Fiber Reinforced Polymer (FRP) Construction Seminar

Ivar Thorson

Department of Advanced Robotics
Istituto Italiano di Tecnologia

August 7, 2012

Seminar Schedule

This seminar should take about 7-8 hours in total:

- Aug 7 (10:00-12:00) Theory, safety, construction techniques.
- Aug 8 (14:30-17:30) Build some test samples.
- Aug 9 (14:30-16:30) Trim, cut, label, break those samples

Please, stop me as soon as you have a question!

WARNING:

Bring appropriate clothes tomorrow or you cannot participate.

DANGER:

Some of the materials you will handle will be poisonous and carcinogenic. Please handle, use, and dispose of them responsibly!

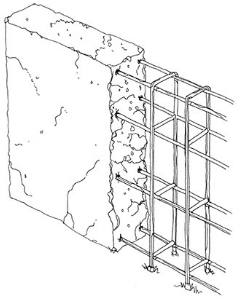
Today's Presentation

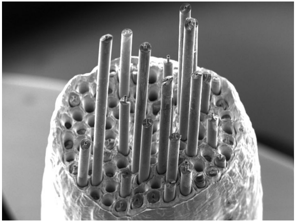
A Brief History

- Glass fibers first made in 1890's as possible silk substitute
- British engineer A.A. Griffith studied crack propagation in increasingly small rods of glass (1920). Discovered that the thinner the fiber, the stronger the glass.
- Macro- properties of glass different from micro- properties: strong tensile strength retained, but much less brittle. Why? The thinner the material, the longer the relative distance between flaws.
- A way to hold the fibers together was badly needed
- First artificial plastics (polyester resins) appeared in 1930's, but only became commercially feasible in the 1950's
- Carbon and Aramid fibers took off in the 1970's
- Now they are used for bathtubs, surfboards, boats, housing insulation, aircraft, cars, wind turbines blades, body armor, spacecraft, etc.

How Composites Work

- Much like reinforced concrete, plywood, or metal crystals in alloys, two materials combine to form a stronger structure
- A matrix of high compressive strength material binds together strands of a high tensile strength material
- Matrix is usually more elastic than fibers
- Matrix deflects until the load is carried by fibers
- Matrix only carries a distributed load a short distance
- Stiff fibers carry load longer distances



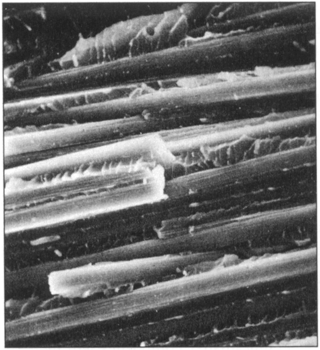


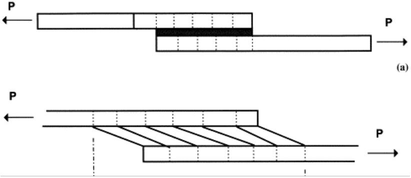
Fibers are typically orders of magnitude stronger than the matrix.

Photos: Emma Kelly. www.femas-ca.eu/main/press_entry_point.php

Extra Resin Is Bad in FRPs

- We desire as little resin as is needed to connect the fibers
- Extra resin is just extra weight; 20-50% optimum depends on fabric
- Better construction methods produce parts with less resin





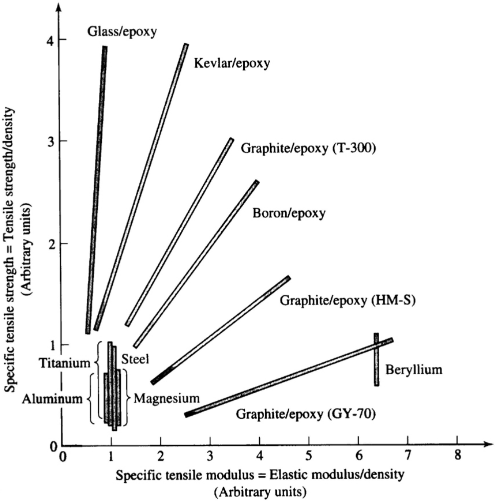
Photos: D. Agrawal and Lawrence J.Broutman. Analysis and Performance of Fiber Composites

Strength Characteristics

Very anisotropic: modeled as cosine to the fourth power between load and fiber orientation. Worst case is load carried only by resin.

- Resin tensile strength: 50MPa, $1.36 g/cm^3$
- Fiber tensile strength: 5000MPa, $1.76 g/cm^3$
- Compare with steel: 800MPa, $8 g/cm^3$

The advantage of composites is having strength ONLY in the directions you need it!



Photos: www.mrl.columbia.edu/ntm/level1/ch05/html/l1c05s03.html

Monocoque ("single shell") Structures

FRPs are best used in monocoque structures: stiff, load-carrying skins with complex shapes.

Benefits:

- Extremely light, strong, and stiff
- One molded part can replace several interconnected parts

Disadvantages:

- Generally not machinable, threadable without metal embedments
- Requires time-consuming mold-making
- Very anisotropic strength properties
- Hard to mass-produce

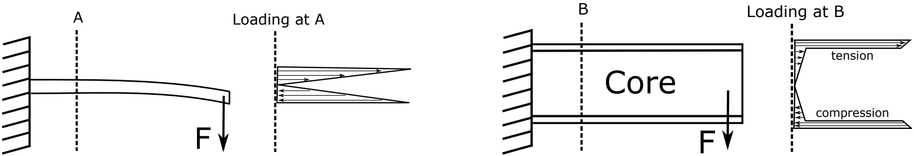
Internal truss structure:

Monocoque CFRP structure:

Photos: en.wikipedia.org/wiki/Space_frame, www.motobug.com

Composite Sandwich Structures

Problem: How can a thin skin carry a load without buckling?



Solution: Make a sandwich structure with a third material between the FRP layers:

- Core materials have only shear loading...but they *are* structural!
- Low density cores add same weight than an extra layer of fabric.
- Increased stiffness, effective strength
- Balsa wood, plastic foams, aramid or metal honeycombs common in aircraft

Glass Fibers

Glass fibers are 5-25μm diameter and (like window glass) are made of a mixture of silicates to reduce the melting temperature of pure SiO_2.

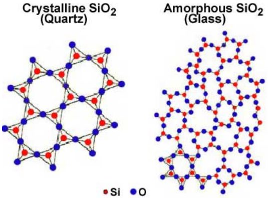
Three common mixtures are named:
Electrical, **C**hemical, and **S**trength.

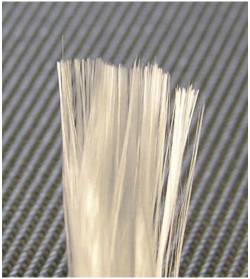
E-glass 54% Si, 15% Al, 17% Ca. (3.4GPa)

C-glass 64% Si, 13% Ca, 8% Mg. (3.3GPa)

S-glass 64% Si, 25% Al, 10% Mg. (4.8GPa)

Other mixes exist for high elasticity, better radiation shielding, optical light transmission, etc.





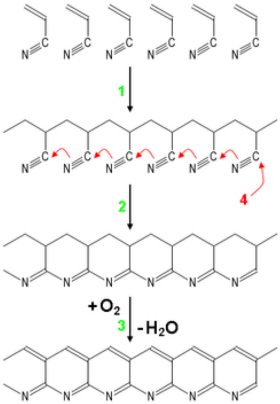
Photos: www.ndt-ed.org/EducationResources/CommunityCollege/Materials/Structure/solidstate.htm, en.wikipedia.org/wiki/File:Glasfaser_Roving.jpg

Carbon Fibers

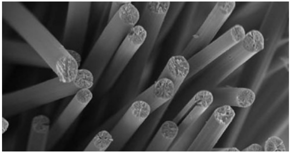
Two manufacturing processes:

PAN From polyacrylonitrile or rayon. More common. Invented 1958, Roger Bacon heated strands of rayon until it carbonized the fibers.

Pitch From petroleum tar pitch. More easily customized for zero thermal expansion, high conductivity, or high stiffness.



Carbon fibers are also known as "graphite", especially when heat treated for additional stiffness or strength. Over 6GPa tensile possible. Fibers typically 5-10μm diameter.



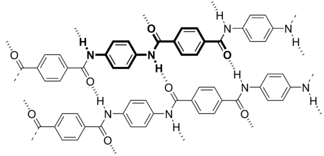
As its tensile strength increases, often so does carbon's stiffness, thermal, and electrical conductivity. Can be 5x glass's stiffness!

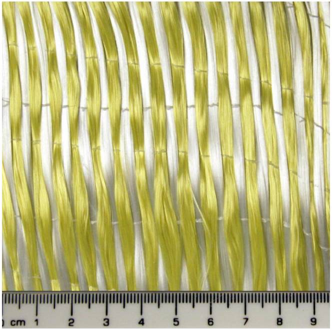
Photos: en.wikipedia.org/wiki/File:PAN_stabilization.PNG, www.utsi.edu/research/carbonfiber/UTSI-CF.htm

Aramids

"Aromatic polyamides" are a synthetic family of fibers including brand names Kevlar, Nomex, Vectran, etc.

- Invented in 1965 by DuPont researcher Stephanie Kwolek
- Really tough, often used in body armor
- Nonconductive, no melting point
- Fire resistant
- Amazingly difficult to cut with scissors
- Excellent abrasion resistance, impact resistance.
- Bonds better to epoxy than other resins.





Photos: www2.dupont.com/Kevlar/en_US/.../KEVLAR_Technical_Guide.pdf, www.nauticexpo.fr/fabricant-bateau/fibre-aramide-22814.html

Other Fibers

Developing new types of composite fibers is an active research field:

Dyneema/Spectra Less dense than water, part of the ultra-high-molecular-weight polyethylene family. Tremendously strong by weight, but so slippery that they are difficult to bond to with polymers.

Metal fibers Boron, aluminum, titanium, silicon carbides, etc

Carbon nanotubes Carbon-based molecules will probably be the highest strength materials for the future because of its unique position on the period table (low molecular weight + a good number of free electron orbitals).

Unwoven Fibers

- Roving (spools) - Often chopped, sprayed into mats for cheap material with isotropic strength properties.


- Unidirectional - Provides strength in a single direction

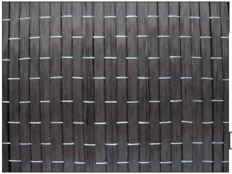
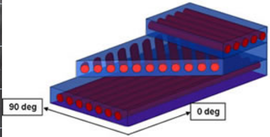



Photo credits: Dusty Cline/Dreamstime.com, www.carbonfiber.com.au/prod16.htm, www.quartus.biz/resources/whitepaper/composite/, www.indiamart.com/shreelaxmienterprise/fiber-glass-products.html,

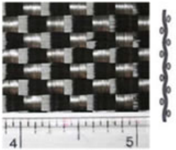
Weaves

Fibers are often woven into fabrics for convenience:

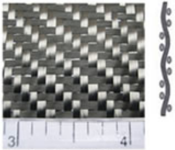
- Plain (Over 1 / Under 1)
- Basket (Pairs of 1/1)
- Twill (2/2, 2/1)
- Crowfoot (3/3, 4/4, 3/2, 4/1, etc)
- Satin (5/5, 6/1, or more!)
- Leno (Twisted pairs so it doesn't unravel)

Generally, the looser the weave, the higher the strength and ability to drape over curved surfaces. But they also unravel much more during handling.

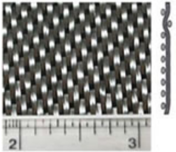
24k, 3k, etc refer to number of fibers per bundle.



24k Plain Weave



3k 2x2 Twill Weave



3k 8-Harness Satin Weave

Photos: www.quartus.biz/resources/whitepaper/composite/

Fibers can be Dangerous

DANGER:

Evidence exists that many synthetic fibers such as these are possibly carcinogenic. Avoid handling with bare hands. *Really* avoid getting them in your lungs! Always use masks when cutting, grinding, or sanding fibers.

Other things to consider:

- Dirt and oils on your hands may affect how well resins bond to the fibers. Cleanliness is important.
- Fibers (and resins) often absorb moisture from the air; ideally they are heated for several hours so it evaporates prior to bonding.
- The more you handle a fabric, the more you will disturb the weave and decrease the strength of the part.
- Orient the fibers in the direction you want to carry load.

Resins

The resin matrix is the other component in FRPs. Usually a plastic (a.k.a. polymer), five considerations are important:

Adhesive strength : How well the resin sticks to the fibers.

Cohesive strength : How well the resin sticks to itself.

Wettability : How well the resin wets out the fibers.

Activity : How well the resin chemistry matches the fibers.

Stability : How the resin resists degradation.

Typically, the tensile strength of the resin is orders of magnitude lower than the fiber strength. Imagine hard plastics vs steel cable to intuit why.

Resin conductivity of heat and electricity is usually very poor, which is a problem for high-temperature environments. Resins lose strength with temperature – which is why it's good to paint composite airplanes white.

Resin Systems

Resins are chemically important because of their myraid uses:

- As structural matrix with fibers
- For gluing cured pieces together
- As a syntactic foam filler (microballoons)
- For gluing metal to composites
- As surface finish or paint substrate
- As a sealant for chemicals/fuel

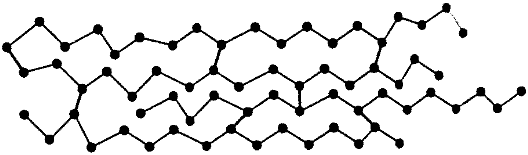
The chemistry of resin must match all of these – bonding must occur to many different materials! Go with one supplier of a "Resin System" and don't mix and match bonding chemicals.

Commonly Used Resins

Polyester Cures in big, cross-linked molecular chains by itself, once hardener starts reaction. Good tolerance for error in mixing. Cheap. 55MPa tensile, 120MPa compressive typical.

Vinylester Lower viscosity, bonds better to kevlar and carbon fiber, slightly stronger than polyester.

Epoxy Stronger because of A+B molecular chemistry: hardening requires two molecules cross-link. Will NEVER cure if improperly mixed. Sticks to almost anything. 75MPa tensile, 140MPa compression typical.



Measuring resin hardness is useful for determining cure

Resins can be Dangerous

DANGER:

Some chemicals in resins can penetrate the skin, causing blindness, severe skin irritation, and cancer! Wear gloves, avoid contact with the skin.

DANGER:

MEKP (methyl ethyl keton peroxide) used as a promotor for poly/vinyl-ester resins, is highly poisonous, and is a high explosive!

DANGER:

Many curing reactions are exothermic. Mixing a large quantity (more than 500ml in a cup) of room-temperature fast-curing resin can cause a fire!

DANGER:

Don't use anything but soap and water when washing off resin off skin: solvents may interact or allow resins to go through your skin more easily.

Other Considerations

- Strength depends on many factors: hand-made vs industrial aircraft parts may differ by a strength factor of 5x, despite same materials.
- High temperatures, pressures can produce dramatically stronger parts, because heat helps resin molecules migrate to find their bonding pairs.
- Post-curing (4-8 hours at +20C cure temp) can help even amateurs.
- Shear strengths of woven fabric is about half tensile or compressive.
- Once cured, most resins are just plastics and are safe to handle.

WARNING:

Poly/vinyl-ester contain styrene, making them somewhat toxic, and meaning they dissolve styrene foams. Use only epoxies with styrene foam!

WARNING:

Poly- and Vinyl-ester resins shrink by a few percent during cure, making them unsuitable for dimensionally accurate molds.

Closed Cell Foam and Wood Cores

Polystyrene "Styrofoam." White or light blue. 16-640 kg/m^3. Don't use expanded bead type.

Polyurethane Yellow or brown in color. Expanding 1- and 2-part liquid foams available. 6-800 kg/m^3. More resistant to solvents than polystyrene.

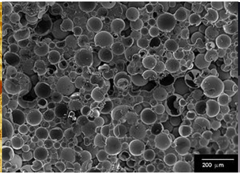
Polyvinylchloride Blue-colored. PVC foam. Can be heat-formed.

Polymethacrylimide Branded Rohacell. Excellent but expensive.

Syntactic Essentially resin diluted with glass micro-spheres.

Balsa Perpendicular-cut wood grains resist crushing better than any equivalent foam. 40-340 kg/m^3.





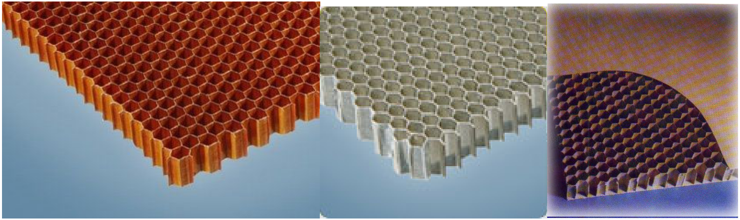
Photos: building.dow.com/na/en/products/insulation/squareedge.htm,

Honeycombs

Higher strength cores can be made using honeycombs:

- **Metal** Aluminum most commonly, but titanium and others exist.
- **Aramid** Nomex paper honeycomb often used commercial aircraft.
- **Paper** Kraft paper is cheap...just don't get it wet!
- **Glass** Expensive, pre-cured fiberglass honeycomb.
- **Carbon** Expensive, pre-cured carbon fiber honeycomb.

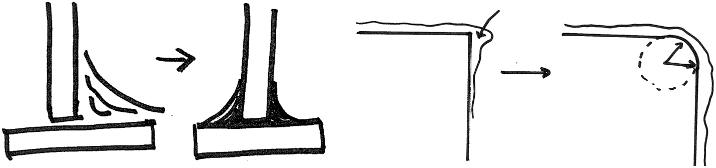
Can only be gently bent into simply (single axis) curved shapes. Harder for an amateur to use than simple foam or wood. Be wary of cell defects!



Photos: www.indiamart.com/universal-metaltek/products.html, www.bombaypack.com/products/product2/product2.htm, www.corecomposites.com/composites/core/honeycomb/nomex/

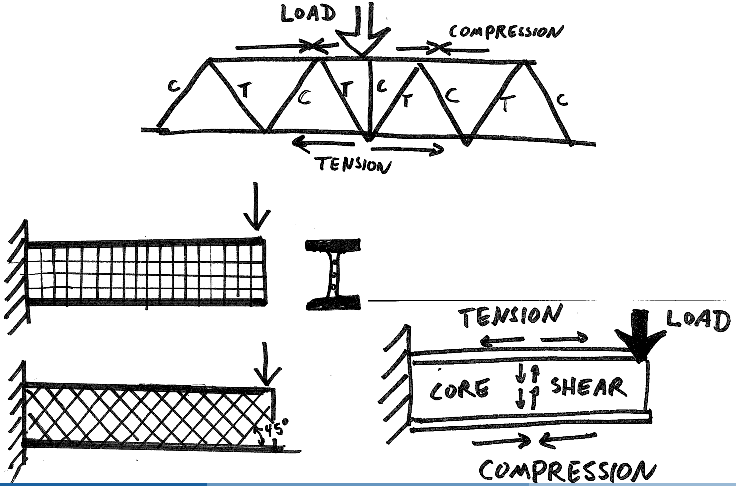
Amateur Design Rules of Thumb

- Use as few pieces as possible to do as much as possible.
- Compound curves create more rigidity than simple curves.
- Compression loads create buckling in thin pieces.
- Torsion loads create compression loads, and are often the limiting factor.
- Avoid stress concentrations and sharp corners whenever possible.
- Embed metal and machine it later to create precision dimensions.
- Real-life strength is hard to predict for amateurs. Build, test to failure, and rebuild if you want certainty.



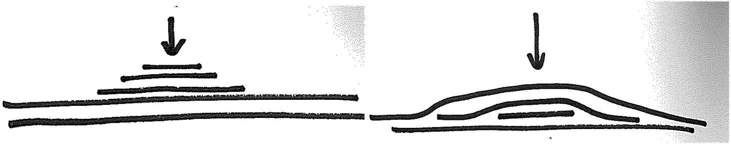
Avoid Stress Concentrations

Orient the fibers in the direction of load. Don't allow shear loading of the fibers, since its shear strength is often half of its tensile or compressive strength; orient the fabric at 45 degrees ("on the bias") in such cases.

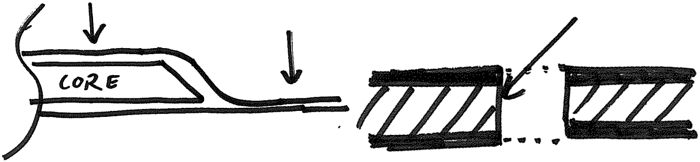


Core Materials

- Core materials must be continuously connected because of shear loading (i.e. always glue foam core pieces together!)
- Core materials often crush easily; add extra layers of fabric at stressed points like corners, supports, or bolt attachments.

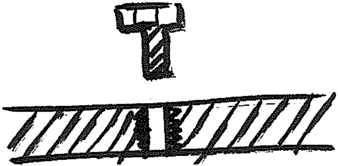


- Do not leave the core material exposed to air; avoid putting holes through the core material because it crushes as the threads tighten.

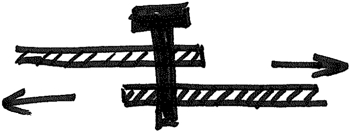


Holes the Wrong Way

- Most amateur FRPs cannot be tapped very well; threading tends to pull the fabric layers apart.

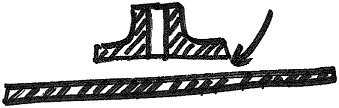


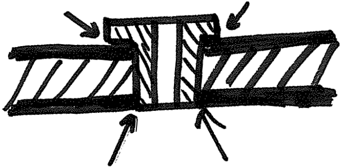
- Shear-loading your bolts is never ideal, but it can work for small loads.



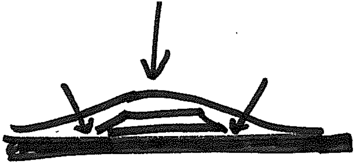
Holes the Right Way

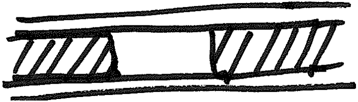
- Low stress parts can use flanges and adhesive, or metal insets





- Medium stress areas should use metal embedments.

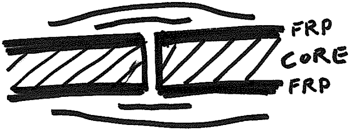


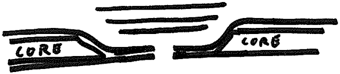


- For high stress parts, wrap unbroken fibers around metal embedments.

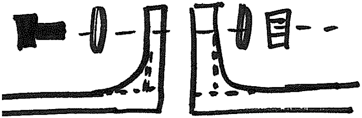
Joining Cured Pieces

- Good bonds can be stronger than the original FRP structure
- Lap joints need not be long, since stress concentrates at edges.
- Butt-joints are easy and can be done with tape-width strips of fabric





- Another way is to use many small bolts, which allows (laborious) diassembly:



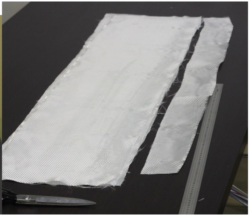
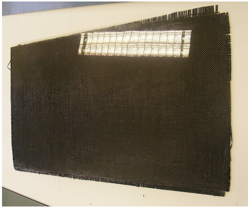
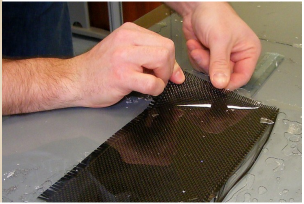
Construction Methods

It's time to see how we can actually build practical things using this technology! We will consider only the simplest construction methods here, and ignore resin infusion, autoclaves, casting and molding, and other industrial considerations.

1. Basic "wet" layup
2. Vacuum-bagged layup
3. Moldless layup
4. Layup in a mold

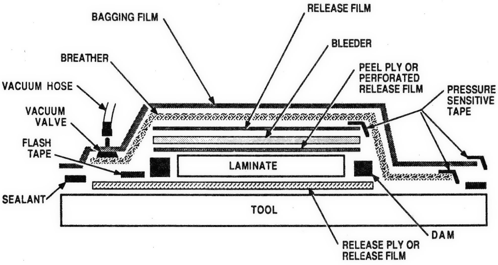
Wet Layup

- Essentially just "painting strong fibers with plastic glue".
- Simple, needs no tools, but makes heavy parts with poor surface finishes

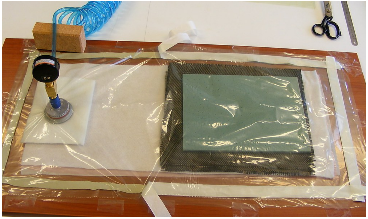





Vacuum Bag Layup

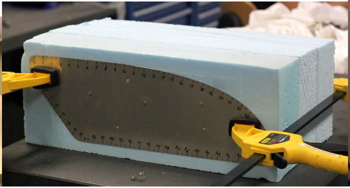
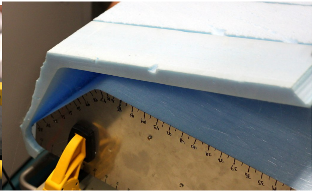
- Use atmospheric pressure to squeeze out unneeded resin, compress fibers
- Accessible technique for amateurs

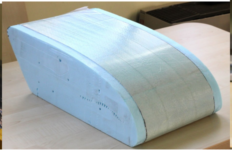
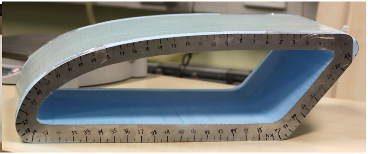
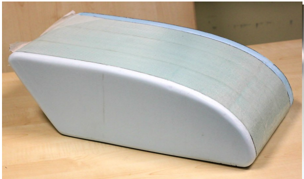


LAYUP SEQUENCE FOR BAGGING OPERATION



Moldless Composite Parts

Doubly-Molded Composite Sandwich Parts

Workshop Preparation

- Clean surfaces are important: keep table, fabric, mold, etc free of dust
- Imperfections in molds and cores become imperfections in your parts.
- The fastest way to a good part is to spend 90% of your time doing careful preparation, and only 10% doing the layup...or you will spend 500% of your time sanding and repairing!
- You only have 30 minutes before the resin starts to harden; prepare everything before mixing any resin!
- Temperature should be 15C to 30C for room-temperature cures. The hotter it is, the less time you have to work. Don't work in direct sunlight on a hot day!
- Humidity should ideally be less than 50%. Some resins are more sensitive to this than others.
- Clean immediately! Cured resin is impossible to remove from tools.

Construction Rules of Thumb

- The goal is to make structures with less than 50% of mass as resin, but still having all the fibers “wet out”. Low viscosity helps.
- Air bubbles are bad, cosmetically and structurally. Absorbed water can become a gas again under low pressures of vacuum bagging, too.
- Work carefully and cleanly; don’t get resin on both gloves, although sometimes getting it on one glove is useful/inevitable.
- It is very useful to have a partner with clean hands to help; sometimes just two hands is not nearly enough.
- If doing a layup on a previously air-cured piece, wipe the surface clean of waxy buildup (amine blush) from the epoxy before beginning.
- Adding peel-ply and removing it after cure provides a rough surface suitable for later bonding

Vacuum Bagging Rules of Thumb

- Don't allow resin to flow into your vacuum pump! Use a bypass.
- Make the bag bigger than you think you will need it; add pleats to the plastic so the vacuum pressure doesn't tear the bag.
- Use gummy tape specifically for this purpose – it's expensive but can be reused and works much better than other tapes
- Tiny, tiny, tiny holes can become big, big, big annoyances.

Cutting and Drilling FRPs

- Thin pieces can be cut or scored with a sharp knife.
- Hacksaws are simple and produce fairly little dust.
- Don't drill too quickly or you may set the resin matrix on fire.
- Dremel tools with abrasive cutting disks work well but produce dust.
- Jigsaws with abrasive blades, tablesaws, bandsaws, also work well for bigger projects.

DANGER:

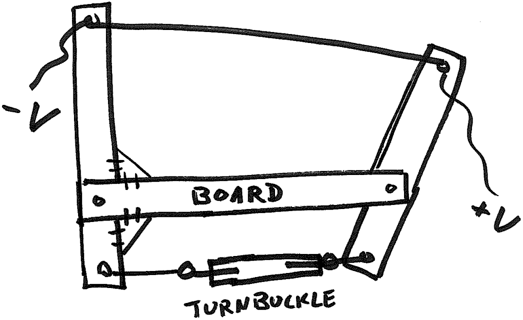
Always wear a quality dust mask rated to the proper particle size!

DANGER:

Clean up your dust with a water-filtered vacuum (shop vacuums are not good enough) and change your clothes afterward so the dust doesn't spread around!

Shaping Foam Cores

- Mechanical means like knives, jigsaws, etc always OK
- Heat forming is pretty hard in practice because foam insulates
- Expanding foams are great for really complex molded parts.
- Polystyrene foams can be cut with a hot wire. Go about 1cm/sec, be smooth, and don't stop.
- Foams used with vacuum bags need tiny perforated pin holes every 2cm through them so air can escape, and beveled edges.



Finishing FRPs

- Boat builders frequently put a thick “gel coat” of resin directly on the mold to have a smooth, impermeable surface. Great if you can tolerate the extra weight – it’s just weak resin though.
- The thinnest fabrics are best when closest to the exterior surface, since they provide a smoother surface with fewer pinholes.
- Kevlar cannot be sanded without its surface becoming like a tennis-ball of yellow fuzz.
- Fiberglass and carbon can be sanded, if you like hard work.
- Use a paint that matches the chemistry of your resin, or add tinted pigments to your resin.

Beginners Wet Layup Notes

- Have your fabric cut and ready before beginning.
- Try not to introduce air into the resin when mixing it.
- Pour the resin on the mold first, and brush it out to avoid surface bubbles.
- Always start working at the center and work outwards. This is true when spreading resin around with a squeegee, when brushing it out, or when adjusting the lay of the fabric.
- Using a layer of plastic can help keep the squeegee clean.
- Stippling the fabric with the tip of the brush can help push resin in.
- It's too hard to wet out >3 layers at a time.
- Wait at least 4-6 hours before handling; its often easy to cut or trim at that point.

Layup on Foam Notes

- Use a glue that can be cut with a hot wire.
- Applying slurry to the foam improves the bond between fabric and foam. Wait 15m for slurry to get gummy before applying fabric.
- Pour the resin on the mold first, and brush it out to avoid surface bubbles.
- Always start working at the center and work outwards. This is true when spreading resin around with a squeegee, when brushing it out, or when adjusting the lay of the fabric.
- Using a layer of plastic can help keep the squeegee clean.
- Stippling the fabric with the tip of the brush can help push resin in.
- Don't do more than 3 layers at a time.
- Wait at least 4-6 hours before handling; its often easy to cut or trim at that point.

Sample Design Strengths

Real life laminates made at room temperature often disappoint:

Material	Tension (MPa)	Compression (MPa)
E-Glass, Polyester	275	250
E-glass, Epoxy	350	275
S-glass	415	310
Carbon	350	275
Kevlar	550	275
Kevlar, Vac-bagged, 110C cure	1000	480
Graphlite^{TM}(unidirectional)	2300	1900

On the other hand, we are free to design and build laminates with few restrictions on shape.

Questions about Strength

How is the stress/strain curve, crushing resistance, and bolt shear strength affected by these variables?

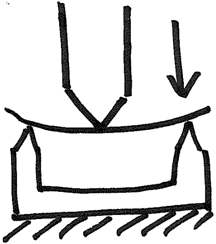
1. Number of plys on one surface (2, 4, 6 plys)
2. Number of plys on other surface (4)
3. Back-side surface fiber orientation (0 or 45 degrees)
4. Core thickness (0, 5, 10mm)
5. Core material (Styrofoam, PVC foam, honeycomb)
6. Vacuum bagging the part during cure (yes or no)
7. Researcher workmanship

Strength Testing

We will perform a simple bend test to estimate tensile strength.

$$\sigma \approx \frac{3FL}{2wd^2}$$

where F is the force, L is the gap length, w is the face width, and d is the depth of the beam.



Sample Format

We will construct eight 100mm x 50mm flat samples. Each sample will have 4 plys on one side, then a core material, and 2-6 more plys on the other side.

4 plys 5mm foam	4 plys 10mm foam
4 plys PVC foam	4 plys Honeycomb
2 plys 5mm foam	6 plys 5mm foam
4 plys no core	4 plys@45deg 5mm foam

Please Label your Samples

Remember to label your samples with:

- Builder name
- Sample weight
- Sample ply count
- Core material
- Core thickness
- Total thickness of laminate
- Fiber orientation
- Vacuum bagged or not

References

Books:

- "Composite Basics" by Andrew C. Marshall
- "Composite Construction for Homebuilt Aircraft" by Jack Lambie
- "Advanced Composite Techniques" by Zeke Smith

Websites:

www.quartus.com/resources/white-papers/composites-101/

www.mrl.columbia.edu/ntm/level1/ch05/html/l1c05s03.html

www.arnabocean.com/index.html