

Role of Fiber Reinforcement

- The mechanical properties of fiber reinforced PMCs dominated by the contribution of the fiber to the composite
- The four main factors that govern the fiber's contribution are:
 - The basic mechanical properties of the fiber itself
 - The orientation of the fiber in the composite
 - The amount of fiber in the composite
 - The surface interaction of the fiber and resin

Composite Preforms

- Chopped strand mat most ubiquitous preform
- Woven preforms can be tailored to achieve the best possible performance at the lowest possible cost.
- 2D woven preforms
- Braided preforms
- Preforms with multidirectional reinforcement.

Glass Fiber Reinforcements (Material Forms)

- Roving (continuous strand)
- Chopped strand (0.125-2" long)
- Woven fabrics
- Continuous strand mat
- Chopped strand mat
- Milled fibers (0.032-0.125" long)

Roving

- Untwisted strand used for woven roving (*heavier than yarn used in fabrics*)
- Popular for fast buildup of laminate thickness where tight contours and drape are not an issue.

Glass Yarn

- Yarn ~ assemblage of fibers, generally <10,000 suitable for use in weaving into textile materials (lighter than roving.)
- Tow ~ large bundle of continuous fibers, generally 10,000 or more (not twisted)

Glass Yarn

- U.S. Yardage System: An exact system for identifying glass-fiber yarns is used because of the wide variety of types available (also TEX system.)
- Yarn nomenclature consists of 2 basic parts, one alphabetical and one numerical.

ECG-150 1/2

- First letter indicates the glass composition
- Second letter indicates whether the fibers are continuous or staple
- Third letter indicates the average diameter of the fibers from which the yarn is made

Glass Yarn

B	100-149	H	400-449
C	150-199	J	450-499
D	200-249	K	500-549
DE	230-279	L	550-599
E	250-299	M	600-649
F	300-349	N	650-699
G	350-399	P	700-749

Code for fiber diameter, $\mu\text{in.}$

Glass Yarn

- The numbers used in glass-yarn nomenclature identify the basic strand weight and the yarn construction.
 - The strand weight is indicated by the first series of numbers, represents $\sim 1/100^{\text{th}}$ of the yards/lb
 - The second series designates the yarn construction
 - The first digit tells how many basic single strands/yarn
 - The second digit indicates the number of basic strands which are plied together.
 - To find the total number of strands in the yarn, multiply these 2 numbers together.

Glass Yarn

ECG 150 1/2

E = electrical glass

C = continuous filament

G = filament diameter $\sim 350\text{-}399\ \mu\text{in.}$

150 = 15,000 yd/lb (nominal yardage)

1/2 = single strands twisted and two of the
twisted strands plied together

Woven Fabrics

- Constructed of interlaced yarns, fibers, or filaments, usu. a planar structure (0.006-0.010”).
- Typically manufactured by interlacing warp (lengthwise) yarns and fill, or weft (crosswise) yarns on conventional weaving looms.
- The principal factors which define a given fabric style are fabric count, warp yarn, fill yarn, and weave.

Woven Fabrics

- Fabric count refers to the number of warp yarns (ends) per inch and the number of filling yarns (picks) per inch.
- Fabric count plus the properties of the warp and fill yarns used to weave fabrics are the principal factors which determine fabric strength.

Woven Fabrics

- The weave of a fabric refers to how warp yarns and fill yarns are interlaced.
- Weave determines the appearance and some of the handling and functional characteristics of a fabric.
- Popular weave patterns include plain, twill, crowfoot satin, long-shaft satin, leno, and unidirectional.

Woven Fabrics

- Plain weave is the oldest and most common textile weave.
- One warp end is repetitively woven over one fill yarn and under the next.
- It is the firmest, most stable construction, providing porosity and minimum slippage.
- Strength is uniform in both directions.

Woven Fabrics

- Twill weaves have one or more warp ends passing over and under two, three or more picks in a regular pattern.
- Such weaves drape better than a plain weave.

Woven Fabrics

- In the crowfoot, and long-shaft satin weaves one warp end is woven over several successive fill yarns, then under one fill yarn.
- A configuration having one warp end passing over four and under one fill yarn is called a five-harness satin weave.
- The satin weave is more pliable than the plain weave.
- It conforms readily to compound curves and can be woven to a very high density.
- Satin weaves are less open than other weaves.
- Strength is high in both directions, **less fiber crimp.**

Woven Fabrics

- The leno weave has two or more parallel warp ends interlocked.
- The unidirectional weave involves weaving a great number of larger yarns in one direction with fewer and generally smaller yarns in the other direction.
- Also available are nonwovens
 - Held together by an occasional small transverse strand or a periodic cross bond with resin.

Woven Roving

- Rovings can be woven into a product called woven roving.
- Heavier and thicker than fabrics
 - typically 12-40 oz./yd²
 - with thicknesses of 0.02-0.05"
- Usually provided in a plain weave.
- Usually molded by hand lay-up.
- Typical applications include: boats and cargo containers.

Stitched Fabrics

- Fabric is binder free, held together only by stitching
- Offer mechanical performance increases of up to 20% in some properties over woven fabrics
 - Parallel non-crimp fibers bear the strain immediately upon being loaded
 - Stress points at warp/weft crossovers eliminated
 - Higher density of fibers can be achieved (more like layers of unidirectional)

Stitched Fabrics

- Available in
 - Unidirectional,
 - 0/90,
 - Multiaxial forms

Mat Reinforcement

- Held together by resinous binders or mechanically bonded by needling.
- Used to fabricate isotropic laminates (15-50% W_f)
- The reinforcing ability of continuous strand mat and chopped strand mat are essentially the same but continuous mat can be molded to more complicated shapes without tearing.
- Reinforcing mats are distinguished by the binders used to hold them together, which may be high or low solubility
 - High solubility binder used in hand layup or wherever rapid wetout and contour matching is important.
 - Low solubility binder used in press molding or wherever the flow of the liquid matrix resin may wash away or disrupt the strands.

Chopped Strand

- Continuous roving can be chopped into short lengths, usu. 0.125-2" long.
- Chopped strands are available with different sizings for compatibility with most plastics.
- Chopped-strand materials are used in premix and wet-slurry molding as well as for reinforcement in thermoplastic molding compounds.

Milled Fibers

- Continuous strands can also be hammer-milled into short nodules of glass ranging in length from 0.015 to 0.25”.
- Many sizing materials are available on milled fibers for compatibility with polyesters, epoxies, etc.
- Milled fibers are generally used to provide anticrazing, body, and dimensional stability to potting compounds, adhesives, patching compounds, and putties.

Coupling Agents

- Mechanical properties of PMCs depend largely on the behavior of the bond between the fibers and matrix
 - Glass is a polar material, it has a strong attraction to water
 - Unprotected glass fibers attract a coating several molecular layers thick of water, which will have an adverse effect on the fiber/matrix bond
 - Bond is improved by coating the fibers with a coupling agent or finish to promote greater adhesion (improves “wetting”, also reduces deterioration of the f/m interface with time.

Coupling Agents

- Coupling agents improve bond strength
- The ideal coupling agent should provide a low modulus flexible layer at the interface that will improve adhesive strength of the fiber/matrix bond and reduce the number of voids in the material.
 - Chrome complexes (bad for the environment)
 - Silane compounds
- Usefulness becomes much more pronounced if the composite is subject to moisture – the coupling agent will prevent the water from having a catastrophic effect on the interface adhesion.

Then what is Sizing?

- **Sizing** is a lubricant applied to the fragile glass yarns prior to weaving to eliminate tearing and destroying the structural integrity of the fabric.
- Common practice to burn off the sizing (700-800°F) → heat cleaned surface, then the **finish** is applied
- Fabric with the sizing still in place called **greige** goods or loom-state.

Carbon Fiber Reinforcements

Material Forms

- Continuous carbon fibers
- Unidirectional tape
- Woven fabrics
- Discontinuous carbon fibers
 - Milled fibers
 - Chopped fibers
 - Longer chopped fibers

Continuous Carbon Fibers

- Available in a variety of forms, including:
 - yarns or tows containing from 400 to 160,000 individual filaments.
 - Unidirectional preimpregnated tapes up to 48" wide
 - Fabrics of many weights and weaves
- Individual carbon filaments, usu. 0.0003" or 8 μm in diameter

Woven Fabrics

- Significant cost savings often realized in molding with fabrics (due to reduced labor requirements), despite more expensive material costs.
- Some fabrics essentially unidirectional
- Satin-weave fabrics, particularly 8HS, retain most of the fiber characteristics in the composite and easily be draped over can complex mold shapes.
- Plain weave fabrics are less flexible and are suitable for flat or simple contoured parts, at a slight sacrifice in fiber-property translation.

Woven Fabrics

- PAN carbon usu. made by weaving carbonized yarn.
- Weaving costs increase with increasing fiber modulus.
- Pitch-derived fibers on the other hand can be woven at an intermediate processing stage, then converted into the high modulus product while in fabric form.
- The strength properties of pitch-based carbon fabrics do not yet approach those of PAN-based products
- Lower cost potential, and continually improving properties make pitch-derived product attractive
- Fabric usu. unfinished or greige (pronounced gray.)
- Carbon fibers cannot be heat cleaned or scoured, therefore cannot be given same lubrication as glass or Kevlar fibers, instead lubricated with 0.5-2% by weight epoxy resin sizing (optimized to improve adhesion.)

Braiding

- Braid consists of three or more continuous fiber tows intertwined to cross one another diagonally without twisting around each other.
- Braids can be made from all types of fiber, including hybrids.
- Repeatability and reduced assembly time with braided preforms compared to hand lay-up translate to lower cost in finished parts.
- New or improved fabrication processes – some combining braided and stitched reinforcements with RTM, filament winding and pultrusion – spell further cost reduction potential.

Braiding

- Tubular-shaped biaxial braided sleeves are the most recognizable form for use in composites (Chinese fingercuffs.)
 - These comprise flexible, free-standing, seamless fiber architecture with two sets of continuous tows running CW and CCW.
 - The common fiber angle or orientation in a biaxial braid is 45° (allows highest degree of conformability for parts with changing cross-sections.)

Braiding

- Triaxial braids use three sets of interwoven tows, incorporating axial fibers to provide unidirectional properties and lock in diameter.
 - Significantly increases stiffness in a finished part.
 - Much less conformable

Braiding

- Overbraiding directly onto a molding tool (mandrel) or core allows automated lay-up of multiple plies and greater variance of braid angle.
- A key advantage of braids is the efficient transfer of load among the fibers, which are continuous and mechanically locked together.
 - Braid can absorb a great deal of impact energy.
- Question of crimp?
 - 10-15% tensile property reduction
 - Boosts interlaminar shear significantly because of nesting

Braiding

- Cost cutting achieved through computer-controlled, automated braiding of net-shaped preforms
- A&P demonstrated new equipment that combines braiding and filament winding
- 3D braid in R&D stages
- Together with advanced RTM, shows great cost cutting potential.
- We will examine some manufacturing case studies later. . .

Prepreg

- Prepreg combines partially cured (B-stage) thermosetting resins with reinforcing fibers.
- Thermoplastics account for <3% of the current prepreg market.
- Nearly 100% of all advanced composite materials “qualified” for structural aerospace applications are prepreg systems that have been qualified down to the specific fiber, resin, and manufacturing method (at a cost of ~\$20 million.)

Prepreg

- By using prepreg, the process of impregnating the fiber is separated from that of laying up the laminate or composite.
- Makes laying up much simpler and quicker, results in laminates of better quality
 - The proportion of resin to fiber is automatically kept constant and uniform
 - Helps ensure optimum strength in the cured laminate
 - Makes it possible to maintain strict control of weight distribution in large and small areas
 - Fiber orientation is also easily controlled
 - Maximizes strength and stiffness where they are needed
 - Minimizes weight of material needed to achieve desired properties

Prepreg

- Disadvantages include:
 - High raw material costs
 - Solvent processing
 - Refrigerated storage
 - Documentation

Prepreg

- Prepreg is good and getting better
 - Most prepreg specs allow 2% void volume
 - Newly designed prepreg machinery with improved process control and solvent deflashing methods has yielded even lower void content.
 - Resin chemistry developments – lowered prepreg costs increased product quality
 - New formulations emerging – no longer require cold storage
 - Emergence of heavy tow reinforcements also lowering costs.
 - Carbon-fiber prepreg <\$8/lb

Prepreg

- Boron prepreg tapes generally include a supporting carrier of woven glass-reinforced plastic fabric.
- Carbon prepreg
 - Cured ply thicknesses of 0.0056-0.0064" most common.

References

- SP Systems Product Literature on CD
- “Composite Preforms,” *The AMPTIAC Newsletter*, Winter 2001, pp.1,7-8.
- Owens Corning website, www.owenscorning.com
- BGF Industries website, www.bgf.com
- ASTM Specification D 579 (fabrics)
- “Not Just Biaxial Anymore,” *High-Performance Composites*, July/August 1998, pp. 33-36.
- “3D Weaving: What, How, and Where,” Dickinson, L., Mohamed, M., and Bogdanovich, A. In Proceedings of the 44th International SAMPE Symposium, pp. 303-311.
- “Prepreg Remains Strong,” *High-Performance Composites*, January/February 1999, pp. 34-36.
- “From Art to Science: A Prepreg Overview,” *High-Performance Composites* May/June 2000, pp. 32-36.
- Composite Materials Handbook, Schwartz, M.M., 1984.