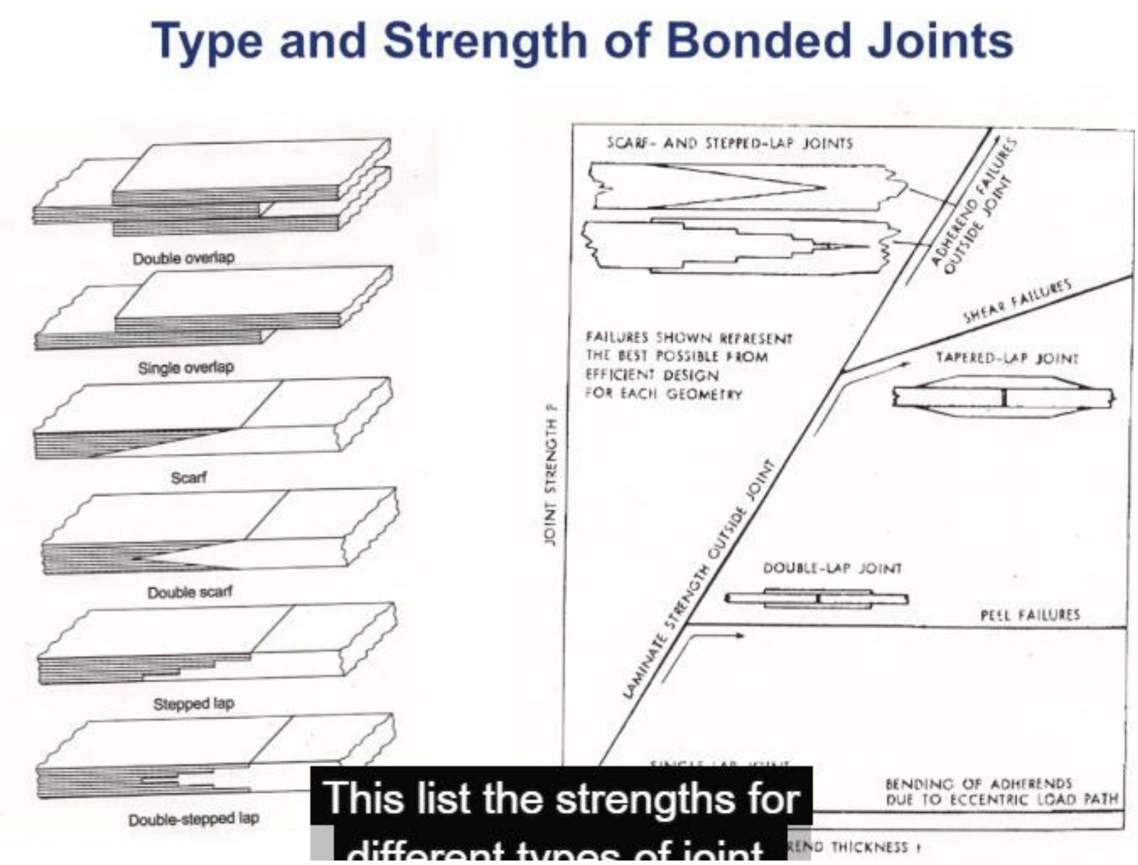
3. Thermography You apply a short time duration of heat to the surface of a composite part. You could use a heat gun. Or you could use heat lamp to generate heat quickly. Then, the surface cools over time. So during the cool down, if this is internal delamination or internal defects, then the cool down rate is going to be different. And the differences are recorded, and the images of defects appear.This is a newer technique.

Repairing

1. wet layup
2. with prepreg
3. bond repair: scarf repair



Generally bolts aren’t used in composite repair because they further weaken the structure.



Scarf repair is the best. In single or double overlap you have a huge shear concentration on the overlap.

Figure 30 - Scarf repair

Strengths and Limitations of Composites

STRENGTHS

- Excellent specific strength and stiffness
- Customizable properties
- Part size/shape potential
- Fatigue resistance
- Corrosion resistance
- Life cycle cost potential

WEAKNESSES

- Weak out-of-plane properties
- Prone to delamination
- Low impact resistance
- Sensitivity to environment
- Mechanical property variability
- Conductivity (response to lightning)
- Galvanic effect on adjoining metals
- Efficiency of joints
- Complexity of analysis and design

Figure 31 – THe joint strength in composites is not very good. So you should design a large part in order to minimize the number of joints.

Cost Study- Metal vs. Composite