A 12 PART WEBINAR SERIES ON:

COMPOSITE MATERIALS ENGINEERING

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YOUR HOST

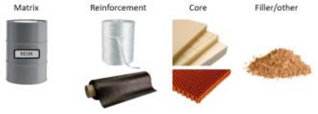
Casey Keulen, Ph.D, P.Eng.
Instructor, UBC and Lead of Cont. Prof. Development, CKN

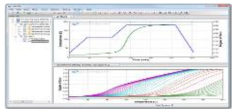
- Ph.D. and M.A.Sc. in Composite Materials Engineering
- Over 15 years experience in industry and academia working on polymer matrix composites in aerospace, automotive, marine, energy, recreation and others
- Experience working with over 150 companies from SME to major international corporations
- Expertise in liquid composite moulding and thermal management

OVERVIEW OF WEBINAR SERIES

- **Series of 12 webinars, 1 hour each**

Introduction
Constituent Materials
Thermal Management

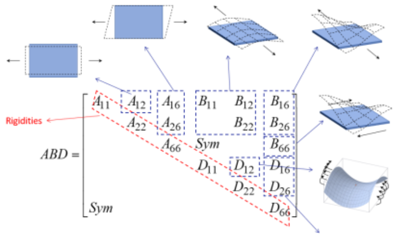




Processing (Manufacturing)
Prepreg Processing
Liquid Composite Moulding

Mechanics of Composites
Micromechanics
Lamina and Laminate Level
Failure

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \varepsilon_0 \\ \kappa \end{Bmatrix}$$



Testing Composites
Common Defects

- **For more information on dates and times visit:**
  https://compositeskn.org/aimevents/

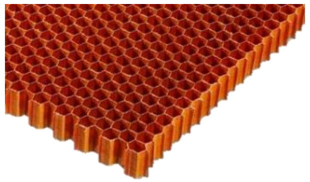
CONSTITUENT MATERIALS: FIBER REINFORCEMENT

- Composite Materials or ‘Composites’ are:
  - *Made from two or more constituent materials with different physical or chemical properties*
  - *Remain separate and distinct on a macroscopic level within the finished structure*
- Typically, the main constituents are reinforcement (fiber) and matrix (resin)
- In this session, we’ll focus on the reinforcement

Reinforcement

Matrix

Core



Filler/other

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Reinforcement

Matrix

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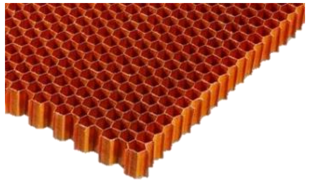


Filler/other

WHAT DOES THE FIBER DO?

- **Bears load and provides**:
  - *Strength*
  - *Stiffness*

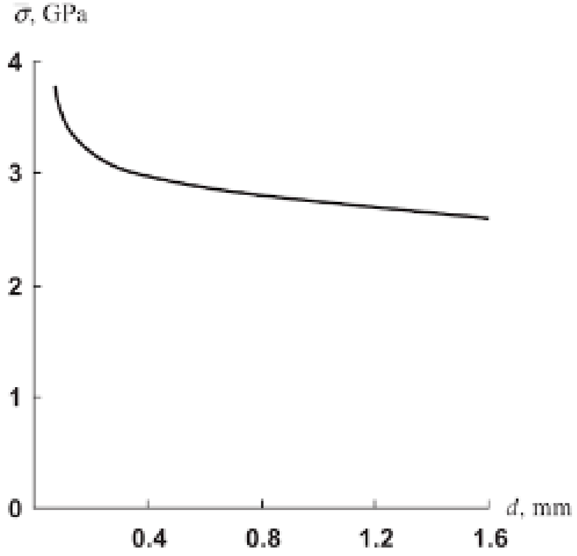
- **Provides unique properties depending on type:**
  - Heat and electricity conduction in the case of carbon
  - Thermal and electrical insulation in the case of glass
  - Abrasion resistance in the case of aramid

- **Desirable characteristics of fiber include:**
  - High strength
  - High stiffness
  - Low density
  - High aspect ratio (L:d)
  - Processability

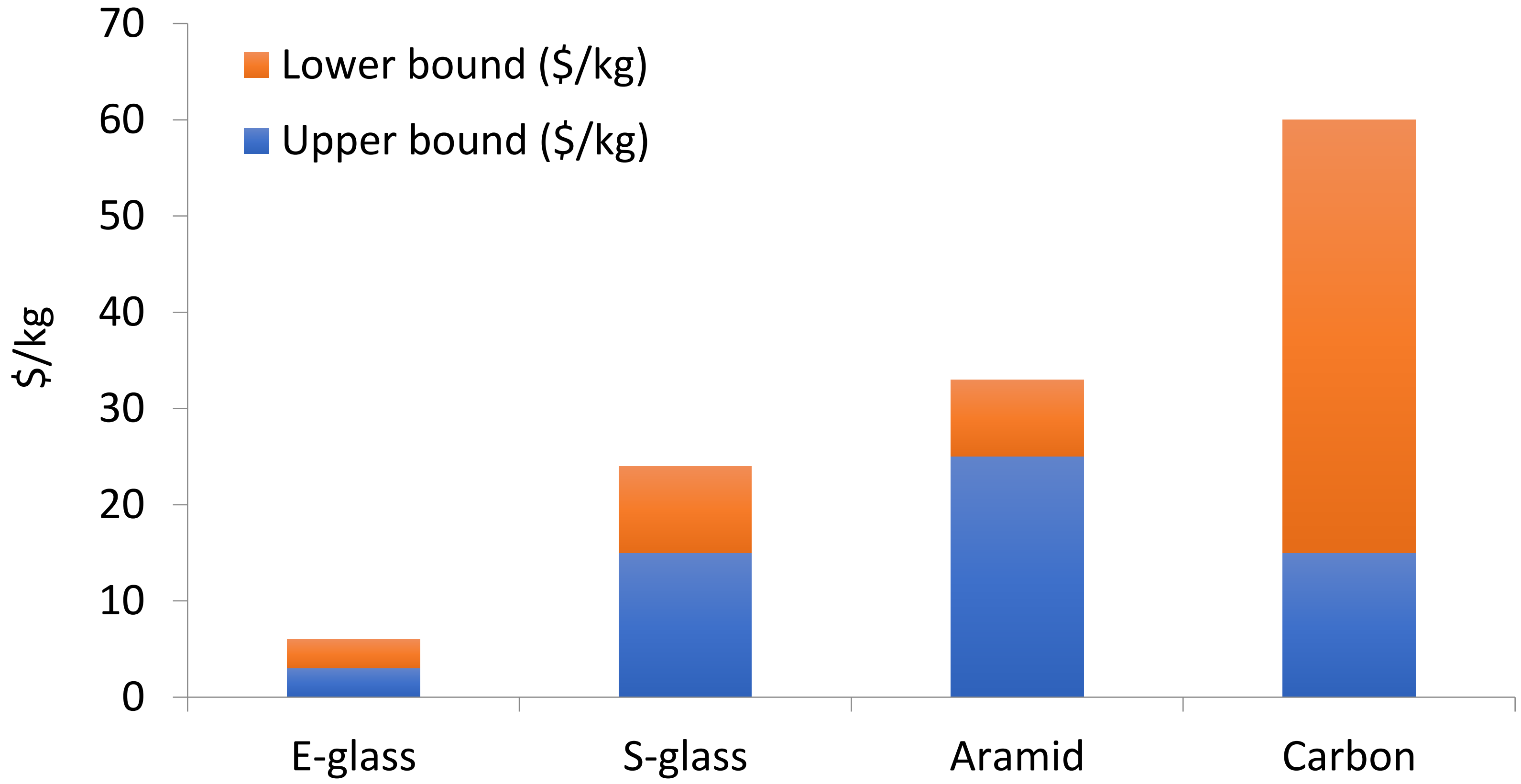
WHY FIBER?

- Advanced composite materials are associated with a very high strength unidirectional ply with relatively low density
- This advantage is mainly provided by the fibers
- How can traditional lightweight materials like glass or graphite be used to make fibers with strength exceeding the strength of structural materials such as aluminum and steel?
  - The strength of a thin wire is usually much higher than strength of the bulk material

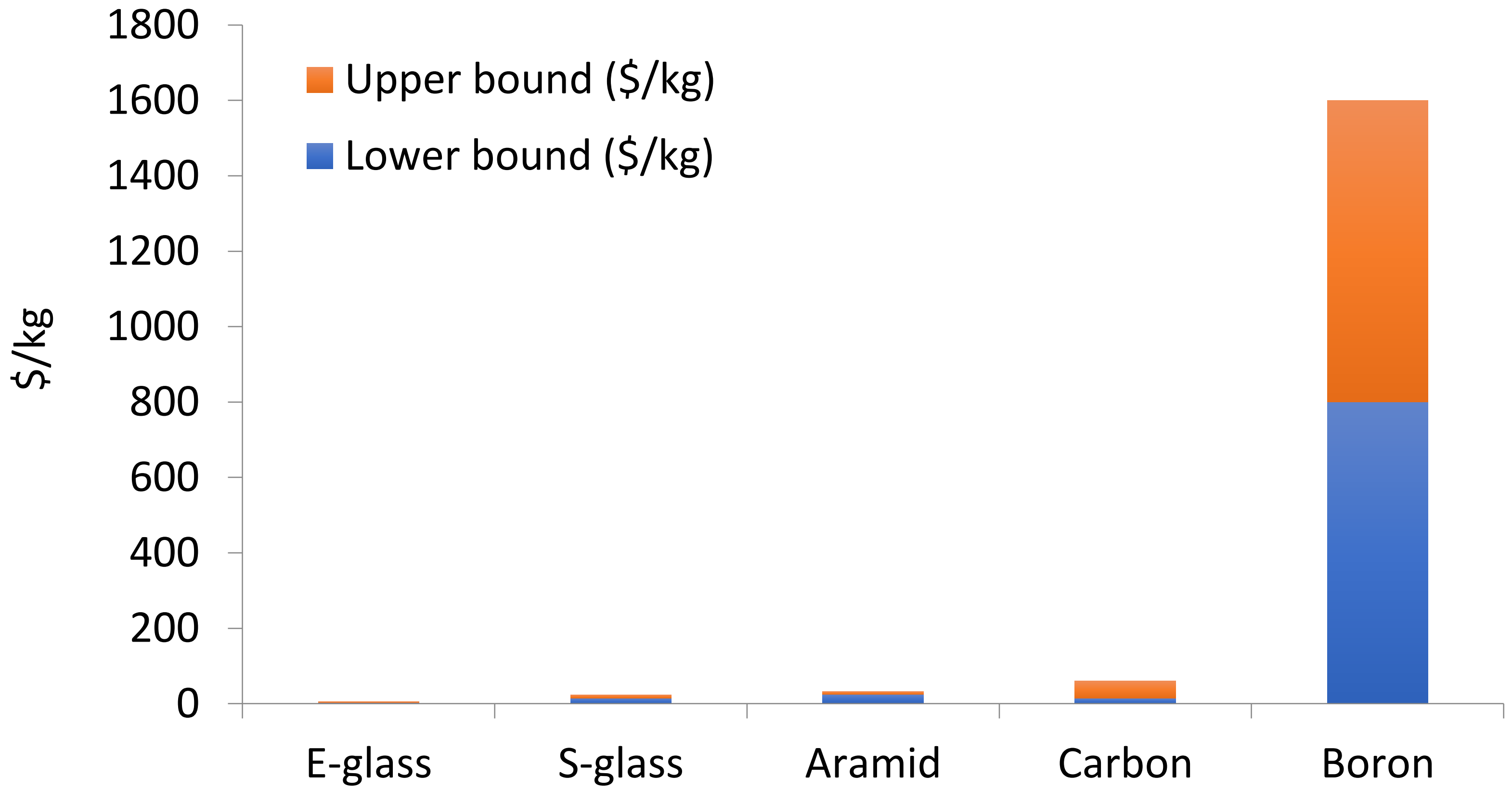
Steel fiber strength vs fiber diameter



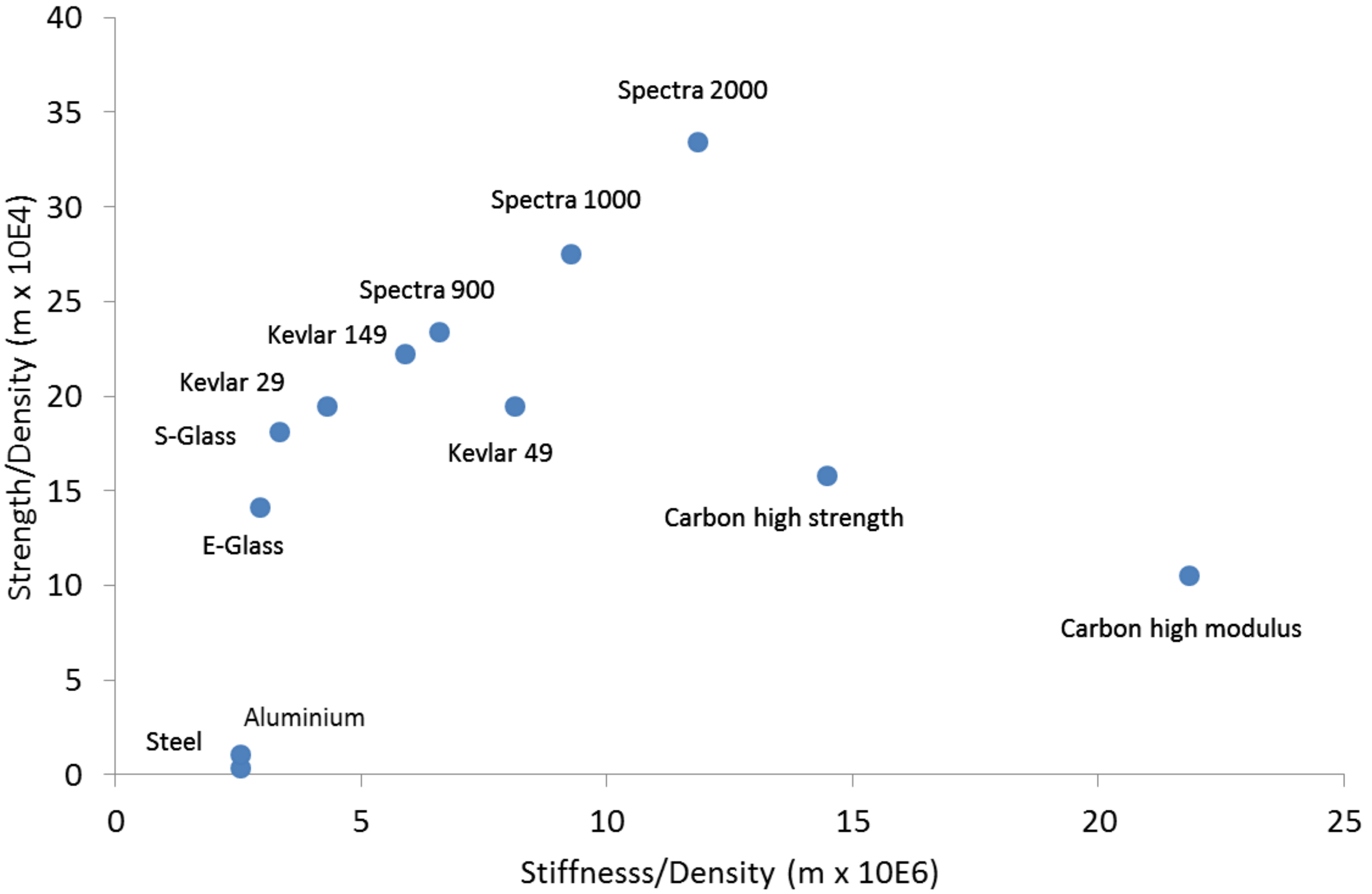
FIBER COST


70
60
50
40
30
20
10
0
$/kg
Lower bound ($/kg)
Upper bound ($/kg)
E-glass
S-glass
Aramid
Carbon

FIBER COST


Upper bound ($/kg)
Lower bound ($/kg)
$/kg
1800
1600
1400
1200
1000
800
600
400
200
0
E-glass
S-glass
Aramid
Carbon
Boron

MATERIAL PROPERTIES



CARBON FIBER HISTORY

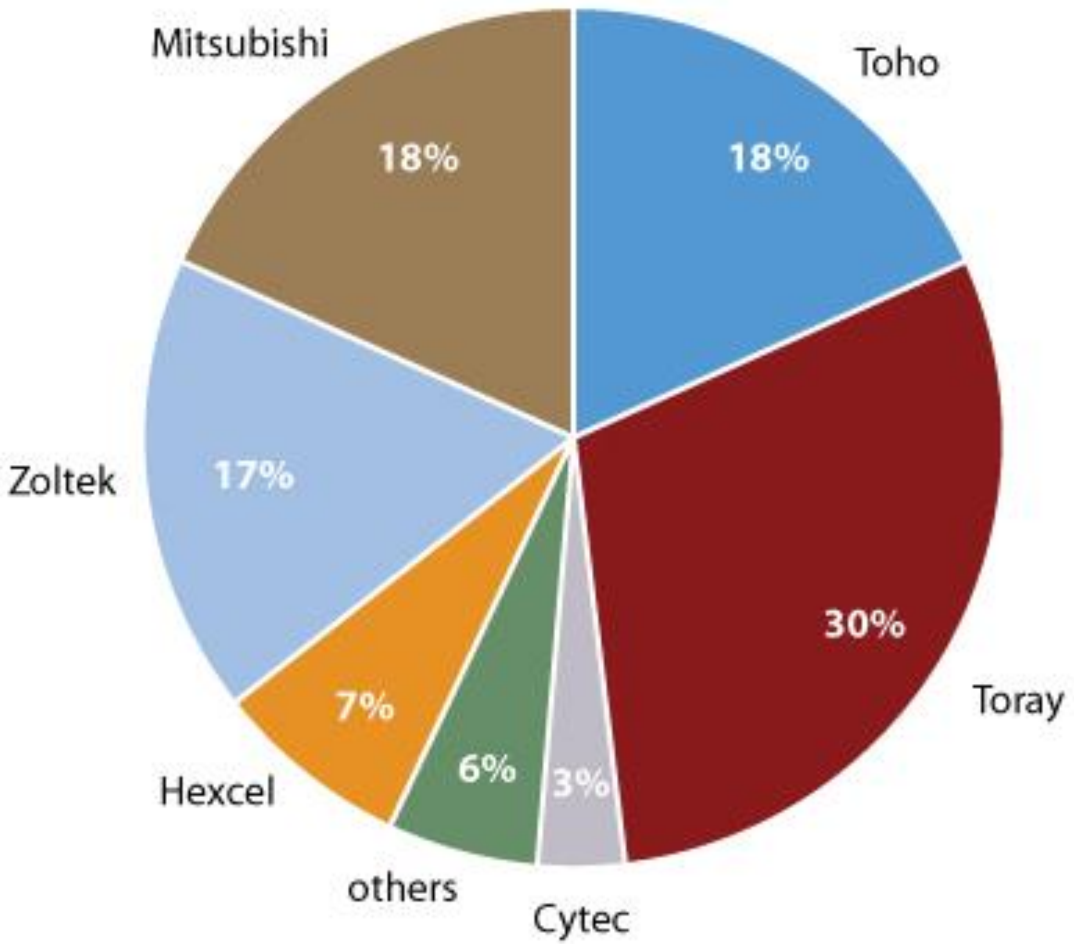

Dr. Roger Bacon


Mr. William Watt


Dr. Akio Shindo

- Late 1950s: Dr. Roger Bacon, was experimenting with different materials, exposing them to high pressures and voltages, when he observed his first graphite fibers, with a diameter smaller than a tenth of a human hair
- Early 1960's: Dr. Akio Shindo (Agency of Industrial Science and Technology, Japan) created process using PAN precursor
- In the 1960s, carbon fibers were mixed with other materials to protect the leading edges, noses and wingtips of aircraft, missiles and space vehicles.

CARBON FIBER MARKET SHARE

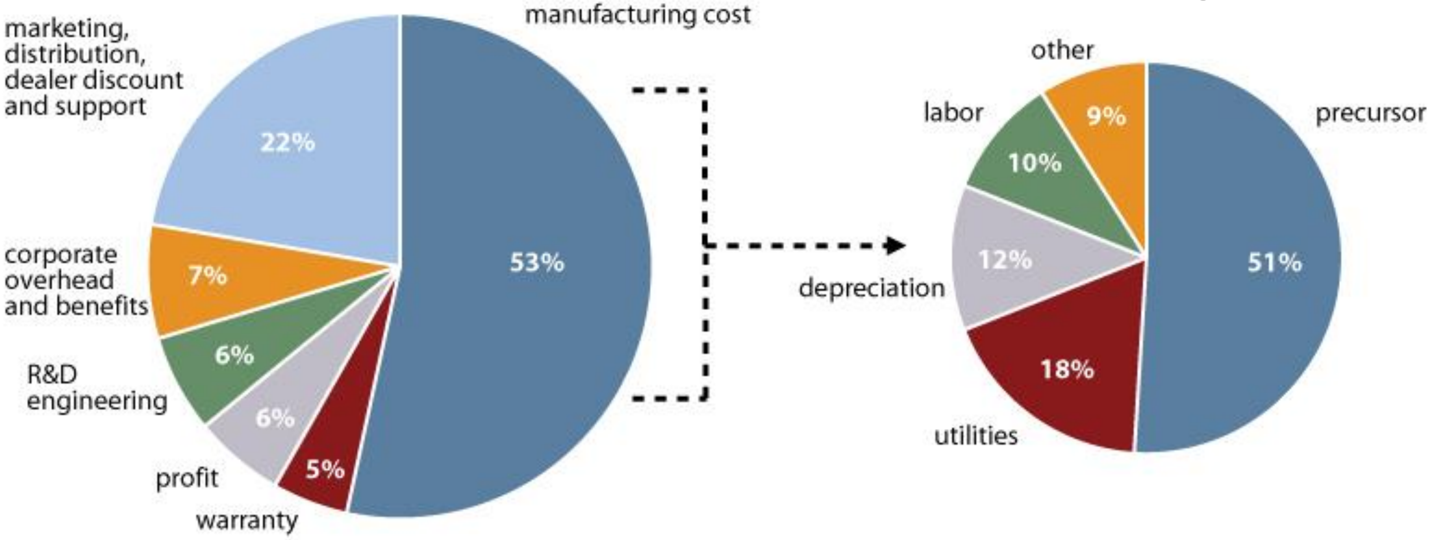


www.RMI.org/ReinventingFire

CARBON FIBER COST BREAKDOWN

Total costs

Manufacturing costs [1]

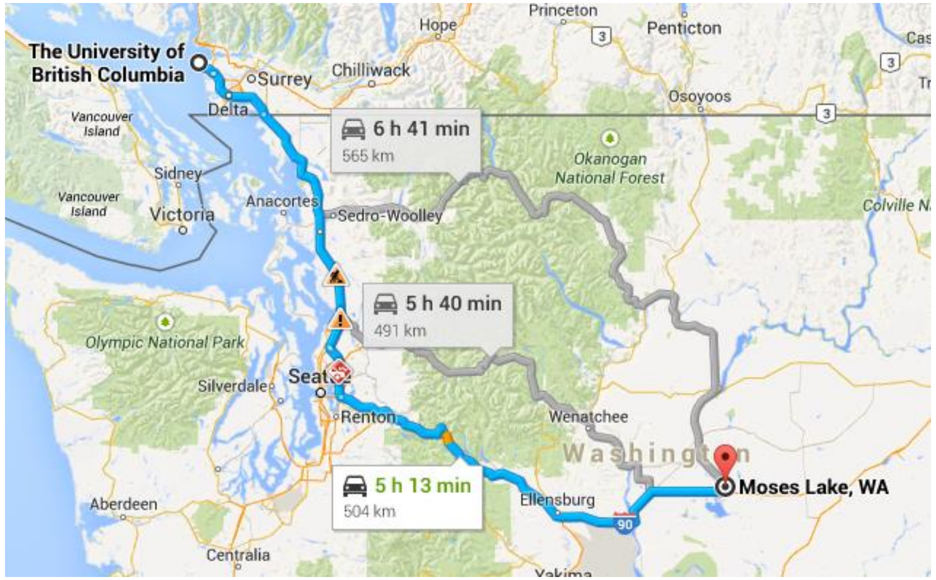


- Precursor development[2]
  - Conventional PAN precursor ~$5/lb
  - Commodity grade PAN textile
    - ~$2-3/lb
    - Zoltex's Panex 35 fiber manufactured from textile grade PAN
  - Polyolefin
    - ~$1-2/lb
  - Lignin
    - Byproduct from wood pulping process, cheap, abundant, renewable
    - Many challenges still to be addressed

[1] http://www.rmi.org/RFGraph-carbon_fiber_cost_breakdown
[2] Elmarakbi, A., Advanced composite materials for automotive applications, Wiley, 2014

CARBON FIBER PRODUCTION PLANT

- BMW and SGL joint venture
- Moses Lake, Washington
- Initially started with 3000 ton capacity in 2011
- Expanded to 6000 tons in 2013
- Third expansion to 9000 tons in 2015
- 640 m production line
- Largest carbon fiber production plant in the world
- BMW plans to need 10% of the world's capacity of carbon fiber[1]




[2]


[3]

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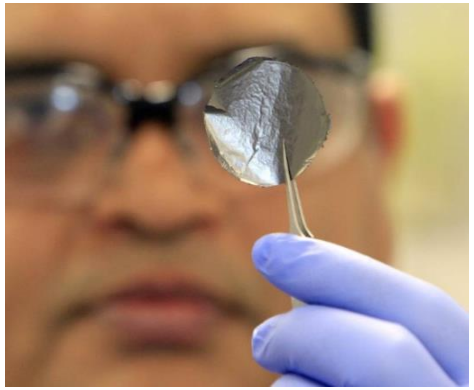
[1] https://www.youtube.com/watch?v=la4Eq8_FBPc
[2] http://www.bimmerpost.com/storyimages/4c59d569-eb1b-452e.jpg
[3] http://www.bmwcoop.com/wp-content/images/2014/03/bmw-carbon-fiber-factory.jpg

CARBON FIBER MICROSTRUCTURE

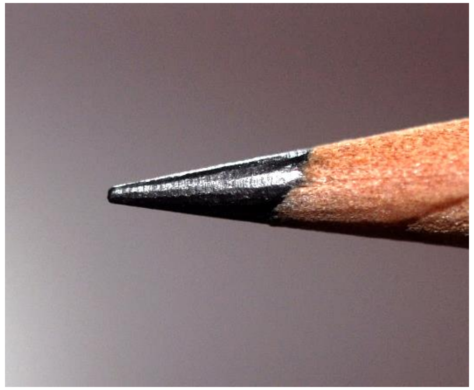
- What are the similarities between these three materials?



Graphene

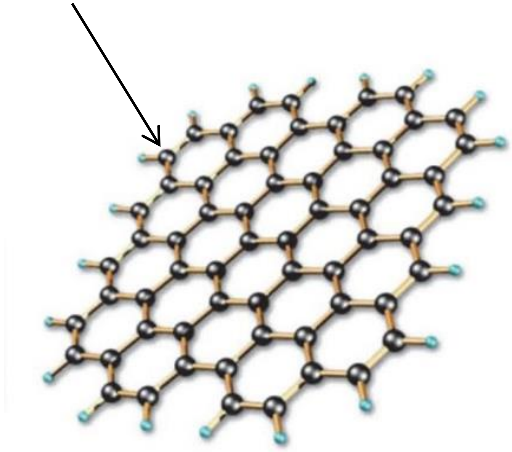
Graphite

Carbon Fiber

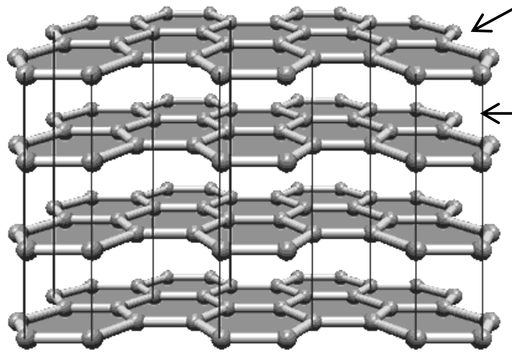


CARBON FIBER MICROSTRUCTURE

- Graphene is a one-atom-thick, two-dimensional honeycomb layer of bonded carbon atoms
- When many graphene layers are stacked regularly in three dimensions and held together with weak forces, graphite is created

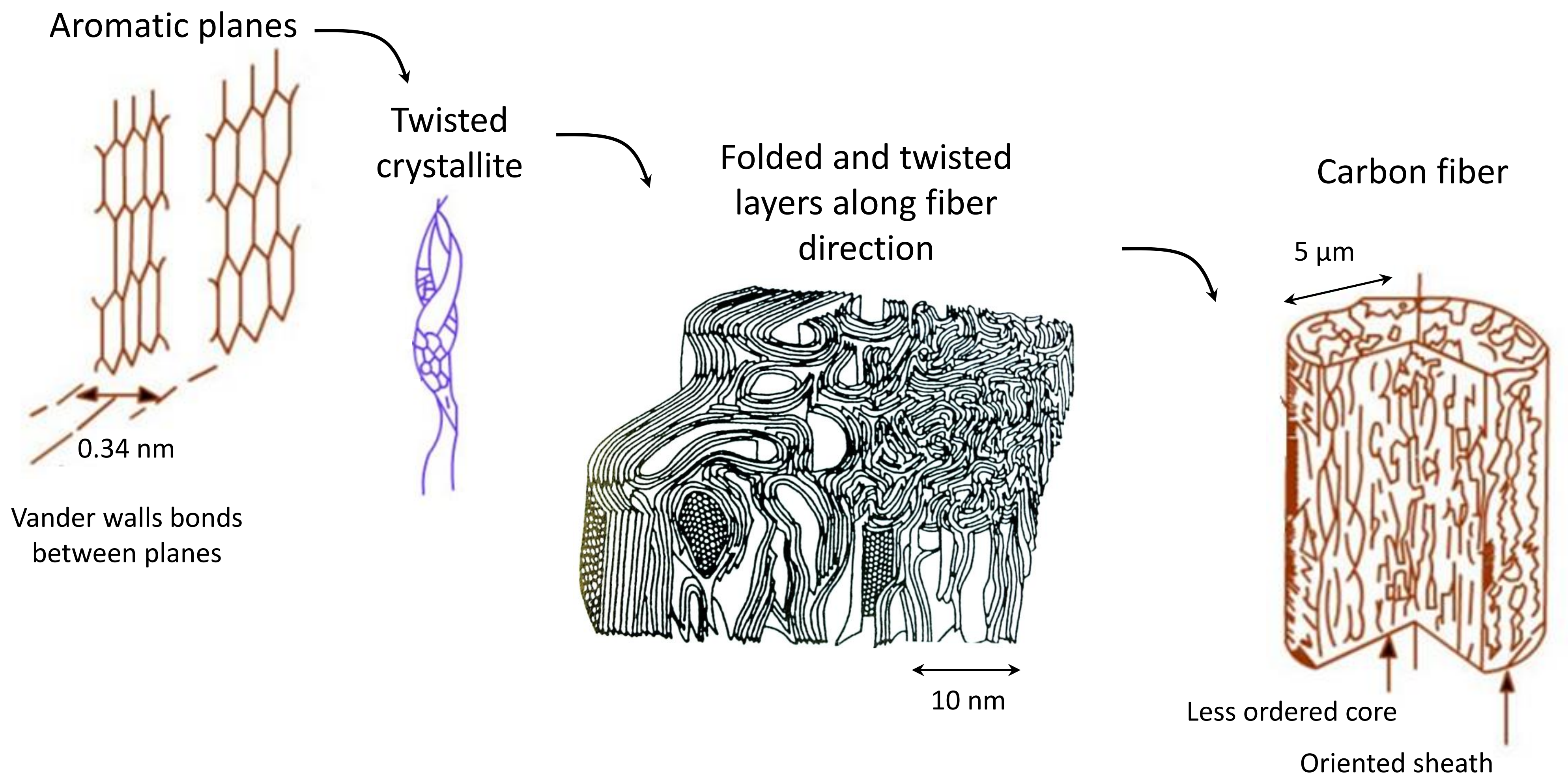


Graphene



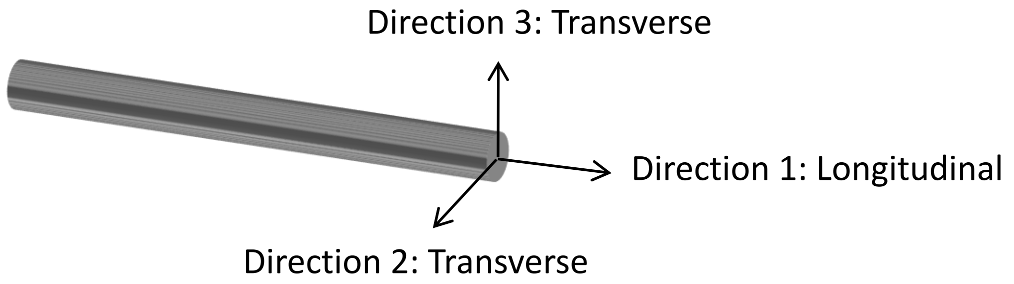
Graphite

CARBON FIBER MICROSTRUCTURE



CARBON FIBER PROPERTIES

- Modulus
  - Longitudinal: 300 – 600 GPa (Compare to 1000 GPa for Graphene)
  - Transverse: 10- 15 GPa
- Tensile Strength
  - Longitudinal: 4 GPa (Compare to 130 GPa for Graphene)
- Coefficient of Thermal Expansion (CTE)
  - Longitudinal $-0.5 \times 10^{-6} \frac{mm}{mm\ ℃}$ ← Negative CTE
  - Transverse: $+5 \times 10^{-6} \frac{mm}{mm\ ℃}$



CARBON FIBER TYPES

- Carbon fibre is manufactured by a highly proprietary process
- Every manufacturer makes a proprietary fiber, specific to their product line

Classification by Modulus

Class	Acronym	Modulus (GPa)
Low modulus	LM	Below 200
Standard modulus	SM	200-250
Intermediate modulus	IM	250-350
High modulus	HM	350-450
Ultrahigh modulus	UHM	Above 450

Classification by Precursor

Precursor
PAN
Pitch
Rayon
Other

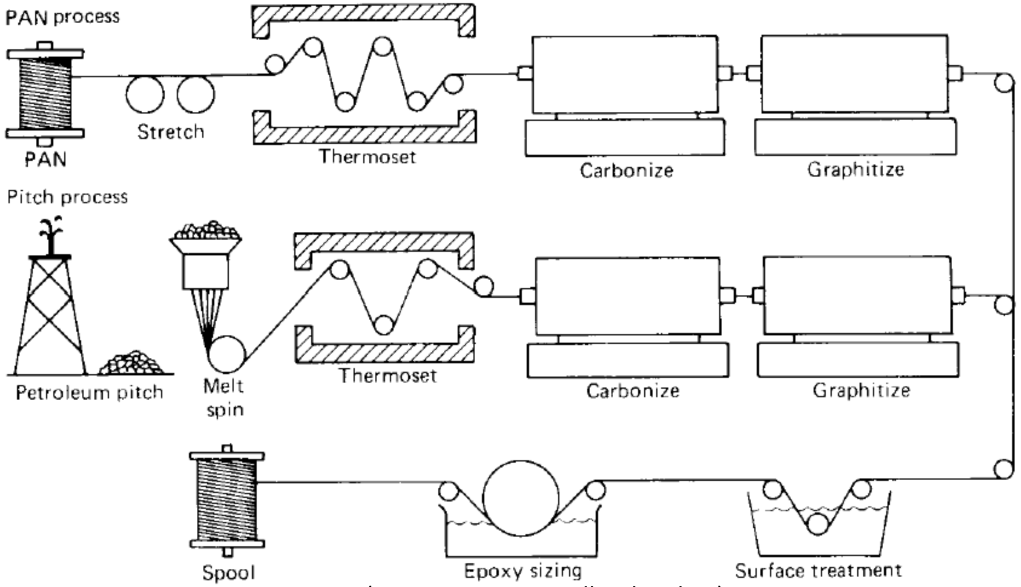
(In order of volume)

CARBON FIBER PRODUCTION

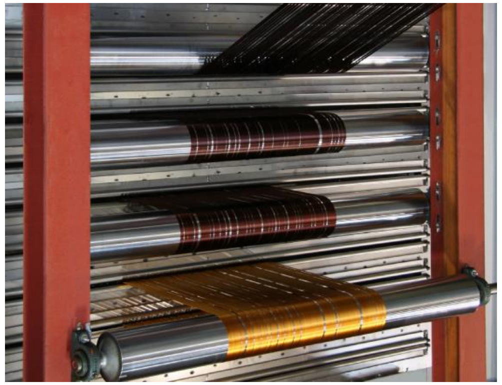
Precursor Unwinding Creel
(Courtesy of Texkimp Ltd.)

Final Product

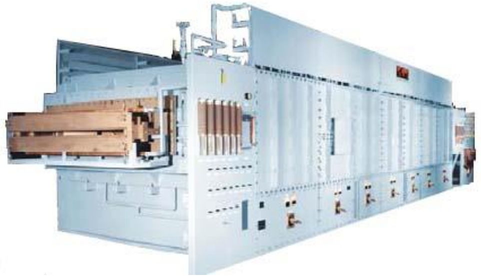
(2-300 ^oC) (1-1500 ^oC) (2500 ^oC)



(Courtesy ASM Handbook Vol 21)



Oxidation
(Courtesy of Despatch Ltd.)



Carbonization Furnace
(Courtesy of Harper Int.)

GLASS FIBER HISTORY

- In 1880 Herman Hammesfahr was awarded a patent for a type of glass fiber cloth with interwoven silk
- 1936: Owens-Corning patented “Fiberglas” (one ‘s’)
- 1938: Glass wool by Owns-Corning
- 1941: Glass fiber cloth by Owns-Corning
- 1942: Owens-Corning was producing composite (fiberglass and polyester) aircraft parts for the war effort

Glass dress, 1893

Glass wool, 1938

Games Slayter, Owens-Corning
Credited with inventing ‘Fiberglas’

GLASS FIBER

- Glass fiber has excellent properties:
  - High strength
  - Fire resistance
  - Corrosion resistance
  - Chemical resistance
  - Dimensional stability
- Major disadvantage vs carbon is density and stiffness
- It is much more economical than carbon fiber

Glass fiber tow

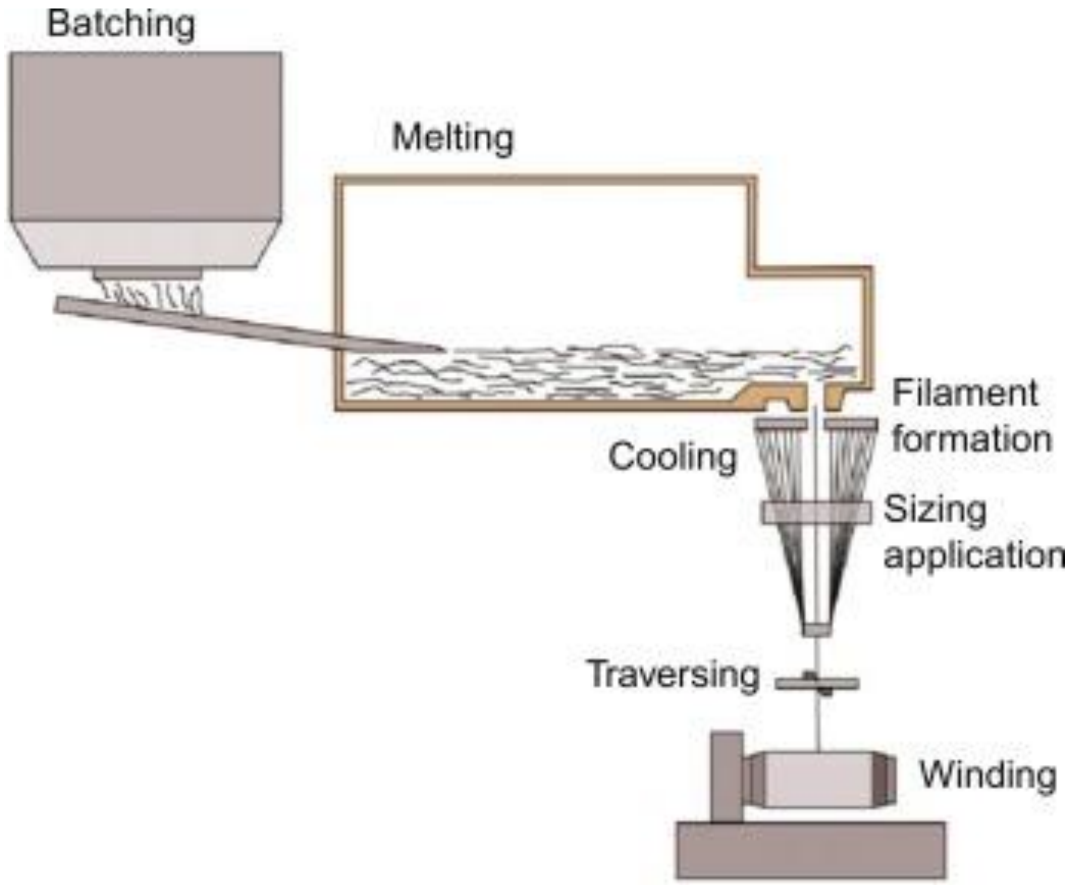
GLASS FIBER CLASSIFICATION

- Designation implies the use, refers to the chemical composition of the glass
- Some designations are specified by ASTM, some aren't
- E-glass is by far the most commonly used grade

Letter	Designation	Characteristic
E	Electrical	Electrical
S	Strength	High strength
S2	Strength	Higher strength than S glass
C	Chemical	High chemical durability
M	Modulus	High stiffness
D	Dielectric	Low dielectric constant

GLASS FIBER PRODUCTION

- Raw glass, as marbles or molten glass, is fed through a precise multi-hole platinum-rhodium bushing
- Molten glass filaments are drawn through at ~25 m/s (90 km/h)
- Sizing is applied
  - Acts as a glaze or filler
  - Protects surface of glass
  - Aids in bonding to matrix



IMPORTANT TERMS

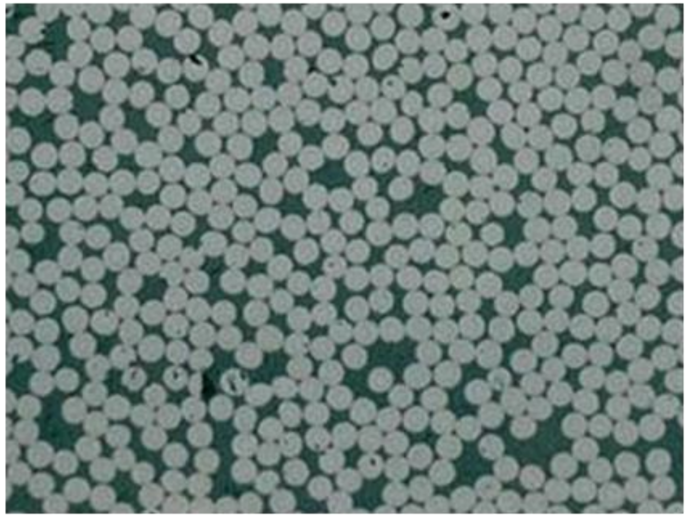
- There are a number of important terms/properties one must understand when selecting/evaluating a reinforcement
- These include:
  - Fiber volume fraction (V_f)
  - Fiber diameter
  - Tow size
  - Areal weight (FAW)
  - Drapeability
  - Permeability
  - Warp and weft/fill
  - Sizing
  - Fiber architecture

FIBER VOLUME FRACTION

- Fiber volume fraction (V_f) refers to the fraction of the volume of a composite that is occupied by fiber
- The remainder is occupied by the matrix, voids, fillers, etc.
- V_f is an indication of the final properties of a composite's:
  - Strength
  - Stiffness
  - Density
  - Fatigue resistance
  - ...

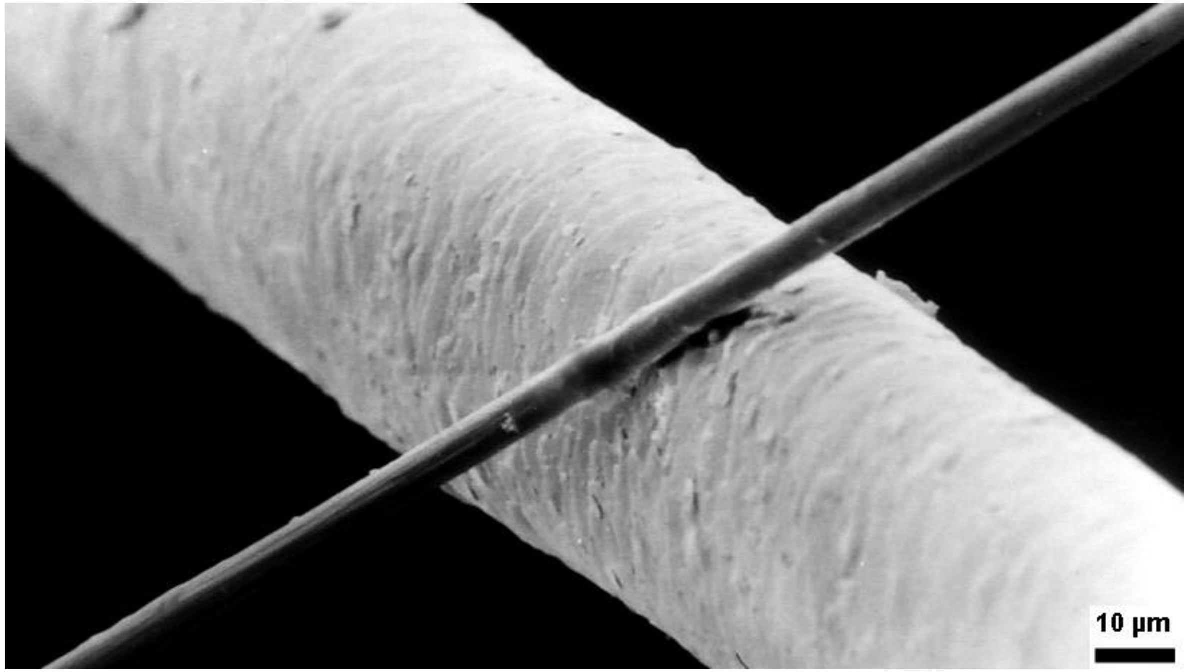
$$V_f = \frac{v_f}{v_c}$$

Where:
V_f = volume fraction of fiber
v_f = volume of fiber
v_c = volume of composite



Cross section of composite

FIBER DIAMETER

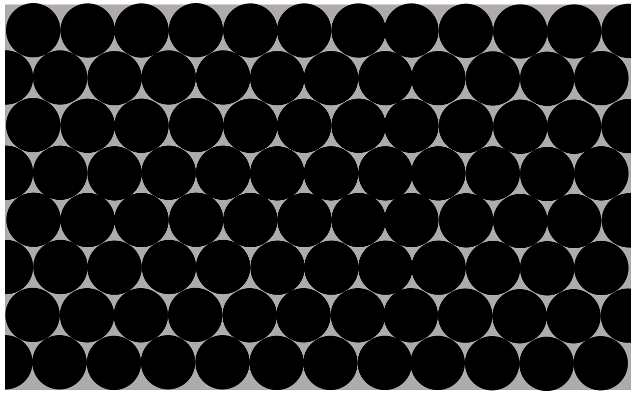


Carbon fiber and a human hair, which is which?

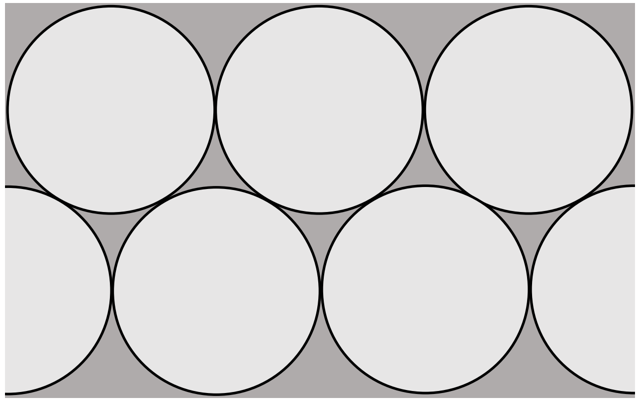
FIBER DIAMETER

- Fiber size:
  - Carbon: ~5 µm diameter
  - Glass: ~20 µm diameter
  - Kevlar 49: ~12 µm diameter

- 6 glass fibers fill the space of 92 carbon fibers



Cross section of carbon fiber (diameter ~5 µm)



Cross section of glass fiber (diameter ~20 µm)

TOW SIZE

- A tow is a bundle or yarn of individual fibers
- The tow size is inherent to the fiber manufacturing process (ie. a tow is manufactured in one process, rather than each fiber individually then bundled together after)
- Typically, smaller tows are stronger because they result in a more homogeneous material
- The larger the tow:
  - The faster it is to deposit material
  - The easier is it for resin to flow between tows
  - Harder for resin to saturate
- Typical tow sizes:
  - 1k
  - 3k
  - 6k
  - 12k
  - 24k
  - 50k

1 inch

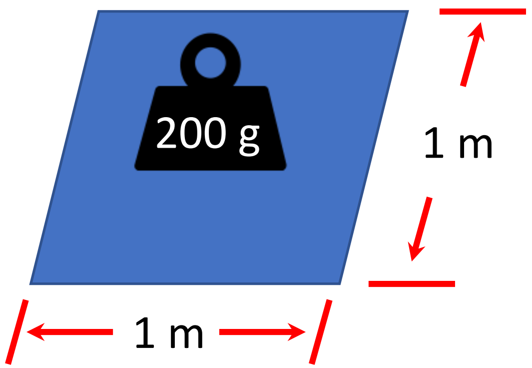
1k tow
24 tows per inch

1 inch

6k tow
11 tows per inch

FIBER AREAL WEIGHT

- Areal weight (or fiber areal weight, FAW) refers to the mass/weight of fiber per unit area
- Typically in g/m^2 (gsm) or $ounces/yard^2$ (often just called ounces)
- For some reason chopped strand mat is often in $ounces/foot^2$ (also often just called ounces)
- FAW depends on tow size and fiber architecture (weaving density, etc.)
- FAW can range from 10 gsm to 2180 gsm or more (~0.3 $ounces/yard^2$ to 64.3 $ounces/yard^2$)
- 200 gsm (6 $ounce/yard^2$) is a fairly common weight



AREAL WEIGHT, Vf, AND THICKNESS

- *The relationship between areal weight, V_f, and thickness:*

$$t = \frac{AW}{\rho_f V_f} n$$

Where:
t = thickness of composite
AW = fiber areal weight
n = number of plys
V_f = volume fraction of fiber
ρ_f = density of fiber

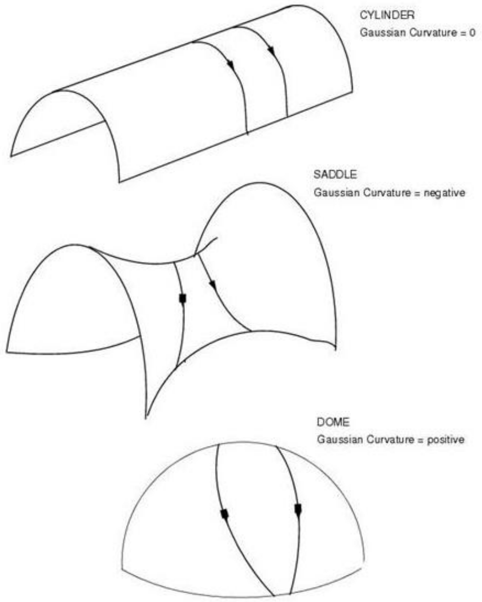
[1]

Manufacturing technique	Fiber volume fractions (V_f), %					
	Random mat		Woven roving		Unidirectional and multiaxial	
	Min	Max	Min	Max	Min	Max
Spray-up	10	20	. . .	. . .	. . .	. . .
Hand lay-up	10	20	25	40	40	50
Vacuum infusion	20	30	40	50	50	65
Resin transfer molding	20	30	40	50	50	65
Prepreg compression molding	. . .	. . .	40	55	50	70
Filament winding	. . .	. . .	. . .	. . .	50	70
Pultrusion	20	30	40	55	50	70

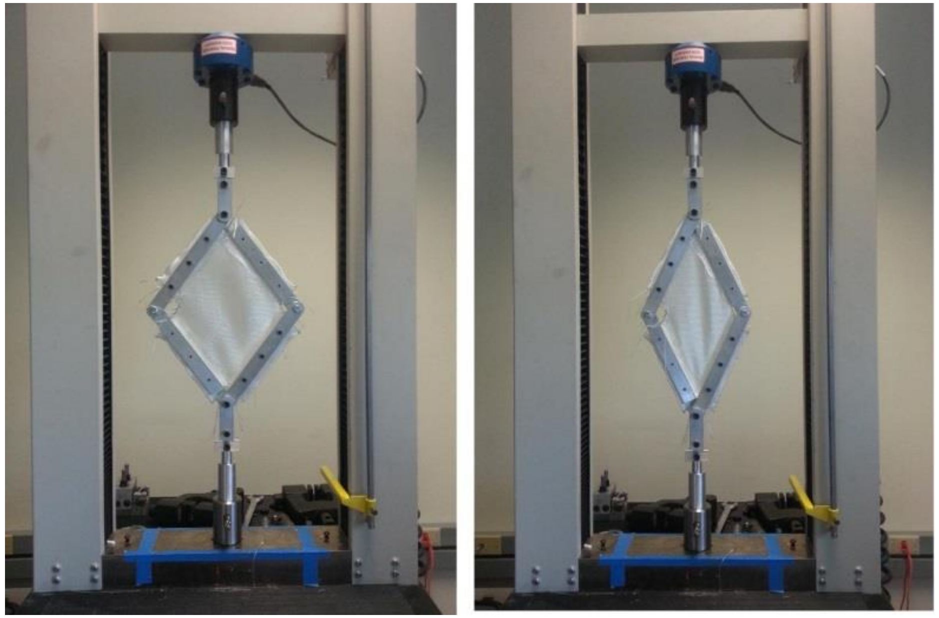
- Can be used to estimate the thickness of a laminate using an expected V_f for a particular process

DRAPEABILITY

- Drapeability refers to how well a material conforms to a complex shape (non-developable surface)
- *Trade-off:* typically the more drapeable a fabric, the less dense the weave (lower V_f), and less stable during processing



Various curvatures



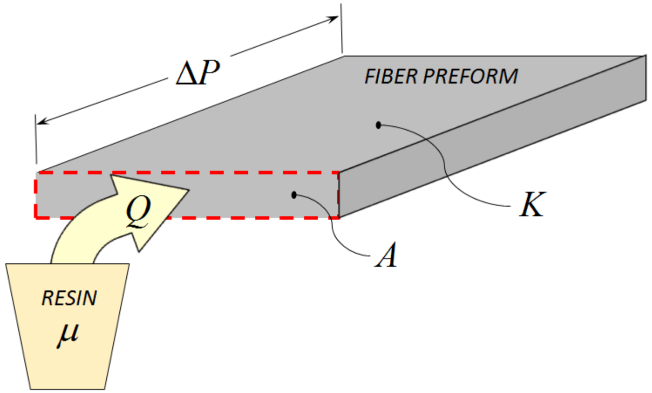
Picture frame test

PERMEABILITY

- Permeability refers to the resistance to flow through a porous material
  - ie resin flow through fiber

- Darcy's law governs flow through porous medium

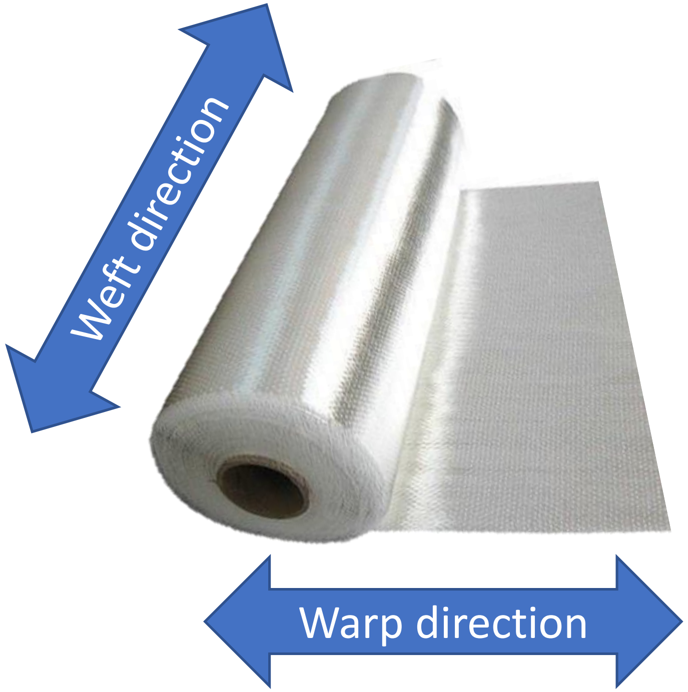
$$Q = -\frac{KA}{\mu}\frac{\Delta P}{x}$$



- Where:
  - Q is the volume flow rate
  - K is the preform permeability
  - μ is the resin viscosity
  - A is the area the resin is entering into (edge area of preform)
  - ΔP is the pressure difference across the preform
  - x is the distance across the pressure difference

WARP AND WEFT

- *Warp* refers to fibers that run along the length of the fabric (0^o direction)
- *Weft* or *fill* refers to fibers that run across the width of the fabric (90^o direction)



SIZING

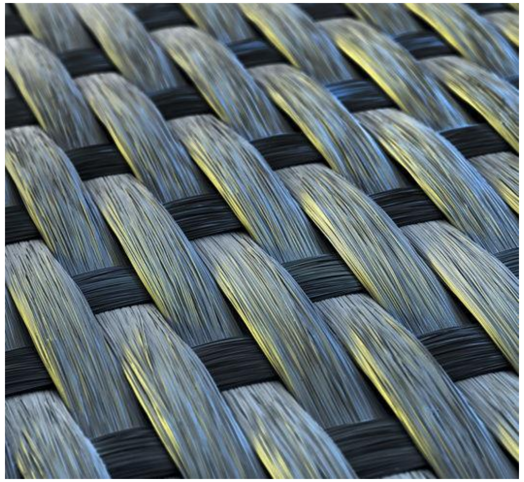
- Sizing is a mixture of various chemicals that fiber and fabric producers coat ("size") their fibers
- Sizing is one of the "black box" technologies in composites and fiber producers are very reticent to reveal much about the formulations they use
- The sizing formulation is very complex and contains one or several polymeric components
- Sizing has many functions:
  - coupling agent (promotes adhesion)
  - lubricant/protection during processing
  - a range of additives (surfactants, plasticizers, anti-static agents, adhesion promoters, anti-foams, rheology modifiers, etc.)

Sizing spray

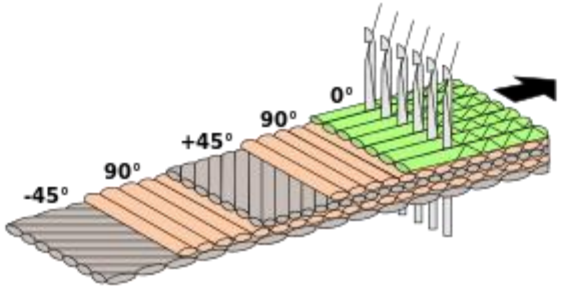
Glass fiber

FIBER ARCHITECTURE

- Fiber architecture refers to how the fiber is assembled
- Most common architectures:
  - Unidirectional
  - Chopped strand mat (CSM) and chopped fiber (chopper gun)
  - Woven fabric
  - Non-crimp fabric (NCF)
  - Braid



Woven fabric



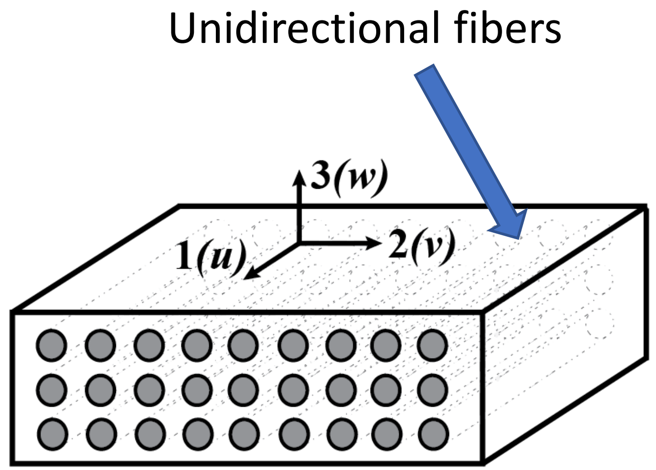
Non-crimp fabric

Mat

Braided tube

FIBER ARCHITECTURE: UNIDIRECTIONAL

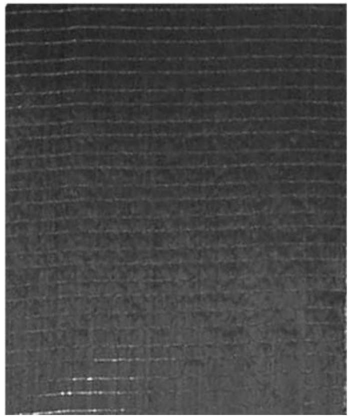
- Unidirectional ('uni') fabric refers to material that is composed of fibers that are all oriented in a single direction
- Essentially a number of tows that are lined up beside each other and spread out to form a continuous group
- Commonly used in aerospace applications
- Pros:
  - Highest volume fraction possible ~65%
  - Design flexibility, can orient laminate in any order
- Cons:
  - Typically less drapeable
  - Less durable (fibers are not interwoven)
  - Fibers must be held together



FIBER ARCHITECTURE: UNIDIRECTIONAL

- Unidirectional fibers must be combined/held together for processing


Stitched

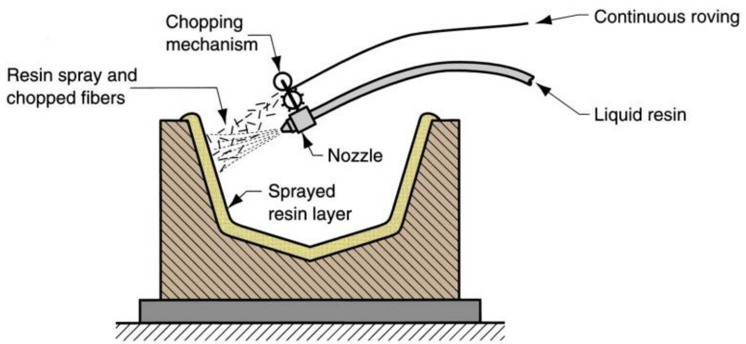

Hot melt


Unidirectional prepreg


Scrim backing

FIBER ARCHITECTURE: CHOPPED FIBER

- A chopper gun takes a tow of fiber, saturates it with resin, cuts it into ~1” and shoots it onto a mould or conveyor belt to make a mat
- Chopped strand mat (CSM) consists of fiber that is chopped up (~1”) and held together with a binder in a mat or fabric form
- Typically the binder dissolves in styrene (broken down by the styrene in polyester and vinyl ester resins)
- Pros:
  - Cheap
  - Very easy to process
  - Isotropic in-plane
- Cons:
  - Lower mechanical properties
  - Low V_f ~20%



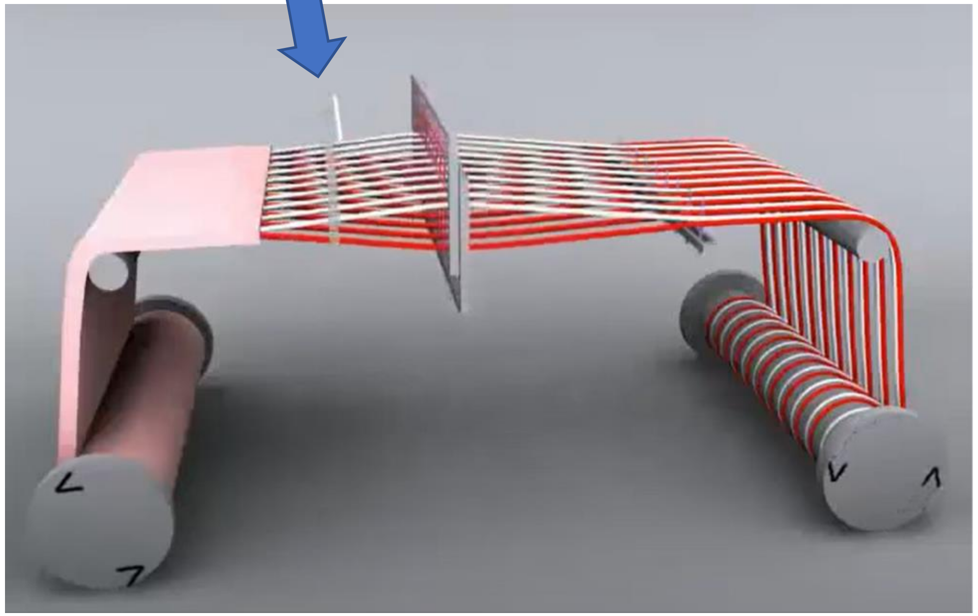
FIBER ARCHITECTURE: WOVEN FABRIC

- Fabric is woven from fiber just like any textile
- The process is common to glass, carbon, aramid, etc.
- Pros:
  - Moderate processability and ease to work with (good balance between drapeability and stability)
  - More durable/damage resistant (inter woven architecture holds itself together)
  - No other materials are required to hold it together
  - Variety of weave patterns available, therefore variety of properties/options available
- Cons:
  - Crimps/kinks from weaving reduce strength vs. unidirectional
  - Lower V_f vs. unidirectional
  - Reduced permeability

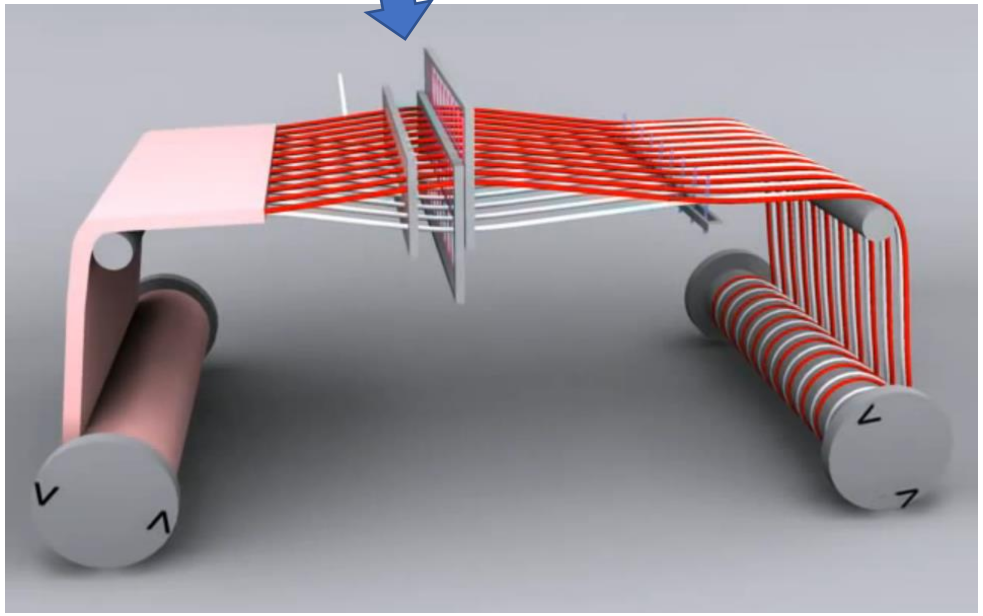
FIBER ARCHITECTURE: WOVEN FABRIC

- Basic principles of the weaving process

Fiber passed through



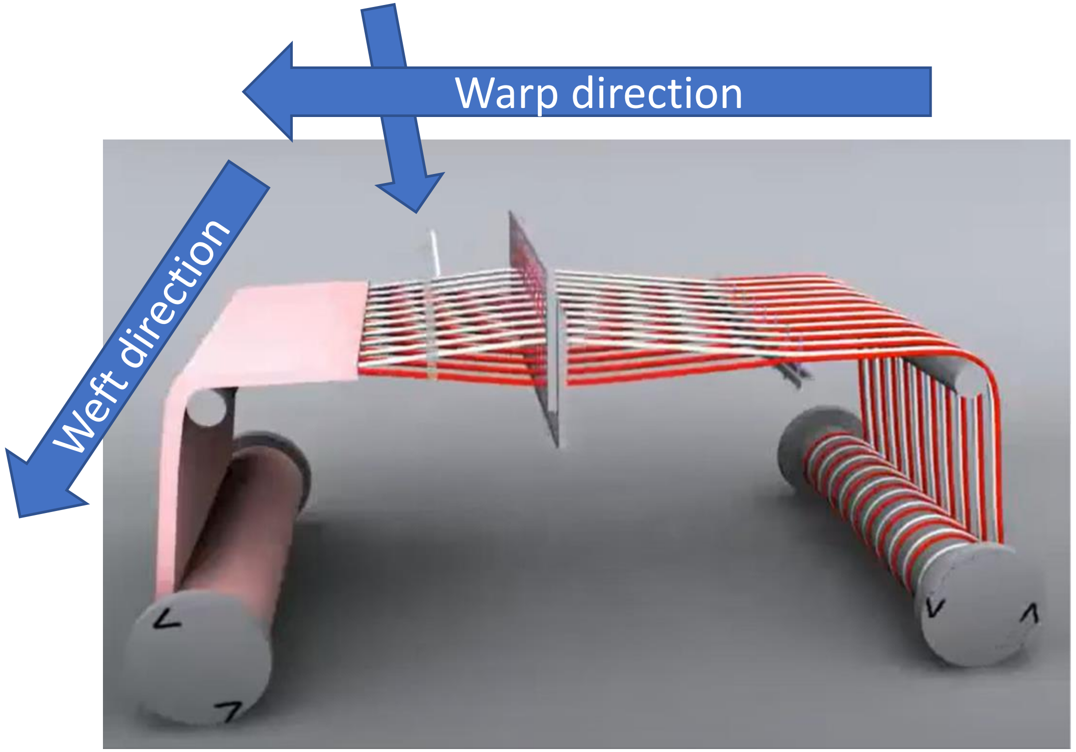
Tows are reversed



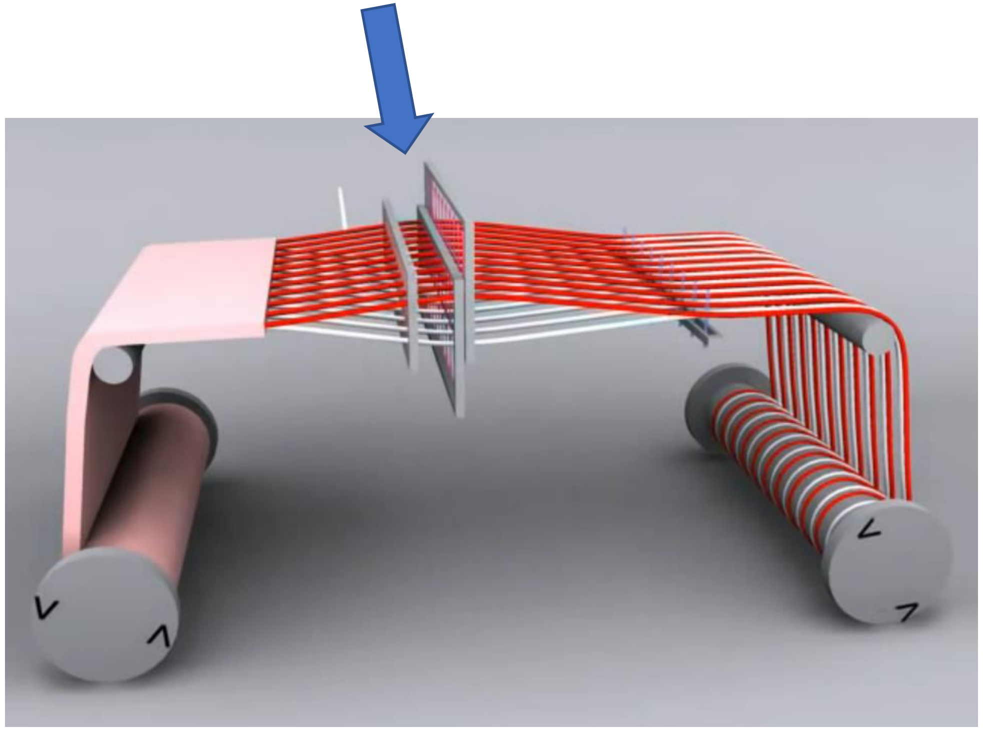
FIBER ARCHITECTURE: WOVEN FABRIC

- Basic principles of the weaving process

Fiber passed through

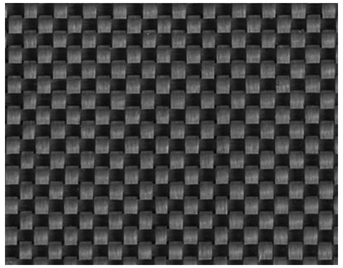


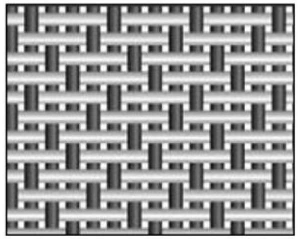
Tows are reversed

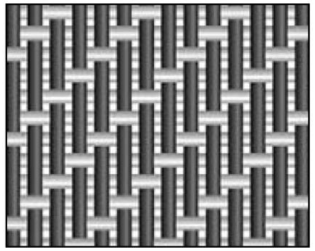


FIBER ARCHITECTURE: WOVEN FABRIC

- Plain Weave: consists of tows that are interlaced in an alternating fashion (over one, under one, over one, under one…)
  - Least drapeable
  - Good fabric stability
- Satin weave: refers to the weft tow crossing under one warp and over *n* warp tows
- The number of warp tows it crosses plus one is the harness number, ie. “four harness satin” travels under one warp and over three
  - Most drapeable
  - Least fabric stability
- Twill falls between plain and satin weaves in terms of drapeability and stability
  - Has characteristic diagonal pattern


Plain weave


Four harness satin weave

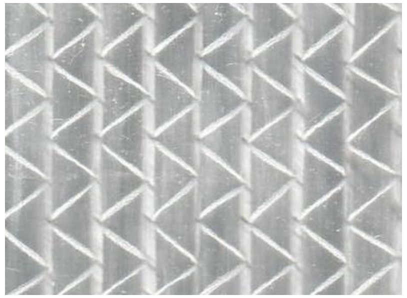

Twill weave

FIBER ARCHITECTURE: NON-CRIMP FABRIC

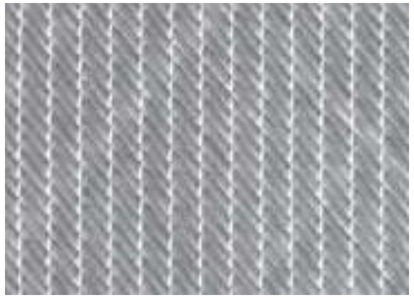
- With non-crimp fabric (NCF), tows are stitched together with a thread
- Because it is not woven together the tows are not crimped
- Pros:
  - No crimp results in better mechanical properties than woven material
  - Higher V_f vs. woven fabric
  - Typically has higher permeability than woven material
  - Good fiber stability
  - Many fiber orientation options, not just $0^o/90^o$ (theoretically any combination is possible)
  - Fabrics can be quite heavy = faster material deposition
- Cons:
  - Stitching remains in the composite after processing
  - Lower V_f vs. unidirectional material
  - Low drapeability

FIBER ARCHITECTURE: NON-CRIMP FABRIC

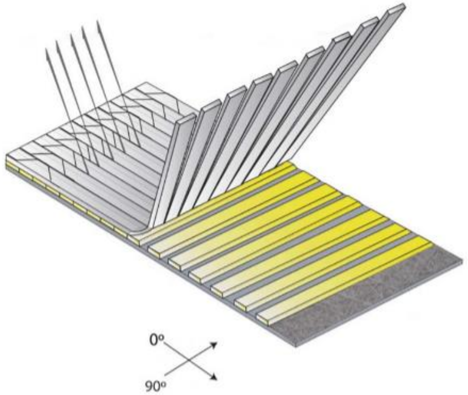
- Examples of various non-crimp fabric styles



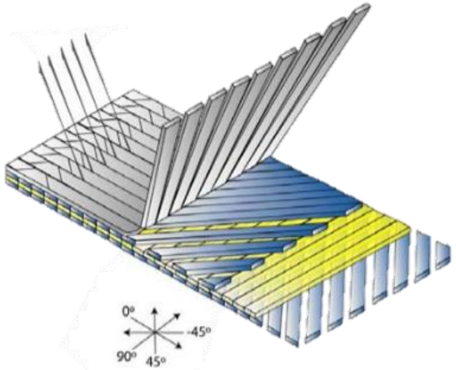
0º on upper surface



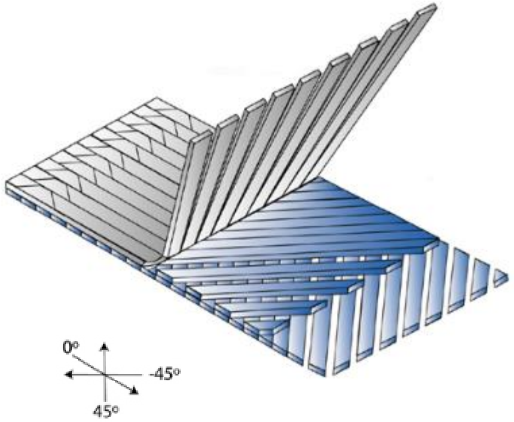
45º on upper surface



0º/90º
(with CSM mat backing)



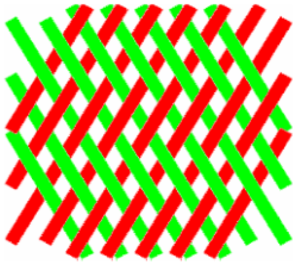
0º/90º/+45º/-45º
(quasi-isotropic)



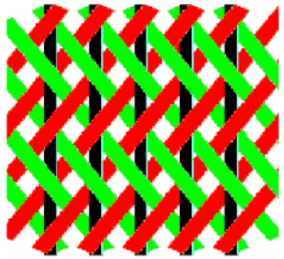
0º/+45º/-45º
(tri-axial)

FIBER ARCHITECTURE: BRAID

- Two or more systems of yarns are intertwined in a crisscross pattern
  - 2 and 3 axial braiding possible
  - Pros:
    - High level of conformability/drapeability
    - Good fabric stability
    - Torsionally rigid
    - Good damage tolerance
  - Cons:
    - Typically have lower V_f
    - Not as well known in industry therefore not used to its full potential



Biaxial braid



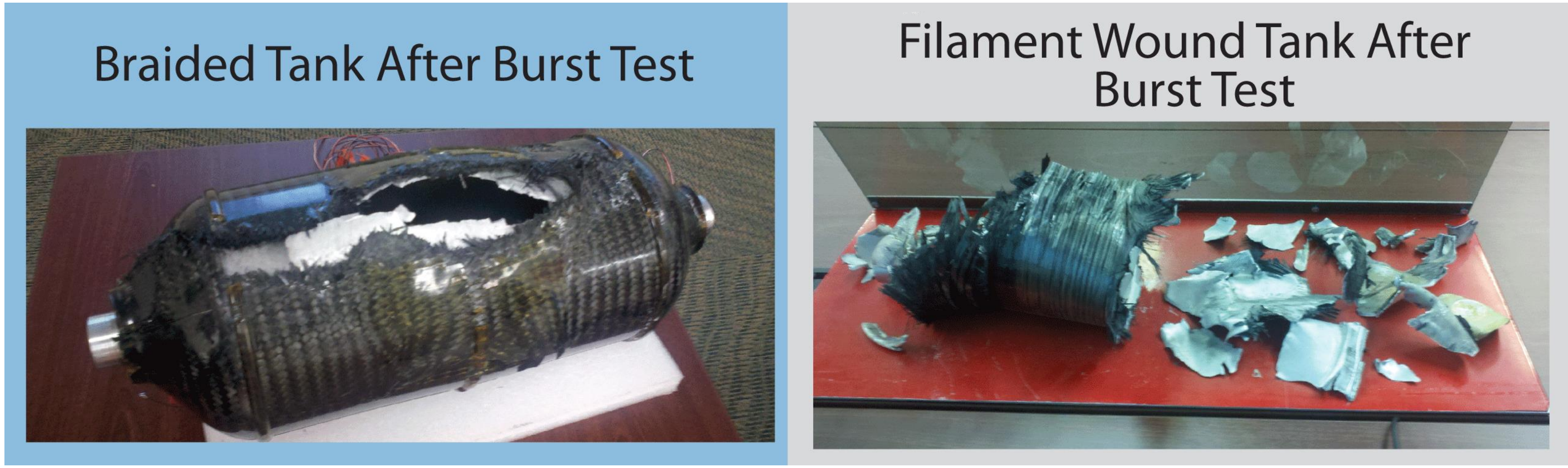
Triaxial braid

Braided tube

Aircraft landing components

FIBER ARCHITECTURE: BRAID DAMAGE TOLERANCE

- Composite pressure vessel



https://www.braider.com/Case-Studies/High-Pressure-CNG--and--Hydrogen-Tanks.aspx

Thank you for joining us!

The next session is:

Session 3: Constituent Materials: Resin

June 3, 2020 @ 9:00 am PST

Questions?

For more information on future dates and times visit:

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