ENGG103 – Materials in Design

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IN DUBAI

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Week 7: Lecture 7 –Composites

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Consultation hours:

12:30-14:30 Tuesday

https://uow.webex.com/meet/ciara

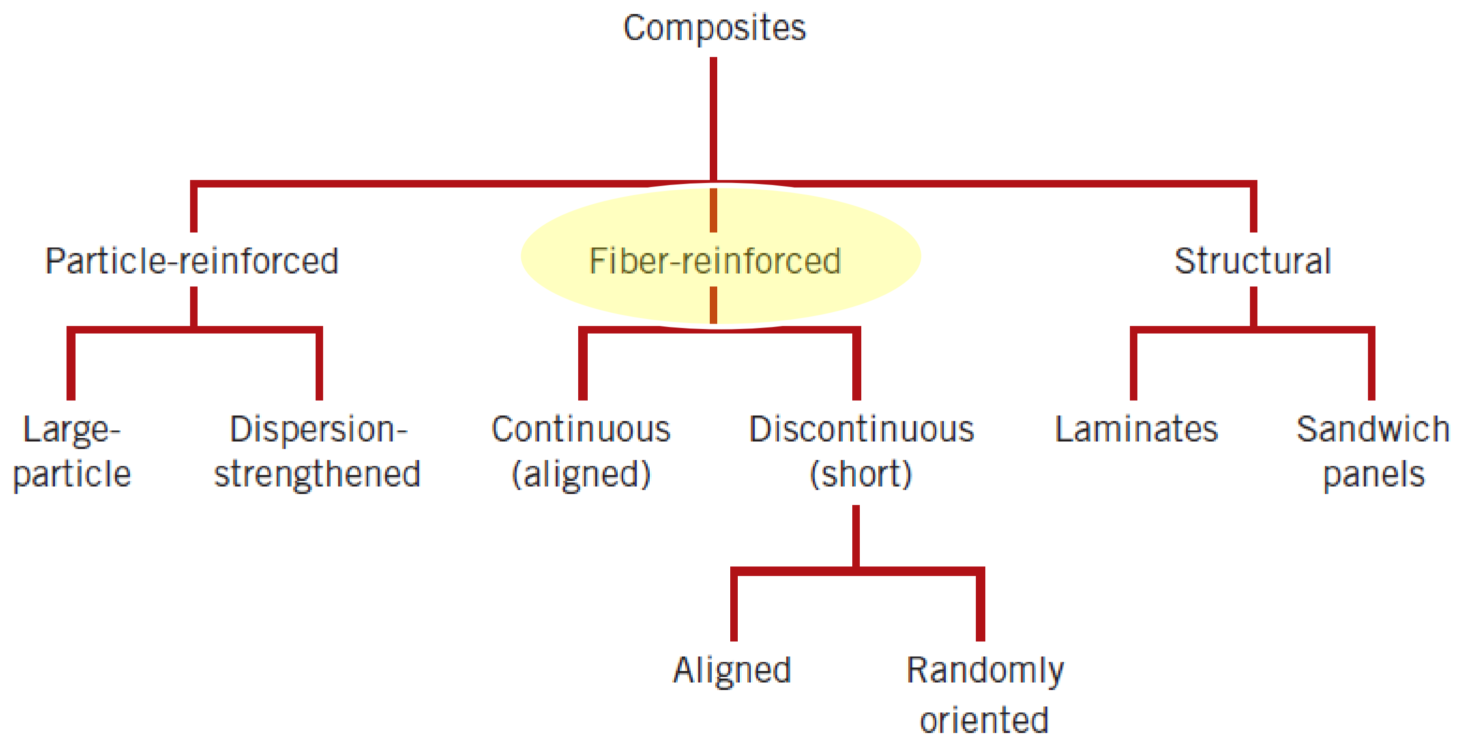
Please email first for appointment.

Objectives

- To provide students with a general awareness of **Fiber reinforced polymer** (FRP) materials and their potential uses
- To provide information on some of the potential uses of FRPs in engineering applications
- To provide guidance for students seeking additional information on FRPs

Composites

A classification scheme for the various composite types



Most composites have been created to improve combinations of mechanical characteristics such as stiffness, toughness, and ambient and high-temperature strength.

Fiber Reinforced Polymer Materials

- Design goals of fiber-reinforced composites often include high strength and/or stiffness on a weight basis.
- Fiber-reinforced composites with exceptionally high specific strengths and moduli have been produced that utilize low-density fiber and matrix materials.
- Longstanding reputation in automotive and aerospace industries
- Over the past 15 years have **FRP** materials been increasingly considered for civil infrastructure applications

FRP costs have decreased

New, innovative solutions needed!

FRPs now recognized as **effective** and **efficient** structural materials

General

- FRPs are ***composite materials***:
  - materials created by the combination of two or more materials, on a macroscopic scale, to form a new and useful material with enhanced properties that are superior to those of the individual constituents alone

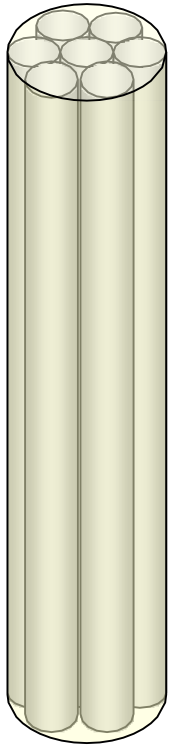
- More familiar composite materials
  - Concrete → stone, sand, and cement paste
  - Reinforced concrete → concrete and steel
  - Wood → cellulose and lignin
  - Bone → collagen and apatite

Constituents

- What is FRP?

Fibres

- Provide strength and stiffness
- Carbon, glass, aramid



Matrix

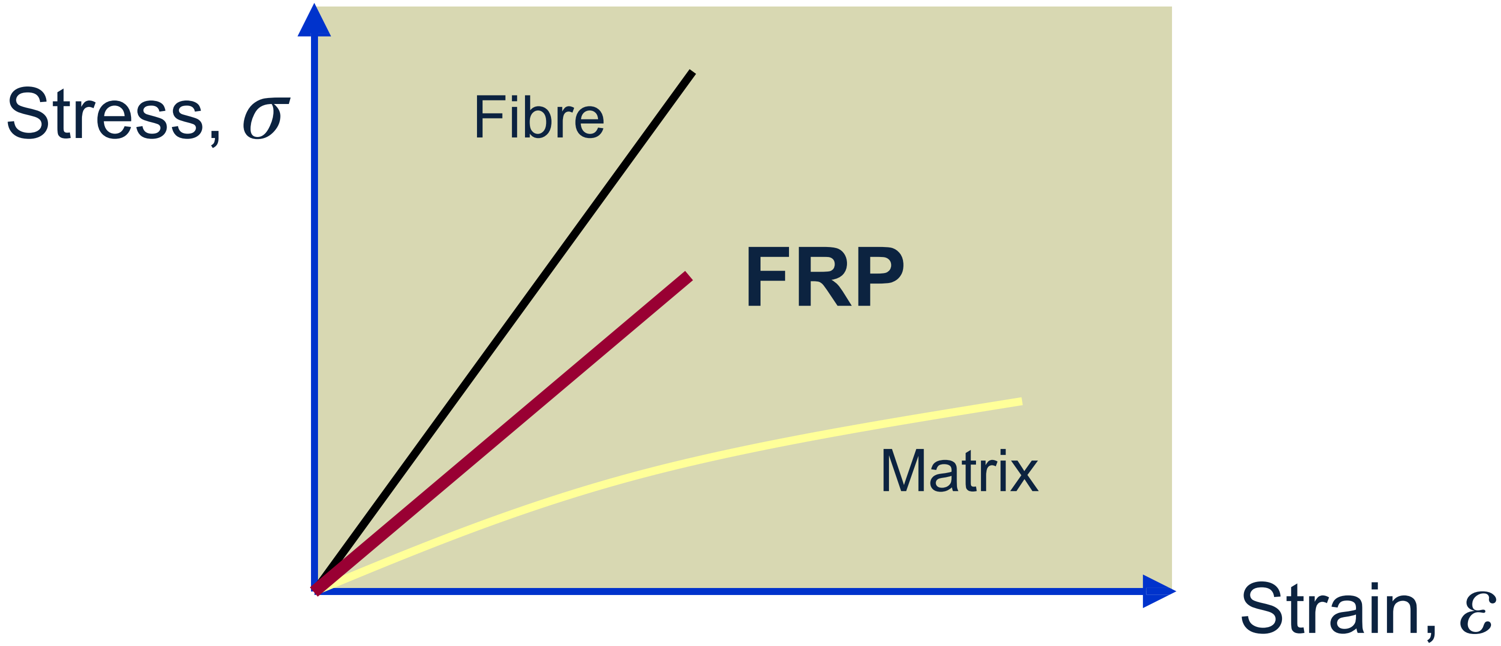
- Protects and transfers load between fibres
- Epoxy, vinylester

Fibre **Composite** **Matrix**

Creates a material with attributes superior to either component alone!
Fibres **and** matrix both play critical roles in the composite material...

Matrix + Fibre = FRP

Constituents



Combing fibres and matrix gives a composite material with superior properties

Polymer-matrix composites (PMCs) consist of a polymer resin as the matrix, with fibers as the reinforcement medium.

- Critical functions of the polymer matrix:

1. **Bind** the fibres together
2. **Protect** the fibres from environment and abrasion
3. **Separate and disperse** the fibres throughout the composite
4. **Transfer force** between the individual fibres

Polymers

- Polymer:
  - An **organic** compound comprised of **long-chain** molecules consisting of smaller repeated units called **monomers**

- Two types:

❶ **Thermoplastics**

→ polyethylene, nylon, polyamide

❷ **Thermosetting polymers**

→ polyester, vinylester, epoxy

Both, thermosetting and thermoplastic polymers can be applied as matrix for fiber-reinforced plastics (FRP)

Both, thermosetting and thermoplastic polymers can be applied as matrix for FRPs

- Their specific properties affect the processing of the appropriate FRPs as well as the final material properties, respectively.

- FRP based on thermosets have excellent mechanical properties due to an irreversibly cross-linked network. Once manufactured these extremely strong materials can no longer be worked and shaped. This limits the use of industrial production processes and the recycling of materials from end-of-life components.

- In contrary, thermoplastics associate through intermolecular forces and can be shaped above their glass transition or melting temperature. This enables process engineering with fast cycle times of e.g. injection molding or extrusion. Thermoplastic FRPs suffer, however, from creep and their relatively low thermal stability.

Fibre Component

Fibers are grouped into three different classifications: whiskers, fibers, and wires

- Fibres provide strength and stiffness
- Properties required of the fibres:

1. high stiffness
2. high ultimate strength
3. low variation of strength between individual fibres
4. stability during handling
5. uniform diameter

- extremely large length-to-diameter ratio

Fibre Component

- 3 fibres commonly used in infrastructure applications
  - **Glass, carbon, aramid (GFRP, CFRP, AFRP)**

- Factors influencing fibre suitability:

❶ Strength

❷ Stiffness

❸ Environment and durability

❹ Cost

❺ Availability

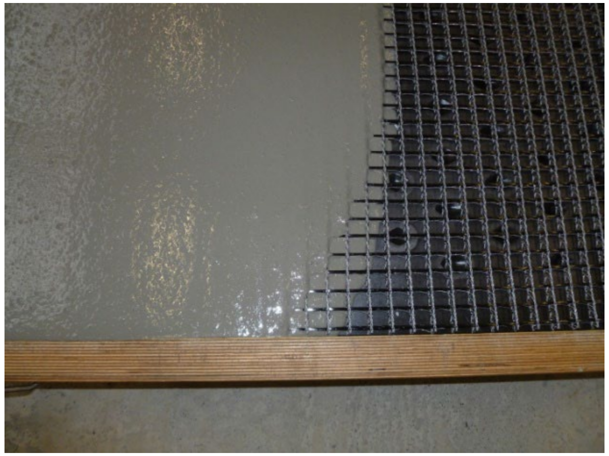
Glass Fibres

- Inexpensive
- Most commonly used
- Several grades available:
  - E-Glass
  - R-Glass
  - AR-Glass (alkali resistant)
- High strength, moderate modulus, medium density
- Used in non weight/modulus critical applications

Carbon Fibres

Fibres

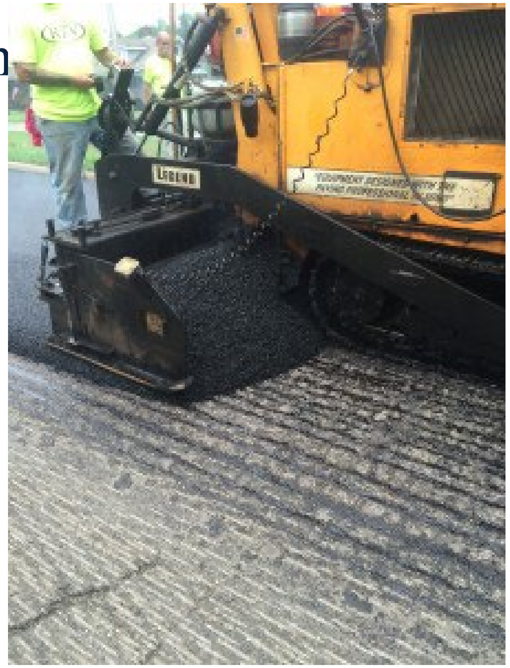
- Significantly higher cost than glass
- Several grades available:
  - Standard modulus → 250-300 GPa
  - Intermediate → 300-350 GPa
  - High → 350-550 GPa
  - Ultra-high → 550-1000 GPa



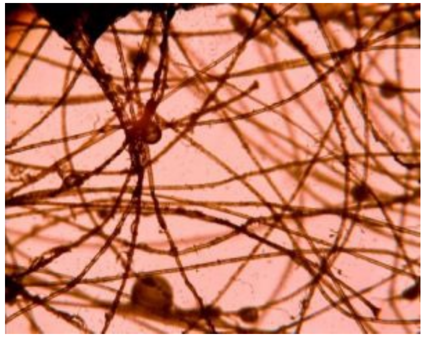
Carbon Fibre Grids Replace Steel as Concrete Reinforcement

- High strength, high modulus, low density
- Superior durability and fatigue characteristics
- Used in weight/modulus critical applications

Aram



- Moderate to high cost
- Two grades available
  - 60 GPa elastic modulus
  - 120 GPa elastic modulus
- High tensile strength, moderate modulus, low density
- Low compressive and shear strength
- Some durability concerns
  - Potential UV degradation
  - Potential moisture absorption and swelling



Fibre Comparison: Stress-Strain

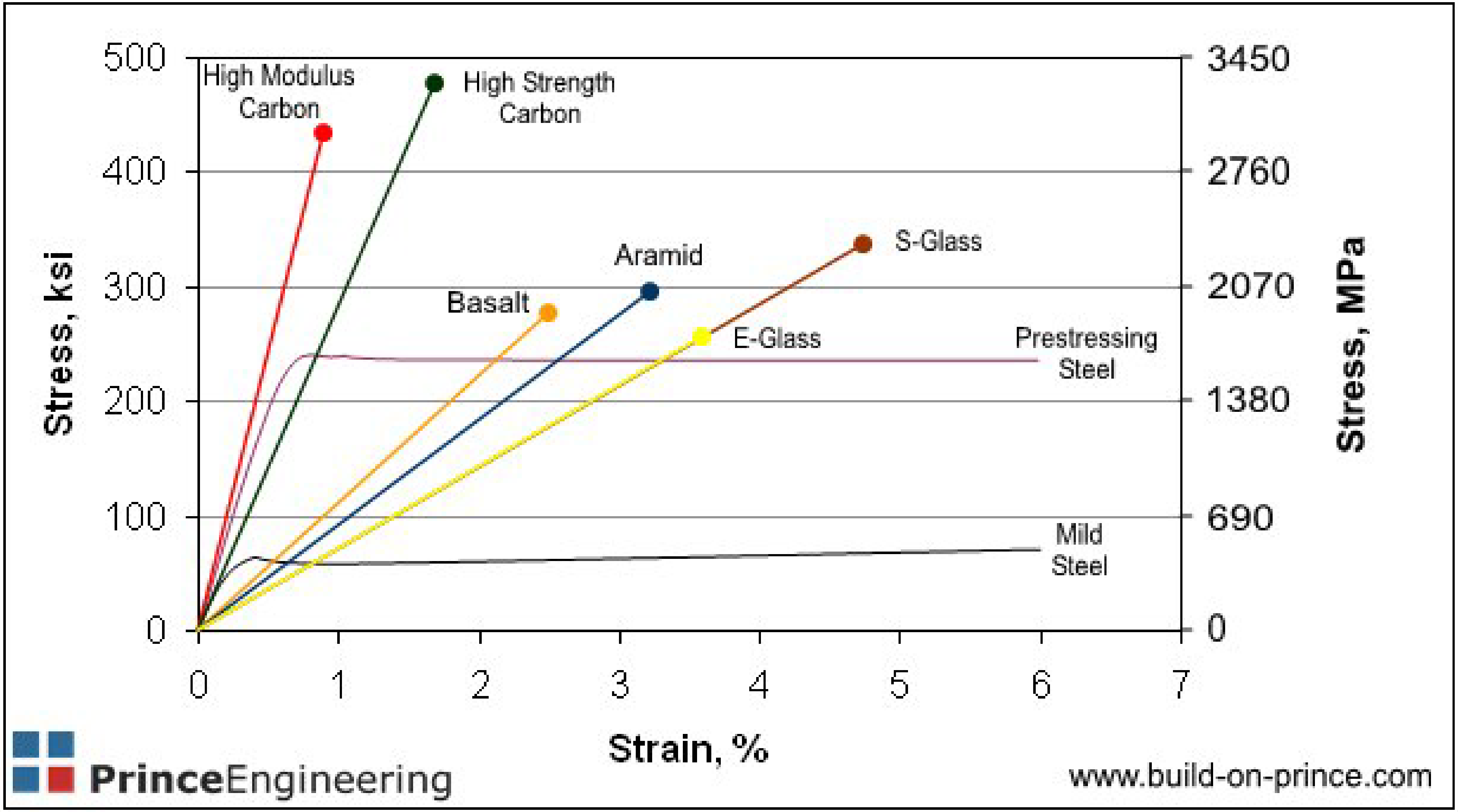


Table 16.5 Properties of Continuous and Aligned Glass-, Carbon-, and Aramid-Fiber Reinforced Epoxy-Matrix Composites in Longitudinal and Transverse Directions. In All Cases the Fiber Volume Fraction Is 0.60

Property	*Glass (E-glass)*	*Carbon (High Strength)*	*Aramid (Kevlar 49)*
Specific gravity	2.1	1.6	1.4
Tensile modulus			
Longitudinal [GPa (10^6 psi)]	45 (6.5)	145 (21)	76 (11)
Transverse [GPa (10^6 psi)]	12 (1.8)	10 (1.5)	5.5 (0.8)
Tensile strength			
Longitudinal [MPa (ksi)]	1020 (150)	1240 (180)	1380 (200)
Transverse [MPa (ksi)]	40 (5.8)	41 (6)	30 (4.3)
Ultimate tensile strain			
Longitudinal	2.3	0.9	1.8
Transverse	0.4	0.4	0.5

Source: Adapted from R. F. Floral and S. T. Peters, "Composite Structures and Technologies," tutorial notes, 1989.

Fibres + Matrix = FRP

- Better overall composite properties are realized when the fiber distribution is uniform.

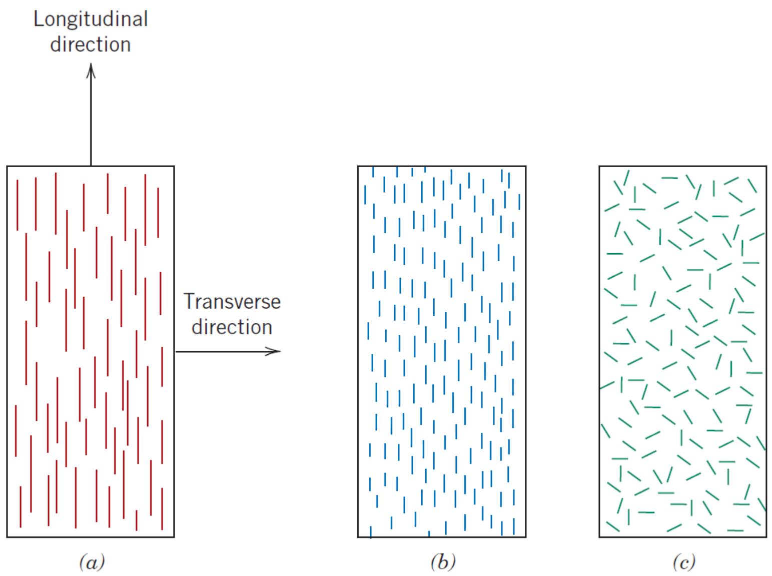
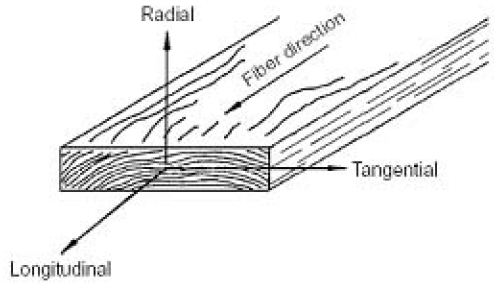


Figure 16.8 Schematic representations of (*a*) continuous and aligned, (*b*) discontinuous and aligned, and (*c*) discontinuous and randomly oriented fiber-reinforced composites.

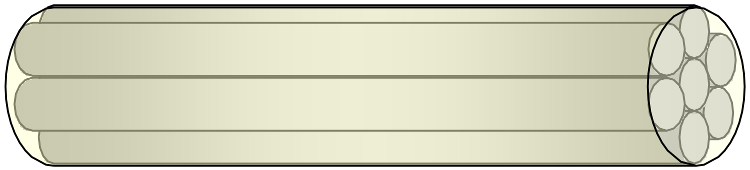
- Overall FRP properties depend on:
  - Mechanical properties of matrix
  - Mechanical properties of fibres
  - Fibre volume fraction
  - Fibre cross sectional area
  - Orientation of fibres within matrix → **Key Factor**
  - Interaction between fibres and matrix
  - Method of manufacturing

The properties of a composite having its fibers aligned are highly anisotropic, that is, dependent on the direction in which they are measured.

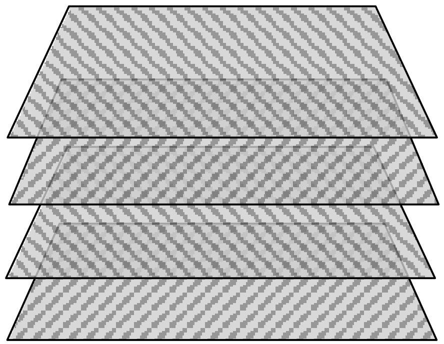
Influence of Fibre Orientation



- FRPs are ***Orthotropic*** materials
  - Properties are directionally dependent
- Unidirectional FRPs
  - Fibres in one direction only
  - Aligned along longitudinal axis
  - Stronger and stiffer in fibre direction



- Multidirectional FRPs (laminates)
  - Fibres in various directions (fibre architecture)
  - Properties can be tailored
  - Behaviour can approach isotropy



- Unidirectional FRPs used in infrastructure applications

To fabricate continuous fiber-reinforced plastics that meet design specifications, the fibers should be uniformly distributed within the plastic matrix and, in most instances, all oriented in virtually the same direction.

1. Pultrusion:
   - FRP bars, structural sections, plates

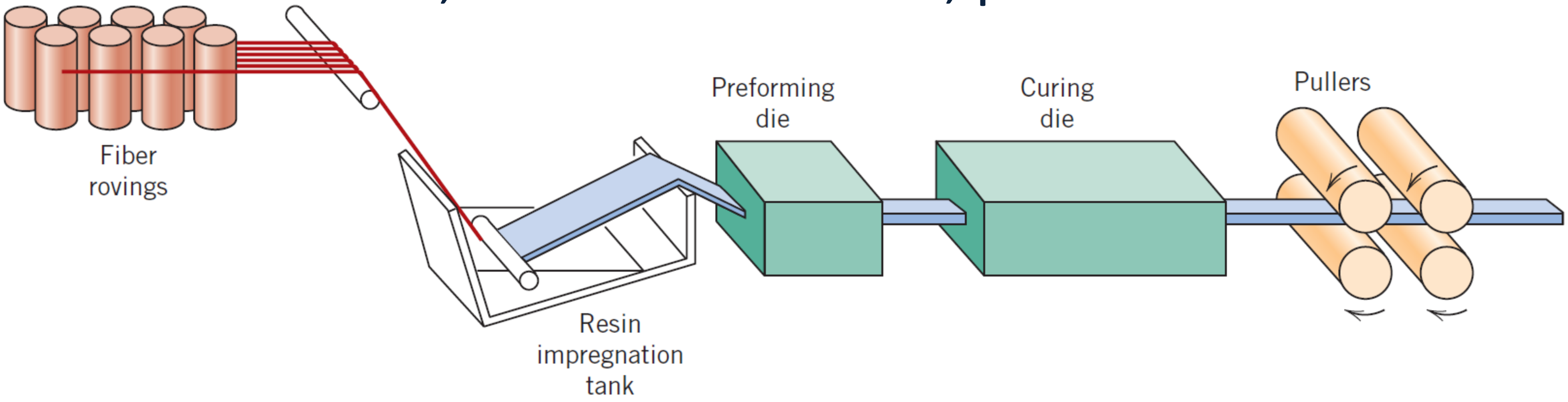
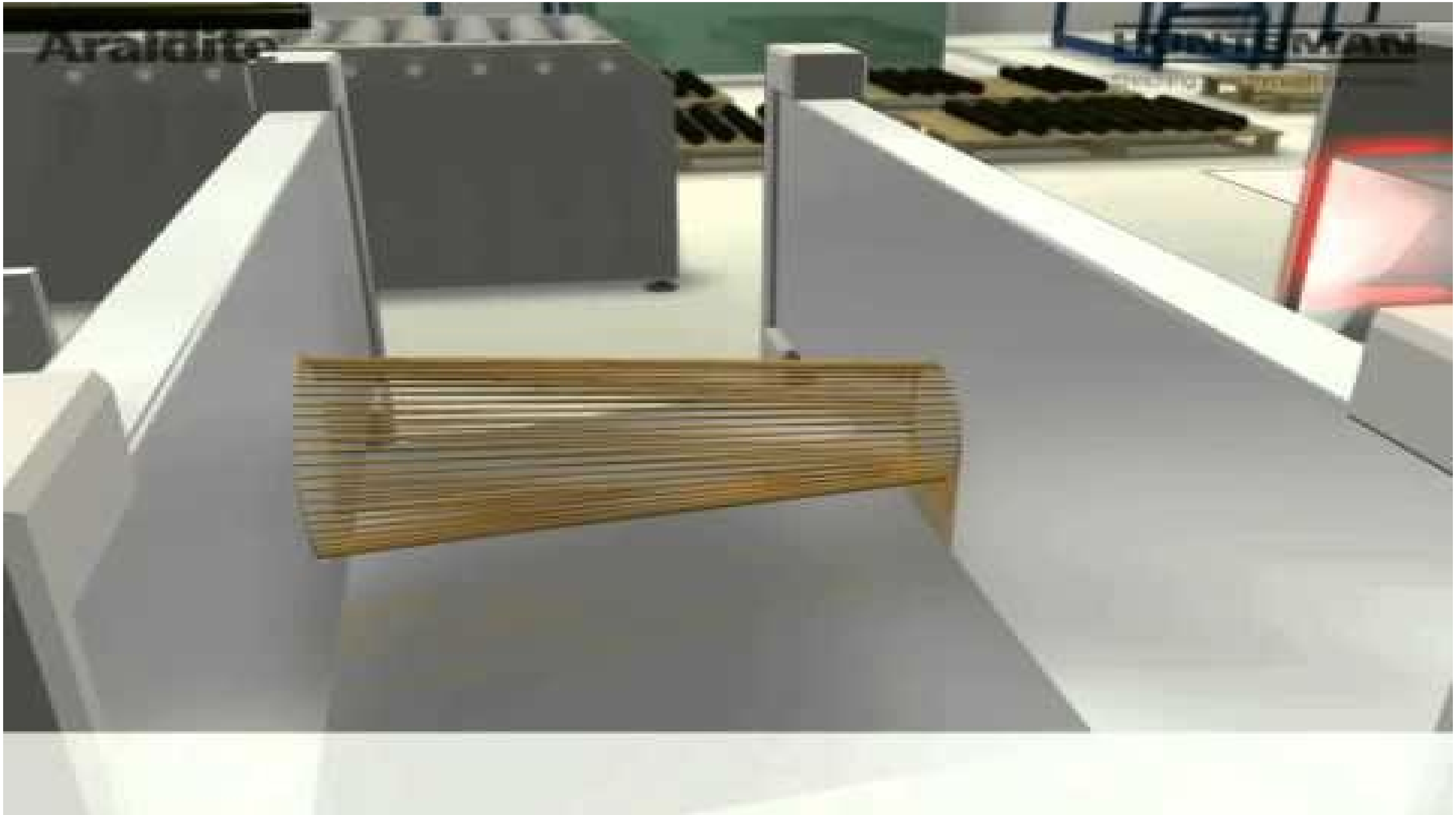


Figure 16.13 Schematic diagram showing the pultrusion process.

Fibre strand pulled from creels… …saturated in polymer resin… …shaped in a heated die… …and the finished product is pulled through

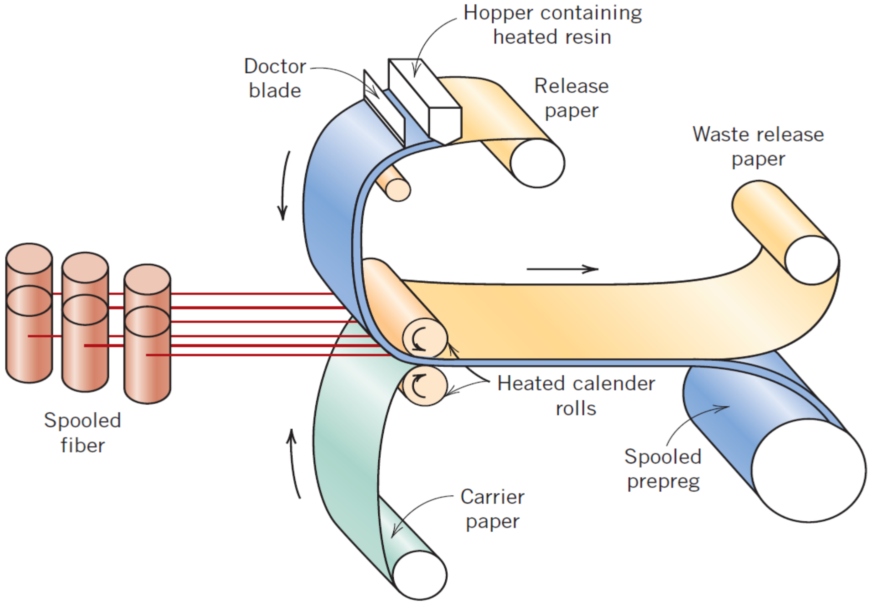

Araldite

Pultrusion

Pultrusion is a continuous process that is easily automated; production rates are relatively high, making it very cost effective. Furthermore, a wide variety of shapes are possible, and there is really no practical limit to the length of stock that may be manufactured.

2. Wet lay up

- FRP sheets for repair applications, laminates



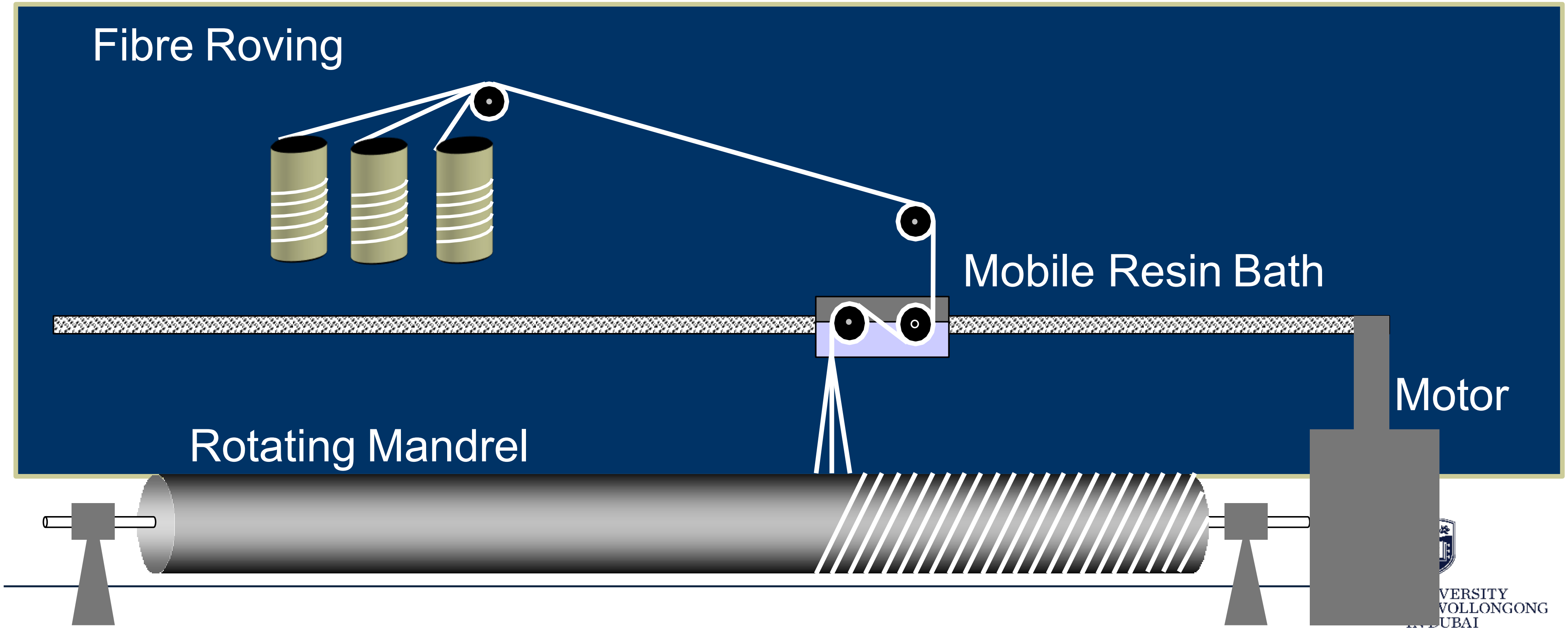
The final **prepreg** product—the thin tape consisting of continuous and aligned fibers embedded in a partially cured resin—is prepared for packaging by winding onto a cardboard core.

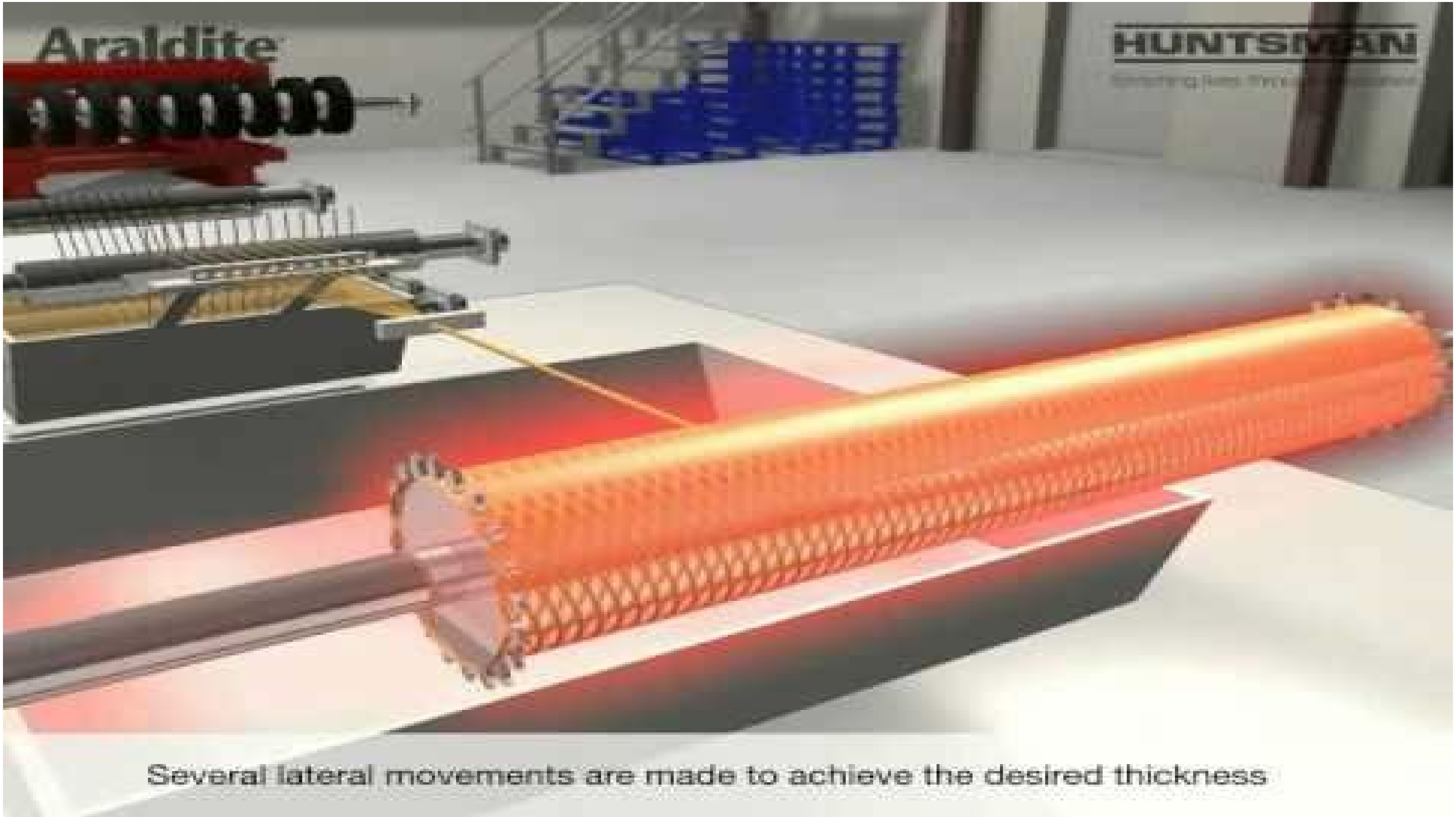
Resin-saturated FRP lamina (fabrics) are placed over a mould or an existing structural member

Filament winding is a process by which continuous reinforcing fibers are accurately positioned in a predetermined pattern to form a hollow (usually cylindrical) shape.

3. Filament winding:

- FRP tubes, poles, tanks, forms




Araldite
HUNTSMAN
Several lateral movements are made to achieve the desired thickness

Mechanical Properties

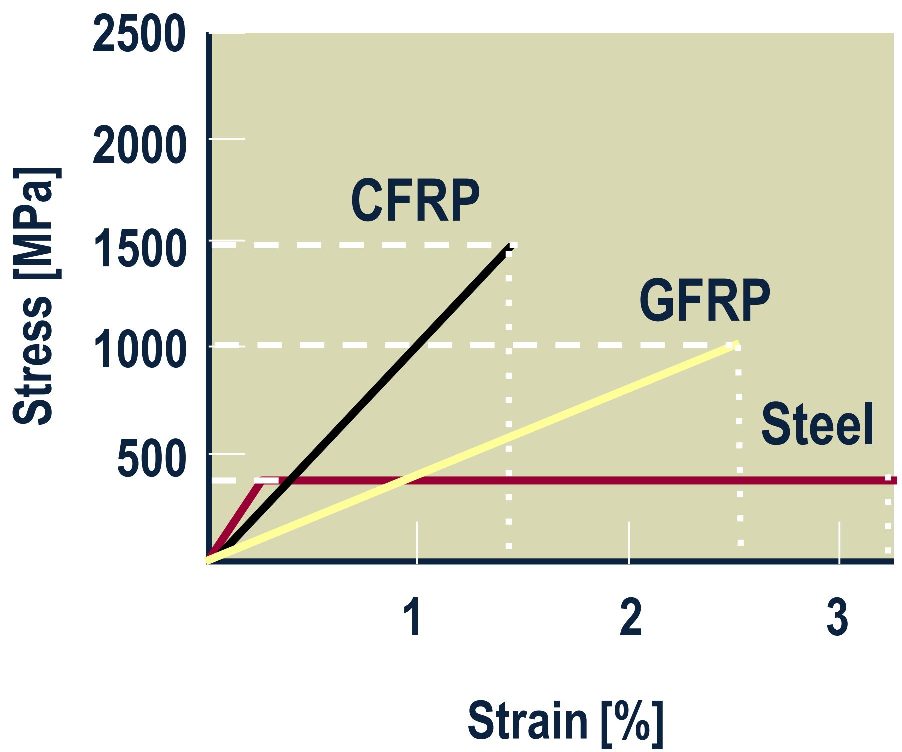
FRP mechanical properties are a function of:

- Type of fibre and matrix
- Fibre volume content
- Orientation of fibres

Here we are concerned mainly with *unidirectional* FRPs!

Mechanical Properties

- FRP properties
  (in general versus steel):
  - Linear elastic behaviour to failure
  - No yielding
  - Higher ultimate strength
  - Lower strain at failure
  - Comparable modulus (carbon FRP)



Quantitative Comparison

Typical Mechanical Properties*

Material	Ultimate Strength	Elastic Modulus	Failure Strain
Glass FRP	517-1207 MPa	30-55 GPa	2-4.5 %
Carbon FRP	1200-2410 MPa	147-165 GPa	1-1.5 %
Aramid FRP	1200-2068 MPa	50-74 GPa	2-2.6 %
Steel	483-690 MPa	200 GPa	>10 %

* Based on 2001 data for specific FRP rebar products

Modulus of Elasticity - Longitudinal Loading

Mechanical Properties

- Greatest stiffness in the fibre direction in tension
- E_{frp} is a function of
  - Fibre modulus, E_f
  - Matrix modulus, E_m
  - Fibre volume ratio, V_f
- Rule of mixtures (unidirectional, in fibre direction):

$$\boxed{E_{frp} = E_m V_m + E_f V_f} = \left(E_f - E_m\right) V_f + E_m$$

Elastic Behavior — Longitudinal Loading

Thus, E_{cl} is equal to the volume-fraction weighted average of the moduli of elasticity of the fiber and matrix phases. Other properties, including density, also have this dependence on volume fractions.

It can also be shown, for longitudinal loading, that the ratio of the load carried by the fibers to that carried by the matrix is

$$\frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m}$$

Example 28.1

A unidirectional fiber composite consists of 60% by volume of Kevlar fibers in a matrix of epoxy. Find the moduli E_{cl} and E_{ct}.

- Comment on the accuracy of your value for E_{ct}.
- Use the moduli given in Table 28.1, and use an average value where a range of moduli is given.

Table 28.1 Properties of Some Fibers and Matrices

Material	Density ρ (Mg m^{-3})	Modulus E (GN m^{-2})	Strength σ_f (GN m^{-2})
Fibers			
Carbon, Type 1	1.95	390	2200
Carbon, Type 2	1.75	250	2700
Cellulose fibers	1.61	60	1200
Glass (E-glass)	2.56	76	1400–2500
Kevlar	1.45	125	2760
Matrices			
Epoxies	1.2–1.4	2.1–5.5	40–85
Polyesters	1.1–1.4	1.3–4.5	45–85

Modulus Longitudinal

$$E_{cl} = E_m V_m + E_f V_f$$

$$E_{cl} = E_m(1 - V_f) + E_f V_f$$

Modulus Transverse

$$E_{ct} = \frac{E_m E_f}{V_m E_f + V_f E_m} = \frac{E_m E_f}{(1 - V_f)E_f + V_f E_m}$$

Tensile Strength

Many fiber composites are made of strong, brittle fibers in a more ductile polymer matrix. Then the stress strain curve looks like the heavy line in Figure 28.2. The figure largely explains itself. The stress strain curve is linear, with slope E until the matrix yields.

From there on, most of the extra load is carried by the fibers which continue to stretch elastically until they fracture.

When they do, the stress drops to the yield strength of the matrix (though not as sharply as the figure shows because the fibers do not all break at once).

When the matrix fractures, the composite fails completely.

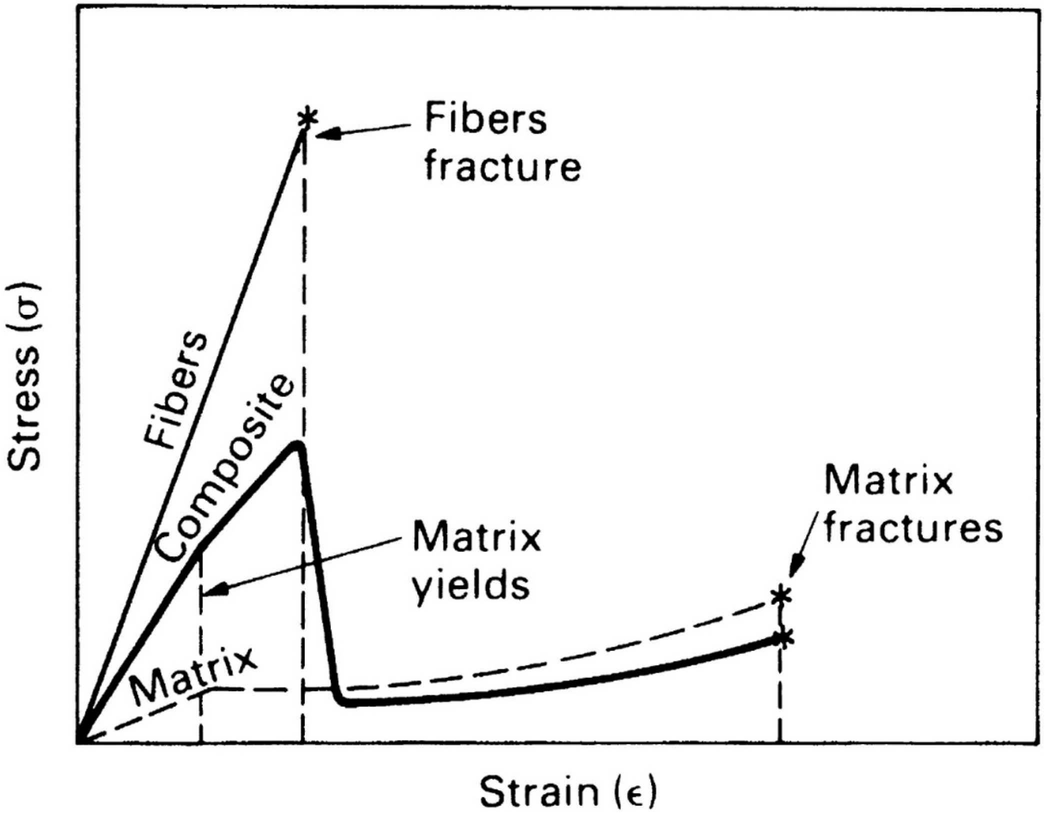


Figure 28.2

Tensile Strength- section 28.4

In any structural application it is the peak stress which matters. At the peak, the fibers are just on the point of breaking and the matrix has yielded, so the stress is given by the **yield strength of the matrix**, σ_y^m ; and the **fracture strength of the fibers**, σ_f^f; combined using a rule of mixtures

$$\sigma_{TS} = V_f \sigma_f^f + (1 - V_f)\sigma_y^m .$$

This is shown as the line rising to the right in Figure 28.3. Once the fibers have fractured, the strength rises to a second maximum determined by the fracture strength of the matrix

$$\sigma_{TS} = (1 - V_f)\sigma_f^m$$

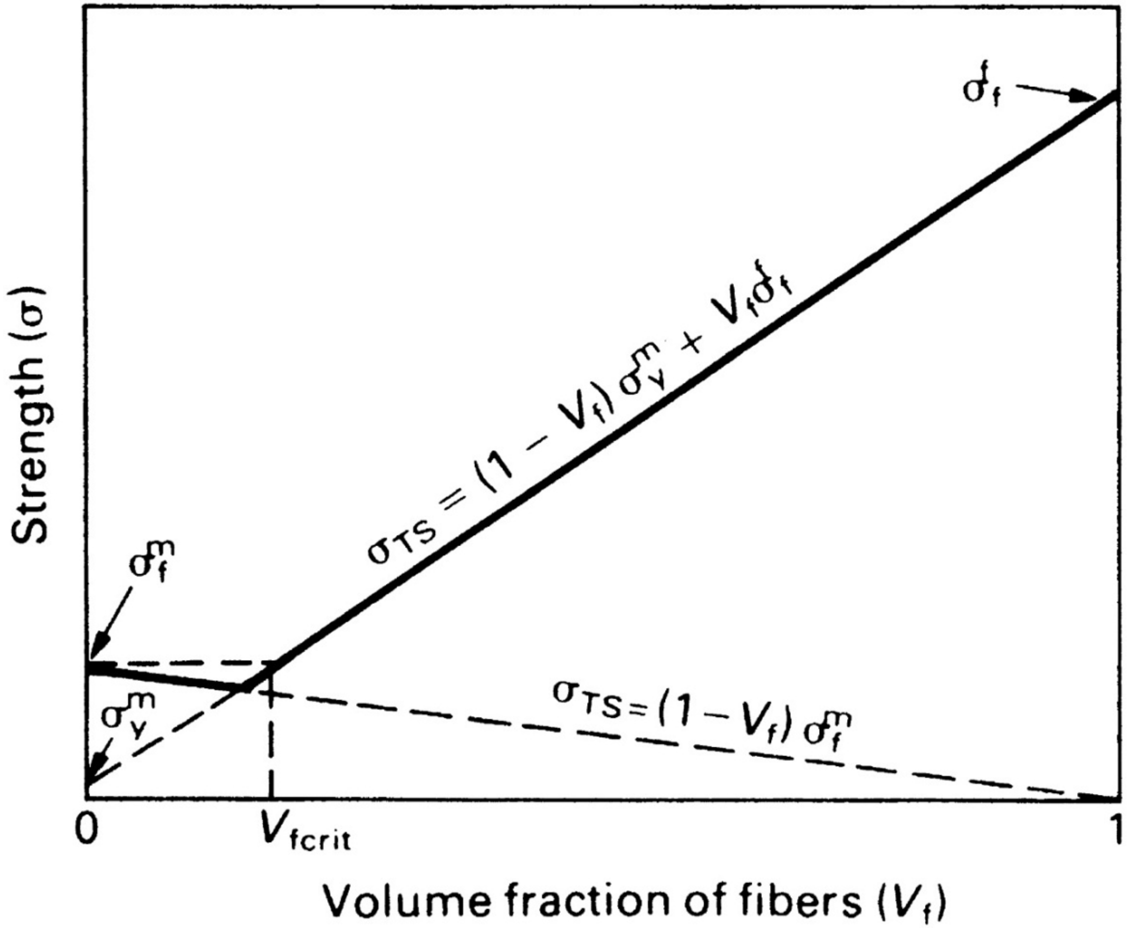


Figure 28.3

- Greatest strength in the fibre direction in tension

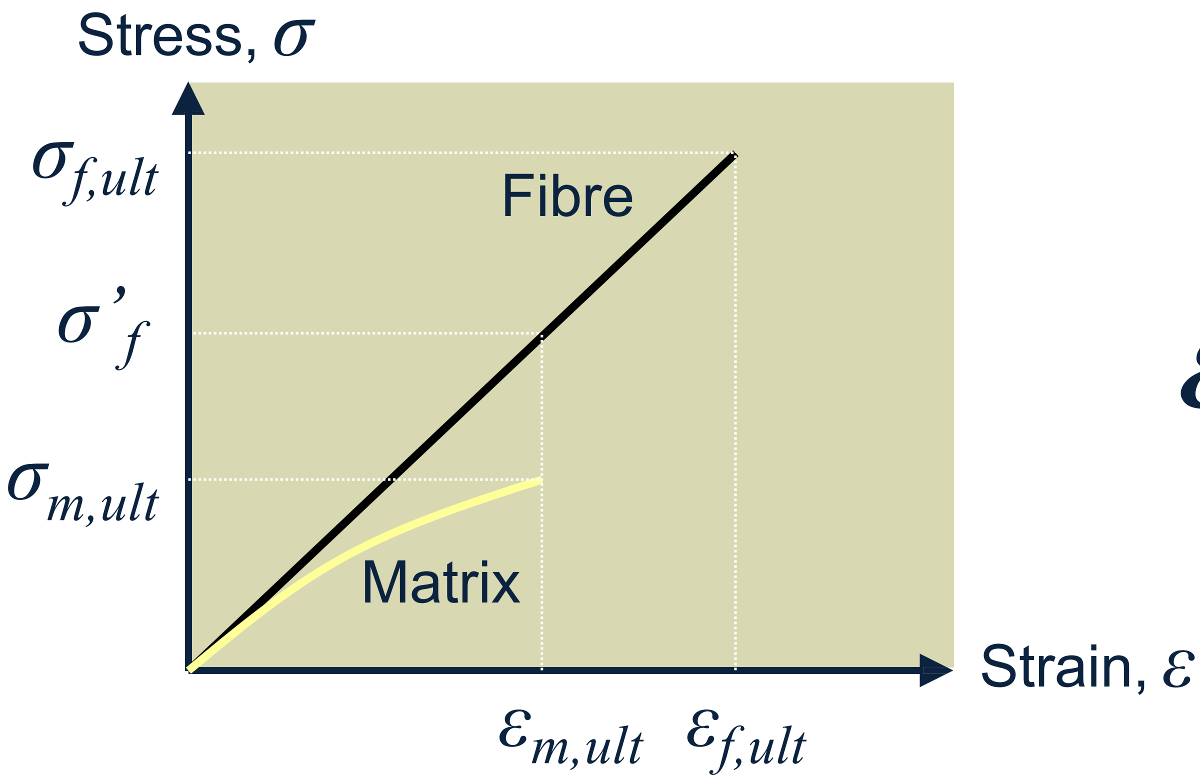
- $\sigma_{frp,ult}$ is a function of

Fibre strength, $\sigma_{f,ult}$

Matrix strength, $\sigma_{m,ult}$

Fibre volume ratio, V_f

Relative failure strains



CASE 1:

$$\varepsilon_{m,ult} < \varepsilon_{f,ult}$$

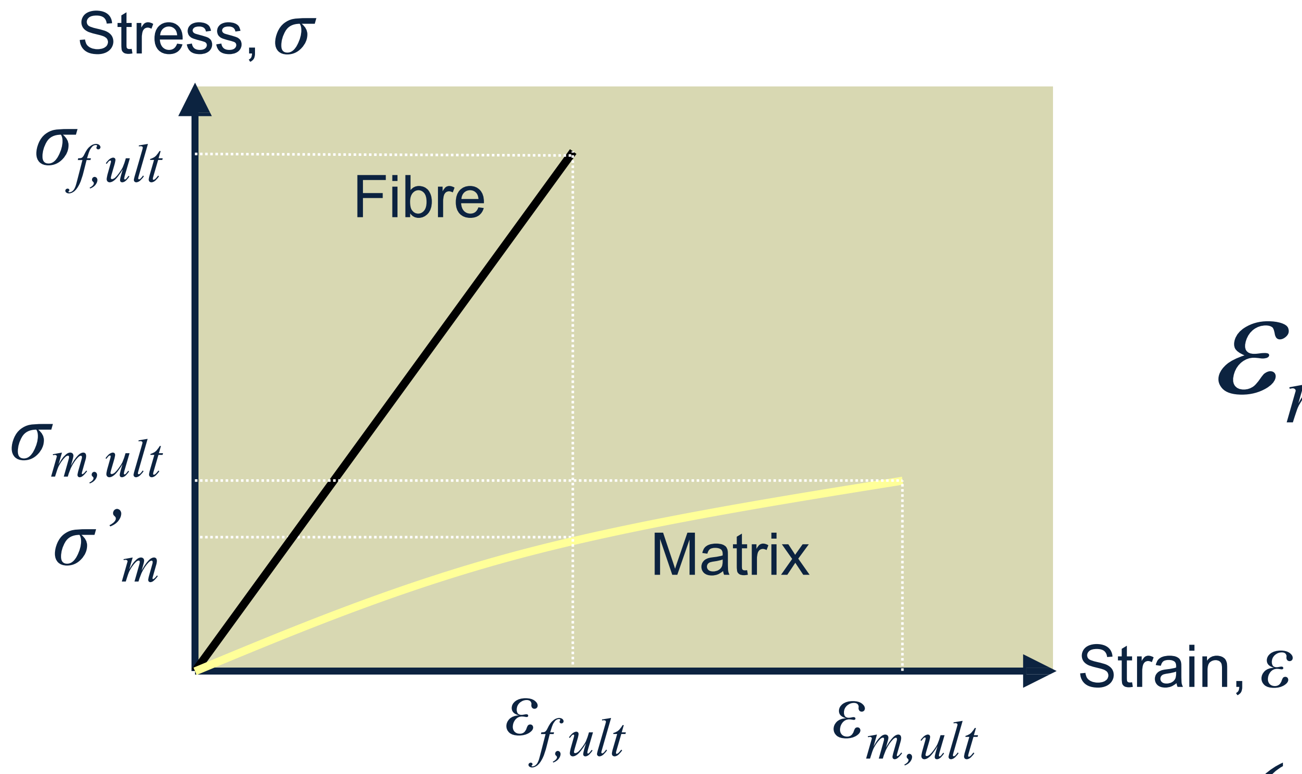
*not common for FRP

If V_f is large $\sigma_{frp,ult} = \sigma_{f,ult} V_f$

If V_f is small $\sigma_{frp,ult} = \sigma'_f V_f + \sigma_{m,ult}(1 - V_f)$

For most FRP used in civil engineering applications, V_f is large (> 0.1)

Strength



CASE 2:

$$\varepsilon_{m,ult} > \varepsilon_{f,ult}$$

If V_f is small $\quad \sigma_{frp,ult} = \sigma_{m,ult}(1 - V_f)$

If V_f is large $\quad \sigma_{frp,ult} = \sigma_{f,ult} V_f + \sigma'_m (1 - V_f)$

For most FRP used in civil engineering applications, V_f is large (> 0.1)

Example 28.2

A unidirectional fiber composite consists of 60% by volume of continuous Type1 Carbon fibers in a matrix of epoxy. Find the maximum tensile strength of the composite. You may assume that the matrix yields in tension at a stress of 40 GN/m^2 .

Table 28.1 Properties of Some Fibers and Matrices

Material	Density ρ (Mg m^{-3})	Modulus E (GN m^{-2})	Strength σ_f (GN m^{-2})
Fibers			
Carbon, Type 1	1.95	390	2200
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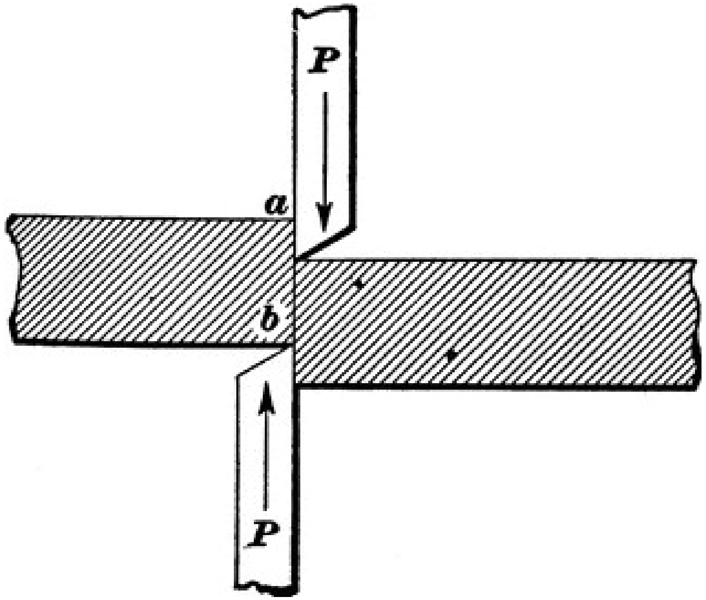
Matrices			
Epoxies	1.2–1.4	2.1–5.5	40–85
Polyesters	1.1–1.4	1.3–4.5	45–85

Tensile Strength

$$\sigma_{TS} = V_f \sigma_f^f + (1 - V_f)\sigma_y^m .$$

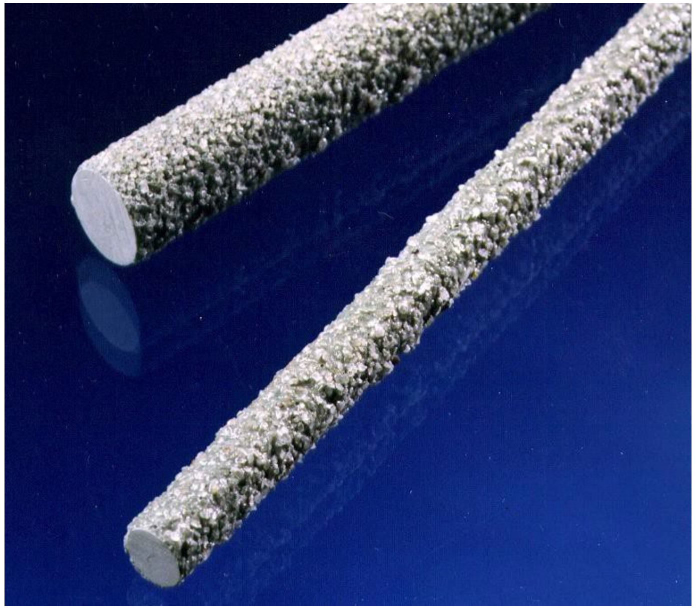
Shear Testing of FRP bars

- Shear strength is a material's ability to resist forces that can cause the internal structure of the material to slide against itself.

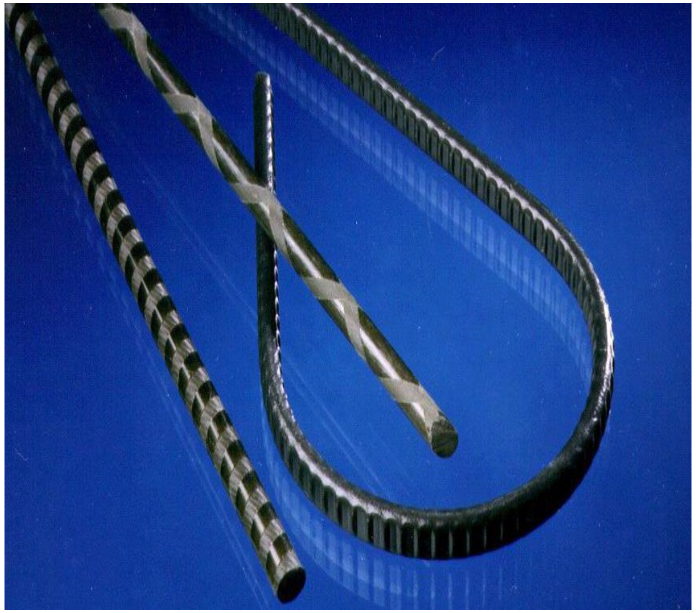


Manufacturing

- To enhance an FRP bar’s mechanical bond with concrete:



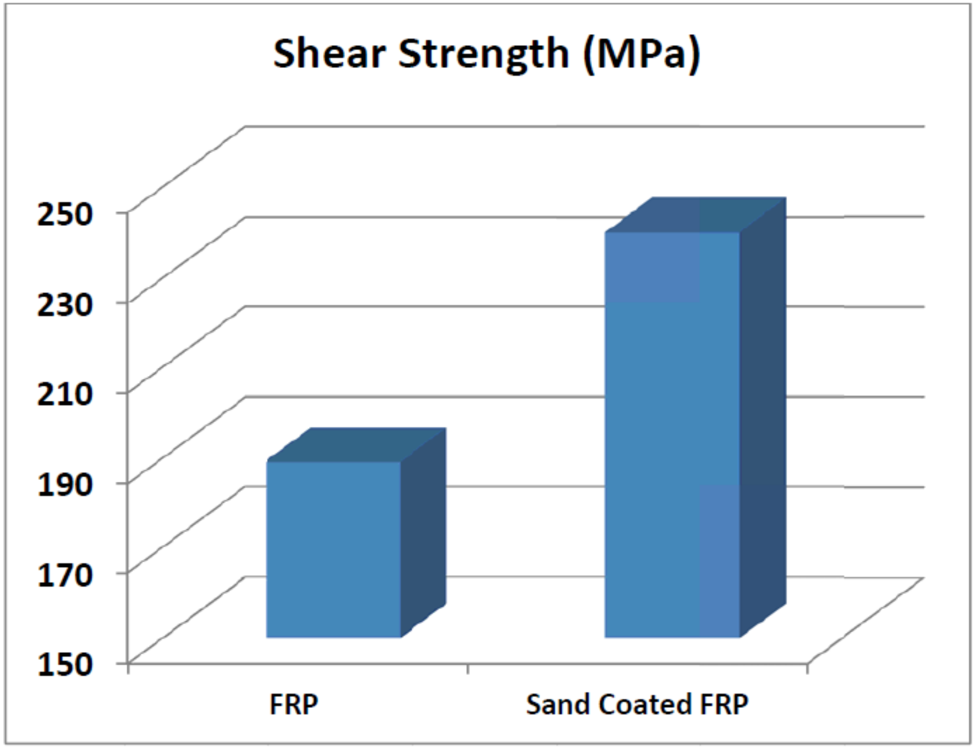
Incorporate sand on the surface…



…or a fibre braid

Shear Testing of FRP bars

Mechanical Properties



Fiberglass sample after shearing

FRP sample

Sand coated FRP sample

Fatigue

- **Fatigue:** degradation or failure of a structural material or element after repeated cycles of loading and unloading
- **Carbon FRPs** display outstanding fatigue behaviour
- **Glass FRPs** display intermediate/satisfactory fatigue resistance
- **Aramid FRPs** are sensitive to fatigue

Creep and Creep-Rupture

- **Creep:** a condition of increasing strain under a sustained (constant) level of stress

- Fibres are relatively insensitive to creep
- Matrix polymers are *visco-elastic* and will creep

- For Unidirectional FRPs loaded in the fibre direction
  - Creep not a significant concern if the sustained stresses are limited, as follows:
    - Glass FRP, 20%
    - Aramid FRP, 30%
    - Carbon FRP, 50%

Environmental Durability

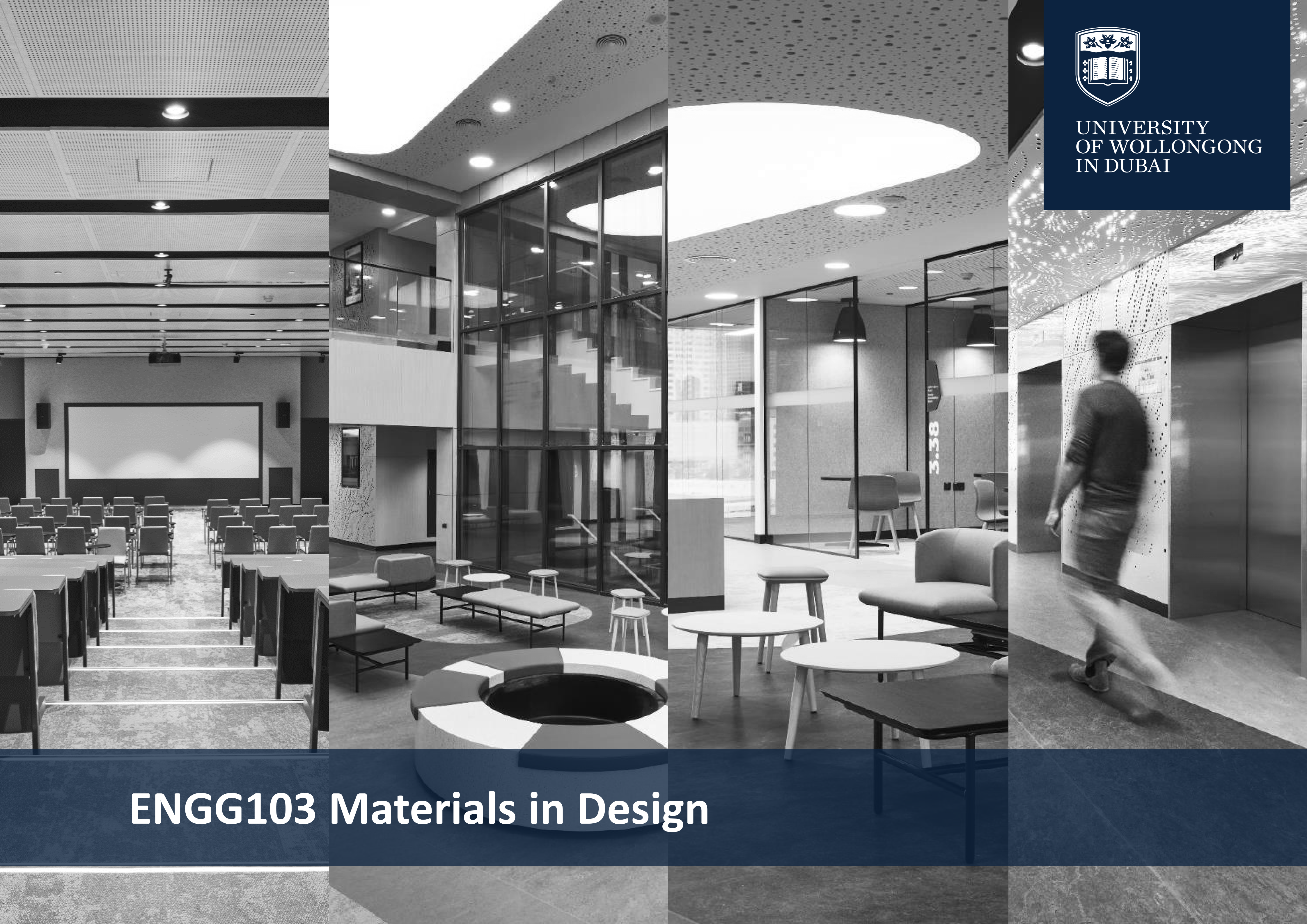
Primary advantage of FRPs

Will not corrode electrochemically

Some durability concerns do exist...

Potentially damaging effects resulting from:

1. Temperature
2. Moisture
3. UV Radiation
4. Alkalinity
5. Fire



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