INTRODUCTION TO STRUCTURAL COMPOSITES

HP Courses

Introduction to Composites.

Presentation by

Dr. Warren B. Leigh

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COMPOSITES FOR STARTERS

These composite courses are based on my knowledge and experience acquired from over 40 years of real industry engineering demands.

This composite course will benefit those who wish to start with foundational knowledge of Composites.

Course modules pragmatically increase the depth of understanding for the composites design and stress analysis subject.

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Integration of Design and manufacturing

Many of the properties and the manufacturing methods of composites are unfamiliar to many Design and Stress Engineers.

It's the integration of these two understandings which is important towards making a successful composite component.

Initial design of a composite concept should give an indication as to its overall performance, weight and cost. This information is extremely useful to the design and manufacturing company. It also means that the client may be given a quick response.

Detailed design follows; includes, further hand calculations, FEA, materials procurement, Optimisation for weight and cost, design validation, coupon and component testing.

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CONTENTS-2

- Classical Lamination Theory
- Laminate Configuration
- 10% RULE: Quick method to determine Composite properties
- Initial design
- Composite filament wound tube. A design example
- Composite Failure criteria
- Composite Delamination Failure
- Composite drapeability and workshop

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CONTENTS-3

- Fatigue
- Composites and fatigue
- Fracture
- Hygrothermal
- Creep notes
- Impact
- Vibration
- Hi-tec and Biocomposites
- Property tolerance of composite material property

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CONTENTS-4

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LECTURE 1.

An Engineers start in Structural Composites

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Great Engineering Opportunities

- The use of carbonfibre and other composite materials is rapidly expanding (12%/ year) and pervades all markets.
- Aerospace, Automotive, Renewables, Sport, Rail
- The opportunities for you are huge.

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For students, managers

- If you are a graduate engineer or company manager excited by Composites
- Where to start in structural composite materials.
- Well, you can start today, right now.

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First Steps

In these courses I will show you;

- The first steps to start to design a composite strong and light.
- Second, for better composite structure, you need to go further and acquire broad and in-depth knowledge.

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An Engineer's approach.

- These courses will address the subject of structural composites from an

  Engineer's approach.

- The main focus of the structural composite courses is on the,

  initial design and composite component sizing.

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What is a composite material.

- The composite materials concept is a material developed from two or more different materials that should give an in-service performance superior or tailored in desired ways than either of the two constituent materials than if they acted alone.

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What is a composite material.

For example,

A galvanised pipe, is a structural steel base material coated with (non-structural) zinc that provides corrosion resistance.

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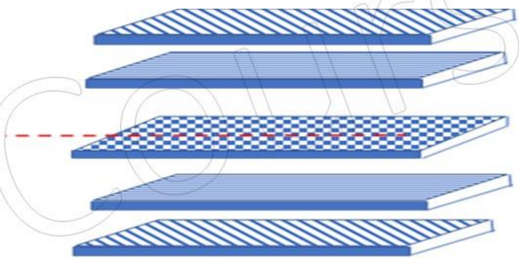
What is a composite material.

In this course we refer to composites materials that are formed by layers of materials such as glassfibre or carbonfibre, i.e laminated.

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A Brief History of Structural Composites
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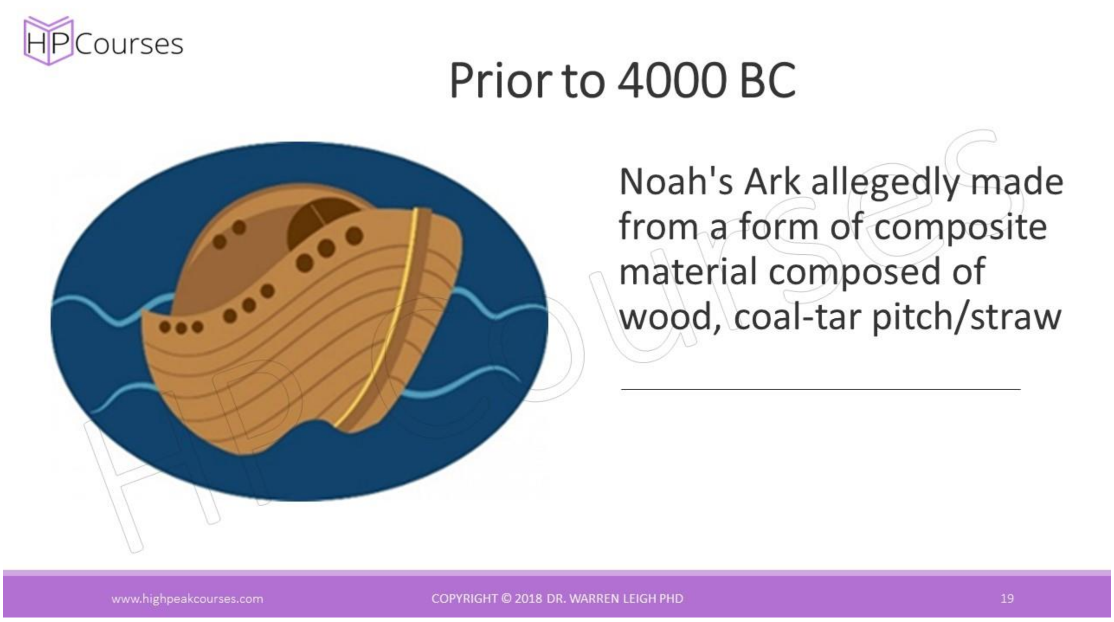
HP Courses
Prior to 4000 BC
Noah's Ark allegedly made from a form of composite material composed of wood, coal-tar pitch/straw
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1500 BC.

Egyptian buildings composed of mud and straw.

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1847.

The Swedish chemist, Berzelius, first saturated polyester.

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1855.

French Ferciment boats.

These are boat structures formed by embedding steel wires into cement. Ref. http://www.ferroboats.com/

Samson C-Strutter. Owned by John Samson of Samson Marine Designs Ltd.

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1914-1916.

Bristol Scout composite aircraft flew in May 1916.

Made from Ash and Spruce wood, wire braced, aluminium sheeting, fabric covered with steel tubing. Top speed 97.5mph. There is one at the bottom of the English Channel.

Courtesy of Bristolscout.wordpress.com (2018)

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1930s.

British company de Havilland composite wood airliner.

A four engine aircraft. The fuselage was a monocoque construction made from layers of birch plywood with a balsa wood core.

(Courtesy of Pinterest, 2018)

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1935.

Owens Corning (USA) introduces the first fine glass fibres.

Manufacturing method discovered by an accident.

Glassfibre. Uni-directional

1950s

Rolls-Royce-RB162 Glassfibre rotor compressor blades.

Included the complete six-stage compressor, rotor blades, stator blades and front bearing housing were designed and made in directional Glassfibre

1963:
Carbonfibre

At the Royal Aircraft Establishment at Farnborough, a proprietary production method of carbonfibre was licensed to three companies: Rolls-Royce, (already making carbonfibre) Morganite, and Courtaulds. By 1968 a carbonfibre fan assembly was made for the Rolls-Royce Conway jet engine.

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1968

Dowty-Rotol first fibreglass propellers for hovercraft.

The Hovercraft SR.N4 carried 254 passengers and 30 vehicles. Powered by four Rolls-Royce Proteus Gas Turbines. These engines drove the 6.4 metre carbonfibre diameter propellers.

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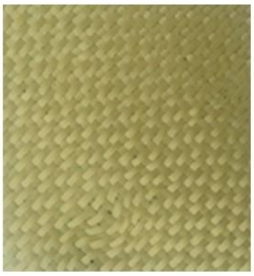
1970s.

Kevlar organic fibre invented in USA.

Kevlar is a high strength aramid fibre. About five times stronger than steel. Kevlar bulletproof vest and helmets.



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1970s.

Royal Navy. H.M.S. Wilton, glassfibre warship. launched in 1972. The glassfibre hull was lightweight, reduction in acoustic signature and a low magnetic signature from the threat of magnetic mines.

Courtesy of Brian Fisher of Shipspotting.com

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1980s.

Introduced into Formula 1 motor Racing.

Upto 70% of the structural weight of the F1 car is made of carbonfibre composite.

Courtesy of Redbull F1 Racing. RB4 car

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1960s-1990s.

The vertical take-off Harrier jump jet. The project started in 1958. By 1961 the aircraft had achieved both vertical and horizontal flight. The Harrier 2, (GR-5) about 1988 had a main box spar produced entirely of carbonfibre composite,

Courtesy of Pinterest 2018.

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1989.

Composite wind turbines. Germany and Denmark.

The glassfibre wind turbine blades at 13 metres long were the longest being made in Germany at the time.

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2004.

Starchaser. Carbonfibre Rocket structure.

A filament wound carbon-fibre Starchaser rocket (Manchester). Length of 8.2 metres (27 ft). Designed altitude of more than 100 km. Largest rocket launched on the UK mainland.

Courtesy of Starchaser 2018.

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Examples of Composite Materials Products

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Industrial applications of composite materials.

The best way to start to understand the world of composite materials is to look at the many ways in which composite materials are applied throughout industry.

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Aerospace.

Aircraft Composite Galley

Aircraft Interiors:
Fabricated from Glassfibre/phenolic composite

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Aircraft: Composites

1990. All carbonfibre composite fuselage. Mockup in wood.
Designed by a British Engineer (PhD). Research done in Germany

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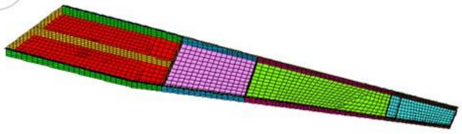
Aircraft: Composites

A380 Fibreglass Composite ¼ scale wing for fuel flow studies.



MSC-Patran FEA composite Simulation.

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Aircraft: Composites

Aircraft wing Composite ¼ scale wing for fuel flow.

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Aircraft Interiors: Crew Rest

Composite Crew rest beds.

Carbonfibre/honeycomb core beams.

A380 Quantas and Singapore Airlines.

These beds are the lightest on record at 12kgs.(Previous 19kgs)

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Space.

The tubular structure designed and manufactured by Huntings Aerospace Ltd for Starchaser Ltd. Manufactured by Filament winding.

Courtesy of Starchaser 2018.

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Automotive.

F-Type Jaguar.

Carbonfibre body parts, eg, bonnet, door skins. (2016)

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Carbonfibre Bodyshell

Invicta Supercar (800bhp) One piece
Carbonfibre bodyshell. 20kg

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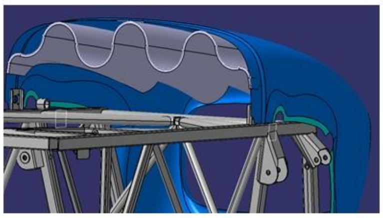
3D Woven Carbonfibre Iso-Grid

Lotus 7. Composite nose concept



Concept: 3D Iso-Grid in car bonnet construction)

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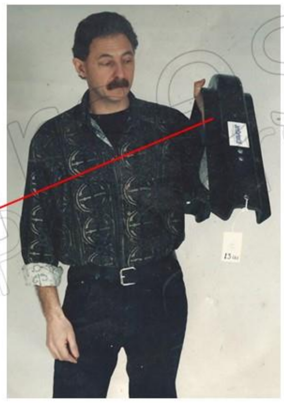
Composite Automotive



Lightweight fuel tank brackets. Final carbonfibre composite version under 2kg weight. (1995)

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Marine.

Glassfibre cruisers made by Brookhouse-Paxford, Huntingdon. (2000)

Courtesy of Brookhouse-Paxford 2018.

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Medical / Sport (2011)

Off-Road Wheelchair designed for mountain rambling.
Hand fabricated (rolled)
carbonfibre composite structure.

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Composite Bikes

A 1986 carbonfibre bike.

Headstock and pedal mounting bearing housing are metal inserts

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Carbon Composite Bicycle & Shoes

Lotus Carbonfibre Olympic Bike (1992.) Mike Burrows design

A Carbonfibre bike of 2015

Photos courtesy of Oli Chapman

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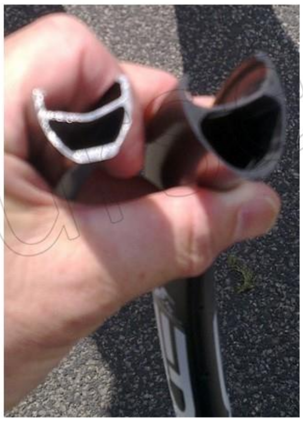
Carbon Composite Wheel Rims

Carbonfibre Composite Wheel.



Carbonfibre Wheel section

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Composite Wind Turbine Blades

Hollow glassfibre 1kW wind turbine blades on test in Dover, UK

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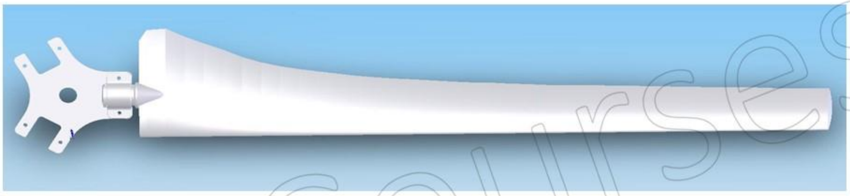
Renewables.

Hollow glassfibre composite 3kW wind turbine blades.

(see our website, www.highpeakcourses.com)

Composite 3kW Wind Turbine Blade



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Rail Industry

Glassfibre-Phenolic composite drivers cab in the ABB Chiltern train 1999.

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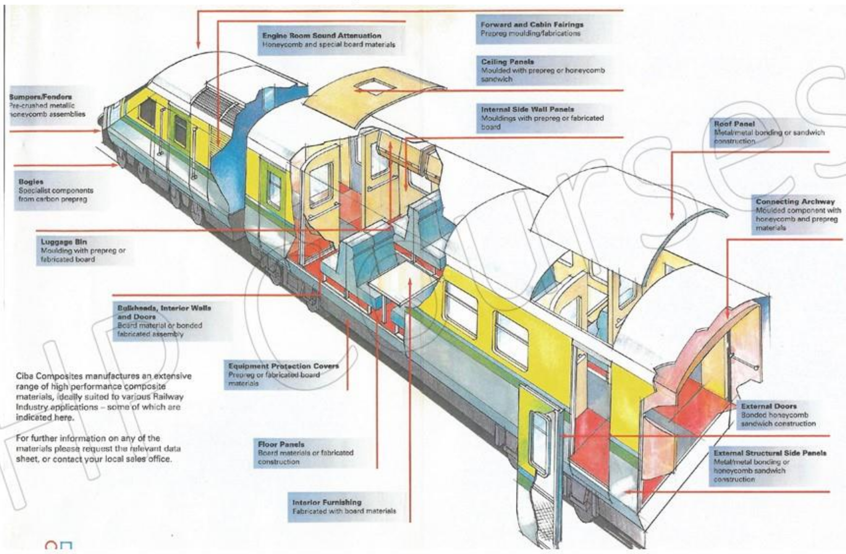
Composites for Trains



Rail Industry

A fabricated Glassfibre Composite Pultruded Railcar maintenance walkway.

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Composite for Rail Infrastructure

Composite Pultruded Cattle guards

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HPCourses Civil and Oil & Gas Composite Structures

Composite foot bridge.
Aberfeldy.

Composite Actuator
control cylinder

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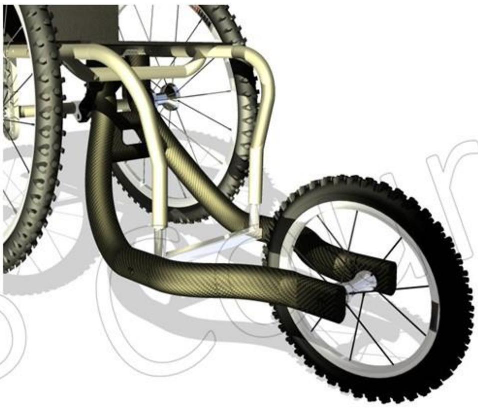
HPCourses Composite Mountain Wheelchair



This off-road wheelchair was designed by a 21 year engineer to help his friend achieve reaching the top on Ben Nevis, the highest mountain in Great Britain and raise money for a Hospice.

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Fibre Properties.
Fibre Architecture
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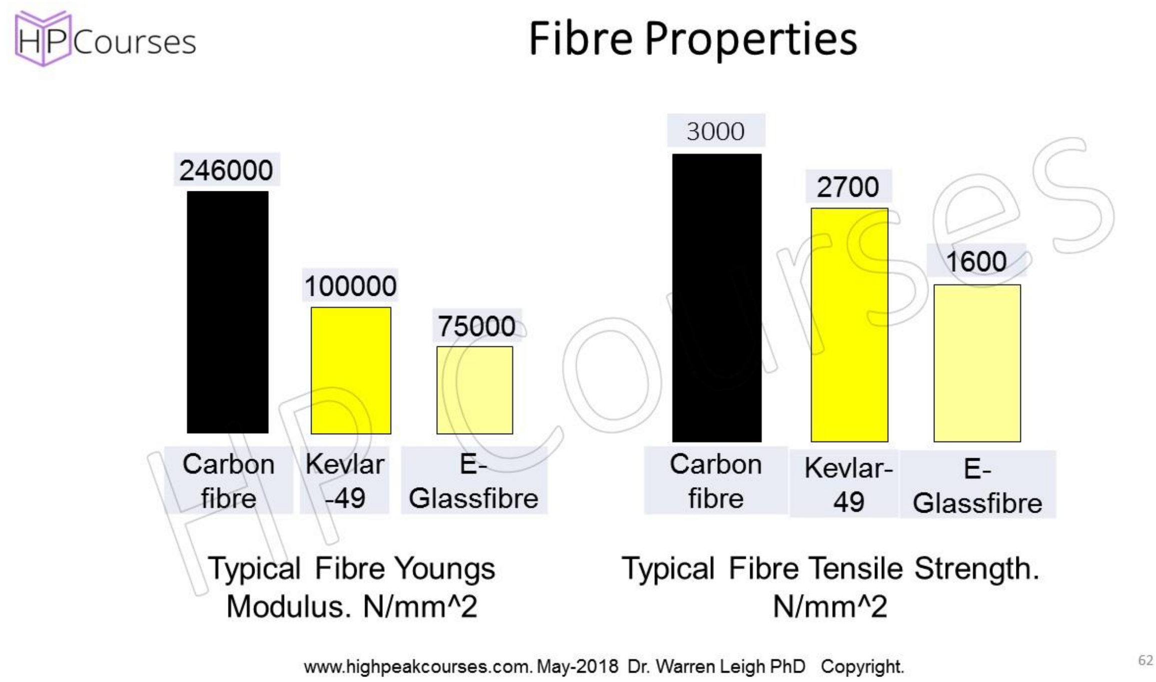
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Fibre Properties
246000
100000
75000
Carbon fibre
Kevlar -49
E-Glassfibre
Typical Fibre Youngs Modulus. N/mm^2
3000
2700
1600
Carbon fibre
Kevlar-49
E-Glassfibre
Typical Fibre Tensile Strength. N/mm^2
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Uni-Directional Fibre Architectures

Uni-Directional Carbonfibre

Uni-Direction Glassfibre

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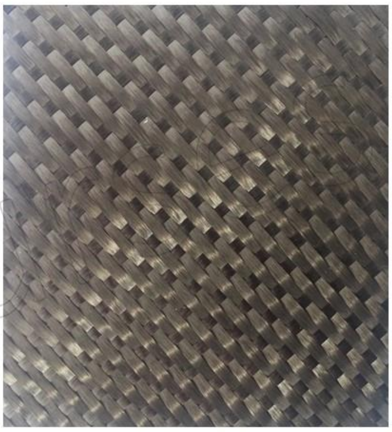
Fibre Architectures

Glassfibre Woven (0/90)



Carbonfibre Woven Satin weave (0/90)

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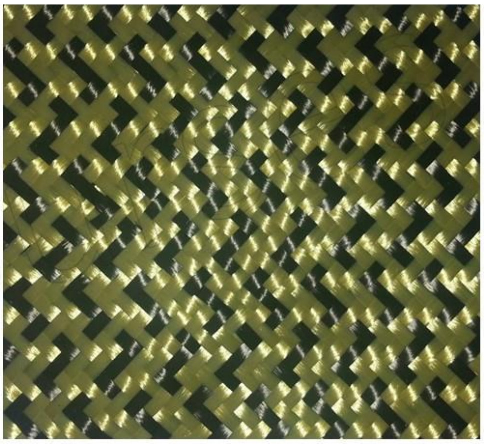
Fibre Architectures


Kevlar Woven (0/90)


Kevlar Woven (0/90)
(with light shining on it)

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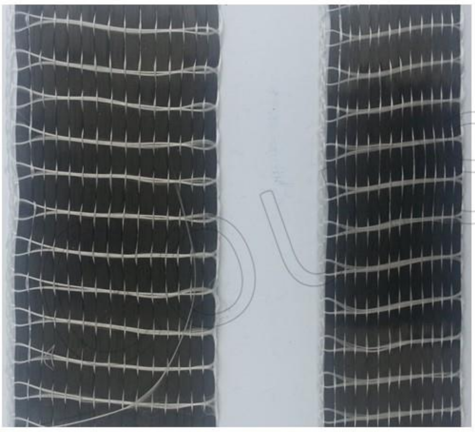
Fibre Architectures


Uni-Directional (UD)
Carbonfibre Tape

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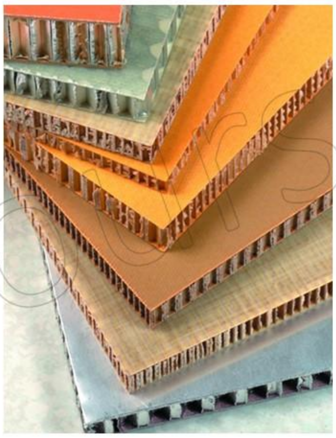
Fibrelam phenolic panels

Fibreglass-Phenolic core panels meet the Fire, Safety and Toxicity (FST) requirements for aircraft interiors.



Fibreglass-Phenolic Panels

Braided Carbonfibre Architectures

Braided Carbonfibre

3D wovenCarbonfibre

By Sigmatex UK

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Fibre Architectures

Carbonfibre tube Braided

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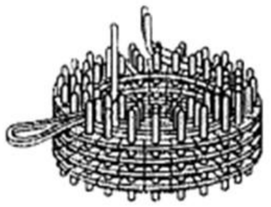
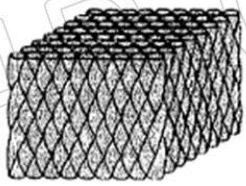
Preform Fibre Architectures

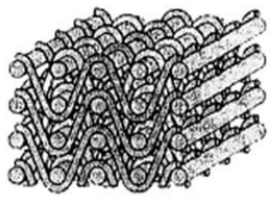


3D Cylindrical

3D Orthoganal



3D Braiding



Angle-Interlock

Ref. Scientific American

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The Merits of using a Composite Material

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Light Weight

- PAYLOAD Improvements. Low weight structures enable more passengers/freight to be carried.
- Offers improved Power to Weight Ratio.
- More fuel efficiency.
- Attaining higher speeds.
- low inertia advantage, eg Trains, ceramic turbochargers

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Consider

- Strength
- Stiffness
- Composite strain limitation
- Deflection limitation
- Matrix strain limitation
- Impact Strain energy absorption
- Manufacturability
- Drapeability
- Minimum weight
- Minimum cost

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COMPOSITE PROPERTIES

- The properties of the fibre reinforcement
- The properties of the matrix in which the reinforcement is placed
- The amount of reinforcement in the matrix .
- The orientation of the reinforcement
- The size and shape of the reinforcement.

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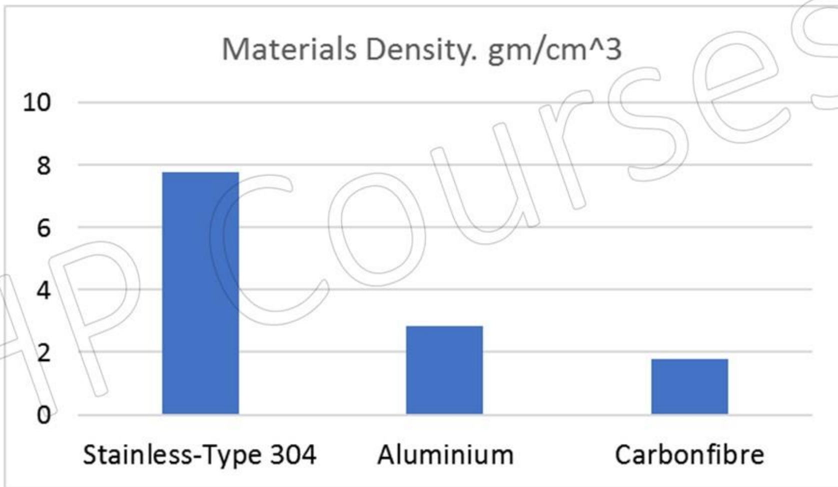
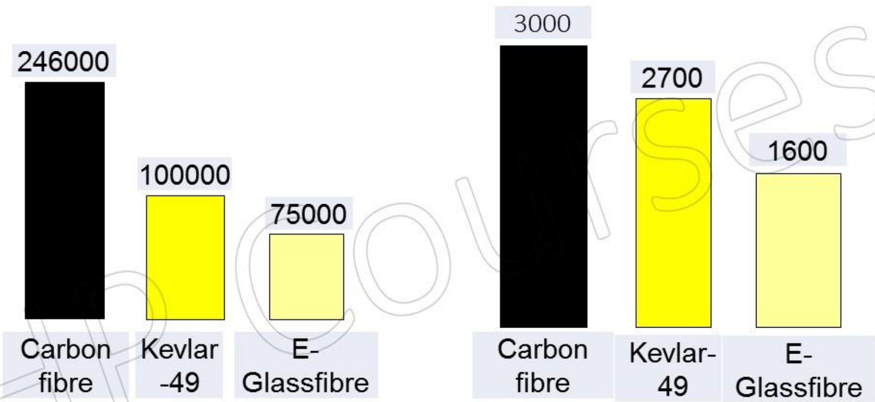
Light Weight kg



Fibre Properties



Typical Fibre Youngs Modulus. N/mm^2

Typical Fibre Tensile Strength. N/mm^2

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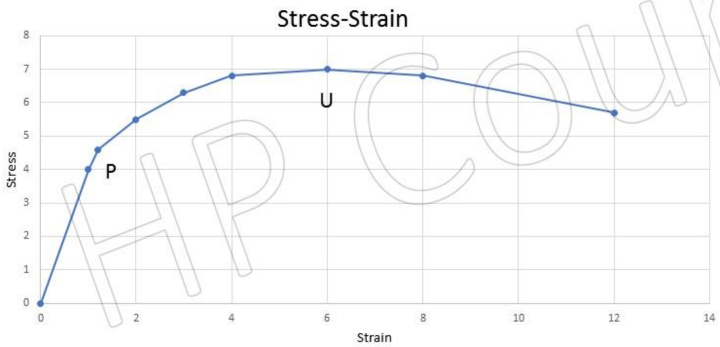
"Metal" Strength (Generic)

- Aluminium or steel equally strong (isotropic) in all directions. Hooke's Law, Linear proportionality "P".



Ultimate Tensile Strength, U

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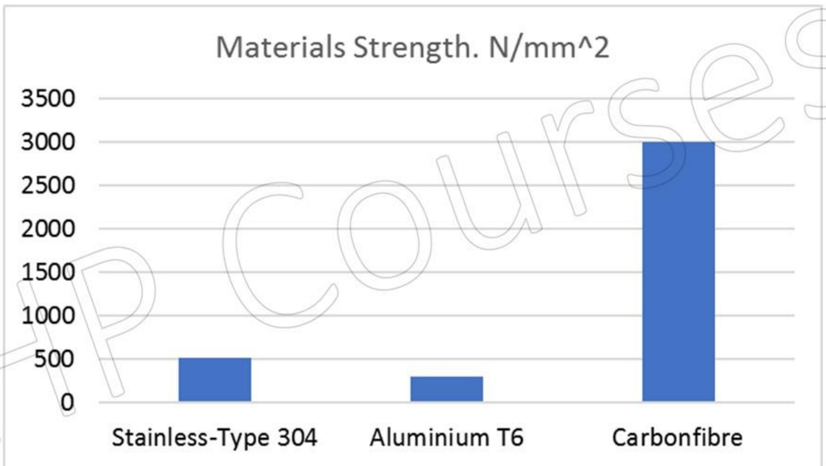
Strength N/mm^2



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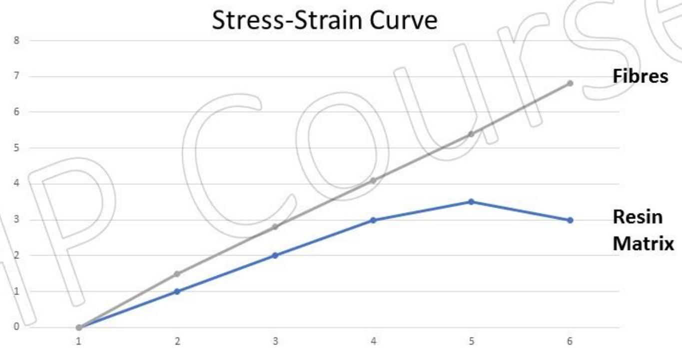
Strength

- Typical Stress-Strain diagrams obtained in industry.



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Strength N/mm^2

There are different way in defining strength;

- Failure of the matrix
- Failure of the fibres
- Maximum load carrying capacity.

More exotic failure theories;

- Hoffman
- Tsai-Wu
- First-Ply
- etc

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Stiffness N/mm^2

Aluminium or steel equally stiff (isotropic) in all directions.
Composites Stiffness can be tailored in a specific direction.

Stiffness based on Young's Modulus N/mm^2.

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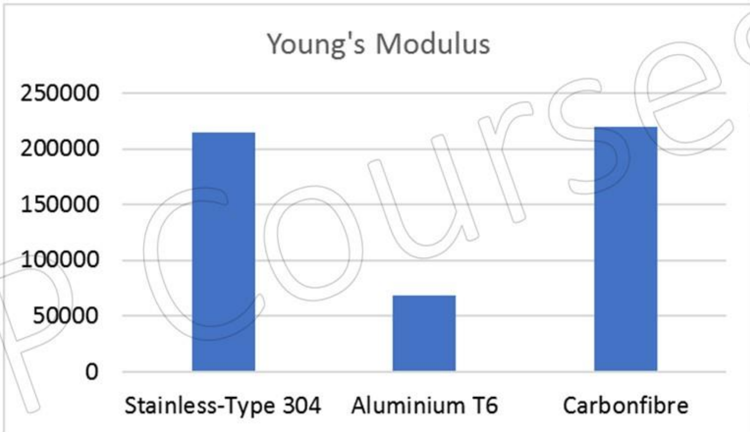
Stiffness N/mm^2



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Delamination

- Composite components can delaminate for a number of reasons.
- Delaminations and cracks can cause premature failure.

Show here pages of A4 paper, then bend to see delamination.

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Delamination

- Design methods exist to minimise delamination.
- A variety of inspection technologies exist.
- For aircraft there exist approved methods of composite repair.

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Manufacturability.

- Composites can be moulded into complicated shapes not previously achievable/affordable with metals.
- Part count reduction can give cost reduction.

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Corrosion resistant

- Composites can resist damage from the weather, salt spray and from harsh chemicals.

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Impact

- Some Composites (Kevlar and Glassfibre) absorb impact and are used in bulletproof vests

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Fire resistant and Toxic emissions

- Epoxy, Polyester and Vinylester resins produce toxic fumes in a fire.
- There are Phenolic resins which meet fire regulations.

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Electrical conductivity

- Fibreglass Composites do not conduct electricity.
- Carbonfibre is electrically conductive.

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Magnetism

- Generally, Composites are not magnetic.
- Becomes magnetic when an electric current runs through the carbonfibre wire.

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Thermal

- The thermal conductivity for Glassfibre and Carbonfibre is lower than that of Aluminium or Steel.
- In-plane Thermal expansion for Glassfibre and Carbonfibre is lower than that of Aluminium or Steel.

Fatigue and Strength reliability

- Strength reliability with reference to fatigue is good when design for fatigue conditions.

Other Performance requirements

- Acoustic
- Creep

Other issues to consider

- Coefficient of Thermal expansion mismatch with metals.
- Resins have temperature limitations.

IMPORTANT:

- As engineers we want to make useful products.
- Importantly, we need to get paid.
- To make a product viable in any material, it should offer financial advantages.

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Composite Waste

Landfill tax at £82.60/tonne
(2015-2016 rate)

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Composites Lightweight.

Power to weight ratio:

Aerospace, Automotive, Rail, Marine, Offshore.

Low weight structures enable more passengers to be carried, i.e. Payload, more fuel efficiency, attaining higher speeds, low inertia, The new Boeing 787 Dreamliner and Airbus A350 consist of over 50% composites.

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Composites Lightweight.

Material	Density	% density to that of Steel
	g/cm^3	
Steel	7.8	
Aluminium	2.8	36
Fibreglass	2.2	28
Carbonfibre/Epoxy	1.8	23

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Strength to Weight Ratio.

Strength-to-weight ratio is a material's strength in relation to how much it weighs. Metals generally have to be made thicker to make the part stronger. Composite materials can be designed to be strong, stiff and light but no thicker.

Glassfibre 5

Steel 1

Carbonfibre 10

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High Strength.

Aluminium or steel equally strong (isotropic) in all directions. Composites can be tailored to be strong in a specific direction. Resist bending in one direction.

Fibreglass 5

Steel 1

Carbonfibre 6

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Corrosion Resistance.

- Composites have high corrosion resistance.
- They resist damage from the weather, salt
- spray and from harsh chemicals.
- Therefore reduced repair cost.

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Hi-impact Resistance.

Some Composites (Kevlar) absorb impact and are used in bulletproof vests, panels, airplanes, buildings, and military vehicles. Shape memory abilities and springback (automotive)

Kevlar wrap for blade containment

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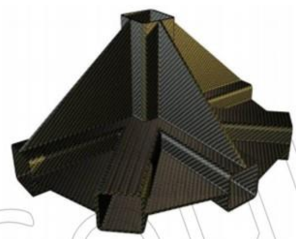
Design Flexibility .



(3D woven. Courtesy Alan Bond)

Composites can be moulded into complicated shapes not previously achievable with metals. Boats built from fibreglass composites improve boat design while lowering costs. The surface finish of composites modified from smooth to pebbly.

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Part count reduction.

Part count reduction gives;
Part cost reduction, when two parts previously made from metal are combined into one composite part. Saves time on erection, fabrication and cuts down on the maintenance needed over the life of the item.

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Dimensional Stability.

Composites offer good shape stability in a range of temperatures under hot/wet conditions. Example, Aircraft wings, altitude temperature stability.

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Electrically non-conductive.

Fibreglass Composites do not conduct electricity. This property makes them suitable for such items as electrical utility poles and the circuit boards in electronics.

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Electrically conductive.

Carbonfibre is electrical conductive.
Carbon particles can contaminate electrical products in the workplace.
Electrical conductivity can be tailored.
Careful in Galvanic circuits, metal (fasteners etc) to carbonfibre.

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Composite Non-Magnetic

Composites are not magnetic. They can be used around sensitive electronic equipment. Used in MRI (magnetic resonance imaging) equipment housing and table. Becomes magnetic when an electric current runs through the carbonfibre wire.

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Composite Radar Transparent

Radiation-absorbent material.
Carbonfibre offers radar absorbency
signals pass through it.

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Carbonfibre Thermal Conductivity

Material	Density g/cm^3	Thermal Conductivity W/m.K
Steel	7.8	43
Aluminium	2.8	205
Fibreglass	2.2	0.05
Carbonfibre/Epoxy	1.8	24

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Layered Composites-Part-1

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How composite material properties are different compared to metals.

- Metals are generally isotropic.
- Examples of Steel, Titanium, Aluminium have equal directional properties.

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Composite Properties

Layered composites consist of a number of material layers or plies stacked on top of each other.

The composite properties will change in accordance with the number and orientation of each type of ply.

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How composite material properties are different, compared to metals.

- Layered Composites of glass, Kevlar, Carbon, Silicon Carbide, Biofibres and Natural fibres are orthotropic.
- These have two different material properties in two mutually perpendicular directions when considered as thin plies.

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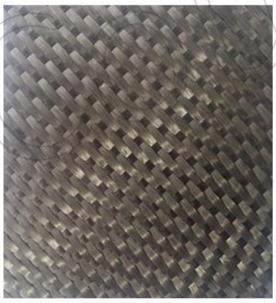
COMPOSITE PROPERTIES

Uni-Directional Carbonfibre

100% of fibres in 0^0 direction

Carbonfibre Woven (0/90)



Approx.
50% of fibres in 0^0 direction
50% of fibres in 90^0 direction

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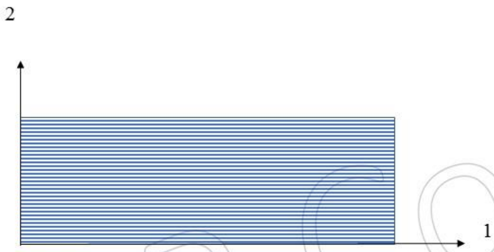
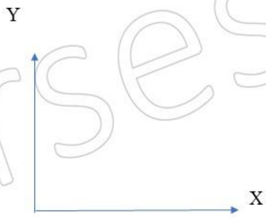
Layered Composite





Plan view.
The Ply material axis

The Reference or Loading axis

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How composite material properties can be tailored to suit your performance requirements

Youngs Modulus for Steel in 1,2,3 ~ 206000N/mm²

Youngs Modulus for Carbonfibre/epoxy in the 1-direction ~ 135000N/mm² (assume)

Youngs Modulus for Carbonfibre/epoxy in the 2-direction ~ 11000N/mm² (assume)

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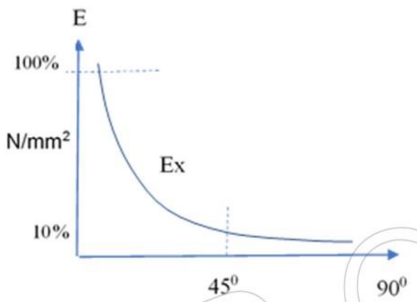
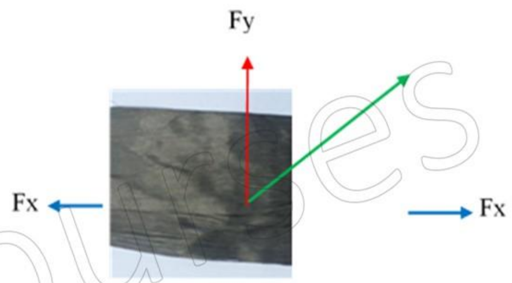
Composite directional Stiffness





Fibres full Young's Modulus (stiffness) and strength in X-direction.

Fibres at 90 degrees to the x-direction obtain less than 10% of full Young's Modulus (stiffness) and strength.

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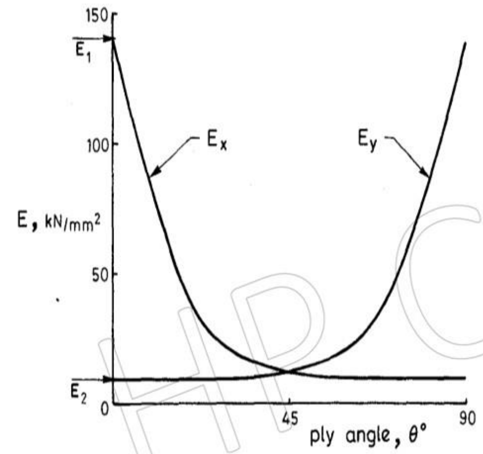
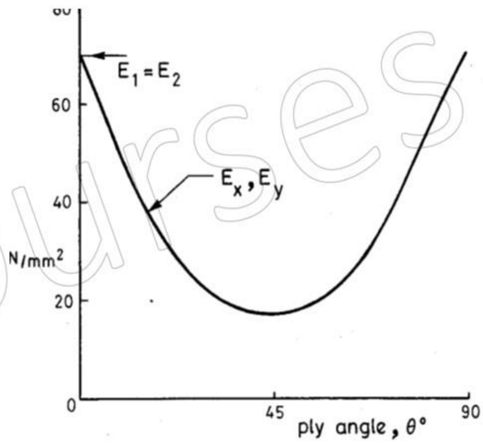
Composite Property performance



Young's modulus variation with Ply angle. Unidirectional ply



Young's modulus variation with Ply angle. Woven ply

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Rule of Mixtures

The Rule of Mixtures is used to initially estimate the composite material properties.

The Rule of Mixtures uses the Volume Fraction of the fibres and that of the resin (matrix).

The equivalent Young's Modulus E1, E2 and Poissons ratio maybe estimated.

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Rule of Mixtures

Derive Youngs modulus from the combination of the fibres and the resin. Rule of mixtures formula may be used.

$$E_c = E_f * V_f + E_m * V_m$$

Example.

Young's Modulus of fibres.	E_f = 76000 N/mm^2
Young's Modulus of matrix.	E_m= 3500 N/mm^2
Volume Fraction of fibres.	Vf = 0.3 (% fibre packing)

$$E_c = (76000 * 0.3) + (3500 * (1- 0.3))$$

$$\mathbf{E_c = 25500\ N/mm^2}$$

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Laminate Architecture

Infinite number of laminate configurations can be constructed:

- Ply Stacking Sequence
- Ply Thickness
- Ply Angle
- Ply Material Type
- Number of Plies

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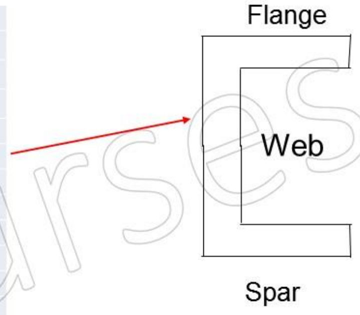
Shear Laminate.

Thickness	Angle
0.29	45
0.29	-45
0.29	0
0.29	45
0.29	-45
0.29	90
0.29	0
0.29	90
0.29	45
0.29	-45
0.29	0
0.29	45
0.29	-45



Exm	36000	Nmm^{-2}	Flexural	32000	Nmm^{-2}
Eyy	36000	Nmm^{-2}	Flexural	25000	Nmm^{-2}
Gxy	27000	Nmm^{-2}	Flexural	30000	Nmm^{-2}

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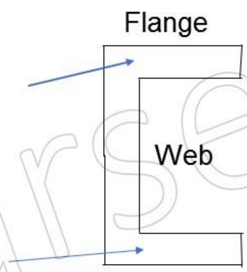
Bending Laminate.

Thickness	Angle
0.22	45
0.22	-45
0.22	0
0.22	0
0.22	0
0.22	90
0.22	90
0.22	45
0.22	-45
0.22	0
0.22	0
0.22	90
0.22	90
0.22	45
0.22	-45



Exm	58000	Nmm^{-2}	Flexural	49000	Nmm^{-2}
Eyy	58000	Nmm^{-2}	Flexural	60000	Nmm^{-2}
Gxy	15000	Nmm^{-2}	Flexural	19000	Nmm^{-2}

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Tailoring Composite directional properties

Strength: By aligning the fibres in the direction of the load we utilise the composites full strength, stiffness and minimum weight.

Stiffness: compatibility can be achieved.

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Questions asked

- Many fabricators of composite items ask,
- How thick should the composite structure be to take the loads.
- How is this determined.
- What do I need to know to do this.

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Start to Design in Composite Materials.

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Composite Analysis Software

GENLAM:	Stephen Tsai. Dos program.
MIC-MAC:	Stephen Tsai. Excel software.
LAP:	Laminate Analysis Program. Imperial College.
COALA:	Composite Analysis. Cranfield University. Dos.
LASBU: Dos.	Composite Analysis. South Bank University.
Compositepro.	USA composite analytical software.
Aerocomp:	Composite Analysis Stress Tool. Excel software.
Optiassist/Genesis:	Composite Optimisation.

CSAMS. Composite Stress Analysis modules. (for 3 year olds +)

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Start to Design in Composite Materials.

- Determine the thickness of the ply material combined with the resin used when cured (tp).

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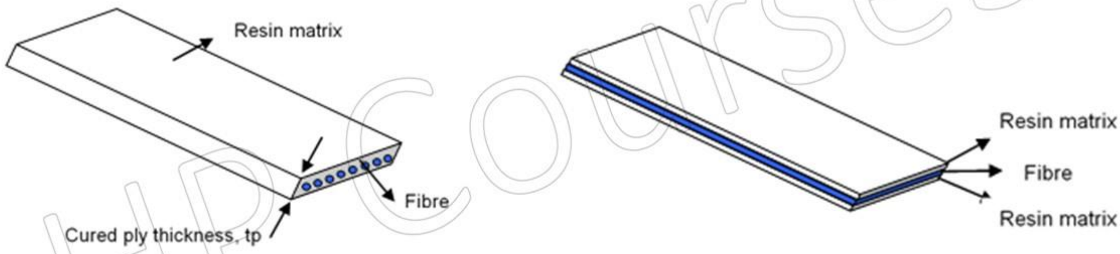
Cured Ply Thickness

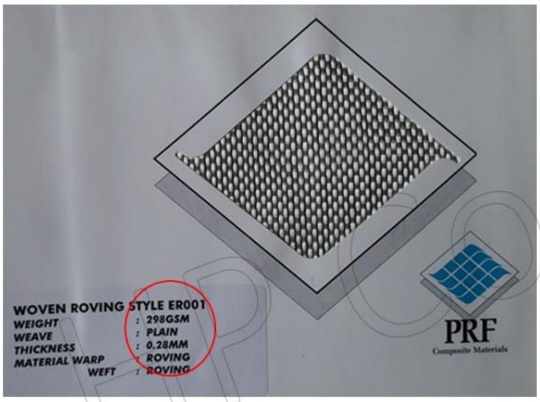


Three essential properties need to know

It's a relationship which includes

- mass (gsm)
- Volume fraction (Vf)
- Fibre Density (gm/cc)

Gsm. The areal weight.



298gsm

Thickness of cloth = 0.28mm

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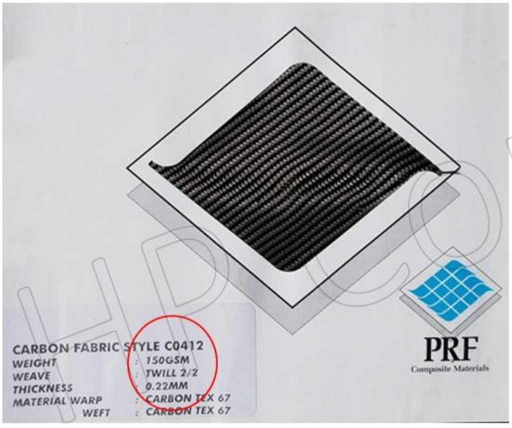
Gsm. The areal weight.



150gsm

Thickness of cloth = 0.22mm

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Volume Fraction, Vf

- is the percentage of fibre volume in the entire volume of a fibre reinforced composite material.
- Higher Vf = Higher mechanical properties, eg Strength
- Influenced by manufacturing parameters, typically in the range of 50% to 65%.

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HPCourses COMPOSITE DIRECTIONAL STIFFNESS

Increase in Young's Modulus is linearly proportional with increase in Volume Fraction.

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HPCourses Volume Fraction, Vf

Volume Fraction. Silicon Carbide Fibre

Fibre:

$$V_{Ff} := \frac{\left(\frac{W_f}{\rho_f}\right)}{\left(\frac{W_f}{\rho_f}\right) + \left(\frac{W_r}{\rho_r}\right) + \left(\frac{W_c}{\rho_c}\right)}$$

$$V_{Ff} = 0.349$$

Titanium Metal Matrix

TMC:

$$V_{Fr} := \frac{\left(\frac{W_r}{\rho_r}\right)}{\left(\frac{W_f}{\rho_f}\right) + \left(\frac{W_r}{\rho_r}\right) + \left(\frac{W_c}{\rho_c}\right)}$$

$$V_{Fr} = 0.651$$

Composite Density:

$$\rho_{comp} := (\rho_f \cdot V_{Ff}) + (\rho_r \cdot V_{Fr}) + (\rho_c \cdot V_{Fc})$$

$\rho_{comp} = 3.99$ gm/cm^3

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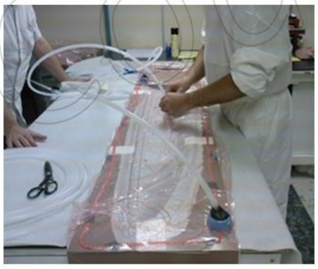
Manufacturing method and Volume Fraction, Vf

- Popular manufacturing is hand lay. (also vacuum-bag)
- Possible Vf = 50% (0.5)



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Examine change in ply thickness

- the fibres, gsm
- the fibre density, g/cc
- volume fraction

I will use CSAMs-COMPOSITES STRUCTURAL ANALYSIS MODULES

CALCULATION OF Ply Thickness

Glassfibre. grams per metre squared $GSM := 220 \frac{kg}{m^2}$

Glassfibre density $\rho g := 2.2 \frac{gm}{cm^3}$

Volume Fraction $Vfg := 0.6$

Thickness $th_c := \frac{GSM}{\rho g \cdot Vfg \cdot 1000}$

$th_c = 0.167mm$

I will use CSAMs-COMPOSITES STRUCTURAL ANALYSIS MODULES

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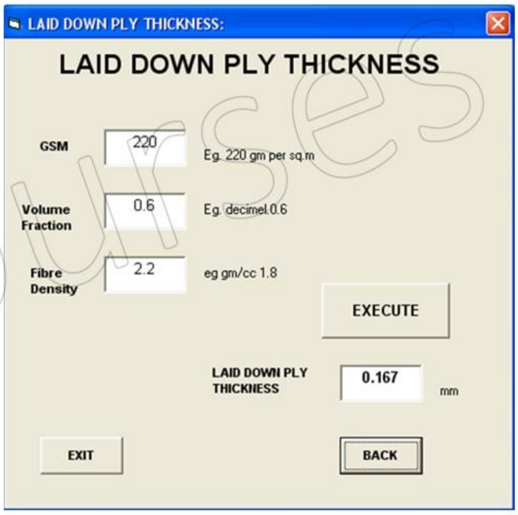
Examine change in ply thickness

Glassfibre composite

(Calculations by CSAMs)

1. the fibres = 220gsm
2. volume fraction = 0.6
3. the fibre density = 2.2g/cc

Cured Ply Thickness = 0.167mm



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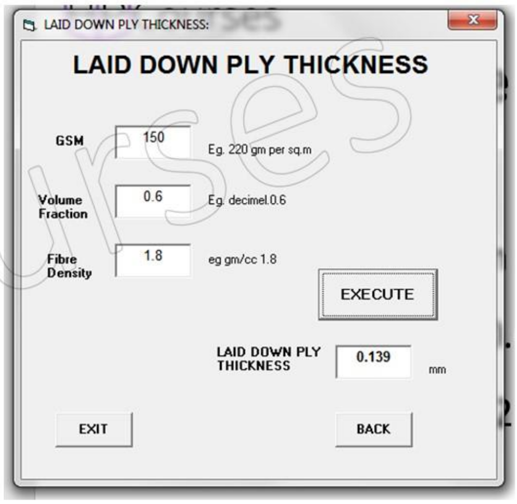
Examine change in ply thickness

Carbonfibre composite

(Calculations by CSAMs)

1. the fibres = 150gsm
2. volume fraction = 0.6
3. the fibre density = 1.8g/cc

Cured Ply Thickness = 0.139mm



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Tailored Composites.

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How composite material properties can be tailored to suit your performance requirements

Youngs Modulus for Steel in 1,2,3 ~ 206000N/mm^2

Youngs Modulus for Carbonfibre in the 1-direction ~ 135000N/mm^2 (generic)

Youngs Modulus for Carbonfibre in the 2-direction ~ 11000N/mm^2 (generic)

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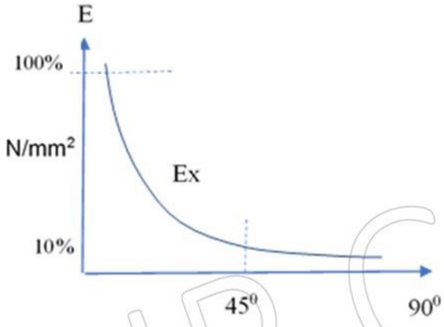
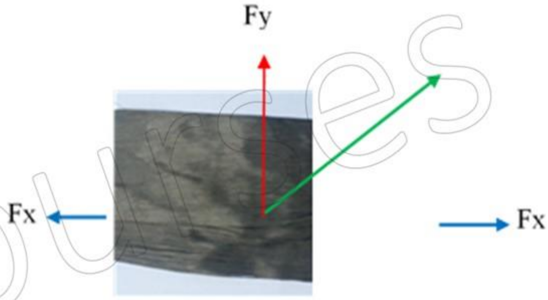
Composite directional Stiffness





Fibres full Young's Modulus (stiffness) and strength in X-direction.

Fibres at 90 degrees to the x-direction obtain offer 10% of full Young's Modulus (stiffness) and strength.

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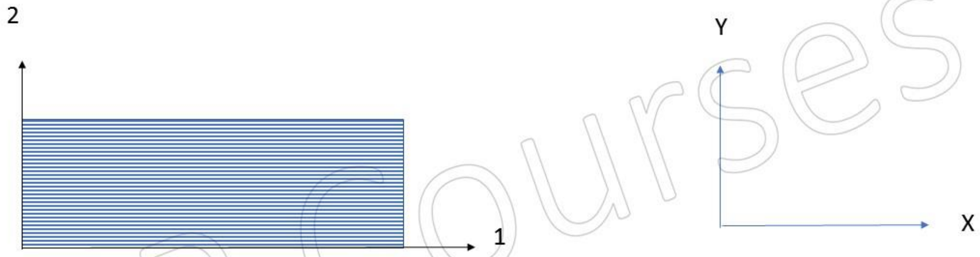
Layered Composite



Plan view.
The Ply material axis

The Reference or Loading axis

When directional strength or stiffness is required, the ply material axes 1-2 can be set at an angle to the loading axis. The two axes need not be coincident.

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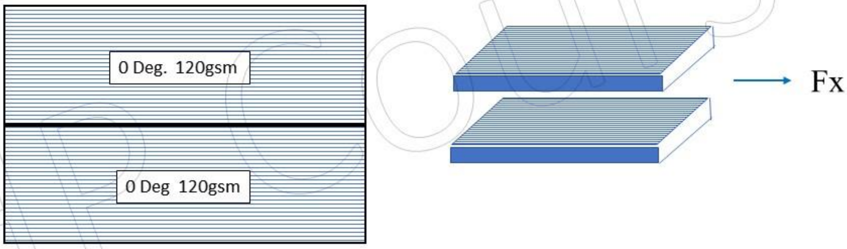
Obtain composite materials properties stiffness, Strength and thickness.

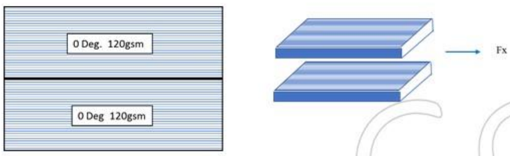
LAY-UP of Laminate. [0/0] **Glassfibre**



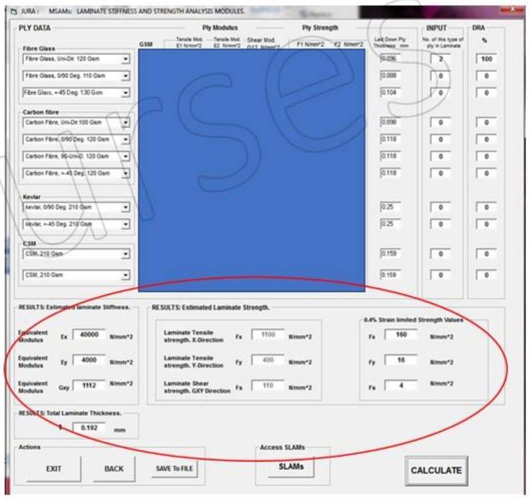
HPCourses

Obtain composite materials properties stiffness, Strength and thickness. (CSAMs)

LAY-UP of Laminate. [0/0] **Glassfibre**



$Ex = 40000\ N/mm^2$
$Ey = 4000\ N/mm^2$
$Fx = 160\ N/mm^2$
$Fy = 16\ N/mm^2$
$Fs = 4\ N/mm^2$
$Gxy = 1112\ N/mm^2$
$tp = 0.096mm$



Tailoring Composite directional Stiffness

By aligning the fibres in the direction of the load we utilise the composites full strength and minimum weight.

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Obtain composite materials Young's Modulus.

To determine the elastic constants of a unidirectional ply

Use the Rule of Mixtures

Youngs Modulus. Glassfibre	$Ef := 76000 \frac{N}{mm^2}$
Youngs Modulus. Epoxy	$Em := 3500 \frac{N}{mm^2}$
Volume Fraction	$Vf := 0.3$
Composite tensile modulus	$Ec := (Vf \cdot Ef) + [Em \cdot (1 - Vf)]$
	$Ec = 25250 \frac{N}{mm^2}$

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TISICS LTD. www.tisics.co.uk

Silicon carbide-Titanium Metal Matrix Compotes:
Property prediction

Titanium-Ti-6AL-4V

$\rho c := 4.42$ gm/cc

$Ec_1 := 110384$ N/mm^2

$Fx_c := 896$ N/mm^2

$\nu_c := 0.3$

Silicon Carbide FIBRE

$\rho w := 3.2$

$Ew_1 := 370000$

$Fx_w := 2950$ N/mm^2

$\nu_g := 0.28$

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TISICS LTD. www.tisics.co.uk

Silicon carbide-Titanium Metal Matrix Composites:
Property prediction

Equivalent Youngs Modulus

$E1_{cal} := (Ew_1 \cdot V_{fw}) + (Ec_1 \cdot V_{fc})$

$E1_{cal} = 201252$ N/mmk^2

Ultimate Strength

$Ftu_{cp} := (Fx_c \cdot V_{fc}) + (Fx_w \cdot V_{fw})$

$Ftu_{cp} = 1615$ N/mm^2

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Layered Composite Part-2

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How composite materials can be tailored for strength, stiffness, thickness and weight.

We will explore a variety of composite laminate architectures,

- Glassfibre
- Carbonfibre .

I will use CSAMs-COMPOSITES STRUCTURAL ANALYSIS MODULES

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COMPOSITE PROPERTIES

Layered composites consist of a number of material layers or plies stacked on top of each other.

The composite properties will change in accordance with the number and orientation of each type of ply.

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LAYERED COMPOSITE

The laminate architecture is defined by,

- the ply angles relative to a reference plane, measured in degrees
- ply material of each individual ply
- the stacking sequence that each ply is laid down on top of each other.

A recognised laminate notation is defined that is used by Stress Engineers, Design Engineers and manufacturing engineers

(+-45/0/(0/90)s

(Examples on next pages)

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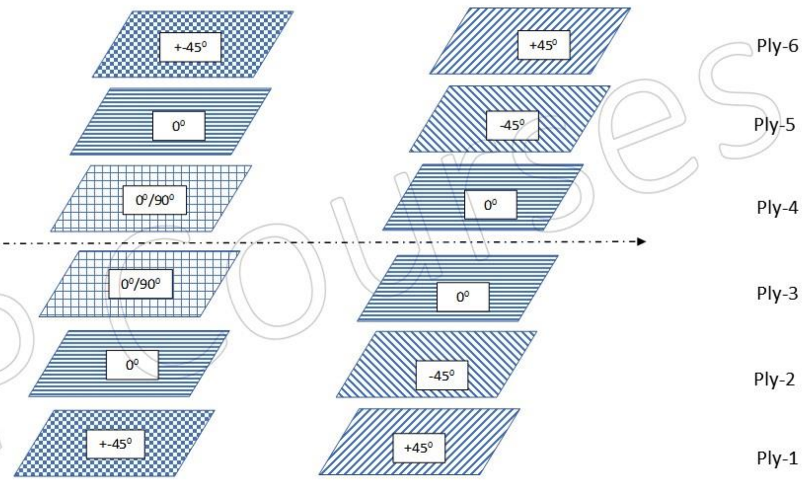
LAYERED COMPOSITE

Individual plies stacked symmetrically about mid-plane



$(+-45/0/(0/90)_2/0/+-45)$ $(+-45/0_2/+-45)$

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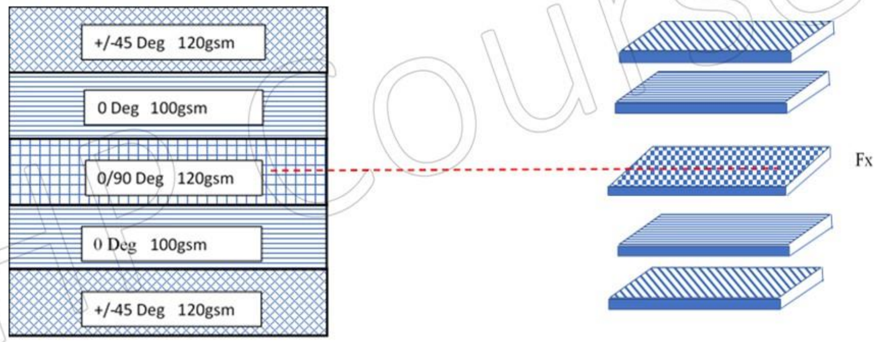
Obtain composite materials properties stiffness, Strength and thickness.

LAY-UP of Laminate. [(+/-45)/0/(0/90)/0/-/(+45)] **Carbonfibre**



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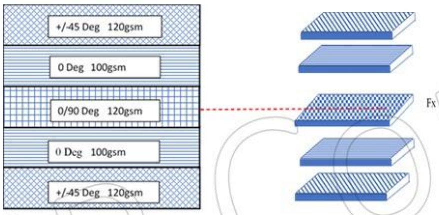
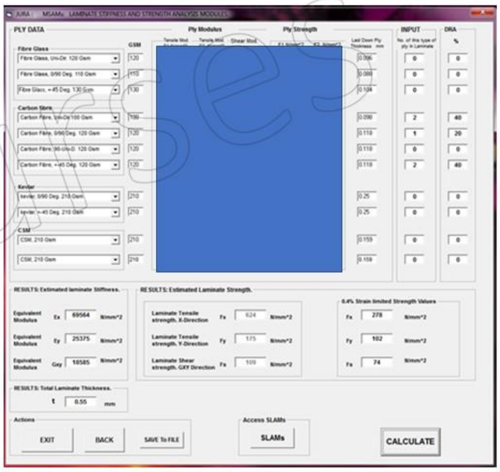
Obtain composite materials properties stiffness, Strength and thickness. (CSAMs)

LAY-UP of Laminate. [(+/-45)/0/(0/90)/0/-/(+45)] **Carbonfibre**





Ex = 69564 N/mm^2
Ey = 25375 N/mm^2
Fx = 278 N/mm^2
Fy = 102 N/mm^2
Fs = 74 N/mm^2
Gxy = 18585 N/mm^2
tp = 0.55mm

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Laminate Configuration Types

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LAMINATE CONFIGURATION TYPES

Laminate architecture configuration classification helps to assist in tailoring of composite performance, in respect of;

- Bend-Twist
- Shear-Membrane
- Anti-Sym Laminate stiffness coupling

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LAMINATE CONFIGURATION TYPES

Recognition of the coupling effects can be beneficial to the desired performance of the composite component.

Equally important is the lack of recognition of coupling effects which may lead to adverse or unexpected behaviour of composite components under loading.

It is important to note that coupling effects are load activated either residual or applied.

These effects can be modified by changing the laminate architecture. However, keep in mind the stiffness and strength requirements.

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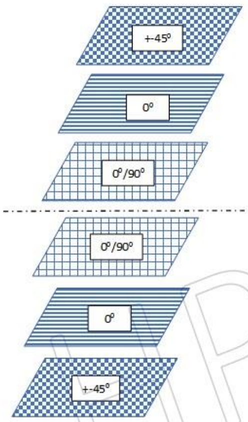
SYMMETRIC (Balanced) COMPOSITE

A balanced laminate avoids or minimises warping during manufacture



(+-45/0/(0/90)2/0/+-45)

or

(+-45/0/(0/90)s

Individual plies stacked symmetrically about mid-plane

Symmetric Laminates

Single oriented ply laminate (SOPL)

Multi oriented ply Laminate (MOPL)

Courtesy of M. Datoo. Mechanics of Fibrous Composites

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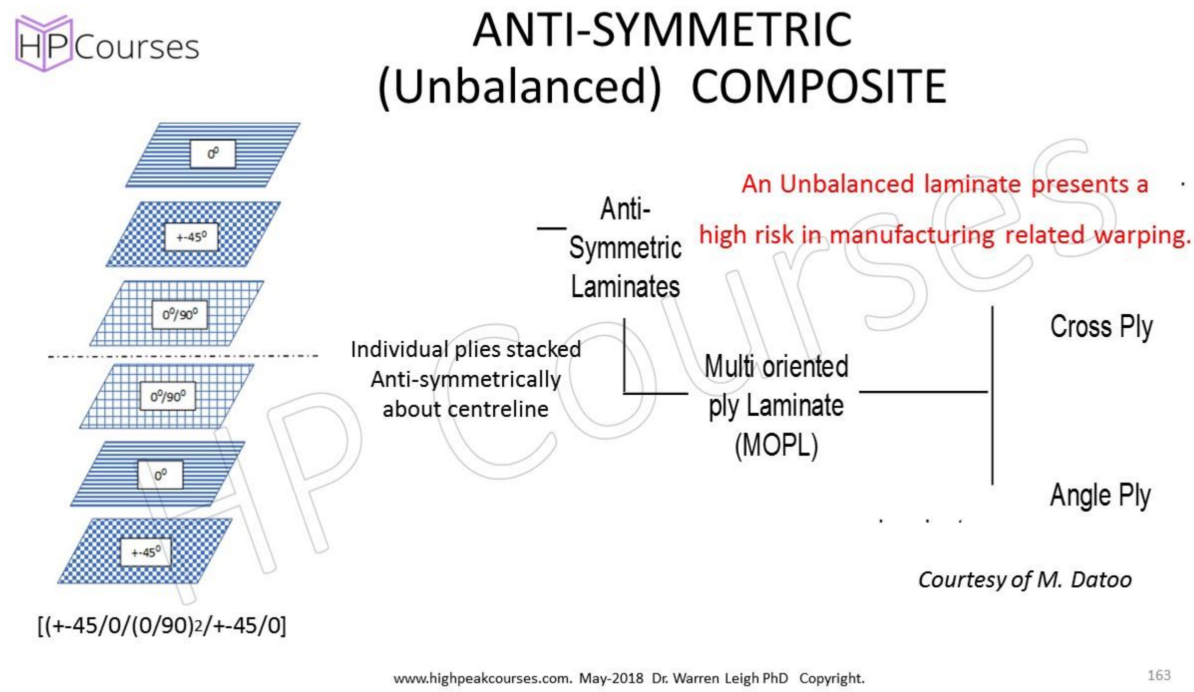
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ANTI-SYMMETRIC
(Unbalanced) COMPOSITE
0°
+-45°
0°/90°
0°/90°
0°
+-45°
[(+-45/0/(0/90)2/+-45/0]
Individual plies stacked
Anti-symmetrically
about centreline
Anti-
Symmetric
Laminates
An Unbalanced laminate presents a
high risk in manufacturing related warping.
Multi oriented
ply Laminate
(MOPL)
Cross Ply
Angle Ply
Courtesy of M. Datoo
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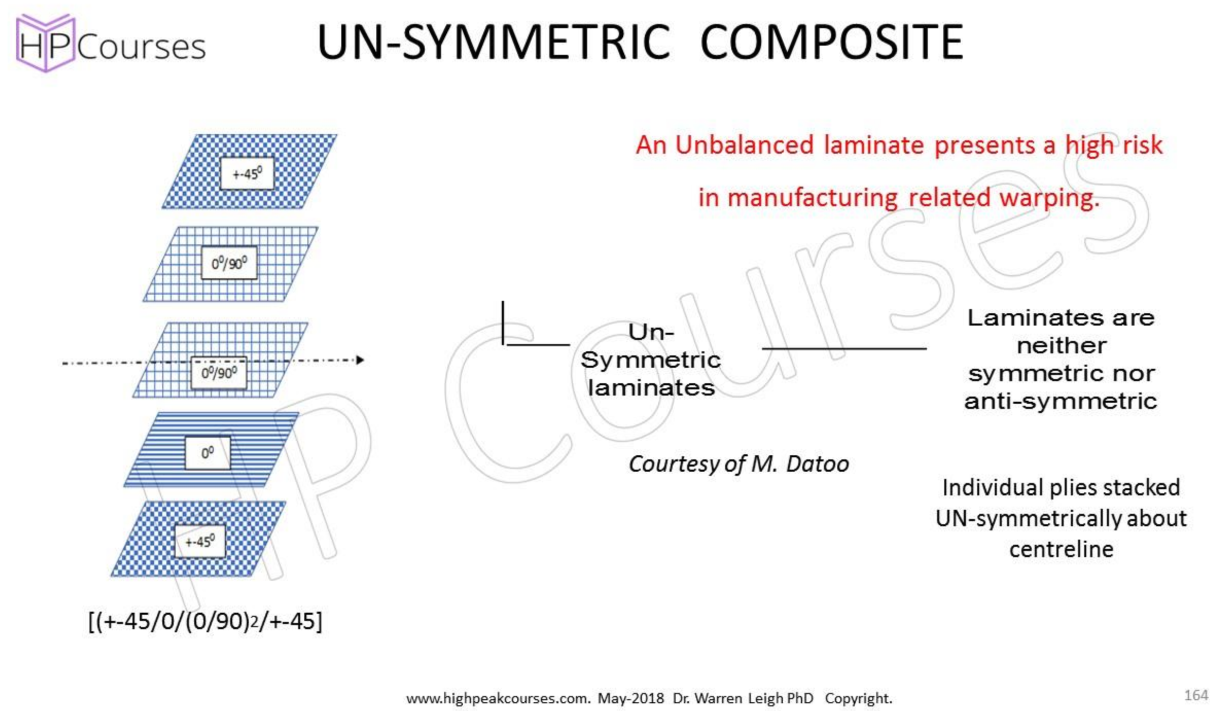
HP Courses
UN-SYMMETRIC COMPOSITE
+-45°
0°/90°
0°/90°
0°
+-45°
[(+-45/0/(0/90)2/+-45]
An Unbalanced laminate presents a high risk
in manufacturing related warping.
Un-
Symmetric
laminates
Laminates are
neither
symmetric nor
anti-symmetric
Courtesy of M. Datoo
Individual plies stacked
UN-symmetrically about
centreline
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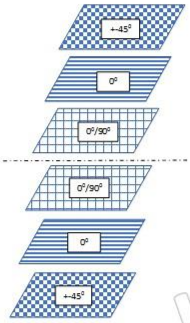
LAYERED COMPOSITES: Stiffness Matrix



The stacking sequence for the laminate affects the bending stiffness.

The laminate stacking sequence does not affect extensional stiffness.

	e_x^o	e_y^o	e_{xy}^o	k_x	k_y	k_{xy}
N_x	A_{11}	A_{12}	A_{13}	B_{11}	B_{12}	B_{13}
N_y	A_{12}	A_{22}	A_{23}	B_{12}	B_{22}	B_{23}
N_{xy}	A_{13}	A_{23}	A_{33}	B_{13}	B_{23}	B_{33}
M_x	B_{11}	B_{12}	B_{13}	D_{11}	D_{12}	D_{13}
M_y	B_{12}	B_{22}	B_{23}	D_{12}	D_{22}	D_{23}
M_{xy}	B_{13}	B_{23}	B_{33}	D_{13}	D_{23}	D_{33}

In Classical lamination theory:

Aij relates to membrane extension.

Bij couple the bending behaviour

Dij relates applied moment to twisting. Called the Bend-Twist

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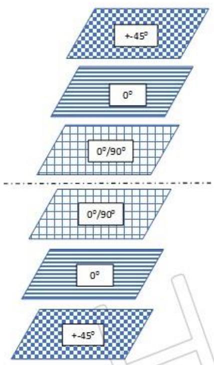
LAYERED COMPOSITES

Classical lamination theory



symmetric laminate

	e_x^o	e_y^o	e_{xy}^o	k_x	k_y	k_{xy}
N_x	A_{11}	A_{12}	A_{13}	B_{11}	B_{12}	B_{13}
N_y	A_{12}	A_{22}	A_{23}	B_{12}	B_{22}	B_{23}
N_{xy}	A_{13}	A_{23}	A_{33}	B_{13}	B_{23}	B_{33}
M_x	B_{11}	B_{12}	B_{13}	D_{11}	D_{12}	D_{13}
M_y	B_{12}	B_{22}	B_{23}	D_{12}	D_{22}	D_{23}
M_{xy}	B_{13}	B_{23}	B_{33}	D_{13}	D_{23}	D_{33}

When Bij terms are zero, then it defines a symmetric laminate about its mid-plane

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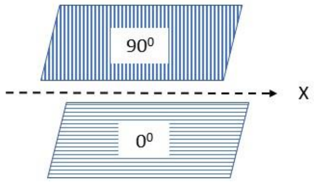
ANTI-SYMMETRIC (Unbalanced) COMPOSITE



[0/90]

Individual plies stacked Anti-symmetrically about centreline.

The coupling terms B11 and B22 are equal and opposite, this means that a membrane force will cause a bending response

$$B = \begin{bmatrix} 1{\cdot}0 & 0 & 0 \\ 0 & -1{\cdot}0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \text{kN}$$

Classical lamination theory

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COUPLING EFFECTS

- Coupling effects are load activated, either residual (curing) or applied.
- Coupling effects in symmetric laminates appear after loading, where a bend will cause a twist and vice-versa.
- The coupling effects of the Bij terms in anti-symmetric laminates can produced pronounced curvature distortion after curing.

Recognition of coupling effects can be beneficial or detrimental to the intended design.

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Classical Lamination Theory

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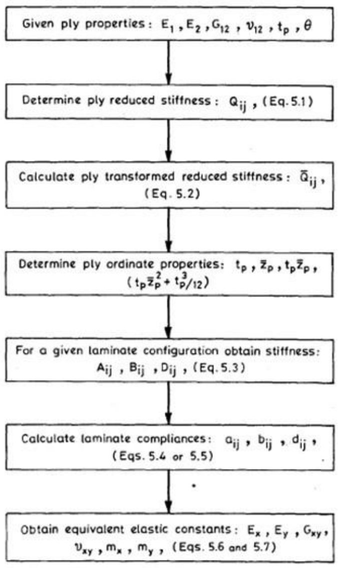
COMPOSITE LAMINATE PROPERTY DERIVATION



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Composite Properties Determination

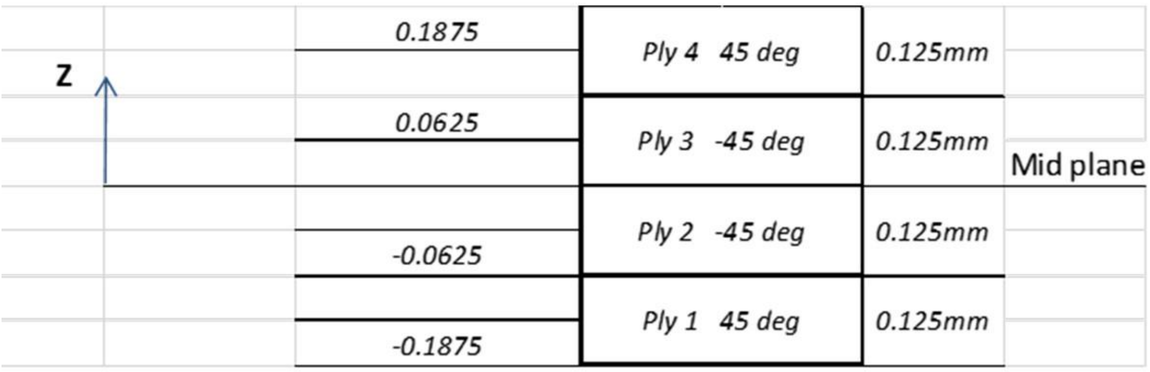

Fig.1: [45/-45/-45/45] Laminate Architecture

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Composite Properties Determination

Calculate Equivalent properties of Young’s Modulus and Poisson’s ratio for Membrane and Bending modes.

See Calculate sheets

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10% Rule:

Quick Method to check

Composite Properties

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10% RULE (Dr. Hart-Smith):

COMPOSITE LAMINATE PROPERTY DERIVATION

Classical lamination theory with its matrix mathematics or Finite Element Analysis is not always needed for calculating the essential properties of layered Composites.

The 10% Rule is a simple method for initial sizing and weight estimates of a Composite architecture.

The transverse properties of a fibre is approximately 10% of the longitudinal strength and stiffness.

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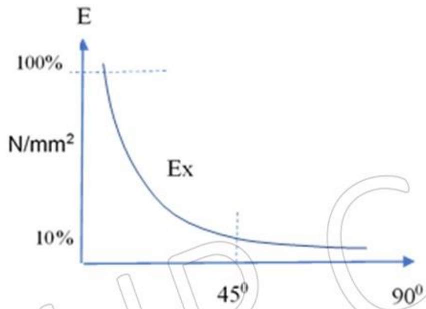
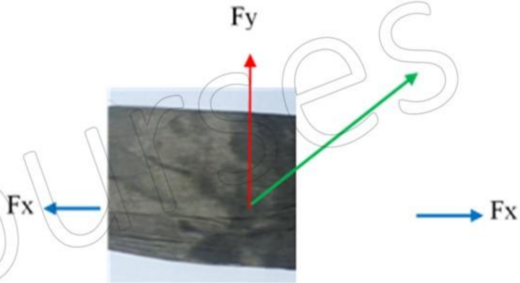
Composite directional Stiffness





Fibres full Young's Modulus (stiffness) and strength in X-direction.

Fibres at 90 degrees to the x-direction obtain less than 10% of full Young's Modulus (stiffness) and strength.

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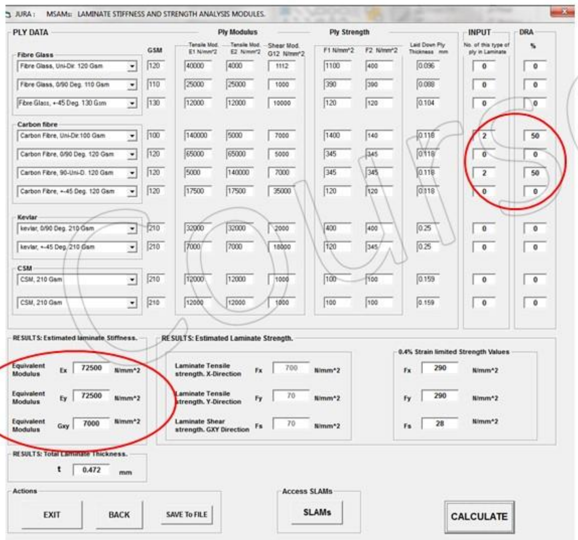
10% RULE:
COMPOSITE LAMINATE PROPERTY DERIVATION



JURA : MSAMs: LAMINATE STIFFNESS AND STRENGTH ANALYSIS MODULES.

PLY DATA	GSM	Tensile Mod. E1 N/mm^2	Tensile Mod. E2 N/mm^2	Shear Mod. G12 N/mm^2	F1 N/mm^2	F2 N/mm^2	Laid Down Ply Thickness mm	INPUT No. of this type of ply in Laminate	DRA %
Fibre Glass									
Fibre Glass, Uni-Dir. 120 Gsm	120	40000	4000	1112	1100	400	0.096	0	0
Fibre Glass, 0/90 Deg. 110 Gsm	110	25000	25000	1000	390	390	0.088	0	0
Fibre Glass, +-45 Deg. 130 Gsm	130	12000	12000	10000	120	120	0.104	0	0
Carbon fibre									
Carbon Fibre, Uni-Dir.100 Gsm	100	140000	5000	7000	1400	140	0.118	2	50
Carbon Fibre, 0/90 Deg. 120 Gsm	120	65000	65000	5000	345	345	0.118	0	0
Carbon Fibre, 90-Uni-D. 120 Gsm	120	5000	140000	7000	345	345	0.118	2	50
Carbon Fibre, +-45 Deg. 120 Gsm	120	17500	17500	35000	120	120	0.118	0	0
Kevlar									
kevlar, 0/90 Deg. 210 Gsm	210	32000	32000	2000	400	400	0.25	0	0
kevlar, +-45 Deg. 210 Gsm	210	7000	7000	18000	120	345	0.25	0	0
CSM									
CSM, 210 Gsm	210	12000	12000	1000	100	100	0.159	0	0
CSM, 210 Gsm	210	12000	12000	1000	100	100	0.159	0	0

RESULTS: Estimated laminate Stiffness.
Equivalent Modulus Ex 72500 N/mm^2
Equivalent Modulus Ey 72500 N/mm^2
Equivalent Modulus Gxy 7000 N/mm^2

RESULTS: Estimated Laminate Strength.
Laminate Tensile strength. X-Direction Fx 700 N/mm^2
Laminate Tensile strength. Y-Direction Fy 70 N/mm^2
Laminate Shear strength. GXY Direction Fs 70 N/mm^2

0.4% Strain limited Strength Values
Fx 290 N/mm^2
Fy 290 N/mm^2
Fs 28 N/mm^2

RESULTS: Total Laminate Thickness.
t 0.472 mm

Actions: EXIT BACK SAVE To FILE
Access SLAMs: SLAMs
CALCULATE

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10% RULE:
COMPOSITE LAMINATE PROPERTY DERIVATION

Carbonfibre: E1 = 140000N/mm^2

90	25%
0	25%
0	25%
90	25%

[Midplane]

[0/90/90/0]

$$Ex_m = (50 \times 1.0) + (50 \times 0.1)/100 \quad = 0.55$$

$$Ex = Ey = 140000 \times 0.55$$

$$EXm = 77000 \frac{N}{mm^2} \quad (Eqivalent\ Young's\ Modulus\ in\ Membrane)$$

** The Membrane Stiffness is unaffected by the position of the individual plies in the stacking sequence.

$$For\ this\ \frac{0}{90}\ Layup, the\ Ex\ and\ Ey\ is\ a\ good\ approximation$$

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COMPOSITE LAMINATE PROPERTY DERIVATION

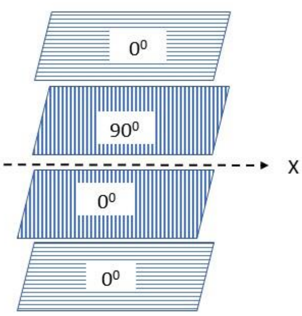
Equivalent Young's Modulus in bending, Exb

0	25%
90	25%
90	25%
0	25%

[Midplane]

[90/0/0/90]

The 0 deg ply has been placed as the outside layer, further away from the midplane has it contributes more bending stiffness to the laminate.



** The Membrane Stiffness is unaffected by the position of the individual plies in the stacking sequence.

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10% RULE:
COMPOSITE LAMINATE PROPERTY DERIVATION

Carbonfibre: E1 = 140000N/mm^2

+45	25%
-45	25%
-45	25%
45	25%

[45/-45/-45/45]

$$Ex = (50 \times 0.1) + (50 \times 0.1)/100 \quad = 0.1$$

$$Ex = Ey = 140000 \times 0.1$$

$$= 14000\ N/mm^{\wedge}2$$

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Stacking Sequence of the plies in a laminate

The laminate stacking sequence does not affect the membrane (extensional) stiffness.

The laminate stacking sequence does affect the bending stiffness.

For initial sizing of a thin walled composite component use the Equivalent Young’s Modulus in Bending.

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Estimated Composite Elastic Constants

Carbonfibre: E1 = 140000N/mm^2

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Initial Design

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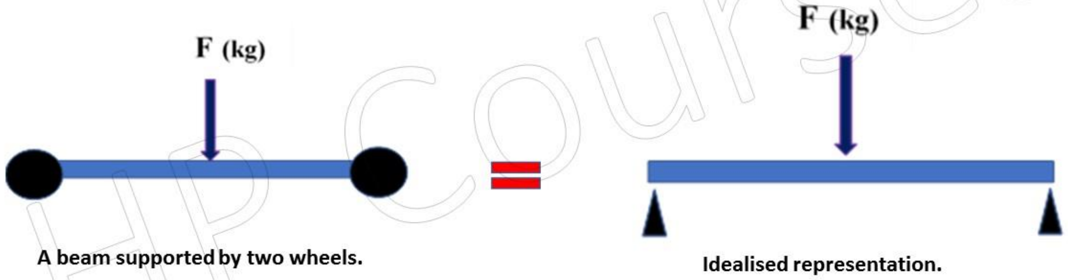
Design Techniques with Composite Materials

Most products can be broken down into Fundamental structures

1. Example: Beams.



Simple Composite Beam

Parametric study in CSAMs

Load = 200kgs

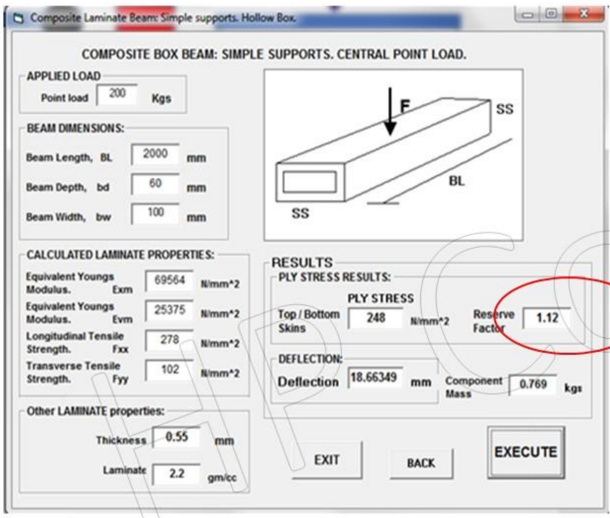
Beam geometry. Length = 2000mm. Depth = 60mm. Width = 100mm.

Young's Equivalent Modulus: Ex = 69564 N/mm^2. Ey = 25375 N/mm^2.

Strength: Fx = 278 N/mm^2. Fy = 102 N/mm^2.

Laminate density = 2.2g/cc (Glassfibre)

Simple Composite Box Beam, Parametric Analysis



RESULTS:
Total Laminate thickness. = 0.55mm
Ply Stress = 248 N/mm^2
Beam central Deflection = 18.67 mm
Beam Weight = 0.77 kgs

Strength Reserve Factor = 1.12
(If RF > 1.0 then structure is acceptable)

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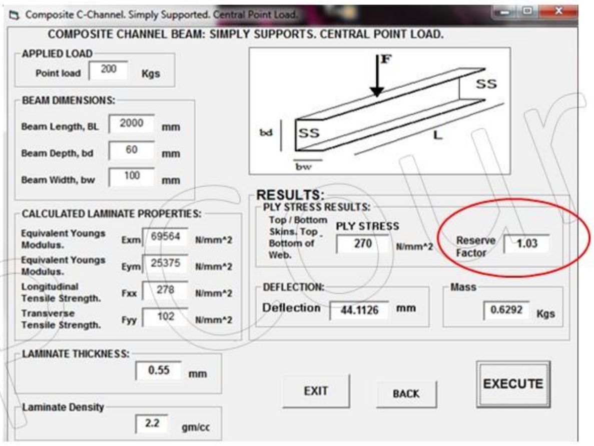
Simple Composite Flange Beam, Parametric Analysis

1. Example: Flange sections-Beam



Strength Reserve Factor = 1.03

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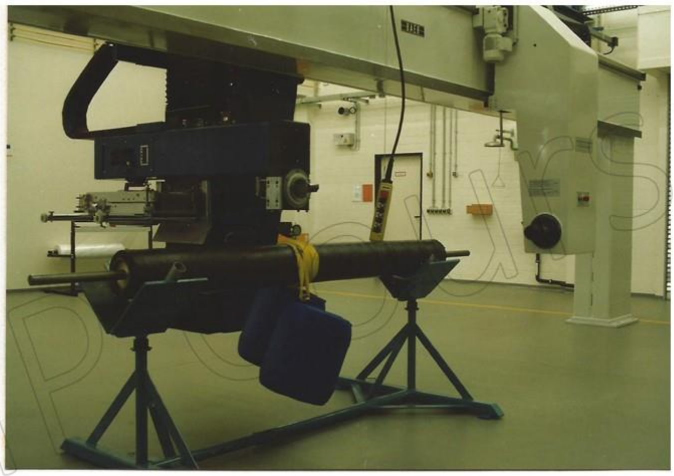
Composite Filament Wound Tube

(1993)

Design Example

Composite Filament wound Tube (1993)



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Carbonfibre Composite Properties

T300 / 914 (CARBON FIBRE / EPOXY)

E1 = 148000 N / MM2	E2 = 9650 N / MM2	E3 = 9650 N / MM2
GXY = 4550 N / MM2	GXZ = 3425 N / MM2	GYZ = 2100 N / MM2
NUXY = 0.252	NUXZ = 0.252	NUYZ = 0.414
FXT = 1314 N / MM2	FXC = 1220 N / MM2	FYT = 43.0 N / MM2
FYC = 168.0 N / MM2	FS = 48.0 N / MM2	
DENSITY = 1.69 GM / CC		

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Stiffness Matrix

$$0^\circ \quad \begin{vmatrix} 148.85 & 2.9 & 0 \\ 2.9 & 9.71 & 0 \\ 0 & 0 & 4.5 \end{vmatrix} \text{ kN/mm}$$

$$90^\circ \quad \begin{vmatrix} 9.71 & 2.9 & 0 \\ 2.9 & 148.85 & 0 \\ 0 & 0 & 4.5 \end{vmatrix} \text{ kN/mm}$$

$$\bar{Q}_{10} \quad \begin{vmatrix} 141 & 6.8 & 22.7 \\ 6.8 & 9.97 & 0.31 \\ 22.7 & 0.31 & 8.4 \end{vmatrix} \text{ kN/mm}$$

$$\bar{Q}_{-10} \quad \begin{vmatrix} 141 & 6.8 & -22.7 \\ 6.8 & 9.97 & -0.31 \\ -22.7 & -0.31 & 8.4 \end{vmatrix} \text{ kN/mm}$$

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Stiffness Matrix

CONSTRUCT 'A' MATRIX

$$A_{11} = \overset{90}{\left[9.71 \times 0.26\right]} + 10\overset{0}{\left[148.85 \times 0.26\right]} + 2\overset{10}{\left[14.1 \times 0.26\right]} + 2\overset{-10}{\left[14.1 \times 0.26\right]}$$

$$A_{11} = \underline{536.2 \text{ kN/mm}}$$

$$A_{22} = \overset{90}{\left[148.85 \times 0.26\right]} + 10\overset{0}{\left[9.71 \times 0.26\right]} + 2\overset{10}{\left[9.97 \times 0.26\right]} + 2\overset{-10}{\left[9.97 \times 0.26\right]}$$

$$A_{22} = \underline{74.3 \text{ kN/mm}}$$

$$A_{33} = \overset{90}{\left[4.5 \times 0.26\right]} + 10\overset{0}{\left[4.5 \times 0.26\right]} + 2\overset{10}{\left[8.4 \times 0.26\right]} + 2\overset{-10}{\left[8.4 \times 0.26\right]}$$

$$A_{33} = \underline{21.6 \text{ kN/mm}}$$

$$A_{12} = \overset{90}{\left[2.9 \times 0.26\right]} + 10\overset{0}{\left[2.9 \times 0.26\right]} + 2\overset{10}{\left[6.8 \times 0.26\right]} + 2\overset{-10}{\left[6.8 \times 0.26\right]}$$

$$A_{12} = \underline{15.37 \text{ kN/mm}}$$

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Young's Equivalent Modulus

$$A = 2 \times 4 \begin{bmatrix} 536.2 & 15.37 & 0 \\ 15.37 & 74.3 & 0 \\ 0 & 0 & 21.6 \end{bmatrix} \text{ kN/mm}$$

$$A = \begin{bmatrix} 4289.6 & 123 & 0 \\ 123 & 594.4 & 0 \\ 0 & 0 & 172.8 \end{bmatrix} \text{ kN/mm}$$

$A_{13} = A_{23} = 0$ LAM. IS IN PLANE ORTHOTROPIC

$$a_{11} = \frac{A_{22}}{A_{11}A_{22} - A_{12}^2} = \frac{594.4 \times 10^3}{(4289.6 \times 10^3 \times 594.4 \times 10^3) - (123 \times 10^3)^2}$$

$$a_{11} = \underline{0.23451347 \times 10^{-6} \text{ N/mm}}$$

MEMBRANE EQUIVALENT YOUNGS MODULUS

$$E_x = \frac{1}{t \cdot a_{11}} = \frac{1}{31.2 \times 0.23451347 \times 10^{-6}}$$

$$= \underline{136671 \text{ N/mm}^2}$$ [ACCEPT THIS VALUE AS AN APPROXIMATION FOR BENDING Ex]

Exm = 136671 Nmm^{-2}

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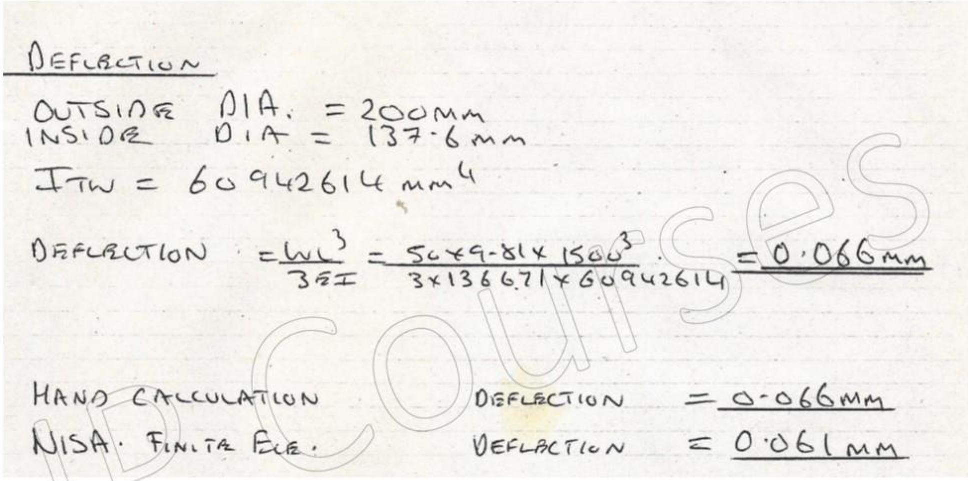
Hand Calculation of deflection



DEFLECTION

OUTSIDE DIA. = 200MM

INSIDE DIA = 137·6 mm

I_{TW} = 60942614 mm^4

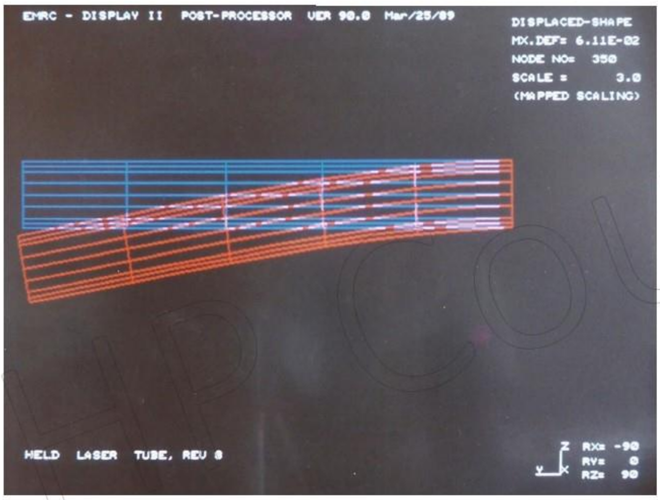
DEFLECTION $= \frac{WL^3}{3EI} = \frac{50 \times 9{\cdot}81 \times 1500^3}{3 \times 136671 \times 60942614}$ = 0·066 mm

HAND CALCULATION DEFLECTION = 0·066MM

NISA. FINITE ELE. DEFLECTION = 0·061 MM

Filament wound Composite Tube

Finite Element Software. NISA



NISA: Maximum Deflection = 0.061mm

Hand Calc: Maximum Deflection = 0.066mm

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Composite Failure Criteria

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Composite failure criteria

Maximum Stress Theory.
Failure occurs if the stress in material axes direction exceeds their respective strength.

Hoffman Theory.
Ply failure occurs when the failure index exceeds the value of 1. F_{12} is assumed to be 0.5.

Tsai-Wu Stress Theory.
Ply failure occurs when the failure index exceeds the value of 1. This theory requires a biaxial test to determine F_{12}

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Composite failure Criteria

First (FPF) to last ply Failure (LPF)

First Ply Failure (FPF) is a method commonly used to predict the strength of a laminate. Determines the stresses in each ply and a failure criterion (Tsai-Wu, Max Stress, etc.) for any of the plies in the layup. With FPF, the laminate is assumed to have failed with the first ply fails.

Progressive Ply Failure (LPF) allows the analyst to see what happens beyond first ply failure. Each ply is evaluated against a specified failure criterion. However, the analysis does not stop at the first failure. That failed ply is removed from the analysis of the laminate and the remaining laminate is loaded again.

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Composite Delamination Failure

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Delamination

Composite components can delaminate for a number of reasons.

- Delaminations and cracks can cause premature failure.
- Buckling failure mode is common in a delaminated composite under compression load.
- Fatigue life may be shortened due to a laminate delamination
- Mitigate delamination, strategically place z-fibres (3D stitching)

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Delamination

- Design methods exist to minimise delamination.
- A variety of inspection technologies exist.
- For aircraft there exist approved methods of composite repair.

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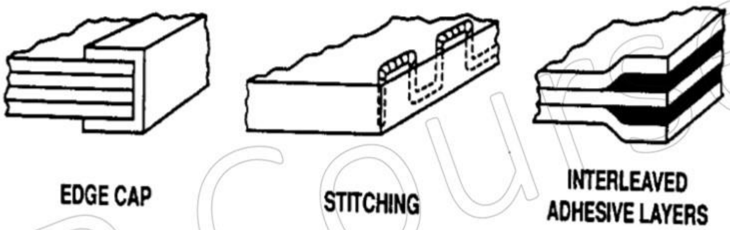
Free Edge Delamination



Edge reinforcement.

Delamination and Impact mitigation techniques

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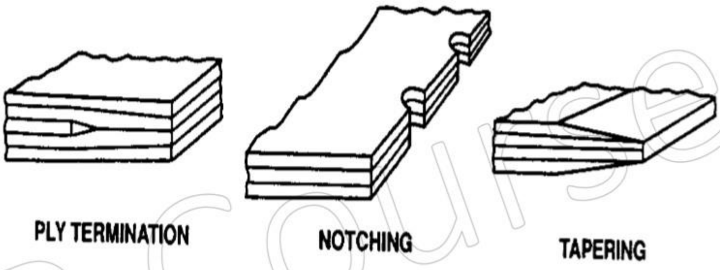
Free Edge Delamination



Edge modification.

Delamination mitigation techniques

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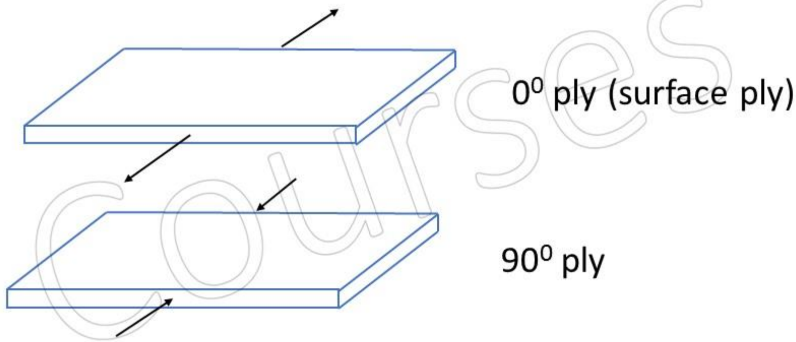
Delamination

Mechanism for Interlaminar direct Stress



The Interlaminar direct Stress
(M. Datoo. Fibrous composites)

$$Fx = \left(\frac{90}{7}\right) * \left(\frac{Mp}{t^2}\right)$$

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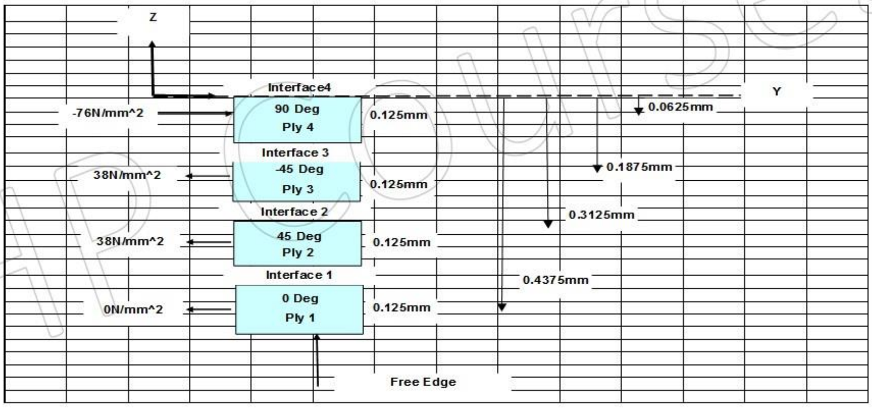
Delamination

2D shell FEA models will not provide edge stress information.
Excel calculation can be set up to provide facture of safety against Edge peel stresses.



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Delamination

Compare the ply interface stress with the allowable Interlaminar shear strength.
Obtain Reserve Factor.

INTERFACE	PLY	PLY ANGLE	INTERLAMINAR STRESSES Fxz	Fyz	Fz	Max. Stress RF
	1	0				
INTERFACE 1			0	0	0	-1659
	2	45				
INTERFACE2			-73	-12	4	13.6
	3	-45				
INTERFACE 3			0	-24	15	3.4
	4	90				
INTERFACE4			0	0	22	2.2

-ve Compressive edge stress

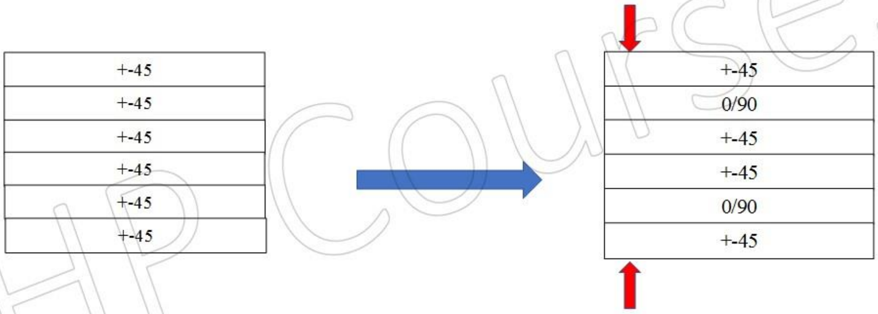
+ve Tensile edge stress

Peeling stress at edge is +ve, i.e is TENSILE, this means that this laminate architecture is prone to delamination.

Delamination

Reduce delamination risk by splitting up the +-45 deg plies of a laminate.

Intention is to create an **compressive** stress normal to the edge.



Interspersed 0/90 to reduce delamination.
However, check stiffness and strength requirements

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Delamination

This laminate architecture creates an **compressive** stress normal to the edge.

Ply	Angle Deg.	Mp	Max. Stress RF
1	90	-0.59	-6.55
2	45	-1.49	-2.61
3	0	-2.09	-1.86
4	-45	-2.41	-1.62

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Delamination notes

Delamination resistance may be improved in laminates by the insertion of a layers of Chopped Strand Mat (CSM).

Buckling load is reduced in the presence of delamination.

Growth of delamination may be modelled with a fracture mechanics approach, assuming that the crack propagates when the energy available (strain energy release rate) reaches the fracture energy of the material.

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Delamination notes

In one example, delamination started to grow at about 20 percent of the laminate ultimate tensile strength.

The adhesively bonded joint is a critical area which can lead to delamination.

Delamination between Balsawood core material and the fibre layers due to blade vibration.

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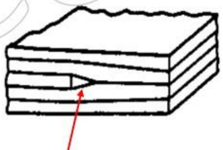
Delamination at Ply Drops

- Ply delamination can occur at ply drop off locations.
- Incidence of delamination from ply drop-offs in the trailing edge spar, leads to an increase of stress in the trailing edge adhesive joint.
- Strengthening the trailing edge spar by joint type selection (eg Scarp etc) and dimensioning (20:1 taper).

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Composite Drapeability
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Composite Drapeability

DRAPE, is the ability of a fabric to conform to a tooling geometry gracefully without rendering any crimping (Desired).
CRIMP, is the waviness of fabric when placed onto a tool (Undesired).

Three styles of woven fabrics are generally available.

- Plain
- Twill
- Satin

These weave types can affect CRIMP and ability of the resin to flow.

CRIMP is not allowed.

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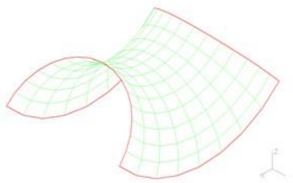
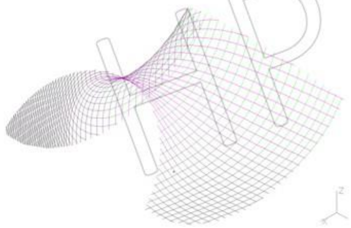
Composite Drapeability



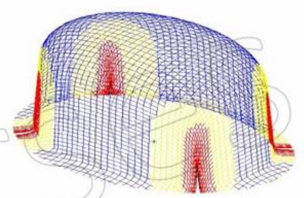
Tooling Meshed



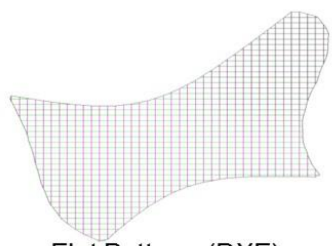
Ply Draped

Drapeability software

- Autolay
- Drape
- Fibresym
- Dr. Klintworth



Red regions are draping problems



Flat Pattern. (DXF)

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Composite Drapeability

DRAPEABILITY WORKSHOP
Autolay

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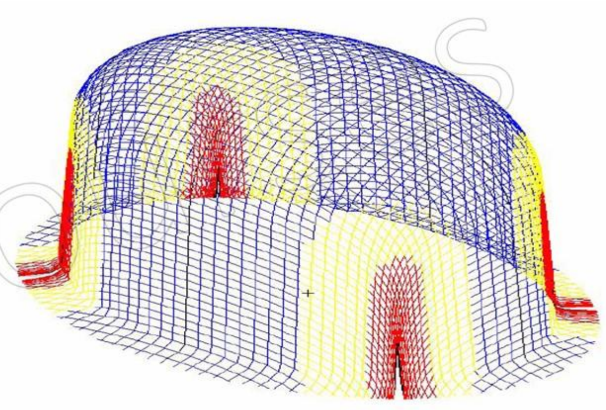
Composite Drapeability

Red regions are draping problems

- Excessive shear
- Incorrect fibre or fabric orientation
- Lack of coverage



Courtesy of Dr. John Klintworth

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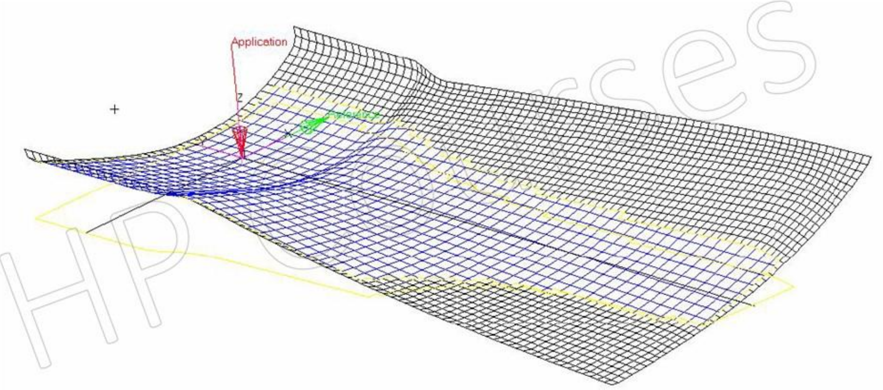
Composite Drapeability



Courtesy of Dr. John Klintworth

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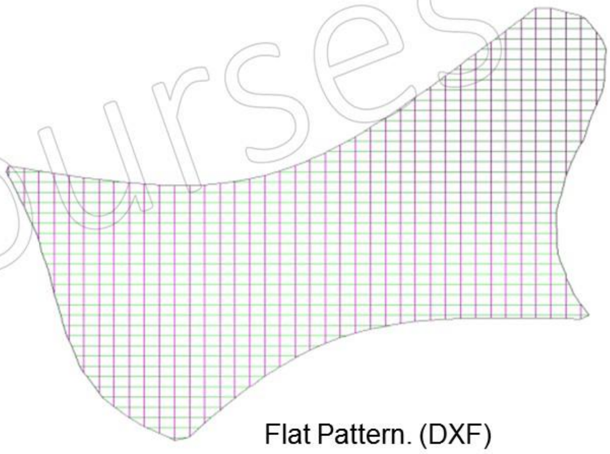
Composite Flat patterns

Flat Pattern (DXF) is sent to the cutting table.

- Shapes are cut automatically
- Computer controlled to minimise waste

Flat Pattern. (DXF)



Flat Pattern. (DXF)

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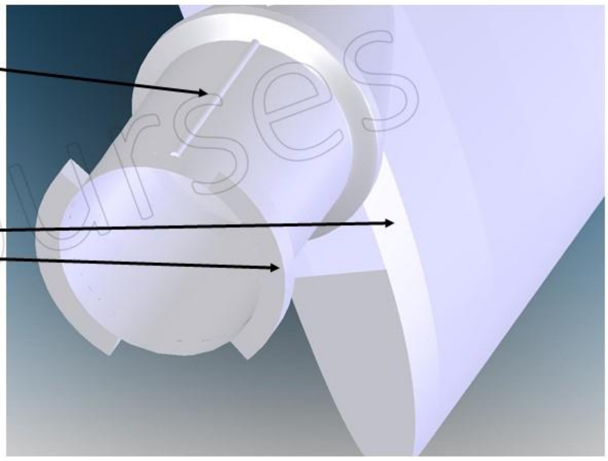
FEA mesh and Drapeability

Requires finer mesh at details and change in direction.

Check material Drapeability at detailed geometry.



Possible solutions. Change;

- the detail shape
- Weave type

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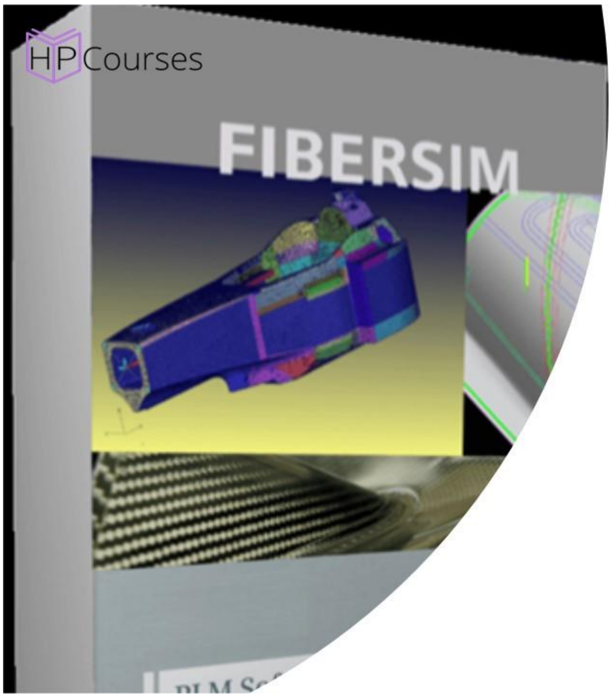

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FIBERSIM

Ply placement simulation

HP Courses

Fibersim

Fibersim is a software that can be connected with Catia-V. It offers modules of design, analysis, and manufacture of composite parts.

Simulation studies using multi-ply based designs with various manufacturing methods. The software includes a Wind Blade design module.

https://www.plm.automation.siemens.com/global/en/products/mechanical-design/composite-design-analysis.html

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Fibersim

NB:

Many engineers who have used this software are CAD based. They may have little fundamental knowledge of Composites and may not understand the implications of a non-symmetric laminates. Their main interest is to ensure that the composite will drape, i.e. manufacturable.

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Composite Drapeability

- Investigate draping possibilities and seeding location
- Confirms fibre alignment
- Predict manufacturing problems
- Produce accurate manufacturing data such as shape cut-out
- Audit ply variations
- Must be accounted for in structural analysis

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Fatigue

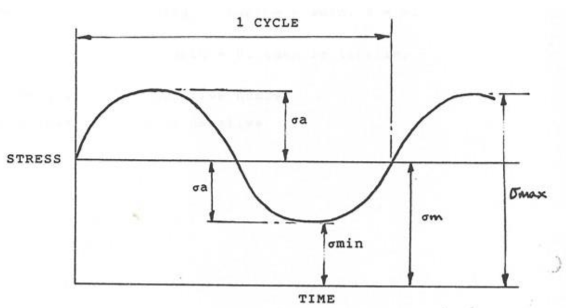
HPCourses

Fatigue

When a load is applied once, it is often called a “Static” load.

In rotating machinery the applied loads are usually cyclic.

This cyclic loading causes a progressive degradation of the material properties and eventual failure by fatigue.



σmax = Max stress
σmin = Max stress
R = Stress Ratio

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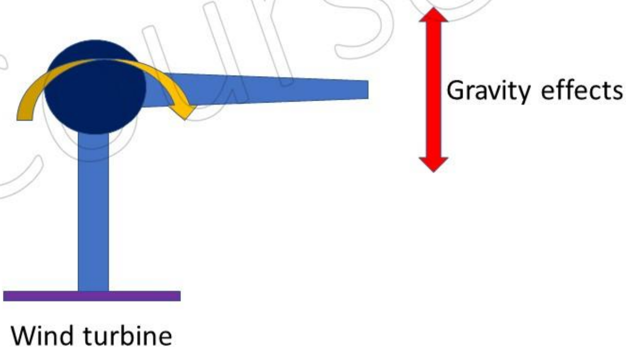
Fatigue

Fatigue damage to the material is caused by cyclic stresses which are lower than the static stress. Cyclic stress due to;

- Flap bending
- Edge bending
- Self weight tension
- Self weight compression
- Stop-start cycles
- etc



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Fatigue

A fatigue failure begins with a small surface crack usually occurring at regions of high stress concentration, i.e, geometrical discontinuity, fillet radius, free edges etc.

The crack grows rapidly under the influence of stress concentrations. The number of revolutions (stress reversals) are recorded against the constant stress until failure occurs. Test are made for different levels of constant stress.

A chart called a S-N curve is made of this data.

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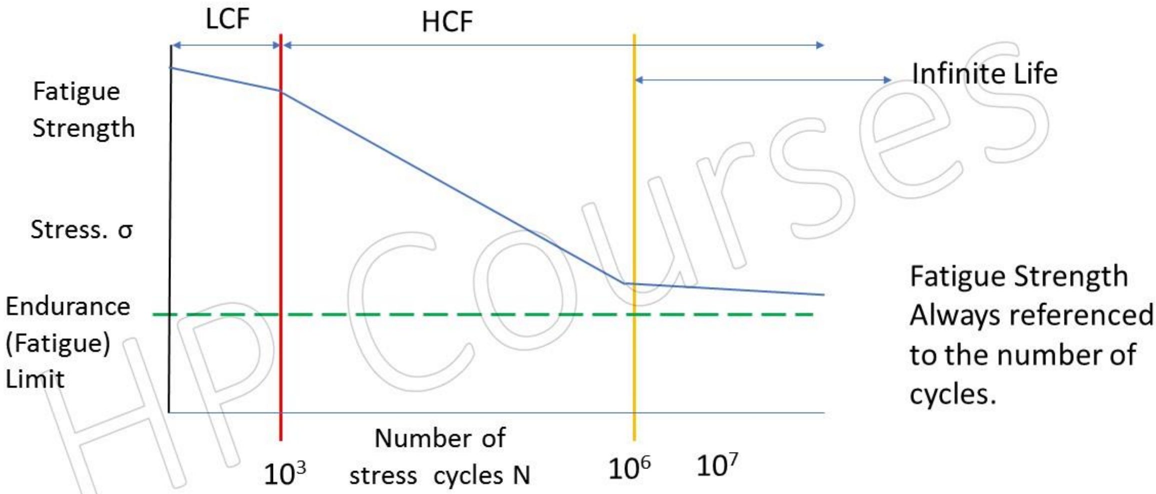
Fatigue: S-N Curve (Log-Normal or Log-Log)



Based on constant stress

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Fatigue

LCF: Low Cycle Fatigue is considered below 10000 cycles

HCF: High Cycle Fatigue is the region beyond 10000 cycles

The Endurance limit is that stress below which no failure will occur by fatigue.

The S-N curve is dependent upon "R" Values.

R = minimum stress/maximum stress

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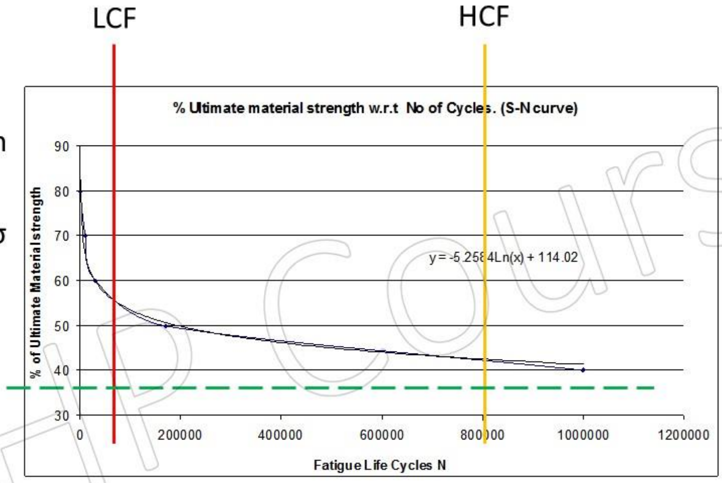
Fatigue: S-N Curve

Fatigue Strength

Stress. σ

Fatigue Limit



N

Fatigue Strength Always referenced to the number of cycles

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Fatigue

More complex loading can occur from loads of differing amplitude.

A cumulative damage law is used to see how much damage each stress amplitude does.

The most widely used in the Palmgren-Miners Law. It is a useful approximation

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Fatigue Damage

A blade subjected to a range of applied loads.

Cumulative damage law is given by "Miner's Law".

It is based on using up fractions of life until unity (failure) is reached.

Miners Law: Cumulative Fatigue Damage

$$\frac{na}{Na} + \frac{nb}{Nb} + \frac{nc}{Nc} + etc = 1.0$$

Where;
ni is a number of cycles of stress
Ni is number of cycles to failure

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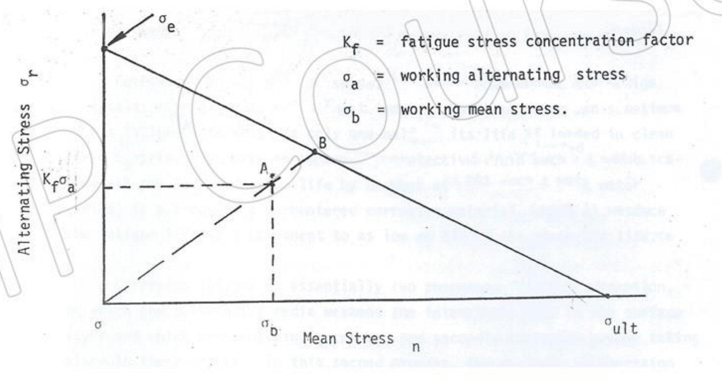
Goodman Diagram

The Goodman diagram allows for the effect of mean stress on a cyclic stress. The curves allows for the effect of a stress concentration.
A Reserve Factor (OB/OA) can be derived.



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Rainflow Analysis

Rainflow analysis method leads to more accurate fatigue life prediction.

Counts amplitude of load with respect to cycle counts.

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Composites and Fatigue

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Fatigue Strength

Composites Fatigue strength influenced by;

- Fibre materials
- Fibre orientation
- Volume fraction
- Layer stacking sequence
- Resin type
- Presence of defects
- Thermal treatment

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Fatigue

Composites typically show fatigue damage progressing as follows;

- matrix cracking (initiated early in the fatigue process)
- fibre-matrix debonding
- ply cracking
- delamination
- fibre breakage
- delamination growth

Ref. C.S.Smith, Reifsnider, Hennecke, Duke

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Fatigue Notes

- High static strength is usually a prerequisite for high fatigue strength.
- Twill weave fibres has superior fatigue performance compared to plain fabric.
- Carbonfibre composite is much less fatigue-critical than glassfibre composite.
- A shear web may be more fatigue-critical than a spar cap.

Fatigue of composites for wind turbines Christoph W. Kensche, DLR, Institute of Structures and Design Pfaffenwaldring 38-40, 70569 Stuttgart, Germany

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Fatigue Notes

- Defects in manufacture and stress concentrations reduce composite fatigue life significantly.
- Fatigue in composites cannot occur unless crack can be initiated in the matrix.
- Significant laminate strength degradation does not occur until fibre fracture.
- Fatigue strength is related to flaws, eg microcracks

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Fatigue Notes

Suggestion: To enhance fatigue life;

a. Consider limiting the strain of the composite to the strain of the matrix cracking.
b. Mitigate stress concentrations.
c. Consider using stiffening strips located away from holes.
d. Consider partial hybrid regions of carbonfibre and Kevlar.
e. Consider alternate laminate stacking sequence.

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Fatigue Notes

A critical failure mode is the composite skin at blade root.

Reports of delamination failure at blade root and trailing edge.

NB: Blade “bumping” causing load redistribution at blade root

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Fatigue Testing

Tension-tension loading is the most common applied loading method for composites.

The way the testing stress is applied is important to the understanding of fatigue failure and life prediction.

Dynamic modulus and damping coefficients derived from vibration acoustic-ultrasonic techniques used to monitor fatigue progression

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Fatigue

The Low Cycle Fatigue (LCF) failure is identified at 2900 cycles (2.6 hours) in a hurricane wind speed of 33ms^{-1}.

Wind velocity	% of Material Ftu	Max. Principal Stress	% above ground stress measured on FEA model	No. of Cycles to Fatigue failure	Time to Failure	Time to Failure	Log Cycles	Log Time
ms^{-1}	%	N.mm^{-2}	%	N	Minutes	Hours	Log (N)	Mins
24.5	41	13	87.5	1000000	52632	877.20	6.00	4.72
30.0	63	20	87.5	15000	789	13.20	4.18	2.90
33.0	72	23	87.5	2900	153	2.60	3.46	2.18
33.5	88	28	87.5	170	9	0.15	2.23	0.95
34.0	97	31	87.5	30	2	0.03	1.48	0.20
35.0	100	32	87.5	15	0.8	0.00	1.18	-0.10

Wind speeds, % of *Ftu* stress level (at 87.5% profile height) w.r.t predicted fatigue life cycles and hours to failure. (35m long cantilever structure)

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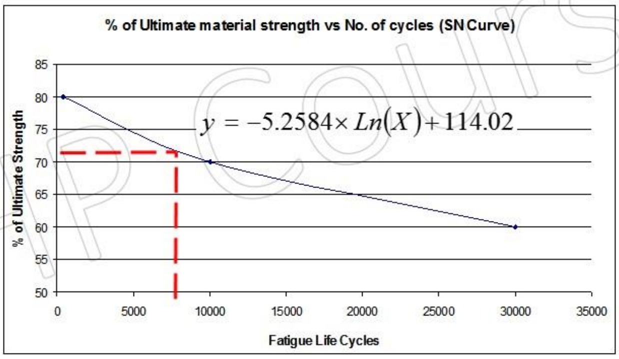
Fatigue

Graphical examination in the low cycle region provides the number of cycles to failure as 7400 (not 2900 cycles, difference is because of low fidelity data).

The amplitude of the cyclic loading has a major effect on the fatigue performance.



Equation 1. defines the *S-N* fatigue life cycle curve.

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Fatigue

The Endurance limit is the highest stress level which the material can withstand for an infinite number of load cycles without failure.

The **endurance limit** appears to occur below the wind speed of $24.2 ms^{-1}$ which corresponds to stress levels at 0.41 of the Ultimate material strength.

Fatigue endurance strength frequently based on 0.4% strain limitation, (but can range from 0.3 to 0.6).

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Fracture Mechanics

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Fracture Mechanics

Composite structural reliability related to flaws.

- Defects within the matrix (resin) example porosity etc, can be the location of crack initiation.
- Microcracks grow.
- Microcracks attain critical size.

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Fracture Mechanics

- Above a certain stress level a crack will form.
- Above a certain level of stress a crack will propagate, i.e. crack initiation stress.
- For a material of known fracture toughness, the critical stress level can be calculated.
- Fracture mechanics can be used to predict the rate of fatigue crack propagation.
- The rate of crack growth per cycle of loading is,

$$da/dn = C(\Delta K)m$$

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Hygrothermal

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Hygrothermal

Non-mechanical loads arising from a thermal exposure invoking a temperature change and a hygroscopic effect whereby the laminate absorbs moisture. The combined action of thermal and hygroscopic events are known as Hygrothermal.

The hygrothermal effect on laminates cause dimensional changes and induces residual tensile and compressive stresses within the laminate.

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Thermal

The ***Stress free temperature*** point is a temperature reached during curing of the composite. Normally, ***cure temperature*** of the laminate is above this value.

It is the temperature difference between the ***Stress free temperature*** condition to ***ambient temperature*** which causes thermal residual stresses in the plies.

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Thermal

Stresses and Strains at different temperature distributions can be determined by classical lamination theory.

Free thermal strain, $e = \propto . \Delta T$

Coefficient of thermal expansion, $\propto$

Change in temperature, ΔT

Residual stress should be algebraically considered, as the effect on the stress status of the laminate may be significant. Residual stresses can cause curing deformations.

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Moisture

- Fibrous composite materials tend to absorb moisture.
- Specifically it is the resin that is susceptible to moisture intake
- Vinylester and polyester resins are prone to moisture degradation
- The plies swell with moisture intake and produce residual strains and stresses.
- There is not a constant moisture distribution through a laminate.

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Moisture Diffusion

Z = through thickness laminate position

C = initial moisture content

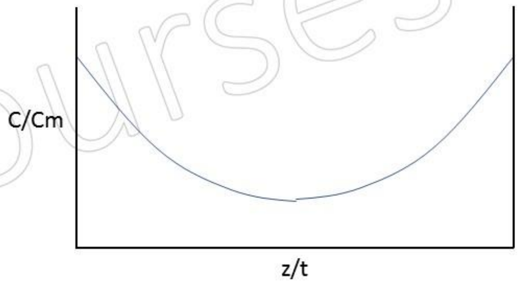
Cm = Maximum moisture content

A constant moisture distribution is a result of long time exposure.

Stresses and Strains can be determined by classical lamination theory.

A constant moisture content does not always give the worst stresses

Ficks equation of diffusion determines the laminate moisture concentration



Typical trend of moisture concentration diffusion through laminate thickness with increasing time

Ref. M. Datoo

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Composite failure-Moisture

To avoid water ingress through resin (matrix) cracks, tensile strains are kept to below 20% or 30% of ultimate.

Strain to failure of the fibre is greater than that of the matrix. Resin cracking occurs before fibre fracture.

Decide if ultimate stresses are based on fibre or resin cracking stresses.

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Composite Hygrothermal

Knock-down factors-1

In the early 1980s, graphs (carpet plots) were produced that related specific composite laminates of angle ply % content to strength/stiffness reduction percentage due to moisture content or service temperature. We named these "knock-down Factors".

Calculated Youngs Modulus or laminate strength would be reduced with respect to the knock-down factors. Typically by 10% or more.

Composite Hygrothermal

Knock-down factors-2

Long term reduction in mechanical properties due to moisture diffusion in glassfibre/vinyester were reported as 20% reduction in Young's Modulus and tensile strength. 30% reduction in compressive strength.

(C. S. Smith, Admiralty Research Establishment, Dunfermline, 1990)

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Creep

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Creep

Creep can be defined as the increase of strain of a composite over a period of time when exposed to a persistent stress field.

Significant creep effects may occur to composite components when exposed to elevated temperatures. Resin-cracking and fibre debonding.

Check with manufacturer of marine qualified composite systems.

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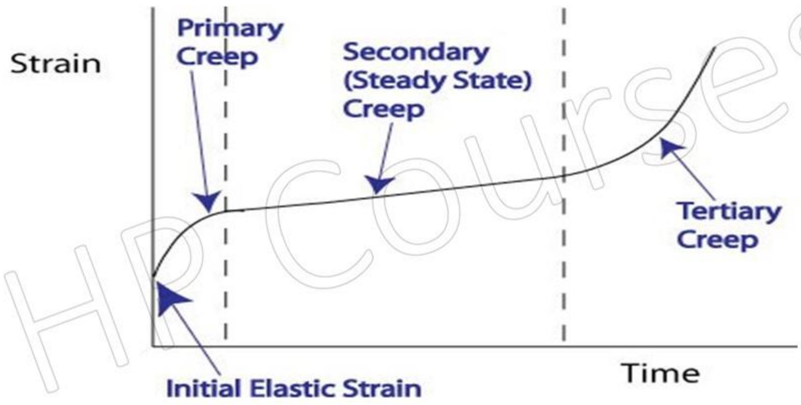
Creep

Generic Creep Curve



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Creep

Stresses in the composite material should be less than the specified creep strength at all stressing conditions at which creep must be considered.

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Impact

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Impact notes

- Impact strength is usually obtained from Charpy or Izod test.
- Glassfibre has a higher impact strength than Kevlar or carbonfibre.
- Glassfibre is not as expensive as Kevlar.
- Kevlar has superior toughness above other fibres, it wont tear.
- Stacking sequence affects strain energy absorption
- Reduction in interlaminar crack length increases energy absorption
- With carbonfibre composites as the Volume fraction increases, energy absorption decreases but depends upon fibre orientation.

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Impact notes

- A +-45 deg ply on the outside facing the impactor dissipates impact energy. Looks good
- Increase damage tolerance of composites by using toughened resins.
- Hybrid of high modulus fibres with high strength fibres offers low weight energy absorbing structures.
- Hybrid of carbonfibre and Kevlar offers significant improvements in energy absorption.
- Interlacing fibreglass between carbonfibre improves the impact resistance.
- Improve impact toughness by modifying the resin with short fibres.

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Impact strength

Material	**Charpy Impact** kJ/m^2
Glassfibre	610
Kevlar	250
High strength carbonfibre	190

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Vibration

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Vibration

Dynamic effects in mechanism of the wind turbine due to frequency of aerodynamic loads during normal rotation are significant.

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Vibration modes

Closed form solutions;

The natural frequency for a rectangular sectioned cantilever.

$$fn = \frac{Kn}{2\pi l^2} * \sqrt{EI/w}$$

Fn = Frequency
E = Youngs Modulus
L = blade length
W = mass per unit length

Useful also for quality control.
Equation can be modified to take into account effects of temperature and centrifugal stress stiffening

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Hi-tec and Bio-Composites

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Uni-Directional Silicon Carbide Fibre

Uni-Directional Silicon Carbide fibre

Properties:

Youngs Modulus = 370000Nmm^{-2}

Density = 3.2gm/cc

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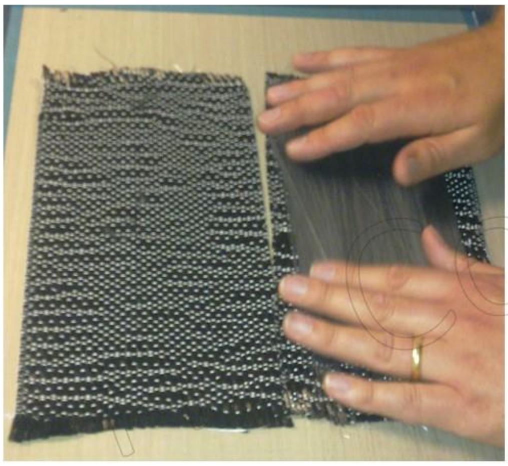
Silicon Carbide Fibre/ CarbonFibre mat



Uni-Directional Silicon Carbide fibre on Carbonfibre 0/90 mat

Silicon Carbide/Carbonfibre Composite

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Sandwich core Composites.

A variety of cell sizes, densities and materials such as thermoplastic, aluminium and aramid papers.

Phenolic Honeycomb core

Check skin wrinkling and dimpling

Recycled cardboard Honeycomb core

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Introduction to BioComposites.

Flax skin and recycled cardboard core

Hemp Fibres in BioResin

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Introduction to BioComposites.

Bio Gearbox cover.
Flax skin and recycled cardboard honeycomb core in BioResin

Sheet of Cork

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BioComposites.

Cocunut Fibre

Used extensively in Headliners of cars for sound proofing and insulation, Example, Mercedes and Volkswagen

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Hybrid BioComposites.

SIC Uni-Directional Fibres, Balsa core in Bio-Resin

SiC-BioComposite

Research partly financed by TSB, (InnovateUK.org)

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Sandwich core Composites.

Balsa core with end grain orientation in the through thickness direction is one of the most structurally efficient and cost affordable core materials. Careful of water penetration which leads to swelling.

Balsa core

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Property tolerance of Composite Materials

A glassfibre material for the wind turbine skins is Triaxial glass fabric 920g/m² made up of the following construction.

Construction	Weight g/m²	Tolerance (+ - %)	Material
0°	425	5	E-Glass
-45	243	5	E-Glass
+45	243	5	E-Glass
Stitching	6	5	PES

This material is supplied to the Wind Turbine market, Cristex Ltd.
But also, checkout, Scott-Bader ltd.

NOTE: The Tolerance %

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Composite Optimisation

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OPTI-ASSIST COMPOSITE OPTIMISATION

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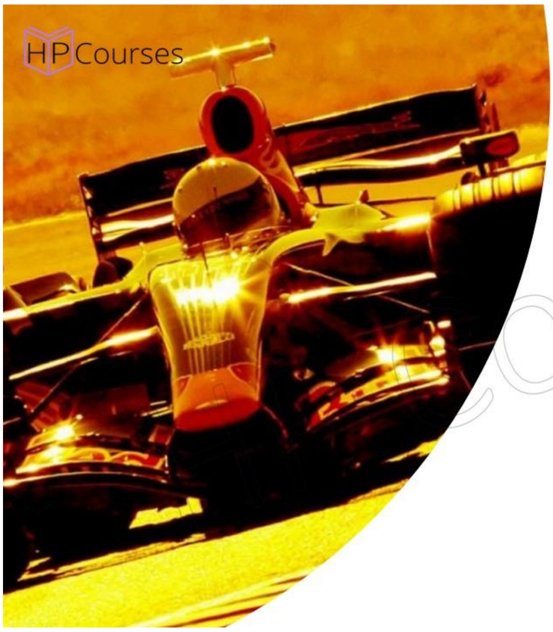

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REDBULL FORMULA ONE

OPTI-ASSIST COMPOSITE OPTIMISATION

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Laminate Bend-Twist

4 Plies. [45/-45]s

Pressure loading: 2.0E-7 N/mm^2

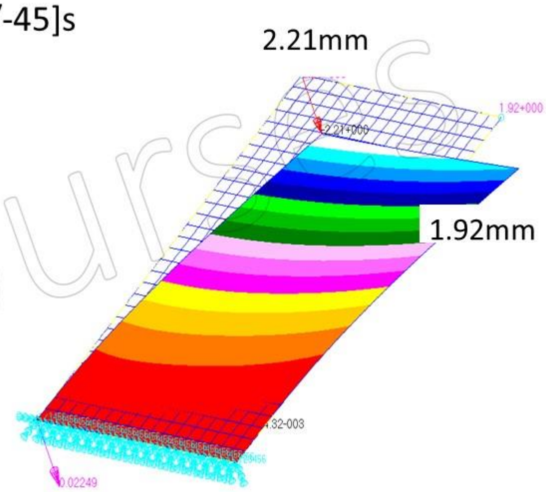
Laminated Composite

Stacking Sequence Convention: Total

Offset: 0.

Stacking Sequence Definition

	Material Name	Thickness	Orientation
1	M55J-UD-363-14	1.400000E-1	4.500000E+1
2	M55J-UD-363-14	1.400000E-1	-4.500000E+1
3	M55J-UD-363-14	1.400000E-1	-4.500000E+1
4	M55J-UD-363-14	1.400000E-1	4.500000E+1



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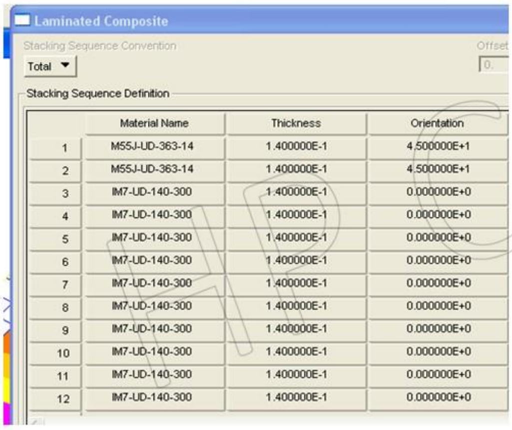
Laminate Bend-Twist

16 Plies. $[45_2/0_{12}/45_2]$.

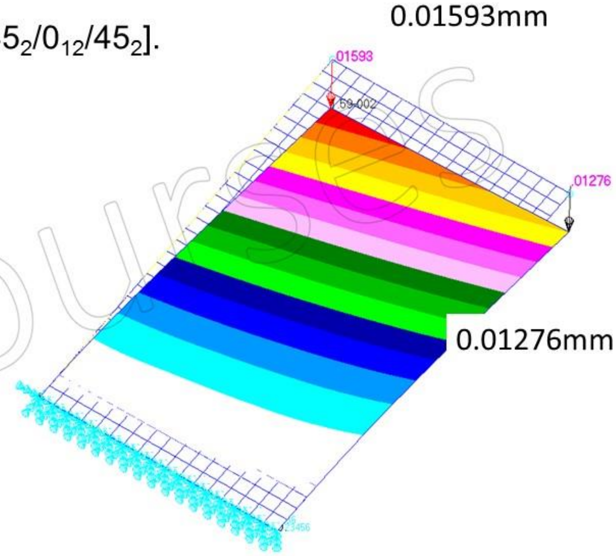
Pressure loading: 2.0E-7 N/mm^2


Laminated Composite

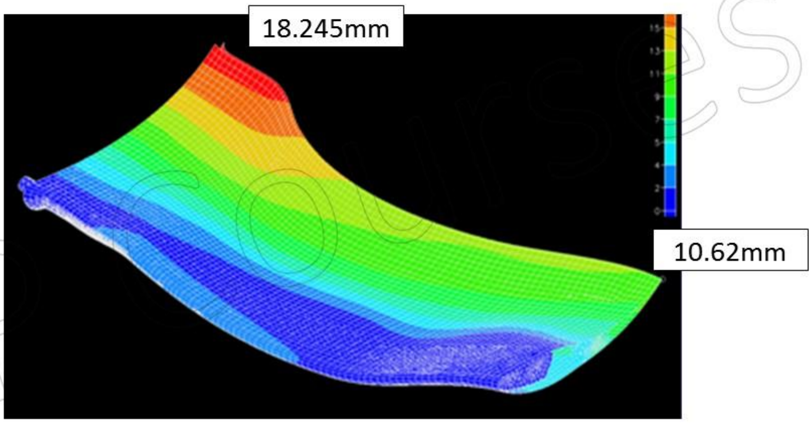
Stacking Sequence Convention: Total

Stacking Sequence Definition

	Material Name	Thickness	Orientation
1	M55J-UD-363-14	1.400000E-1	4.500000E+1
2	M55J-UD-363-14	1.400000E-1	4.500000E+1
3	IM7-UD-140-300	1.400000E-1	0.000000E+0
4	IM7-UD-140-300	1.400000E-1	0.000000E+0
5	IM7-UD-140-300	1.400000E-1	0.000000E+0
6	IM7-UD-140-300	1.400000E-1	0.000000E+0
7	IM7-UD-140-300	1.400000E-1	0.000000E+0
8	IM7-UD-140-300	1.400000E-1	0.000000E+0
9	IM7-UD-140-300	1.400000E-1	0.000000E+0
10	IM7-UD-140-300	1.400000E-1	0.000000E+0
11	IM7-UD-140-300	1.400000E-1	0.000000E+0
12	IM7-UD-140-300	1.400000E-1	0.000000E+0



Composite aero-structural optimisation



DEFLECTION

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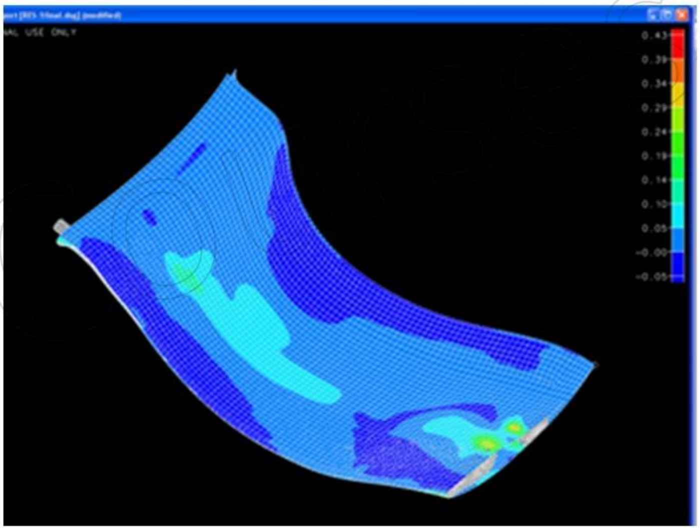
Composite Failure index contours

FAILURE INDEX

Tsai-Hill

Tsia-WU



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Composites: Various issues

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Various issues on selecting a composite material for your project.

Service conditions. i.e what are the operating conditions

- Hot conditions
- Wet conditions

Performance requirements.

- Weight reduction (Do you have a weight target)
- **Deflection limitation**

There can be constraints other than strength. Perhaps t exceed a wing of an aircraft should not touch the ground when it is full of fuel.

Various issues on selecting a composite material for your project.

- **Corrosion resistant**

Is the component exposed to a corrosion environment.

- **Volume production**

How big is the market for this composite component.

- **Cost effective**

What are your cost targets.

Why make it in carbonfibre when glassfibre will do?.

Various issues on selecting a composite material for your project.

Composite Material Selection.

Selecting the right composite material system requires a broad understanding of aspects of composite materials.

The materials system needs to be appropriate for the production volume envisaged.

Tooling (and repair) amortisation considered.

Can the composite product be manufactured by a one tooling method rather than matched tooling (eg VARIM as opposed to RTM).

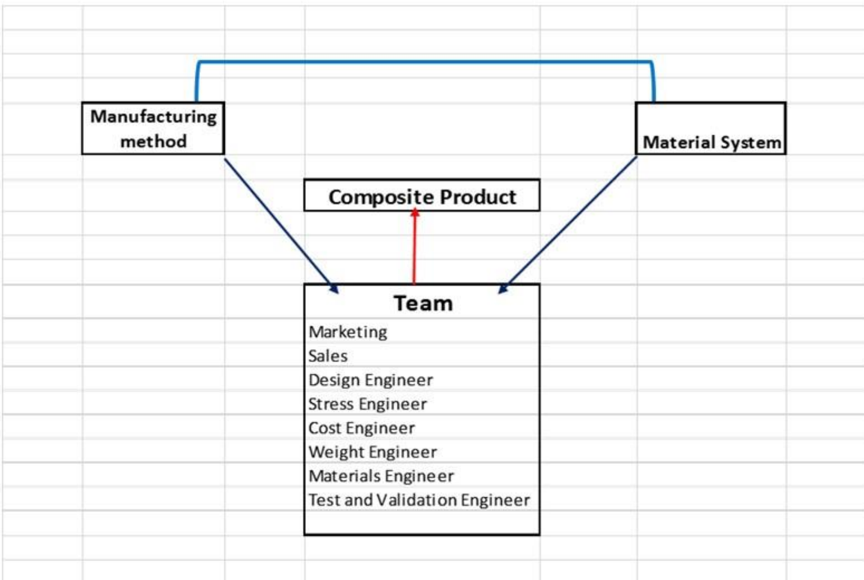
Various issues on selecting a composite material for your project.

- **Specific loading**

There can exist many loading cases.

An aircraft galley has a basic of six loading directions to consider.

A basic Industrial knowledge map for a composite product.



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Validation Test

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Property Test Methods

Experimental determination of laminate properties may be required to confirm theoretical estimates of stiffness and strength.

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Property Test Methods

GENERAL DYNAMICS
Convair Division

COMPOSITE MATERIALS
Material Property Tests

- Basic physical property tests
  1. Specific gravity (ASTM D792)
  2. Resin content and fiber volume (ASTM D3172 or GDC Spec. 0-75224)
  3. Glass transition temperature (ASTM D3418)
  4. Measure per ply thickness
- Basic mechanical property tests to support Structural Analysis
  1. Tension (ASTM D3039)
  2. Compression (ASTM D3410)
  3. In-plane shear (Iosipescu)

  Optional Tests
  4. Interlaminar shear (ASTM-D2344)
  5. Coefficient of thermal expansion (ASTM E831)
  6. Interlaminar tension
- Basic thermophysical property tests to support Thermal Analysis
  1. Thermal conductivity
  2. Specific heat

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Property Test Methods

- Volume Fraction
- Ply thickness
- Tensile Strength
- Tensile Modulus
- Poisson's Ratio

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Property Test Methods

Remove resin in acid bath to check laminate contents and stacking sequence

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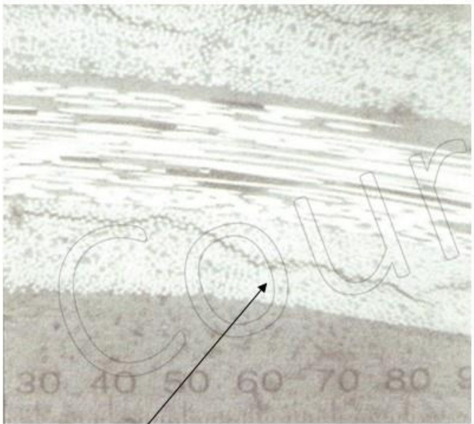
Property Test Methods

Carbonfibre-Glassfibre in Vinylester.



Longitudinal cracks within sample resulted in 45% reduction in strength and Youngs Modulus