**Introduction**

To fully appreciate the role and application of composite materials to a structure, an understanding is required of the component materials themselves and of the ways in which they can be processed. This guide looks at basic composite theory, properties of materials used, various processing techniques commonly found and applications of composite products.

In its most basic form a composite material is one which is composed of at least two elements working together to produce material properties that are different to the properties of those elements on their own. In practice, most composites consist of a bulk material (the 'matrix'), and a reinforcement of some kind, added primarily to increase the strength and stiffness of the matrix. This reinforcement is usually in fibre form. Today, the most common man-made composites can be divided into three main groups:

Polymer Matrix Composites (PMC's) These are the most common and will the main area of discussion in this guide. Also known as FRP - Fibre Reinforced Polymers (or Plastics) - these materials use a polymer-based resin as the matrix, and a variety of fibres such as glass, carbon and aramid as the reinforcement.

Metal Matrix Composites (MMC's) - Increasingly found in the automotive industry, these materials use a metal such as aluminium as the matrix, and reinforce it with fibres such as silicon carbide.

Ceramic Matrix Composites (CMC's) - Used in very high temperature environments, these materials use a ceramic as the matrix and reinforce it with short fibres, or whiskers such as those made from silicon carbide and boron nitride.

Polymer Matrix Composites

Resin systems such as epoxies and polyesters have limited use for the manufacture of structures on their own, since their mechanical properties are not very high when compared to, for example, most metals. However, they have desirable properties, most notably their ability to be easily formed into complex shapes.

Materials such as glass, aramid and boron have extremely high tensile and compressive strength but in 'solid form' these properties are not readily apparent. This is due to the fact that when stressed, random surface flaws will cause each material to crack and fail well

below its theoretical 'breaking point'. To overcome this problem, the material is produced in fibre form, so that, although the same number of random flaws will occur, they will be restricted to a small number of fibres with the remainder exhibiting the material's theoretical strength. Therefore a bundle of fibres will reflect more accurately the optimum performance of the material. However, fibres alone can only exhibit tensile properties along the fibre's length, in the same way as fibres in a rope.

It is when the resin systems are combined with reinforcing fibres such as glass, carbon and aramid, that exceptional properties can be obtained. The resin matrix spreads the load applied to the composite between each of the individual fibres and also protects the fibres from damage caused by abrasion and impact. High strengths and stiffness, ease of moulding complex shapes, high environmental resistance all coupled with low densities, make the resultant composite superior to metals for many applications.

Since Polymer Matrix Composites combine a resin system and reinforcing fibres, the properties of the resulting composite material will combine something of the properties of the resin on its own with that of the fibres on their own.
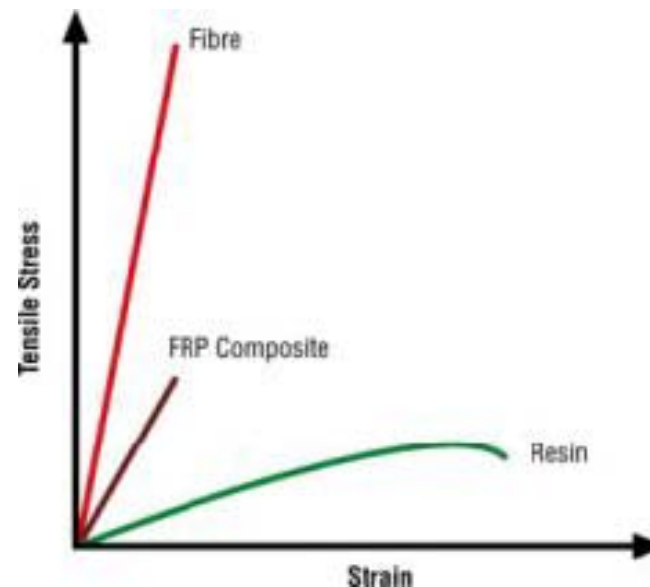
Overall, the properties of the composite are determined by:

i) The properties of the fibre ii) The properties of the resin iii) The ratio of fibre to resin in the composite (Fibre Volume Fraction)   iv) The geometry and orientation of the fibres in the composite

The first two will be dealt with in more detail later. The ratio of the fibre to resin derives largely from the manufacturing process used to combine resin with fibre, as will be described in the section on manufacturing processes. However, it is also influenced by the type of resin system used, and the form in which the fibres are incorporated. In general, since the mechanical properties of fibres are much higher than those of resins, the higher the fibre volume fraction the higher will be the mechanical properties of the resultant composite. In practice there are limits to this, since the fibres need to be fully coated in resin to be effective, and there will be optimum packing of the generally circular cross-section fibres. In addition, the manufacturing process used to combine fibre with resin leads to varying amounts of imperfections and air inclusions. Typically, with a common hand lay-up process as widely used in the boat-building industry, a limit for Fibre Volume Fraction is approximately 30-40%. With the higher quality, more sophisticated and precise processes used in the aerospace industry, Fibre Volume Fractions approaching 70% can be successfully obtained.

The geometry of the fibres in a composite is also important since fibres have their highest mechanical properties along their lengths, rather than across their widths. This leads to the highly anisotropic properties of composites, where, unlike metals, the mechanical properties of the composite are likely to be very different when tested in different directions. This means that it is very important when considering the use of composites to understand at the design stage, both the magnitude and the direction of the applied loads. When correctly accounted for, these anisotropic properties can be very advantageous since it is only necessary to put material where loads will be applied, and thus redundant material is avoided.

It is also important to note that with metals the properties of the materials are largely determined by the material supplier, and the person who fabricates the materials into a finished structure can do little to change those 'in-built' properties. However, a composite material is formed at the same time as the structure is itself being fabricated. This means that the person who is making the structure is creating the properties of the resultant composite material, and so the manufacturing processes they use have an unusually critical part

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to play in determining the performance of the resultant structure.

**Loading**

There are four main direct loads that any material in a structure has to withstand: tension, compression, shear and flexure.

Tension
The figure below shows a tensile load applied to a composite. The response of a composite to tensile loads is very dependent on the tensile stiffness and strength properties of the reinforcement fibres, since these are far higher than the resin system on its own.



**Compression**
The figure below shows a composite under a compressive load. Here, the adhesive and stiffness properties of the resin system are crucial, as it is the role of the resin to maintain the fibres as straight columns and to prevent them from buckling.
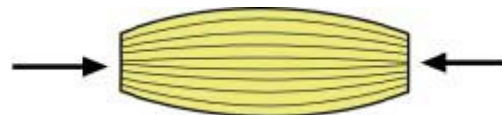
**PRO-LITE Technical Information**
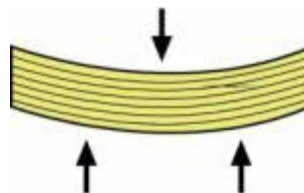*Guide to Composites*

**Shear**
The figure below shows a composite experiencing a shear load. This load is
trying to slide adjacent layers of fibres over each other. Under shear loads the resin plays the major role, transferring the stresses across the composite. For the composite to perform well under shear loads the resin element must not only exhibit good mechanical properties but must also have high adhesion to the reinforcement fibre. The interlaminar shear strength (ILSS) of a composite is often used to indicate this property in a multi-layer composite ('laminate').
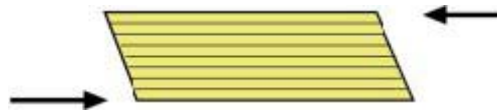
**Flexure**
Flexural loads are really a combination of tensile, compression and shear loads. When loaded as shown, the upper face is put into compression, the lower face into tension and the central portion of the laminate experiences shear.

**Comparison with Other Structural Materials**

Due to the factors described above, there is a very large range of mechanical properties that can be achieved with composite materials. Even when considering one fibre type on its own, the composite properties can vary by a factor of 10 with the range of fibre contents and orientations that are commonly achieved. The comparisons that follow therefore show a range of mechanical properties for the composite materials. The lowest properties for each material are associated with simple manufacturing processes and material forms (e.g. spray lay-up glass fibre), and the higher properties are associated with higher technology manufacture (e.g. autoclave moulding of unidirectional glass fibre prepreg), such as would be found in the aerospace industry.

For the other materials shown, a range of strength and stiffness (modulus) figures is also given to indicate the spread of properties associated with different alloys, for example.
The above figures clearly show the range of properties that different composite materials can display. These properties can best be summed up as high strengths and stiffnesses combined with low densities. It is these properties that give rise to the characteristic high strength and stiffness to weight ratios that make composite structures ideal for so many applications. This is particularly true of applications which involve movement, such as cars, trains and aircraft, since lighter structures in such applications play a significant part in making these applications more efficient.
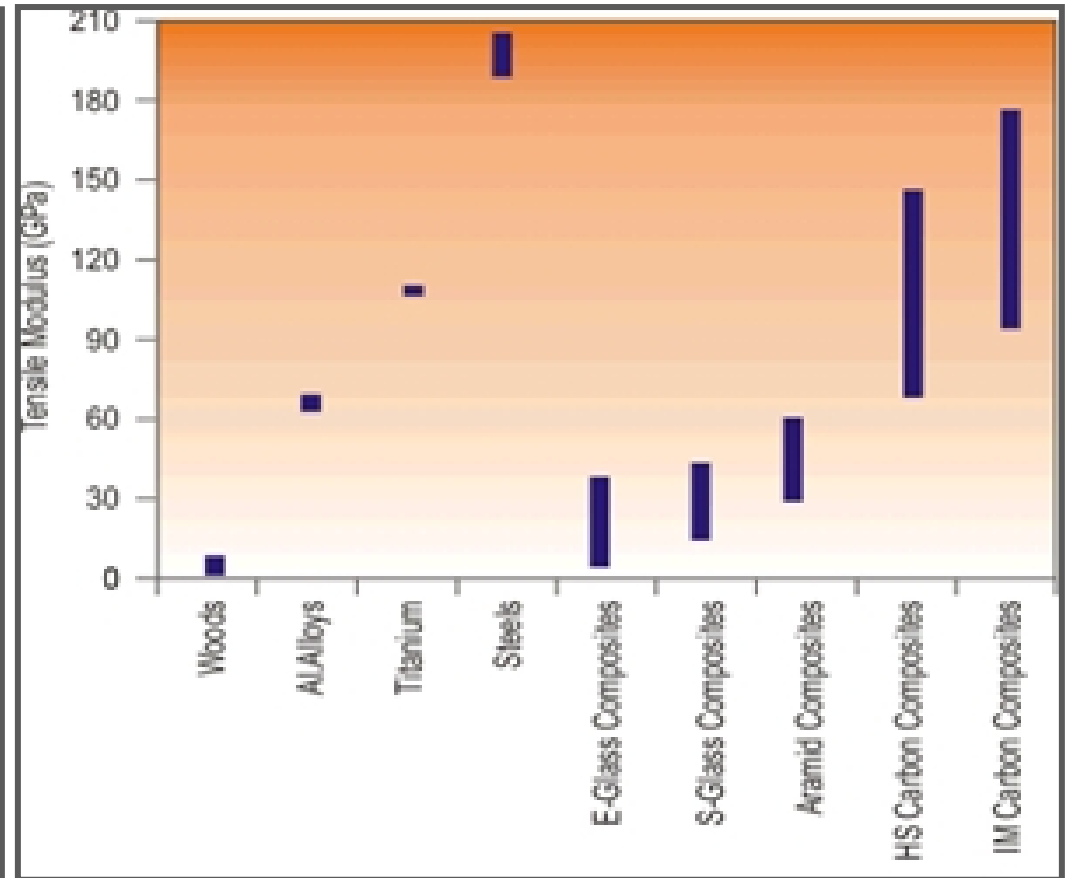
The strength and stiffness to weight ratio of composite materials can best be illustrated by the following graphs that plot 'specific' properties. These are simply the result of dividing the mechanical properties of a material by its density. Generally, the properties at the higher end of the ranges illustrated in the previous graphs are produced from the highest density variant of the material. The spread of specific properties shown in the following graphs takes this into account.

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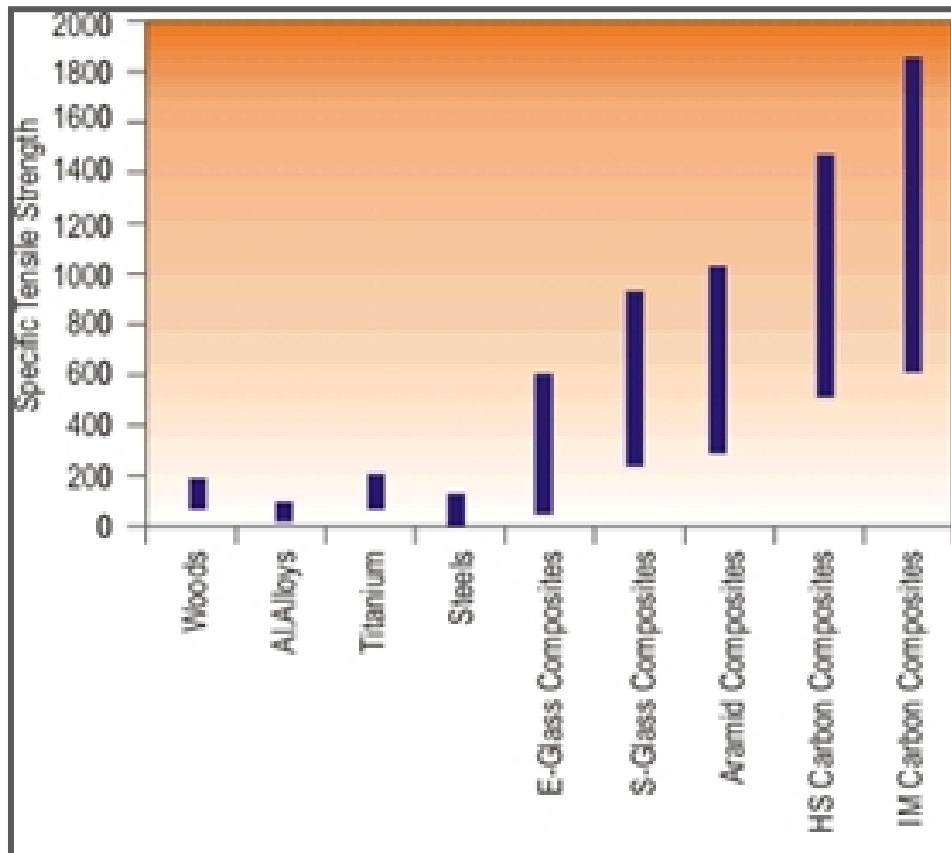## Guide to Composites
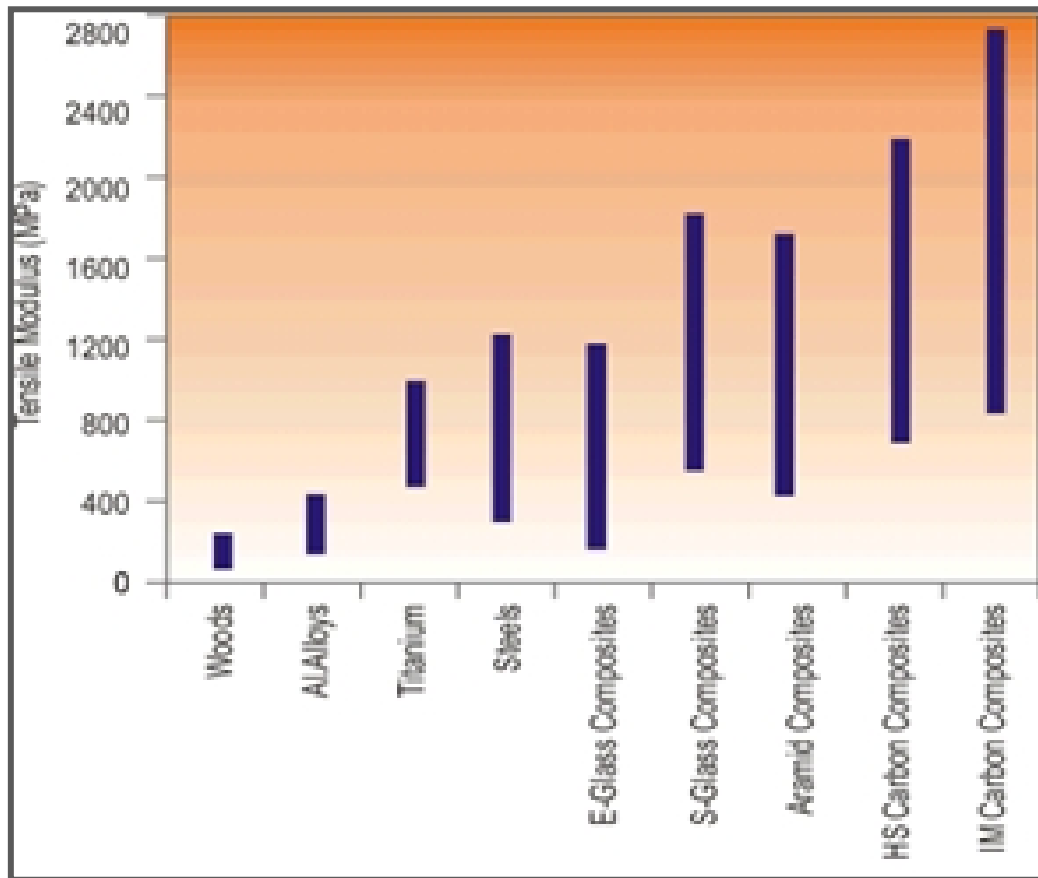


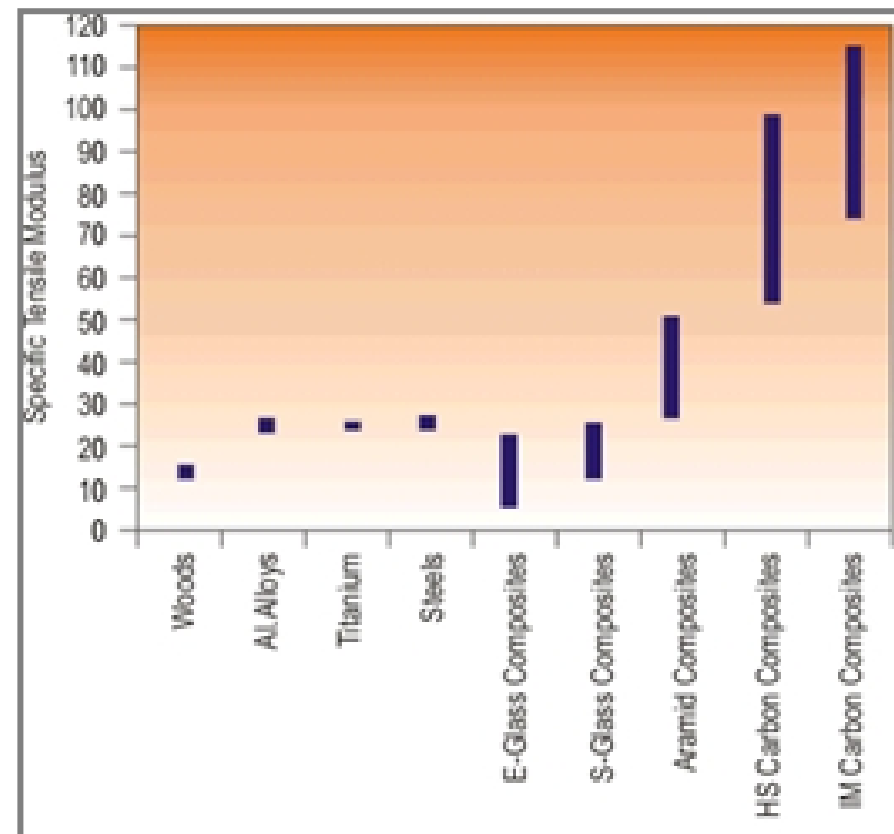**Tensile Strength of Common Structural Materials**

**Tensile Modulus of Common Structural Materials**

**Specific Tensile Strength of Common Structural Materials**



**Specific Tensile Modulus of Common Structural Materials**

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Further comparisons between laminates made from the different fibre types are given later in this guide in the section on 'Reinforcements'.

**Design Philosophy**

Imagine for a minute that composites do not exist and then consider what one would need from a material for any product, which has to work in an
aggressive environment such as the sea, for example. This material we seek needs to be easily shaped, it has to be happy in a hot or cold salty environment and ideally it needs little equipment to turn it from a raw material into a product. It would also help if the material is low in weight, relatively inexpensive and can be tailored with regards to strength and stiffness. And by the way, as we may be making a car or an expensive yacht, we would like the material to be any colour and glossy.

It is easy now to see why composites (fibre reinforced polymers or plastics) have become the mainstay material in the marine designers' drawer of materials.

However, a designer in the 1940's would now be extremely surprised to see the proliferation of fibres, resins, sandwich core materials and manufacturing processes, which abound in the composites industry. Since the first boat was made in glass reinforced polyester resin, now some sixty years ago, we have transgressed to high impact resistance aramid fibres (Kevlar) to high strength and stiffness carbon fibres using heat cured resin systems.

Not that this progress has been without problems. Most people know about blistering, no more so than the unfortunate boat owner whose boat is looking like a bad attack of mini-mumps. Also, because it is a material that requires little in the way of equipment, (a bucket and a brush) it has been so often used by the inexperienced, leading to poor products and unfortunately, problems. This gave the material a bad press on many occasions. But progress has been made and composites are now used widely in almost every application.

So let us take a look at the real benefits of composites and basically how they work.

Fibre reinforced polymers are what this says – a fibre of some sort held within a resin matrix. The most common fibres are glass, aramid (Kevlar) and carbon. The most common resins are polyester, vinyl ester and epoxy. Phenolic resins are also available and incidentally, the oldest type. They have better fire resistance, but because they are more difficult to use, they are not common within the marine industry.

The fibres may be random or directional. Because of the variation in strength and stiffness of the fibres, an immediate advantage can be seen – it is possible to 'engineer' the required strength or stiffness and the direction in which these properties are required.

Glass reinforced polyester is the cheapest and the most widely used composite. The basic manufacturing process is simple – a bucket of mixed resin (resin, accelerator and catalyst), a brush to apply the resin and some fibre. The more sophisticated manufacturing methods now include resin infusion, where the resin is drawn into a closed mould under vacuum. The mould already contains the fibre, in thicknesses and direction to suit the load or stiffness requirement. Whole boat hulls are now made by this method – one-shot manufacture.

At the more expensive end, and the higher property end also, we have carbon and aramid fibres. These are often in pre-impregnated (pre-preg) form that is the fibre has been coated with a heat curing resin. To prevent curing before use, the pre-preg is kept at low temperature.

It is this huge range of fibres, resins, manufacturing processes and supporting sandwich core materials, which give composites the real advantage over other materials. It is also the real advantage that is not always immediately appreciated by those new to the material.

A misconceived disadvantage is the apparent high cost of the higher strength and stiffness carbon and aramid fibres. This tends to make designers believe that the end product will be expensive when compared to glass reinforced polyester or even metals. But, carbon and aramid have much improved strength and stiffness over glass fibre. Aramid is also very tough. Furthermore, when the specific strength and stiffness (i.e. property divided by material density) is compared to metals, the composites are significantly better. More strength or stiffness per kilogram of material. Also less weight means less material. The higher material costs are then compensated.

If we now consider the fact that the moulded surface will be very smooth and fair (as opposed to look of welded aluminium alloy which

requires filling and fairing), the fact that the material will not degrade in the salty environment and there will be no painting required, we will equate costs to the more conventional metal structure. Despite therefore the apparent high raw material cost, we end up with a cost-effective product.

It is this philosophy of composite material selection that is used by the experienced designers to create many of the other well-designed and engineered products in composites. However, a small word of warning – if the materials are not fully understood and they are used by inexperienced designers, errors can be dramatic. When they are used correctly, composites can be shown to be the designers' path to the optimum structure and composites are very happy to be used in a wide variety of applications.

**Resin Systems**

Any resin system for use in a composite material will require the following properties:

1       Good mechanical properties
2       Good adhesive properties
3       Good toughness properties
4       Good resistance to environmental degradation

Mechanical Properties of the Resin System
The figure below shows the stress / strain curve for an 'ideal' resin system.
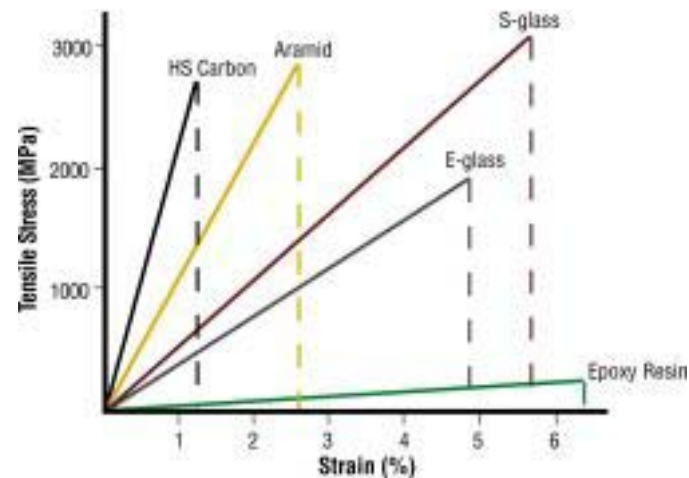The curve for this resin shows high ultimate strength, high stiffness (indicated by the initial gradient) and a high strain to failure. This means that the resin is initially stiff but at the same time will not suffer from brittle failure.
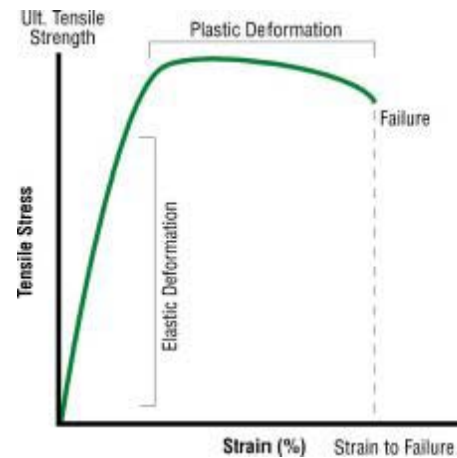
It should also be noted that when a composite is loaded in tension, for the full mechanical properties of the fibre component to be achieved, the resin must be able to deform to at least the same extent as the fibre. The figure below gives the strain to failure for E-glass, S-glass, aramid and high-strength grade carbon fibres on their own (i.e. not in a composite form). Here it can be seen that, for example, the S-glass fibre, with an elongation to break of 5.3%, will require a resin with an elongation to break of at least this value to achieve maximum tensile properties.

**Adhesive Properties of the Resin System**
High adhesion between resin and reinforcement fibres is necessary for any resin system. This will ensure that the loads are transferred efficiently and will prevent cracking or fibre / resin debonding when stressed.

Toughness Properties of the Resin System
Toughness is a measure of a material's resistance to crack propagation, but in a composite this can be hard to measure accurately. However, the stress / strain curve of the resin system on its own provides some indication of the material's toughness. Generally the more deformation the resin will accept before failure the tougher and more crack-resistant the material will be. Conversely, a resin system with a low strain to failure will tend to create a brittle composite, which cracks easily. It is important to match this property to the elongation of the fibre reinforcement.

Environmental Properties of the Resin System
Good resistance to the environment, water and other aggressive substances, together with an ability to withstand constant stress cycling, are properties essential to any resin system. These properties are particularly important for use in a marine environment.

Resin Types

The resins that are used in fibre reinforced composites can also be referred to as 'polymers'. All polymers exhibit an important common property in that they are composed of long chain-like molecules consisting of many simple repeating units. Man-made polymers are generally called 'synthetic resins' or simply 'resins'. Polymers can be classified under two types, 'thermoplastic' and 'thermosetting', according to the effect of heat on their properties.

Thermoplastics, like metals, soften with heating and eventually melt, hardening again with cooling. This process of crossing the softening or melting point on the temperature scale can be repeated as often as desired without any appreciable effect on the material properties in either state. Typical thermoplastics include nylon, polypropylene and ABS, and these can be reinforced, although usually only with short, chopped fibres such as glass.

Thermosetting materials, or 'thermosets', are formed from a chemical reaction in situ, where the resin and hardener or resin and catalyst are mixed and then undergo a non-reversible chemical reaction to form a hard, infusible product. In some thermosets, such as

Phenolic resins, volatile substances are produced as by-products (a 'condensation' reaction). Other thermosetting resins such as polyester and epoxy cure by mechanisms that do not produce any volatile by products and thus are much easier to process ('addition' reactions). Once cured, thermosets will not become liquid again if heated, although above a certain temperature their mechanical properties will change significantly. This temperature is known as the Glass Transition Temperature (Tg), and varies widely according to the particular resin system used, its degree of cure and whether it was mixed correctly. Above the Tg, the molecular structure of the thermoset changes from that of a rigid crystalline polymer to a more flexible, amorphous polymer. This change is reversible on cooling back below the Tg. Above the Tg properties such as resin modulus (stiffness) drop sharply, and as a result the compressive and shear strength of the composite does too. Other properties such as water resistance and colour stability also reduce markedly above the resin's Tg.

Although there are many different types of resin in use in the composite industry, the majority of structural parts are made with three main types, namely polyester, vinylester and epoxy.
Polyester Resins

Polyester resins are the most widely used resin systems, particularly in the marine industry. By far the majority of dinghies, yachts and workboats built in composites make use of this resin system.

Polyester resins such as these are of the 'unsaturated' type. Unsaturated polyester resin is a thermoset, capable of being cured from a liquid or solid state when subject to the right conditions. It is usual to refer to unsaturated polyester resins as 'polyester resins', or simply as 'polyesters'. There is a whole range of polyesters made from different acids, glycols and monomers, all having varying properties.

There are two principle types of polyester resin used as standard laminating systems in the composites industry. Orthophthalic polyester resin is the standard economic resin used by many people. Isophthalic polyester resin is now becoming the preferred material in industries such as marine where its superior water resistance is desirable.

The figure below shows the idealised chemical structure of typical polyester. Note the positions of the ester groups (CO - O - C) and the reactive sites ($C^* = C^*$) within the molecular chain.

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*denotes reactive sites

Ester groups

n = 3 to 6
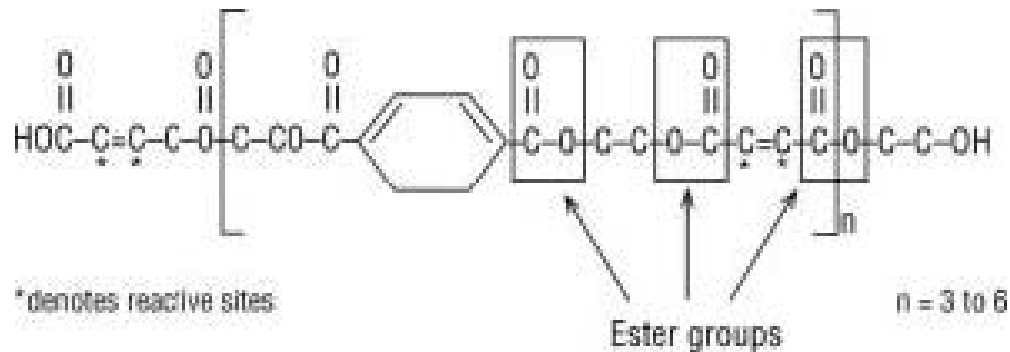
Most polyester resins are viscous, pale coloured liquids consisting of a solution of polyester in a monomer which is usually styrene. The addition of styrene in amounts of up to 50% helps to make the resin easier to handle by reducing its viscosity. The styrene also performs the vital function of enabling the resin to cure from a liquid to a solid by 'cross-linking' the molecular chains of the polyester, without the evolution of any by-products. These resins can therefore be moulded without the use of pressure and are called 'contact' or 'low pressure' resins. Polyester resins have a limited storage life as they will set or 'gel' on their own over a long period of time. Often small quantities of inhibitor are added during the resin manufacture to slow this gelling action.

For use in moulding, a polyester resin requires the addition of several ancillary products. These products are generally:

Catalyst Accelerator Additives: Thixotropic; Pigment; Filler; Chemical/fire resistance

A manufacturer may supply the resin in its basic form or with any of the above additives already included. Resins can be formulated to the moulder's requirements ready simply for the addition of the catalyst prior to moulding. As has been mentioned, given enough time an unsaturated polyester resin will set by itself. This rate of polymerisation is too slow for practical purposes and therefore catalysts and accelerators are used to achieve the polymerisation of the resin within a practical time period. Catalysts are added to the resin system shortly before use to initiate the polymerisation reaction. The catalyst does not take part in the chemical reaction but simply activates the process. An accelerator is added to the catalysed resin to enable the reaction to proceed at workshop temperature and/or

at a greater rate. Since accelerators have little influence on the resin in the absence of a catalyst, they are sometimes added to the resin by the polyester manufacturer to create a 'preaccelerated' resin.

The molecular chains of the polyester can be represented as follows, where 'B' indicates the reactive sites in the molecule.
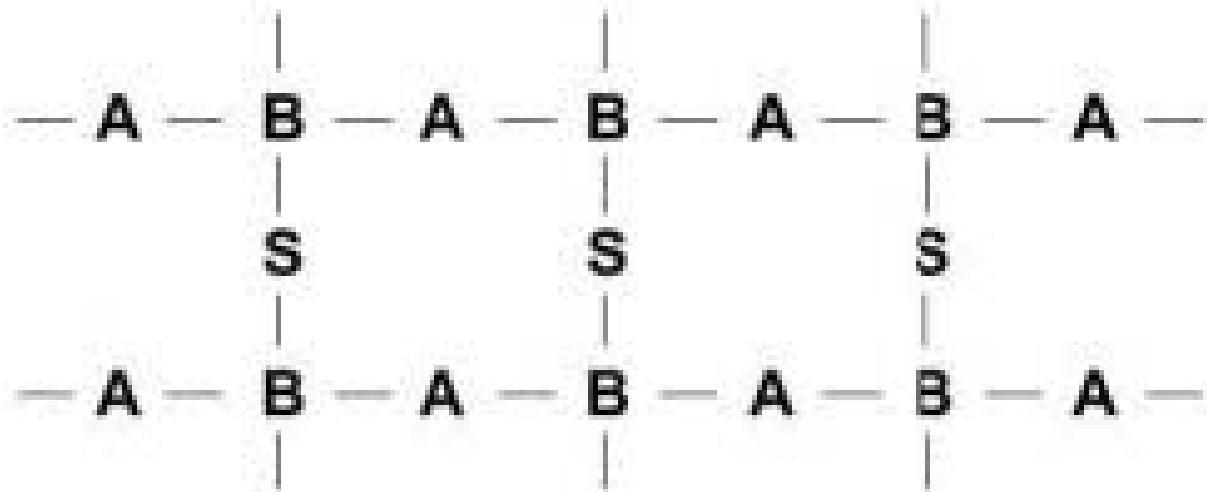
$$-A-B-A-B-A-B-A$$
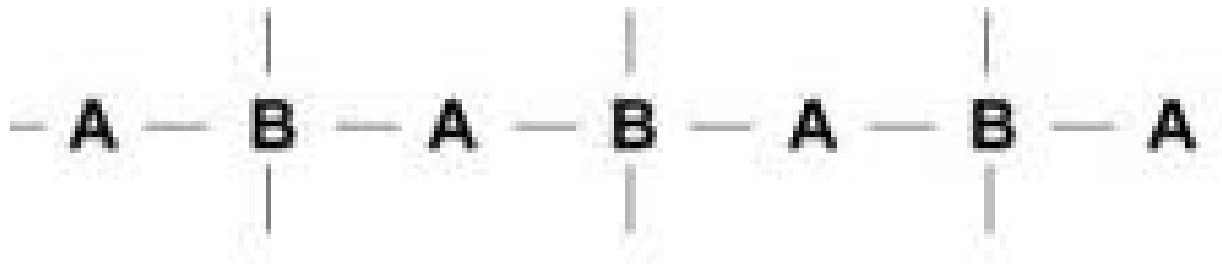
**Schematic Representation of Polyester Resin (Uncured)**

With the addition of styrene 'S ', and in the presence of a catalyst, the styrene cross-links the polymer chains at each of the reactive sites to form a highly complex three-dimensional network as follows:

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$$-A-B-A-B-A-B-A-$$



Schematic Representation of Polyester Resin (Cured)

The polyester resin is then said to be 'cured'. It is now a chemically resistant (and usually) hard solid. The cross-linking or curing process is called 'polymerisation'. It is a non-reversible chemical reaction. The 'side-by-side' nature of this cross-linking of the molecular chains tends to means that polyester laminates suffer from brittleness when shock loadings are applied.

Great care is needed in the preparation of the resin mix prior to moulding. The resin and any additives must be carefully stirred to disperse all the components evenly before the catalyst is added. This stirring must be thorough and careful as any air introduced into the resin mix affects the quality of the final moulding. This is especially so when laminating with layers of reinforcing materials as air bubbles can be formed within the resultant laminate which can weaken the structure. It is also important to add the accelerator and catalyst in carefully measured amounts to control the polymerisation reaction to give the best material properties. Too much catalyst

will cause too rapid a gelation time, whereas too little catalyst will result in under-cure.

Colouring of the resin mix can be carried out with pigments. The choice of a suitable pigment material, even though only added at about 3% resin weight, must be carefully considered as it is easy to affect the curing reaction and degrade the final laminate by use of unsuitable pigments.

Filler materials are used extensively with polyester resins for a variety of reasons including:

To reduce the cost of the moulding To facilitate the moulding process To impart specific properties to the moulding

Fillers are often added in quantities up to 50% of the resin weight although such addition levels will affect the flexural and tensile strength of the laminate. The use of fillers can be beneficial in the laminating or casting of thick components where otherwise considerable exothermic heating can occur. Addition of certain fillers can also contribute to increasing the fire-resistance of the laminate.

**Vinylester Resins**

Vinylester resins are similar in their molecular structure to polyesters, but differ primarily in the location of their reactive sites, these being positioned only at the ends of the molecular chains. As the whole length of the molecular chain is available to absorb shock loadings this makes vinylester resins tougher and more resilient than polyesters. The vinylester molecule also features fewer ester groups. These ester groups are susceptible to water degradation by hydrolysis which means that vinylesters exhibit better resistance to water and many other chemicals than their polyester counterparts, and are frequently found in applications such as pipelines and chemical storage tanks.

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The figure below shows the idealised chemical structure of a typical vinylester. Note the positions of the ester groups and the reactive sites (C* = C*) within the molecular chain.



*denotes reactive sites

Ester groups

$n = 1$ to $2$
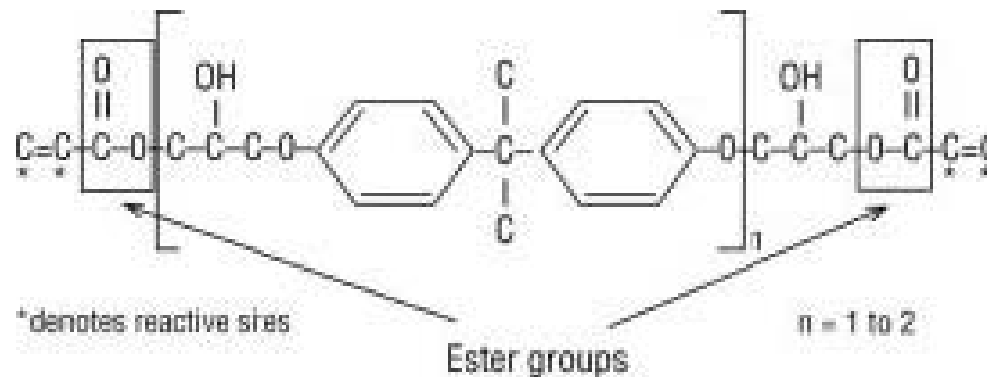
The molecular chains of vinylester, represented below, can be compared to the schematic representation of polyester shown previously where the difference in the location of the reactive sites can be clearly seen: With the reduced number of ester groups in a vinylester when compared to a polyester, the resin is less prone to damage by hydrolysis. The material is therefore sometimes used as a barrier or 'skin' coat for a polyester laminate that is to be immersed in water, such as in a boat hull. The cured molecular structure of the vinylester also means that it tends to be tougher than a polyester, although to really achieve these properties the resin usually needs to have an elevated temperature post cure.

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```
     |                                           |
  —B—A—A—A—A—A—B—
     |                                           |
```

Schematic Representation of Vinylester Resin (Uncured)

```
        |                         |
     —B—A—A—A—A—A—B—
        |                         |
        S                         S
        |                         |
  —B—A—A—A—A—A—B—B—A—A—A—A—A—B—
        |                         |                              |
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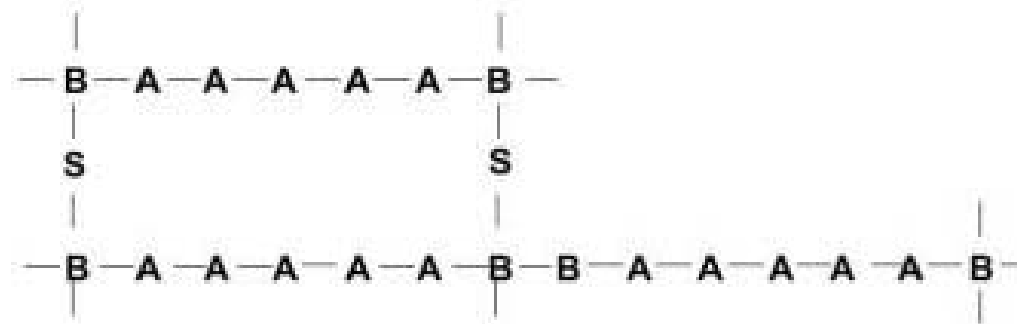
Schematic Representation of Vinylester Resin (Cured)

Epoxy Resins

The large family of epoxy resins represent some of the highest performance resins of those available at this time. Epoxies generally out-perform most other resin types in terms of mechanical properties and resistance to environmental degradation, which leads to their almost exclusive use in aircraft components. As a laminating resin their increased adhesive properties and resistance to water degradation make these resins ideal for use in applications such as boat building. Here epoxies are widely used as a primary construction material for high-performance boats or as a secondary application to sheath a hull or replace water-degraded polyester resins and gel coats.

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The term 'epoxy' refers to a chemical group consisting of an oxygen atom bonded to two carbon atoms that are already bonded in some way. The simplest epoxy is a three-member ring structure known by the term 'alphaepoxy' or '1,2-epoxy'. The idealised chemical structure is shown in the figure below and is the most easily identified characteristic of any more complex epoxy molecule.

$$CH_2 - CH -$$
$$\diagdown \diagup$$
$$O$$

**Idealised Chemical Structure of a Simple Epoxy (Ethylene Oxide)**

Usually identifiable by their characteristic amber or brown colouring, epoxy resins have a number of useful properties. Both the liquid resin and the curing agents form low viscosity easily processed systems. Epoxy resins are easily and quickly cured at any temperature from 5°C to 150°C, depending on the choice of curing agent. One of the most advantageous properties of epoxies is their low shrinkage during cure, which minimises fabric 'print-through' and internal stresses. High adhesive strength and mechanical properties are enhanced by a high degree of electrical insulation and good chemical resistance. Epoxies find uses as adhesives, caulking compounds, casting compounds, sealants, varnishes and paints, as well as laminating resins for a variety of industrial applications.

Epoxy resins are formed from a long chain molecular structure similar to vinylester with reactive sites at either end. In the epoxy resin, however, these reactive sites are formed by epoxy groups instead of ester groups. The absence of ester groups means that the epoxy resin has particularly good water resistance. The epoxy molecule also contains two ring groups at its centre which are able to absorb both mechanical and thermal stresses better than linear groups and therefore give the epoxy resin very good stiffness, toughness and heat resistant properties.

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The figure below shows the idealised chemical structure of a typical epoxy. Note the absence of the ester groups within the molecular chain.
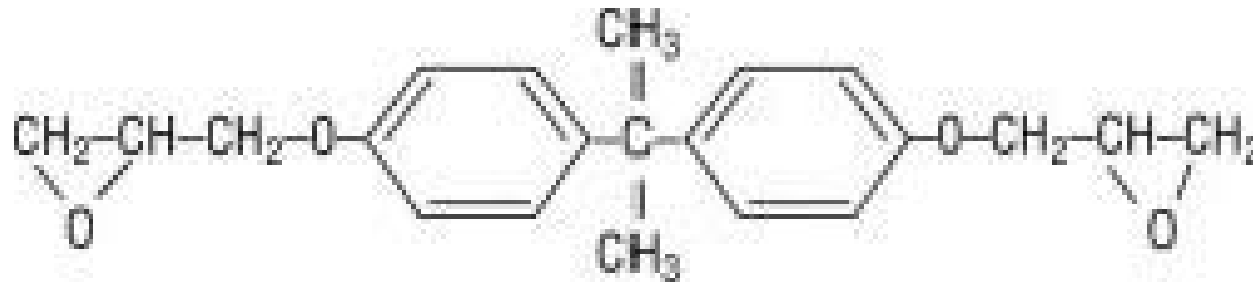


poxies differ from polyester resins in that they are cured by a 'hardener' rather than a catalyst. The hardener, often an amine, is used to cure the epoxy by an 'addition reaction' where both materials take place in the chemical reaction. The chemistry of this reaction means that there are usually two epoxy sites binding to each amine site. This forms a complex three-dimensional molecular structure.

Since the amine molecules 'co-react' with the epoxy molecules in a fixed ratio, it is essential that the correct mix ratio is obtained between resin and hardener to ensure that a complete reaction takes place. If amine and epoxy are not mixed in the correct ratios, unreacted resin or hardener will remain within the matrix which will affect the final properties after cure. To assist with the accurate mixing of the resin and hardener, manufacturers usually formulate the components to give a simple mix ratio which is easily achieved by measuring out by weight or volume.

Gelation, Curing and Post-Curing

On addition of the catalyst or hardener a resin will begin to become more viscous until it reaches a state when it is no longer a liquid and has lost its ability to flow. This is the 'gel point'. The resin will continue to harden after it has gelled, until, at some time later, it has obtained its full hardness and properties. This reaction itself is accompanied by the generation of exothermic heat, which, in turn, speeds the reaction. The whole process is known as the 'curing' of the resin. The speed of cure is controlled by the amount of accelerator in a polyester or vinylester resin and by varying the type, not the quantity, of hardener in an epoxy resin. Generally polyester resins produce a more severe exotherm and a faster development of initial mechanical properties than epoxies of a similar

working time.

With both resin types, however, it is possible to accelerate the cure by the application of heat, so that the higher the temperature the faster the final hardening will occur. This can be most useful when the cure would otherwise take several hours or even days at room temperature. A quick rule of thumb for the accelerating effect of heat on a resin is that a 10°C increase in temperature will roughly double the reaction rate. Therefore if a resin gels in a laminate in 25 minutes at 20°C it will gel in about 12 minutes at 30°C, providing no extra exotherm occurs. Curing at elevated temperatures has the added advantage that it actually increases the end mechanical properties of the material, and many resin systems will not reach their ultimate mechanical properties unless the resin is given this 'post cure'. The post cure involves increasing the laminate temperature after the initial room temperature cure, which increases the amount of cross-linking of the molecules that can take place. To some degree this post cure will occur naturally at warm room temperatures, but higher properties and shorter post cure times will be obtained if elevated temperatures are used. This is particularly true of the material's softening point or Glass Transition Temperature (Tg), which, up to a point, increases with increasing post cure temperature.

Adhesive Properties

It has already been discussed how the adhesive properties of the resin system are important in realising the full mechanical properties of a composite. The adhesion of the resin matrix to the fibre reinforcement or to a core material in a sandwich construction are important. Polyester resins generally have the lowest adhesive properties of the three systems described here. Vinylester resin shows improved adhesive properties over polyester but epoxy systems offer the best performance of all, and are therefore frequently found in many high-strength adhesives. This is due to their chemical composition and the presence of polar hydroxyl and ether groups. As epoxies cure with low shrinkage the various surface contacts set up between the liquid resin and the adherends are not disturbed during the cure. The adhesive properties of epoxy are especially useful in the construction of honeycomb-cored laminates where the small bonding surface area means that maximum adhesion is required.

The strength of the bond between resin and fibre is not solely dependent on the adhesive properties of the resin system but is also affected by the surface coating on the reinforcement fibres. This 'sizing' is discussed later under 'Reinforcements'
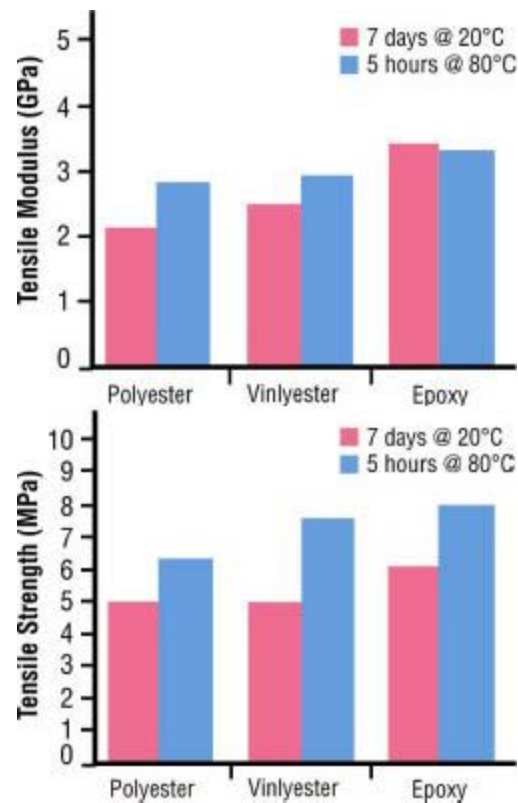
Mechanical Properties

Two important mechanical properties of any resin system are its tensile strength and stiffness. The two figures below show results for

tests carried out on commercially available polyester, vinylester and epoxy resin systems cured at 20°C and 80°C.



After a cure period of seven days at room temperature it can be seen that a typical epoxy will have higher properties than a typical polyester and vinylester for both strength and stiffness. The beneficial effect of a post cure at 80°C for five hours can also be seen.

Also of importance to the composite designer and builder is the amount of shrinkage that occurs in a resin during and following its
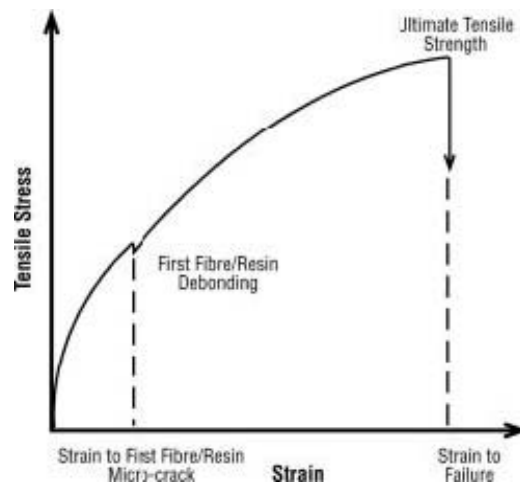
cure period. Shrinkage is due to the resin molecules rearranging and re-orientating themselves in the liquid and semi-gelled phase. Polyester and vinylesters require considerable molecular rearrangement to reach their cured state and can show shrinkage of up to 8%. The different nature of the epoxy reaction, however, leads to very little rearrangement and with no volatile by-products being evolved; typical shrinkage of an epoxy is reduced to around 2%. The absence of shrinkage is, in part, responsible for the improved mechanical properties of epoxies over polyester, as shrinkage is associated with built-in stresses that can weaken the material. Furthermore, shrinkage through the thickness of a laminate leads to 'print-through' of the pattern of the reinforcing fibres, a cosmetic defect that is difficult and expensive to eliminate

Micro-Cracking

The strength of a laminate is usually thought of in terms of how much load it can withstand before it suffers complete failure. This ultimate or breaking strength is the point it which the resin exhibits catastrophic breakdown and the fibre reinforcements break. However, before this ultimate strength is achieved, the laminate will reach a stress level where the resin will begin to crack away from those fibre reinforcements not aligned with the applied load, and these cracks will spread through the resin matrix. This is known as 'transverse micro-cracking' and, although the laminate has not completely failed at this point, the breakdown process has commenced. Consequently, engineers who want a long-lasting structure must ensure that their laminates do not exceed this point under regular service loads.

The strain that a laminate can reach before micro cracking depends strongly on the toughness and adhesive properties of the resin system. For brittle resin systems, such as most polyesters, this point occurs a long way before laminate failure, and so severely limits the strains to which such laminates can be subjected. As an example, recent tests have shown that for a polyester/glass woven roving laminate, micro-cracking typically occurs at about 0.2% strain with ultimate failure not occurring until 2.0% strain. This equates to a usable strength of only 10% of the ultimate strength.

As the ultimate strength of a laminate in tension is governed by the strength of the fibres, these resin micro-cracks do not immediately reduce the ultimate properties of the laminate. However, in an environment such as water or moist air, the micro-cracked laminate will absorb considerably more water than an uncracked laminate. This will then lead to an increase in weight, moisture attack on the resin and fibre sizing agents, loss of stiffness and, with time, an eventual drop in ultimate properties.

Increased resin/fibre adhesion is generally derived from both the resin's chemistry and its compatibility with the chemical surface treatments applied to fibres. Here the well-known adhesive properties of epoxy help laminates achieve higher micro cracking strains. As has been mentioned previously, resin toughness can be hard to measure, but is broadly indicated by its ultimate strain to failure.

Fatigue Resistance

Generally composites show excellent fatigue resistance when compared with most metals. However, since fatigue failure tends to result from the gradual accumulation of small amounts of damage, the fatigue behaviour of any composite will be influenced by the toughness of the resin, its resistance to micro cracking, and the quantity of voids and other defects which occur during manufacture. As a result, epoxy-based laminates tend to show very good fatigue resistance when compared with both polyester and vinylester, this being one of the main reasons for their use in aircraft structures.

Degradation from Water Ingress

An important property of any resin, particularly in a marine environment, is its ability to withstand degradation from water ingress. All resins will absorb some moisture, adding to a laminate's weight, but what is more significant is how the absorbed water affects the

resin and resin/fibre bond in a laminate, leading to a gradual and long-term loss in mechanical properties. Both polyester and vinylester resins are prone to water degradation due to the presence of hydrolysable ester groups in their molecular structures. As a result, a thin polyester laminate can be expected to retain only 65% of its inter-laminar shear strength after immersion in water for a period of one year, whereas an epoxy laminate immersed for the same period will retain around 90%.
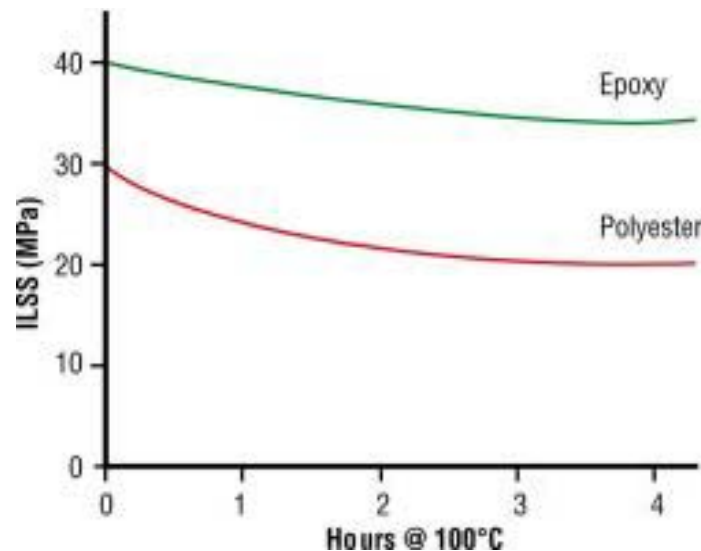


The figure above demonstrates the effects of water on an epoxy and polyester woven glass laminate, which have been subjected to a water, soak at 100°C. This elevated temperature soaking gives accelerated degradation properties for the immersed laminate.

Osmosis

All laminates in a marine environment will permit very low quantities of water to pass through them in vapour form. As this water passes through, it reacts with any hydrolysable components inside the laminate to form tiny cells of concentrated solution. Under the osmotic cycle, more water is then drawn through the semi-permeable membrane of the laminate to attempt to dilute this solution. This

water increases the fluid pressure in the cell to as much as 700 psi. Eventually the pressure distorts or bursts the laminate or gelcoat, and can lead to a characteristic 'chicken-pox' surface. Hydrolysable components in a laminate can include dirt and debris that have become trapped during fabrication, but can also include the ester linkages in a cured polyester, and to a lesser extent, vinylester.

Use of resin rich layers next to the gel coat are essential with polyester resins to minimise this type of degradation, but often the only cure once the process has started is the replacement of the affected material. To prevent the onset of osmosis from the start, it is necessary to use a resin which has both a low water transmission rate and a high resistance to attack by water. When used with reinforcements with similarly resistant surface treatment and laminated to a very high standard, blistering can then be virtually eliminated. A polymer chain having an epoxy backbone is substantially better than many other resin systems at resisting the effects of water. Such systems have been shown to confer excellent chemical and water resistance, low water transmission rate and very good mechanical properties to the polymer.

Resin Comparison Summary

The polyesters, vinylesters and epoxies discussed here probably account for some 90% of all thermosetting resin systems used in structural composites. In summary the main advantages and disadvantages of each of these types are:

**Polyesters**

**Advantages:**
Easy to use
Lowest cost of resins available (£1-2/kg)

**Disadvantages:**
Only moderate mechanical properties
High styrene emissions in open moulds
High cure shrinkage Limited range of working times

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**Vinylesters**

Advantages: Very high chemical/environmental resistance Higher mechanical properties than polyesters

Disadvantages: Post cure generally required for high properties High styrene content Higher cost than polyesters (£2-4/kg) High cure shrinkage

**Epoxies**

Advantages: High mechanical and thermal properties High water resistance Long working times available
Temperature resistance can be up to 140°C wet / 220°C dry
Low cure shrinkage

**Disadvantages:**
More expensive than vinylesters (£3-15/kg)
Critical mixing
Corrosive handling

**Other Resin Systems used in Composites**

Besides polyesters, vinylesters and epoxies there are a number of other thermosetting resin systems that are used where their unique properties are required:

**Phenolics**
Primarily used where high fire-resistance is required, phenolics also retain their properties well at elevated temperatures. For room-temperature curing materials, corrosive acids are used which leads to unpleasant handling. The condensation nature of their curing process tends to lead to the inclusion of many voids and surface defects, and the resins tend to be brittle and do not have

high mechanical properties. Typical costs: £2-4/kg.

**Cyanate Esters**
Primarily used in the aerospace industry. The material's excellent dielectric properties make it very suitable for use with low dielectric fibres such as quartz for the manufacture of radomes. The material also has temperature stability up to around 200°C wet. Typical costs: £40/kg.

**Polyurethane's**
High toughness materials sometimes hybridised with other resins, due to relatively low laminate mechanical properties in compression. Uses harmful isocyanates as curing agent. Typical costs: £2-8/kg

**Bismaleimides (BMI)**
Primarily used in aircraft composites where operation at higher temperatures (230°C wet/250°C dry) is required. e.g. engine inlets, high-speed aircraft flight surfaces. Typical costs: >£50/kg.

**Polyimides**
Used where operation at higher temperatures than bismaleimides can stand is required (use up to 250°C wet/300°C dry). Typical applications include missile and aero-engine components. Extremely expensive resin (>£80/kg), which uses toxic raw materials in its manufacture. Polyimides also tend to be hard to process due to their condensation reaction emitting water during cure, and are relatively brittle when cured. PMR15 and LaRC160 are two of the most commonly used Polyimides for composites.

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Resin systems such as BMI's and Polyimides are typically used for high temperature aircraft parts.

**Release Agents**

Whether release agents are incorporated into the resin matrix or applied externally to the mould surface, correct selection can optimise not only cycle time, but also consistency of surface finish maintaining detail, minimising post mould operation prior to painting or bonding, even helping with fibre wet out.

To work well a release agent must fit within the scope of the overall process and be cost effective. Application must be simple with clearly defined steps, drying times should be short and cure time if any must not delay the process. The product must not contain any ingredients which will affect the final product properties or post mould treatments. Finally release must be smooth and clean with no pre-release prior to cure.

Qualification costs are high and suppliers should ensure their products and chemical pre-cursors are available long term, anticipating changes in legislation and using safe ingredients whenever possible.

**Internal Mould Release Agent (IMR)**

A product dissolved in the resin mix, which is highly soluble in the carrier solvent i.e. styrene. During cure the product drops out of solution and migrates to the surface due to volumetric shrinkage, pressure and temperature.

The following criteria are desirable:

Total solubility in the system Minimal effect on cure Minimal effect on colour No negative and preferably positive influence on physical properties   No silicone, non-stearate and no natural waxes which would adversely affect painting or bonding adhesives A consistent clean release with no build-up or mould fouling caused by deposits Measurable reduction in cycle time

Using an internal requires careful introduction. Each release agent application is not an individual event, it is part of a long running sequence. Each moulding relies as much on previous moulding as it does on the IMR it deposits during its own cycle. (This is a continuous process in pultrusion).
IMR's are more commonly associated with mechanised processes, but can assist in difficult highly detailed hand lay-up mouldings.

One major advantage is consistency and in high volume production, externally applied release systems rely solely on operator skill, not always meeting the requirements of the designer or formulating chemist.

**External Mould Release Agent**

Externals are applied to the mould surface and as such rely on care and attention during application to ensure successful release.

The following criteria are desirable:

Easy application with no complex instructions No harmful solvents Good wetting of all surfaces i.e. should not shrink back when applied Surface tension should be correct for gel coat application Quick drying Easy to polish Transfer to moulding should be easily removed, (preferably with water) Predictable multiple release

Wax release agents are used typically in low volume manufacturing where products are individual and cycle times are not critical, semi-permanents are used in high volume applications.

The semi-permanent system is ideal for all contact mouldings, large or small, giving exceptional surface finish with low maintenance, but without critical application procedures. In high production processes such as RTM, the use of semi-permanent systems maximises cycle times because of their consistent release properties.

**Gelcoats and Barrier Layers**

As the fibre reinforced plastics industry has grown and become more sophisticated, so has the demand for protective coatings and barrier layers. The first materials marketed as protective coatings for composites were preformulated, compounded products called gelcoats, which are used as 'inmould' coatings. Today, this has become a highly specialised business involving colour technology, air release requirements, thick film build-up and rapid cure times to produce in-mould finished surfaces with excellent gloss, colour and surface integrity retention after years of environmental exposure. The new gelcoats provide both excellent protection for structural laminates as well as the levels of gloss and colour retention demanded by the motor industry.

In the marine industry problems resulting from osmosis, in the form of surface blistering, prompted the development of fibre reinforced barrier or skin coats to be used immediately behind gelcoats in the form of match performance systems designed to minimise water pick-up and the possibilities of blister formation.

Generally, in pipe, tank and chemical plant component manufacture it is essential to protect the structural laminate from the environment to be contained. Often this can be achieved with a fibre reinforced barrier coat 2 to 3mm thick manufactured using surface tissue, light weight fibre mats and cloths using a suitable chemically resistant resin. In such cases gelcoats are not used because a pure resin without additives provides a greater level of chemical resistance. Hence, the resin-rich surface tissue provides the initial chemical resistant surface and will contain around 95% resin by weight, which is further supported by a resin-rich, structural laminate barrier layer before the final GRP structure is manufactured.

In this Section the need and performance of specialised protection systems for composite materials will be discussed with reference to the various market requirements.

**Introduction to Coatings**

Many applications where reinforced plastics are used are structural but, generally, there is a need for an aesthetic, protective surface finish with low maintenance requirements. The most common finish used on glass fibre reinforced polyester resin (GRP) is gelcoat. Apart from affording protection to the structural laminate gelcoats improve durability, reduce fibre pattern on the surface and provide a finished surface from the mould, thereby eliminating the need to paint.

In the early days of the GRP industry it was not uncommon to mix a thixotrope with the laminating resin for use as a resin-rich surface but demands from the fabricator for reduced air entrapment and coloured finishes gradually lead to the availability of formulated gelcoat systems, generally, compounded by resin producers. It is not surprising that the early use of gelcoats was mainly in the marine market, since this was the first major industry to use GRP on a large scale for structural component construction.

Not all resin system can be used successfully in environments where resistance to water is essential. Hence, the development of isophthalic acid based resin systems with improved water resistance and low water absorption, compared to orthopthalic acid based systems, resulted in a range of gelcoats becoming available for the GRP market. Water absorption of resins and its effect on the durability of GRP has been the subject of many publications and a summary for orthophthalic acid based versus isophthalic acid based resins was presented by Clarke and Norwood in 1979.

Over the years a range of gelcoats has been developed to meet demands other that simply water resistance, for example, for mould making, for brush application, for spray application and to provide fire resistance. In addition, gelcoats can be supplied coloured to a standard colour range or matched to meet specific customer needs.

It is often important to protect a structural laminate with more than just a gelcoat alone; in the 1970's blister formation in GRP boats and swimming pools resulted in investigations to find the means to reduce or even eliminate the problem. The mechanism of blister formation was well established over 25 years ago but solutions were not then, readily available. At first an important lesson to be learnt was that the problem was not simply concerned with the resin alone but was influenced by glass binder type, workshop conditions, workshop practices, the level of cure and the surface condition after delays in laminating. From this understanding, research resulted in the matched performance skin coat for boats where the gelcoat and laminate system in the first one or two layers of reinforcement were matched to give similar water resistant and mechanical performance characteristics. In fact, accelerated testing showed that GRP systems could be produced, cost effectively, that were unlikely to blister during the life-time use of many components and certainly not

within the first 20 years or so.

The storage of chemicals is demanding for any material but GRP is resistant to many environments and is often chosen as the material of construction in preference to more traditional materials. However, some chemicals are particularly corrosive to glass fibre reinforcement, via a strain corrosion mechanism and, hence, the structural laminate requires protection by a barrier layer. Such layers are considered non-structural and are often manufactured from a different resin to that used for constructing the structural laminate. The barrier layer is often constructed using surface tissue, which can be based on glass or polymer fibres depending upon the environment to be continued, supported by several layers of laminate to a thickness of a least 3mm.

Solvents are very corrosive to many polyester resins and careful consideration must be given to the choice of resin for the barrier layer for the storage of solvents and fuels. With the correct choice of resin and barrier layer construction, underground fuel storage tanks have been shown to survive, in perfect condition, for in excess of 25 years.

**Gelcoats**

**Traditional System**s

Even though gelcoats were not used in the early days of the GRP industry the need for resin-rich surfaces to protect structural laminates was an established practice :

to improve the durability of components to protect the laminate from the environment to reduce fibre pattern to provide a smooth aesthetic finish to eliminate the need for painting

In order to reduce drainage, introduce colour and improve air-release, fabricators used additives in the resin to ensure the resin-rich surface layer was of appropriate thickness with sufficient integrity to provide the desired finish. Of course, manufacturing a coating in the moulding shop resulted in variability from batch to batch and gradually the resin manufacturers introduced a range of formulated gelcoats offering the following advantages:

correct dispersion of thixotropes, surfactants, pigments and accelerators    excellent air release characteristics precise colour matching

the need to have only to add one component, the catalyst, in the moulding shop.

Hence, the fabricator now had access to quality surface coatings for laminates of consistent quality and whilst there was a price to pay for such systems, it was more than off-set by the savings made in labour and wastage, by attempting to manufacture complex coatings in the workshop.

Gelcoats are available in brush and spray versions and are best put down at a thickness of 0.5mm (approximately 500 g/m²). If they are too thin, poor cure occurs and fibre pattern will result. If they are too thick, crazing and cracking can occur and the laminate will be more susceptible to reverse impact, star cracking damage.

A variety of base resins can be used to manufacture gelcoats with the most common based on isophthalic acid type resins. The choice of isophthalic acid based resins rather than orthophthalic acid based resins results from the superior water resistance of isophthalic acid based resins, their superior blister resistance and their superior toughness as indicated by their excellent tensile elongation to break compared to orthophthalic acid based resins.

**Recent Gelcoat Developments**

Over the years the need for improved gloss and colour retention in gelcoats have been recognised and the development of improved base resins with improved UV resistant additives has resulted in gelcoats that can be weathered under severe conditions without loss of gloss or colour, discernible to the naked eye.

As well as the demand for improved durability, there is a demand for reduced styrene emission gelcoats and now low styrene content, low styrene emission gelcoats are available in both brush and spray forms. Such systems have been well tested and proven. They are blister resistant and are approved by the major marine approval authorities, such as Lloyds Register of Shipping and det Norske Veritas.

**Blister Resistance**

The importance of the matched performance system which requires matching performance characteristics of the gelcoat and the 'skin

coat' immediately behind it to ensure optimum water absorption characteristics and hence, reduce the possibility of blister formation, has been proven over the past 15 -20 years by boat builders in the UK.

The use of isophthalic acid - neopentyl glycol (NPG) based gelcoats and skin coats offer even better resistance to blister formation that isophthalic acid-propylene glycol based resins but at increased cost. The contribution of the polyvinyl acetate (PVA) binders, used on glass fibre as a size and binder, must not be ignored as a major contributor to blistering in GRP. Hence, skin coat construction should be with powder bound (PB) chopped strand mat (CSM) and not emulsion bound (EB) CSM.

**Chemical Resistant Barrier Layers**

The main function of the barrier layer is to reduce or delay the ingress of the environment into the structural laminate. It has been shown that the flexural strength degradation of laminates is proportional to the amount of water going through the laminates, regardless of time. Since water permeation is controlled by solubility and diffusion processes and diffusion rate increases exponentially with temperature, it is likely that the solubility of water in a resin matrix is the primary factor controlling laminate degradation up to about 60?C, above which temperature activated diffusion becomes rate controlling. Regester showed that neither hydrochloric acid nor sulphuric acid fully penetrated a 2.5 mm thick GRP barrier layer after 6 months at 100?C and that sodium chloride, with the same chloride ion concentration as the hydrochloric acid, penetrated to a much lesser extent. It was concluded from this that sulphate anions penetrate primarily by wicking along the fibre-resin interface, whereas chloride anions diffuse through the resin matrix and, in the case of sodium chloride, sodium cations are easily polarised, increasing their effective diameter and decreasing their diffusion rate. Since electrical neutrality must be maintained within the laminate, then the slowest moving ion will determine the penetration rate. Hence, seawater has less effect on laminate properties than distilled or tap water. It, therefore, follows that the thickness of the barrier layer and the resistance of its materials of construction delay environmental penetration, thereby protecting the structural laminate from possible degradation and failure.

In the chemical plant industry, barrier layers used for protecting GRP are either thermoplastic liners or GRP liners manufactured in a resin-rich fibre reinforced form using resin with resistance to the environment to be contained.

For mild operating conditions a clear gelcoat, backed up with a surface tissue reinforced layer will provide acceptable chemical resistance. However, for more corrosive environments a single or double glass or synthetic veil reinforced liner should be allowed to

cure before the CSM reinforced part of the barrier layer is fabricated to provide a non-structural liner with a minimum thickness of 2.5 mm.

Solvents are especially aggressive towards GRP but, again, it has been shown that the correct choice of barrier layer can provide a long term solution for the storage of fuels in underground tanks providing the necessary corrosion resistance to both the internal environment and the external, often aggressive, soil conditions has been taken into account. In order to achieve the highest level of solvent resistance it is essential to use fully cured (involving a high temperature post cure), highly cross-linked resin systems. The level of degradation of GRP in contact with solvents results in varying levels of swelling, absorption, whitening, surface crazing and cracking depending upon the type of solvent or blend of solvents in contact with it. Often blends of solvents are more aggressive, because of synergistic solvent effects, than the individual solvent components alone. A particular example of this problem is a test fuel blend of octane, toluene and methanol which is far more aggressive to GRP than the component solvents alone.

However, highly cross-linked isophthalic acid based polyester resin has been shown to be very resistant to this solvent blend and hence, suitable for the manufacture of underground petroleum storage tanks. Again, the correct choice of surface tissue and liner construction enhances the long term performance of GRP petroleum storage tanks.

**Coatings Conclusions**

The long term performance of composite structures is heavily dependent upon the level of protection provided to resist the corrosive nature of the environment to which such structures will be exposed during their working lives.

In many situations, formulated gelcoats can be used to provide the in-mould finish necessary to provide life-time environmental protection to building panels, land transport components and marine structures. In more demanding chemical plant applications, careful choice of chemical resistant resins and barrier layer construction are essential for satisfactory performance of fibre reinforced structures.

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**Reinforcements**

The role of the reinforcement in a composite material is fundamentally one of increasing the mechanical properties of the neat resin system. All of the different fibres used in composites have different properties and so affect the properties of the composite in different ways. The properties and characteristics of common fibres are explained below.

However, individual fibres or fibre bundles can only be used on their own in a few processes such as filament winding (described later). For most other applications, the fibres need to be arranged into some form of sheet, known as a fabric, to make handling possible. Different ways for assembling fibres into sheets and the variety of fibre orientations possible lead to there being many different types of fabrics, each of which has its own characteristics. These different fabric types and constructions are explained later.
Properties of Reinforcing Fibres

The mechanical properties of most reinforcing fibres are considerably higher than those of un-reinforced resin systems. The mechanical properties of the fibre/resin composite are therefore dominated by the contribution of the fibre to the composite.



The four main factors that govern the fibre's contribution are:

1       The basic mechanical properties of the fibre itself.
2       The surface interaction of fibre and resin (the 'interface').
3       The amount of fibre in the composite ('Fibre Volume Fraction').
4       The orientation of the fibres in the composite.

The basic mechanical properties of the most commonly used fibres are later. The surface interaction of fibre and resin is controlled

by the degree of bonding that exists between the two. This is heavily influenced by the treatment given to the fibre surface, and a description of the different surface treatments and 'finishes' is also given here.

The amount of fibre in the composite is largely governed by the manufacturing process used. However, reinforcing fabrics with closely packed fibres will give higher Fibre Volume Fractions (FVF) in a laminate than will those fabrics which are made with coarser fibres, or which have large gaps between the fibre bundles. Fibre diameter is an important factor here with the more expensive smaller diameter fibres providing higher fibre surface areas, spreading the fibre/matrix interfacial loads. As a general rule, the stiffness and strength of a laminate will increase in proportion to the amount of fibre present. However, above about 60-70% FVF (depending on the way in which the fibres pack together) although tensile stiffness may continue to increase, the laminate's strength will reach a peak and then begin to decrease due to the lack of sufficient resin to hold the fibres together properly.

Finally, since reinforcing fibres are designed to be loaded along their length, and not across their width, the orientation of the fibres creates highly 'direction-specific' properties in the composite. This 'anisotropic' feature of composites can be used to good advantage in designs, with the majority of fibres being placed along the orientation of the main load paths. This minimises the amount of parasitic material that is put in orientations where there is little or no load.

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**Basic Properties of Fibres and Other Engineering Materials**

| Material Type | Tensile Str. (MPa) | Tensile Modulus (GPa) | Typical Density (g/cc) | Specific Modulus |
|---|---|---|---|---|
| Carbon HS | 3500 | 160 - 270 | 1.8 | 90 - 150 |
| Carbon IM | 5300 | 270 - 325 | 1.8 | 150 - 180 |
| Carbon HM | 3500 | 325 - 440 | 1.8 | 180 - 240 |
| Carbon UHM | 2000 | 440+ | 2.0 | 200+ |
| Aramid LM | 3600 | 60 | 1.45 | 40 |
| Aramid HM | 3100 | 120 | 1.45 | 80 |
| Aramid UHM | 3400 | 180 | 1.47 | 120 |
| Glass - E glass | 2400 | 69 | 2.5 | 27 |
| Glass - S2 glass | 3450 | 86 | 2.5 | 34 |
| Glass - quartz | 3700 | 69 | 2.2 | 31 |
| Aluminium Alloy (7020) | 400 | 69 | 2.7 | 26 |
| Titanium | 950 | 110 | 4.5 | 24 |
| Mild Steel (55 Grade) | 450 | 205 | 7.8 | 26 |
| Stainless Steel (A5-80) | 800 | 196 | 7.8 | 25 |
| HS Steel (17/4 H900) | 1241 | 197 | 7.8 | 25 |

**Laminate Mechanical Properties**

The properties of the fibres only show part of the picture. The properties of the composite will derive from those of the fibre, but also the way it interacts with the resin system used, the resin properties itself, the volume of fibre in the composite and its orientation. The following diagrams show a basic comparison of the main fibre types when used in a typical high-performance unidirectional epoxy prepreg, at the fibre volume fractions that are commonly achieved in aerospace components.
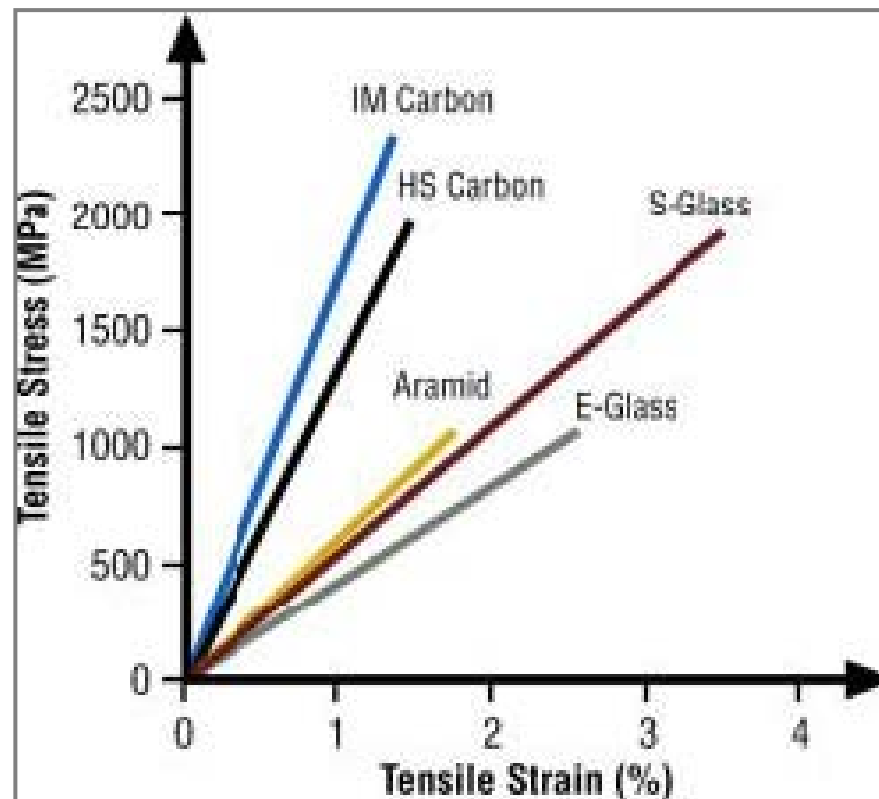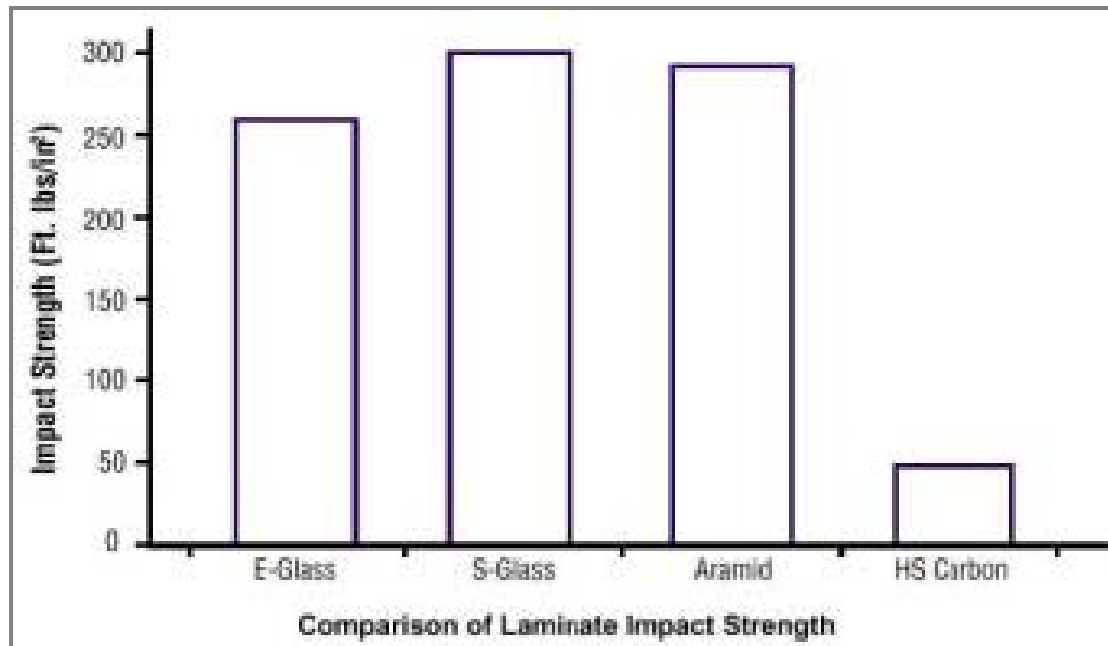
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These graphs show the strengths and maximum strains of the different composites at failure. The gradient of each graph also indicates the stiffness (modulus) of the composite; the steeper the gradient, the higher its stiffness. The graphs also show how some fibres, such as aramid, display very different properties when loaded in compression, compared with loading in tension.

Laminate Impact Strength



Comparison of Laminate Impact Strength

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Impact damage can pose particular problems when using high stiffness fibres in very thin laminates. In some structures, where cores are used, laminate skins can be less than 0.3mm thick. Although other factors such as weave style and fibre orientation can significantly affect impact resistance, in impact-critical applications, carbon is often found in combination with one of the other fibres. This can be in the form of a hybrid fabric where more than one fibre type is used in the fabric construction. These are described in more detail later.

Comparative Fibre Cost
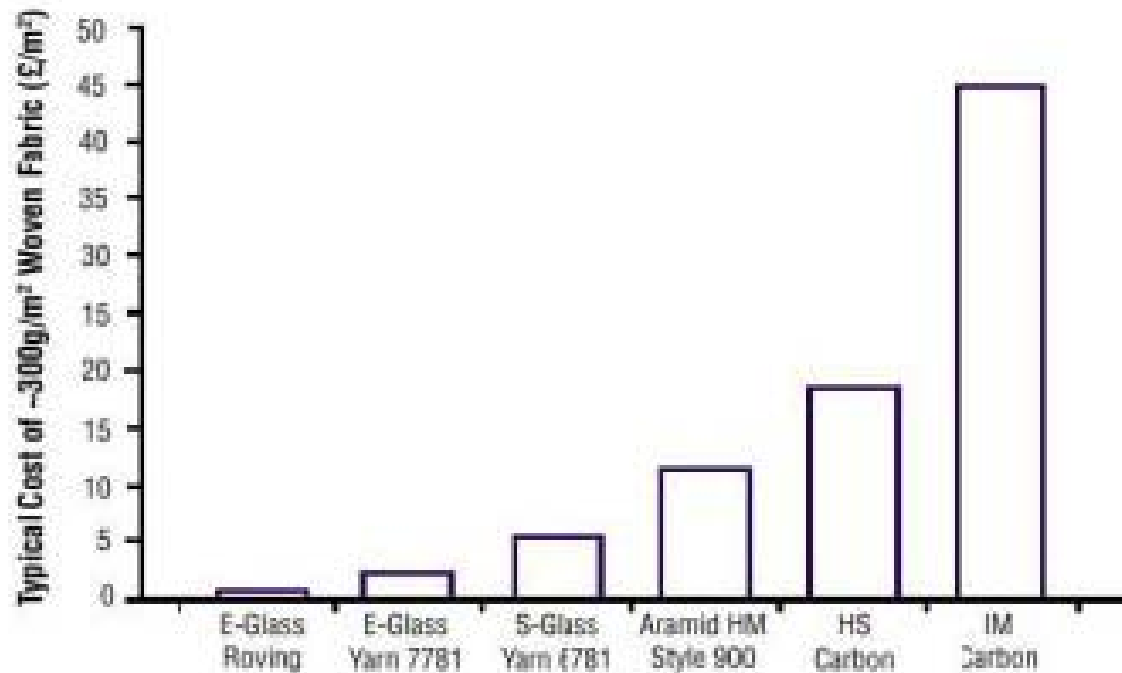
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The figures above are calculated on a typical price of a 300g woven fabric. Most fibre prices are considerably higher for the small bundle size (tex) used in such lightweight fabrics. Where heavier bundles of fibre can be used, such as in unidirectional fabrics, the cost comparison is slightly different.
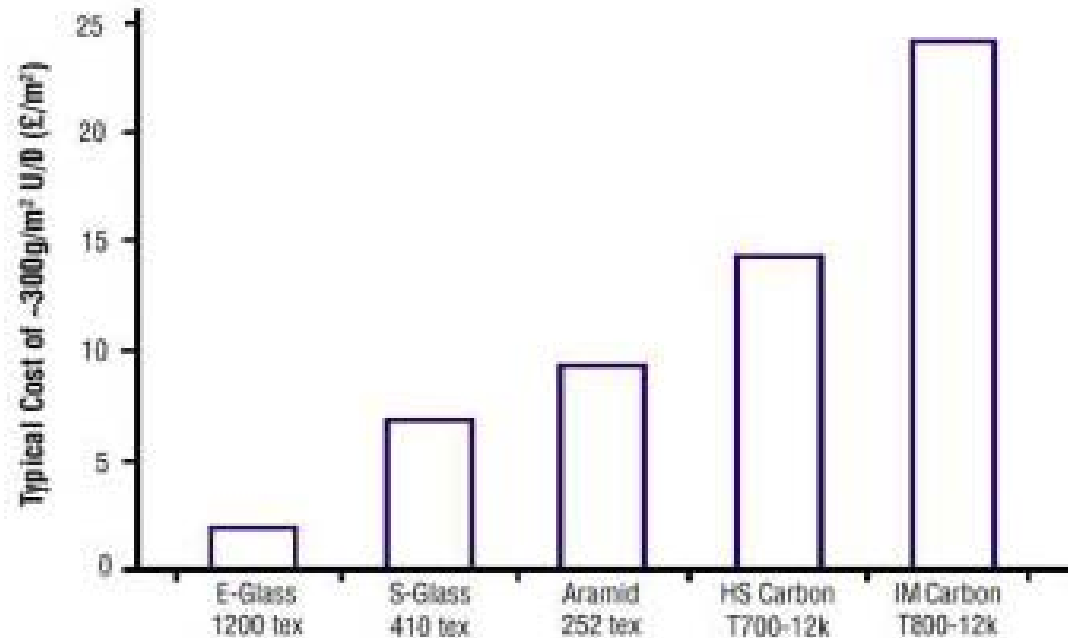
**Glass Fibre / Glass Fiber**

By blending quarry products (sand, kaolin, limestone, colemanite) at 1,600C, liquid glass is formed. The liquid is passed through micro-fine bushings and simultaneously cooled to produce glass fibre filaments from 5-24m in diameter. The filaments are drawn together into a strand (closely associated) or roving (loosely associated), and coated with a "size" to provide filament cohesion and protect the glass from abrasion.

By variation of the "recipe", different types of glass can be produced. The types used for structural reinforcements are as follows:

E-glass (electrical) - lower alkali content and stronger than A glass (alkali). Good tensile and compressive strength and stiffness, good electrical properties and relatively low cost, but impact resistance relatively poor. Depending on the type of E glass the price ranges from about £1-2/kg. E-glass is the most common form of reinforcing fibre used in polymer matrix composites.
C-glass (chemical) - best resistance to chemical attack. Mainly used in the form of surface tissue in the outer layer of laminates used in chemical and water pipes and tanks.

R, S or T-glass – manufacturer's trade names for equivalent fibres having higher tensile strength and modulus than E glass, with better wet strength retention. Higher ILSS and wet out properties are achieved through smaller filament diameter. S-glass is produced in the USA by OCF, R-glass in Europe by Vetrotex and T-glass by Nittobo in Japan. Developed for aerospace and defence industries, and used in some hard ballistic armour applications. This factor, and low production volumes mean relatively high price. Depending on the type of R or S glass the price ranges from about £12-20/kg.

**E Glass Fibre Types**

E Glass fibre is available in the following forms:

Strand - a compactly associated bundle of filaments. Strands are rarely seen commercially and are usually twisted together to give yarns.

Yarns - a closely associated bundle of twisted filaments or strands. Each filament diameter in a yarn is the same, and is usually

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between 4-13m. Yarns have varying weights described by their 'tex' ( the weight in grammes of 1000 linear metres) or denier ( the weight in lbs of 10,000 yards), with the typical tex range usually being between 5 and 400.

Rovings - a loosely associated bundle of untwisted filaments or strands. Each filament diameter in a roving is the same, and is usually between 13-24m. Rovings also have varying weights and the tex range is usually between 300 and 4800. Where filaments are gathered together directly after the melting process, the resultant fibre bundle is known as a direct roving. Several strands can also be brought together separately after manufacture of the glass, to give what is known as an assembled roving. Assembled rovings usually have smaller filament diameters than direct rovings, giving better wet-out and mechanical properties, but they can suffer from catenary problems (unequal strand tension), and are usually higher in cost because of the more involved manufacturing processes.

It is also possible to obtain long fibres of glass from short fibres by spinning them. These spun yarn fibres have higher surface areas and are more able to absorb resin, but they have lower structural properties than the equivalent continuously drawn fibres.

Aramid Fibre / Aramid Fiber

Aramid fibre is a man-made organic polymer (an aromatic polyamide) produced by spinning a solid fibre from a liquid chemical blend. The bright golden yellow filaments produced can have a range of properties, but all have high strength and low density giving very high specific strength. All grades have good resistance to impact, and lower modulus grades are used extensively in ballistic applications. Compressive strength, however, is only similar to that of E glass.

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Although most commonly known under its Dupont trade name 'Kevlar', there are now a number of suppliers of the fibre, most notably Akzo Nobel with 'Twaron'. Each supplier offers several grades of aramid with various combinations of modulus and surface finish to suit various applications. As well as the high strength properties, the fibres also offer good resistance to abrasion, and chemical and thermal degradation. However, the fibre can degrade slowly when exposed to ultraviolet light.

Aramid fibres are usually available in the form of rovings, with texes ranging from about 20 to 800. Typically the price of the high modulus type ranges from £15-to £25 per kg.

Carbon Fibre/ Carbon Fiber

Carbon fibre is produced by the controlled oxidation, carbonisation and graphitisation of carbon-rich organic precursors which are already in fibre form. The most common precursor is polyacrylonitrile (PAN), because it gives the best carbon fibre properties, but fibres can also be made from pitch or cellulose. Variation of the graphitisation process produces either high strength fibres (@ ~2,600°C) or high modulus fibres (@ ~3,000°C) with other types in between. Once formed, the carbon fibre has a surface treatment applied to improve matrix bonding and chemical sizing which serves to protect it during handling.

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When carbon fibre was first produced in the late sixties the price for the basic high strength grade was about £200/kg. By 1996 the annual worldwide capacity had increased to about 7,000 tonnes and the price for the equivalent (high strength) grade was £15-40/kg. Carbon fibres are usually grouped according to the modulus band in which their properties fall. These bands are commonly referred to as: high strength (HS), intermediate modulus (IM), high modulus (HM) and ultra high modulus (UHM). The filament diameter of most types is about 5-7mm. Carbon fibre has the highest specific stiffness of any commercially available fibre, very high strength in both tension and compression and a high resistance to corrosion, creep and fatigue. Their impact strength, however, is lower than either glass or aramid, with particularly brittle characteristics being exhibited by HM and UHM fibres.

## Strength and Modulus Figures for Commercial PAN-based Carbon Fibres

| Grade | Tensile Modulus (GPa) | Tensile Strength (GPa) | Country of Manufacture |
|---|---|---|---|
| **Standard Modulus (<265GPa) (also known as "High Strength")** | | | |
| T300 | 230 | 3.53 | France/Japan |
| T700 | 235 | 5.3 | Japan |
| HTA | 238 | 3.95 | Germany |
| UTS | 240 | 4.8 | Japan |
| 34-700 | 234 | 4.5 | Japan/USA |
| AS4 | 241 | 4.0 | USA |
| T650-35 | 241 | 4.55 | USA |
| Panex 33 | 228 | 3.6 | USA/Hungary |
| F3C | 228 | 3.8 | USA |
| TR50S | 235 | 4.83 | Japan |
| TR30S | 234 | 4.41 | Japan |
| **Intermediate Modulus (265-320GPa)** | | | |
| T800 | 294 | 5.94 | France/Japan |
| M30S | 294 | 5.49 | France |
| IMS | 295 | 4.12/5.5 | Japan |
| MR40/MR50 | 289 | 4.4/5.1 | Japan |
| IM6/IM7 | 303 | 5.1/5.3 | USA |
| IM9 | 310 | 5.3 | USA |
| T650-42 | 290 | 4.82 | USA |
| T40 | 290 | 5.65 | USA |
| **High Modulus (320-440GPa)** | | | |
| M40 | 392 | 2.74 | Japan |
| M40J | 377 | 4.41 | France/Japan |
| HMA | 358 | 3.0 | Japan |
| UMS2526 | 395 | 4.56 | Japan |
| MS40 | 340 | 4.8 | Japan |
| HR40 | 381 | 4.8 | Japan |
| **Ultra High Modulus (~440GPa)** | | | |
| M46J | 436 | 4.21 | Japan |
| UMS3536 | 435 | 4.5 | Japan |
| HS40 | 441 | 4.4 | Japan |
| UHMS | 441 | 3.45 | USA |

Information from manufacturer's datasheets

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**Fibre Type Comparisons**

Comparing the properties of all of the fibre types with each other, shows that they all have distinct advantages and disadvantages. This makes different fibre types more suitable for some applications than others. The following table provides a basic comparison between the main desirable features of generic fibre types. 'A' indicates a feature where the fibre scores well, and 'C' indicates a feature where the fibre is not so good.

| Property | Aramid | Carbon | Glass |
|---|---|---|---|
| High Tensile Strength | B | A | B |
| High Tensile Modulus | B | A | C |
| High Compressive Strength | C | A | B |
| High Compressive Modulus | B | A | C |
| High Flexural Strength | C | A | B |
| High Flexural Modulus | B | A | C |
| High Impact Strength | A | C | B |
| High Interlaminar Shear Strength | B | A | A |
| High In-plane Shear Strength | B | A | A |
| Low Density | A | B | C |
| High Fatigue Resistance | B | A | C |
| High Fire Resistance | A | C | A |
| High Thermal Insulation | A | C | B |
| High Electrical Insulation | B | C | A |
| Low Thermal Expansion | A | A | A |
| Low Cost | C | C | A |

**Other Fibres**

There are a variety of other fibres which can be used in advanced composite structures but their use is not widespread. These include:

Polyester
A low density, high tenacity fibre with good impact resistance but low modulus. Its lack of stiffness usually precludes it from inclusion in a composite component, but it is useful where low weight, high impact or abrasion resistance, and low cost are required. It is mainly used as a surfacing material, as it can be very smooth, keeps weight down and works well with most resin types.

Polyethylene
In random orientation, ultra-high molecular weight polyethylene molecules give very low mechanical properties. However, if dissolved and drawn from solution into a filament by a process called gel-spinning, the molecules become disentangled and aligned in the direction of the filament. The molecular alignment promotes very high tensile strength to the filament and the resulting fibre. Coupled with their low S.G. (<1.0), these fibres have the highest specific strength of the fibres described here. However, the fibre's tensile modulus and ultimate strength are only slightly better than E-glass and less than that of aramid or carbon. The fibre also demonstrates very low compressive strength in laminate form. These factors, coupled with high price, and more importantly, the difficulty in creating a good fibre/matrix bond means that polyethylene fibres are not often used in isolation for composite components.
Quartz
A very high silica version of glass with much higher mechanical properties and excellent resistance to high temperatures (1,000°C+). However, the manufacturing process and low volume production lead to a very high price (14mm - £74/kg, 9mm - £120/kg).

Boron
Carbon or metal fibres are coated with a layer of boron to improve the overall fibre properties. The extremely high cost of this fibre restricts it use to high temperature aerospace applications and in specialised sporting equipment. A boron/carbon hybrid, composed of carbon fibres interspersed among 80100mm boron fibres, in an epoxy matrix, can achieve properties greater than either fibre alone, with flexural strength and stiffness twice that of HS carbon and 1.4 times that of boron, and shear strength exceeding that of either fibre.

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### Ceramics

Ceramic fibres, usually in the form of very short 'whiskers' are mainly used in areas requiring high temperature resistance. They are more frequently associated with non-polymer matrices such as metal alloys.

### Natural

At the other end of the scale it is possible to use fibrous plant materials such as jute and sisal as reinforcements in 'low-tech' applications. In these applications, the fibres' low S.G. (typically 0.5-0.6) mean that fairly high specific strengths can be achieved.

### Fibre Finishes

Surface finishes are nearly always applied to fibres both to allow handling with minimum damage and to promote fibre/matrix interfacial bond strength. With carbon and aramid fibres for use in composite applications, the surface finish or size applied usually performs both functions. The finish is applied to the fibre at the point of fibre manufacture and this finish remains on the fibre throughout the conversion process into fabric. With glass fibre there is a choice of approach in the surface finish that can be applied.

**Glass Fibre Finishe**s

Glass fibre rovings that are to be used in direct fibre processes such as prepregging, pultrusion and filament winding, are treated with a 'dual-function' finish at the point of fibre manufacture.

Glass fibre yarns, however, when used for weaving are treated in two stages. The first finish is applied at the point of fibre manufacture at quite a high level and is purely for protection of the fibre against damage during handling and the weaving process itself. This protective finish, which is often starch based, is cleaned off or 'scoured' after the weaving process either by heat or with

chemicals. The scoured woven fabric is then separately treated with a different matrix-compatible finish specifically designed to optimise fibre to resin interfacial characteristics such as bond strength, water resistance and optical clarity.

**Carbon Fibre Finishes**

Finishes, or sizes, for carbon fibres used in structural composites are generally epoxy based, with varying levels being used depending on the end use of the fibre. For weaving the size level is about 1-2% by weight whereas for tape prepregging or filament winding (or similar single-fibre processes), the size level is about 0.5-1%. The chemistry and level of the size are important not only for protection and matrix compatibility but also because they effect the degree of spread of the fibre. Fibres can also be supplied unsized but these will be prone to broken filaments caused by general handling. Most carbon fibre suppliers offer 3-4 levels of size for each grade of fibre.

**Aramid Fibre Finishes**

Aramid fibres are treated with a finish at the point of manufacture primarily for matrix compatibility. This is because aramid fibres require far less protection from damage caused by fibre handling. The main types of fibre treatment are composite finish, rubber compatible finish (belts and tyres) and waterproof finish (ballistic soft armour). Like the carbon fibre finishes, there are differing levels of composite application finish depending on the type of process in which the fibre will be used.

**Fabric Types and Constructions**

In polymeric composite terms, a fabric is defined as a manufactured assembly of long fibres of carbon, aramid or glass, or a combination of these, to produce a flat sheet of one or more layers of fibres. These layers are held together either by mechanical interlocking of the fibres themselves or with a secondary material to bind these fibres together and hold them in place, giving the assembly sufficient integrity to be handled.

Fabric types are categorised by the orientation of the fibres used, and by the various construction methods used to hold the fibres together.

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The four main fibre orientation categories are: Unidirectional, Woven, Multiaxial, and Other/random. These are described in the following pages.

**Unidirectional Fabrics**

A unidirectional (UD) fabric is one in which the majority of fibres run in one direction only. A small amount of fibre or other material may run in other directions with the main intention being to hold the primary fibres in position, although the other fibres may also offer some structural properties. Some weavers of 0/90° fabrics term a fabric with only 75% of its weight in one direction as a unidirectional, whilst for others the unidirectional designation only applies to those fabrics with more than 90% of the fibre weight in one direction. Unidirectionals usually have their primary fibres in the 0° direction (along the roll a warp UD) but can also have them at 90° to the roll length (a weft UD).

True unidirectional fabrics offer the ability to place fibre in the component exactly where it is required, and in the optimum quantity (no more or less than required). As well as this, UD fibres are straight and uncrimped. This results in the highest possible fibre properties from a fabric in composite component construction. For mechanical properties, unidirectional fabrics can only be improved on by prepreg unidirectional tape, where there is no secondary material at all holding the unidirectional fibres in place. In these prepreg products only the resin system holds the fibres in place.

**Unidirectional Construction**

There are various methods of maintaining the primary fibres in position in a unidirectional including weaving, stitching, and bonding. As with other fabrics, the surface quality of a unidirectional fabric is determined by two main factors: the combination of tex and thread count of the primary fibre and the amount and type of the secondary fibre. The drape, surface smoothness and stability of a fabric are controlled primarily by the construction style, while the area weight, porosity and (to a lesser degree) wet out are determined by selecting the appropriate combination of fibre tex and numbers of fibres per cm.

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Warp or weft unidirectionals can be made by the stitching process (see information in the 'Multiaxial' section of this publication). However, in order to gain adequate stability, it is usually necessary to add a mat or tissue to the face of the fabric. Therefore, together with the stitching thread required to assemble the fibres, there is a relatively large amount of secondary, parasitic material in this type of UD fabric, which tends to reduce the laminate properties. Furthermore the high cost of set up of the 0° layer of a stitching line and the relatively slow speed of production means that these fabrics can be relatively expensive.
Woven Fabrics

For applications where more than one fibre orientation is required, a fabric combining 0° and 90° fibre orientations is useful.

Woven fabrics are produced by the interlacing of warp (0°) fibres and weft (90°) fibres in a regular pattern or weave style. The fabric's integrity is maintained by the mechanical interlocking of the fibres. Drape (the ability of a fabric to conform to a complex surface), surface smoothness and stability of a fabric are controlled primarily by the weave style. The following is a description of some of the more commonly found weave styles:
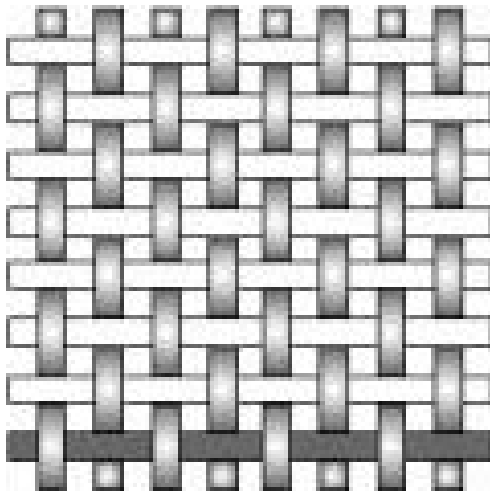


**Plain**
Each warp fibre passes alternately under and over each weft fibre. The fabric is symmetrical, with good stability and reasonable porosity. However, it is the most difficult of the weaves to drape, and the high level of fibre crimp imparts relatively low mechanical properties compared with the other weave styles. With large fibres (high tex) this weave style gives excessive crimp and therefore it tends not to be used for very heavy fabrics.

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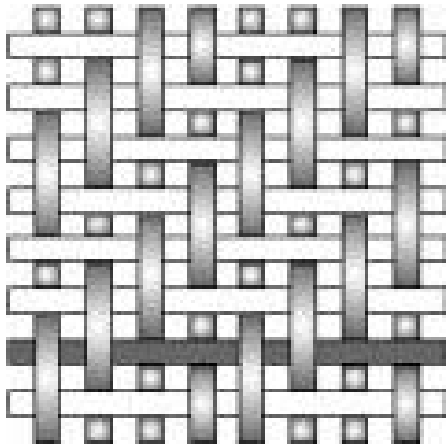
**Twill**

One or more warp fibres alternately weave over and under two or more weft fibres in a regular repeated manner. This produces the visual effect of a straight or broken diagonal 'rib' to the fabric. Superior wet out and drape is seen in the twill weave over the plain weave with only a small reduction in stability. With reduced crimp, the fabric also has a smoother surface and slightly higher mechanical properties.
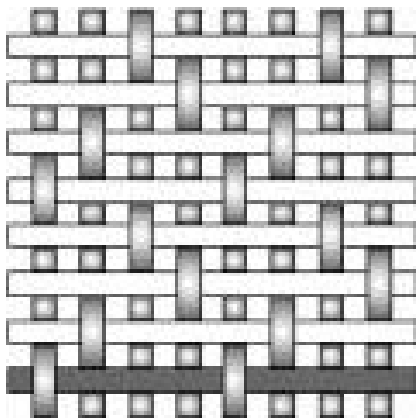
**Satin**

Satin weaves are fundamentally twill weaves modified to produce fewer intersections of warp and weft. The 'harness' number used in the designation (typically 4, 5 and 8) is the total number of fibres crossed and passed under, before the fibre repeats the pattern. A 'crowsfoot' weave is a form of satin weave with a different stagger in the re-peat pattern. Satin weaves are very flat, have good wet out and a high degree of drape. The low crimp gives good mechanical properties. Satin weaves allow fibres to be woven in the closest proximity and can produce fabrics with a close 'tight' weave. However, the style's low stability and asymmetry needs to be considered. The asymmetry causes one face of the fabric to have fibre running predominantly in the warp direction while the other face has fibres running predominantly in the weft direction. Care must be taken in assembling multiple layers of these fabrics to ensure that stresses are not built into the component through this asymmetric effect.

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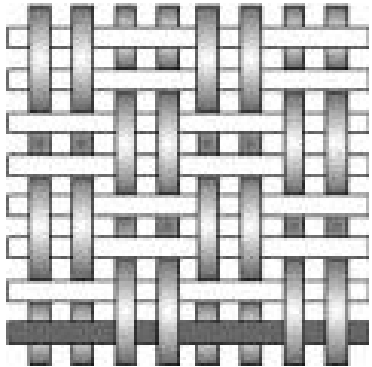
### Basket

Basket weave is fundamentally the same as plain weave except that two or more warp fibres alternately interlace with two or more weft fibres. An arrangement of two warps crossing two wefts is designated 2x2 basket, but the arrangement of fibre need not be symmetrical. Therefore it is possible to have 8x2, 5x4, etc. Basket weave is flatter, and, through less crimp, stronger than a plain weave, but less stable. It must be used on heavy weight fabrics made with thick (high tex) fibres to avoid excessive crimping.
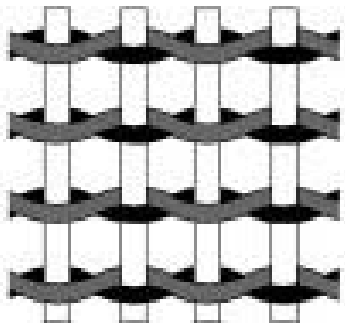
### Leno

Leno weave improves the stability in 'open' fabrics which have a low fibre count. A form of plain weave in which adjacent warp fibres are twisted around consecutive weft fibres to form a spiral pair, effectively 'locking' each weft in place. Fabrics in leno weave are normally used in con-junction with other weave styles because if used alone their openness could not produce an effective composite component.
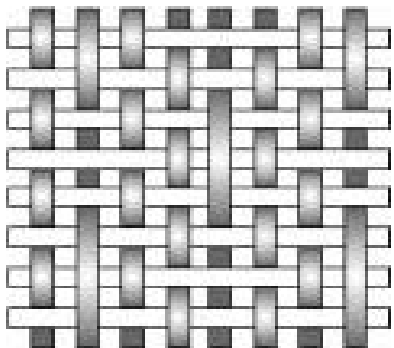
### Mock Leno

A version of plain weave in which occasional warp fibres, at regular intervals but usually several fibres apart, deviate from the alternate under-over interlacing and instead interlace every two or more fibres. This happens with similar frequency in the weft direction, and the overall effect is a fabric with increased thickness, rougher surface, and additional porosity.
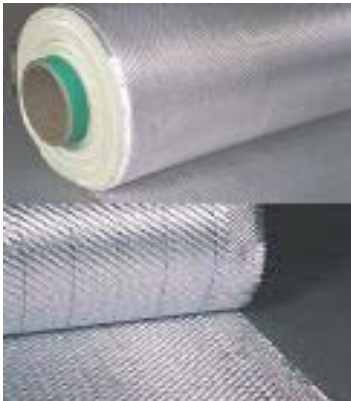
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Weave Styles - Comparison of Properties

| Property | Plain | Twill | Satin | Basket | Leno | Mock leno |
|---|---|---|---|---|---|---|
| Good stability | •••• | ••• | •• | •• | ••••• | ••• |
| Good drape | •• | •••• | ••••• | ••• | • | •• |
| Low porosity | ••• | •••• | ••••• | •• | • | ••• |
| Smoothness | •• | ••• | ••••• | •• | • | •• |
| Balance | •••• | •••• | •• | •••• | •• | •••• |
| Symmetrical | ••••• | ••• | • | ••• | • | ••••• |
| Low crimp | •• | ••• | ••••• | •• | ••/••••• | •• |

••••• = excellent, •••• = good, ••• = acceptable, •• = poor, • = very poor

### Woven Glass Yarn Fabrics vs Woven Rovings

Yarn-based fabrics generally give higher strengths per unit weight than roving, and being generally finer, produce fabrics at the lighter end of the available weight range. Woven rovings are less expensive to produce and can wet out more effectively. However, since they are available only in heavier texes, they can only produce fabrics at the medium to heavy end of the available weight range, and are thus more suitable for thick, heavier laminates.

**Hybrid Fabrics**

The term hybrid refers to a fabric that has more than one type of structural fibre in its construction. In a multi-layer laminate if the properties of more than one type of fibre are required, then it would be possible to provide this with two fabrics, each containing the fibre type needed. However, if low weight or extremely thin laminates are required, a hybrid fabric will allow the two fibres to be presented in just one layer of fabric instead of two. It would be possible in a woven hybrid to have one fibre running in the weft direction and the second fibre running in the warp direction, but it is more common to find alternating threads of each fibre in each warp/weft direction. Although hybrids are most commonly found in 0/90° woven fabrics, the principle is also used in 0/90° stitched, unidirectional and multiaxial fabrics. The most usual hybrid combinations are:

**Carbon / Aramid**
The high impact resistance and tensile strength of the aramid fibre combines with high the compressive and tensile strength of carbon. Both fibres have low density but relatively high cost.

**Aramid / Glass**
The low density, high impact resistance and tensile strength of aramid fibre combines with the good compressive and tensile strength of glass, coupled with its lower cost.

**Carbon / Glass**
Carbon fibre contributes high tensile compressive strength and stiffness and reduces the density, while glass reduces the cost.

**Multiaxial Fabrics**

In recent years multiaxial fabrics have begun to find favour in the construction of composite components. These fabrics consist of one or more layers of long fibres held in place by a secondary non-structural stitching tread. The main fibres can be any of the structural fibres available in any combination. The stitching thread is usually polyester due to its combination of appropriate fibre properties (for binding the fabric together) and cost. The stitching process allows a variety of fibre orientations, beyond the simple 0/90° of woven

fabrics, to be combined into one fabric. Multiaxial fabrics have the following main characteristics:

**Advantages**
The two key improvements with stitched multiaxial fabrics over woven types are:
        (i) Better mechanical properties, primarily from the fact that the fibres are always straight and non-crimped, and that more orientations of fibre are available from the increased number of layers of fabric.
        (ii) Improved component build speed based on the fact that fabrics can be made thicker and with multiple fibre orientations so that fewer layers need to be included in the laminate sequence.

**Disadvantages**
Polyester fibre does not bond very well to some resin systems and so the stitching can be a starting point for wicking or other failure initiation. The fabric production process can also be slow and the cost of the machinery high. This, together with the fact that the more expensive, low tex fibres are required to get good surface coverage for the low weight fabrics, means the cost of good quality, stitched fabrics can be relatively high compared to wovens. Extremely heavy weight fabrics, while enabling large quantities of fibre to be incorporated rapidly into the component, can also be difficult to impregnate with resin without some automated process. Finally, the stitching process, unless carefully controlled, can bunch together the fibres, particularly in the 0° direction, creating resin-rich areas in the laminate.

Fabric Construction
The most common forms of this type of fabric are shown in the following diagrams:
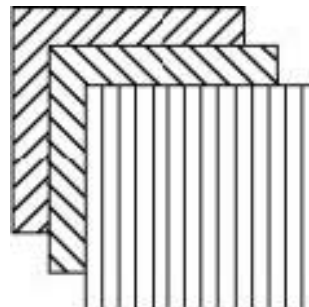
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There are two basic ways of manufacturing multiaxial fabrics:

Weave & Stitch
With the 'Weave & Stitch' method the +45° and -45° layers can be made by weaving weft Unidirectionals and then skewing the fabric, on a special machine, to 45°. A warp unidirectional or a weft unidirectional can also be used unskewed to make a 0° and 90° layer If both 0° and 90° layers are present in a multi-layer stitched fabric then this can be provided by a conventional 0/90° woven fabric. Due to the fact that heavy rovings can be used to make each layer the weaving process is relatively fast, as is the subsequent stitching together of the layers via a simple stitching frame.
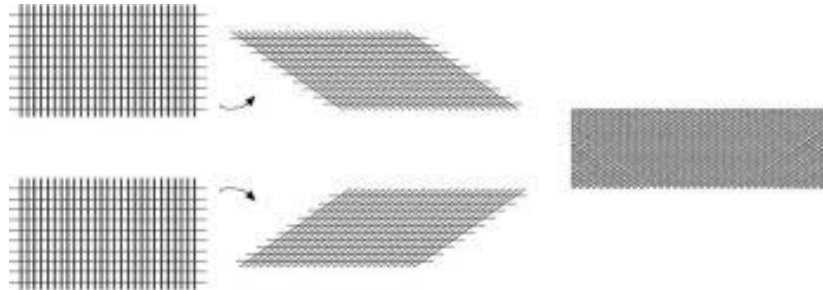


To make a quadraxial (four-layer: +45°, 0°, 90°, -45°) fabric by this method, a weft unidirectional would be woven and skewed in one direction to make the +45° layer, and in the other to make the -45° layer. The 0° and 90° layers would appear as a single woven fabric. These three elements would then be stitched together on a stitching frame to produce the final four-axis fabric.

Simultaneous Stitch
Simultaneous stitch manufacture is carried out on special machines based on the knitting process, such as those made by Liba, Malimo, Mayer, etc. Each machine varies in the precision with which the fibres are laid down, particularly with reference to keeping the fibres parallel. These types of machine have a frame which simultaneously draws in fibres for each axis/layer, until the required layers have been assembled, and then stitches them together, as shown in the diagram below.

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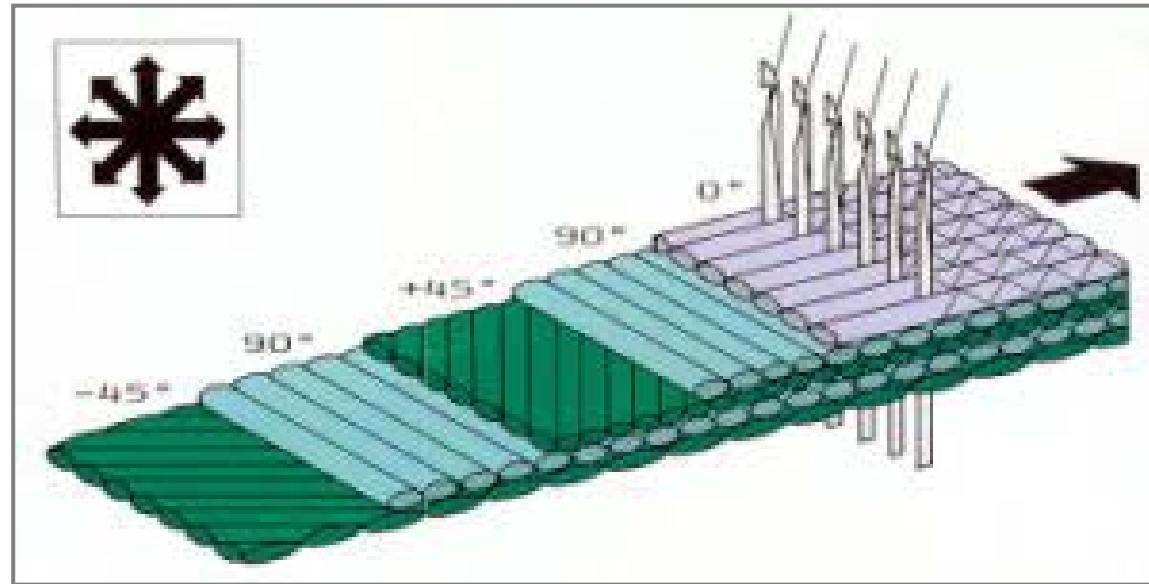


Other/Random Fabrics

Chopped Strand Mat
Chopped strand mat (CSM) is a non-woven material which, as its name implies, consists of randomly orientated chopped strands of glass which are held together - for marine applications - by a PVA emulsion or a powder binder. Despite the fact that PVA imparts superior draping handling and wetting out characteristics users in a marine environment should be wary of its use as it is affected by moisture and can lead to osmosis like blisters. Today, chopped strand mat is rarely used in high performance composite components as it is impossible to produce a laminate with a high fibre content and, by definition, a high strength-to-weight ratio.

Tissues
Tissues are made with continuous filaments of fibre spread uniformly but randomly over a flat surface. These are then chemically bound together with organic based binding agents such as PVA, polyester, etc. Having relatively low strength they are not primarily used as reinforcements, but as surfacing layers on laminates in order to provide a smooth finish. Tissues are usually manufactured with area weights of between 5 and 50g/sqm. Glass tissues are commonly used to create a corrosion resistant barrier through resin enrichment at the surface. The same enrichment process can also prevent print-through of highly crimped fabrics in gelcoat surfaces.

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Braids

Braids are produced by interlacing fibres in a spiral nature to form a tubular fabric. The diameter of the tube is controlled by the number of fibres in the tube's circumference, the angle of the fibres in the spiral, the number of intersections of fibre per unit length of the tube and the size (tex) of the fibres in the assembly. The interlacing can vary in style (plain, twill, etc.) as with 0/90° woven fabrics. Tube diameter is normally given for a fibre angle of ±45° but the braiding process allows the fibres to move between angles of about 25° and 75°, depending on the number and tex of the fibres. The narrow angle gives a small diameter whereas the wider angle gives a large diameter. Therefore along the length of one tube it is possible to change the diameter by variation of the fibre angle - a smaller angle (relative to zero) giving a smaller diameter and vice versa. Braids can be found in such composite components as masts, antennae, drive shafts and other tubular structures that require torsional strength.



**Core Materials**

Engineering theory shows that the flexural stiffness of any panel is proportional to the cube of its thickness. The purpose of a core in a composite laminate is therefore to increase the laminate's stiffness by effectively 'thickening' it with a low-density core material. This can provide a dramatic increase in stiffness for very little additional weight.

The figure below shows a cored laminate under a bending load. Here, the sandwich laminate can be likened to an I-beam, in which the laminate skins act as the I-beam flange, and the core materials act as the beam's shear web. In this mode of loading it can be seen

that the upper skin is put into compression, the lower skin into tension and the core into shear. It therefore follows that one of the most important properties of a core is its shear strength and stiffness.
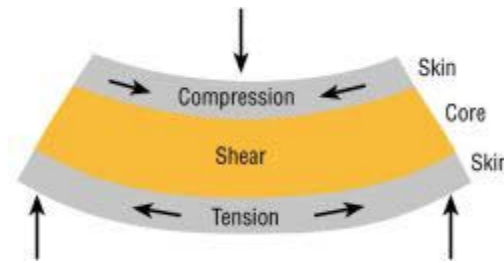


In addition, particularly when using lightweight, thin laminate skins, the core must be capable of taking a compressive loading without premature failure. This helps to prevent the thin skins from wrinkling, and failing in a buckling mode.
Polyurethane Foams

The polyurethane foam world is very large and diverse - chances are good you are sitting on some kind of flexible polyurethane foam right now - but the useful products for composite-core applications are rigid foams.

The term "rigid polyurethane foam" comprises two polymer types: Polyisocyanurate formulations, and polyurethane formulas. There are distinct differences between the two, both in the manner in which they are produced, and in the performance of the results.

Polyisocyanurate foams

Polyisocyanurate foams (or "trimer foams")are generally low density, insulation-grade foams, usually made in large blocks via a continuous extrusion process. These blocks are then put through cutting machines to make sheets and other shapes. Polyisocyanurate foams have excellent insulating value, good compressive-strength properties, and temperature resistance up to 300 degrees F. They are made in high volumes at densities between 1.8 and 6 lbs per cubic foot, and are reasonably inexpensive. Their stiff, brittle consistency, and their propensity to shed dust (friability) when abraded can serve to identify these foams.

It is this friability that limits the utility of polyisocyanurate foams in composite panel applications, as this lack of toughness at the foam surface can cause failure of the foam-to-laminate bond under conditions of vibration or flexure. For this reason, structural use of these foams is often limited to internal-mould shapes for stringers and hat-section reinforcements in FRP boat construction. Here the foam has no supportive function but to provide a form for the fiber-and-resin composite laid over it.

Other uses include under-slab insulation in cold-storage buildings, and below-grade insulation for other building structures.

Polyurethane foams

Polyurethane foams, on the other hand, are considerably different, and more useful in composite constructions. These foams are made in large blocks in either a continuous-extrusion process, or in a batch-process. The blocks are then cut to make sheets or other shapes. They are sometimes also individually moulded into discrete part-shapes.



Isocyanate foam polymers, while not as heavily cross-linked as polyisocyanurate materials, offer many cost-efficient advantages for users. Foam densities range from approximately 2 pounds per cubic foot, up to 50 pounds per cubic foot. Unlike thermoplastic foams (PVC, SAN), the unit cost of polyurethane foam increases in a more linear fashion with density; e.g., a 20-pound per cubic foot polyurethane foam will be approximately twice the cost of a 10-pound foam.

There can be considerable differences in foam strength, at the same density, depending on the foam production process used. This results from differences in chemical formulation required to make foams via different production methods, and the curing temperature of the foam while in production.

Also, if flammability is a concern, it is useful to know what kind of blowing-agent is employed to create cells in the foam. Many producers use carbon-dioxide (a by-product of the foam-making chemical reaction) to create cells in their foams. Other producers have switched from chlorofluorocarbon (HCFC, HFC) blowing agents to pentane in low-density foam manufacturing processes, which can have a deleterious effect on flame-resistance.

Polyurethane polymer foams can be made considerably tougher and less-friable than the polyisocyanurate foams, mostly at the expense of some modulus and high-temperature strength properties. Nevertheless, these foams can be useful (depending on formulation) to temperatures as high as 275 degrees F, while retaining a substantial portion of their strength and toughness. This allows them also to be used in panel applications along with high-temperature curing pre-pregs, cured in ovens or autoclaves.

Typical applications include use as an edge close-out for honeycomb aircraft-interior panels, structural shapes (transom cores, bulkhead core, stringers, motor-mounts etc.) in FRP boat building, impact-limiters and crash-pads, RTM cores, mould-patterns and plugs, sports-equipment core material, and composite tooling.

Polyisocyanurate/Polyurethane Foams

There are producers of polyisocyanurate/polyurethane foams, a blending of the two foam types, trying to get the best of both worlds. These foams offer some improvements in strength values (compared to polyurethane foams) and a reduction of friability (compared to polyisocyanurate foams) with a sacrifice in temperature resistance.

Still, the result of this combination is a compromise, and may not present the best properties of both polymers in some applications. These foams are limited to densities of 2-8 pounds per cubic foot.

PVC Foam

PVC foams came into use as core materials in the 70's. As sandwich structures in marine applications began to be optimised, a need for a lowdensity, consistent, moisture resistant core material was realized. Formulations were refined over the years and the characteristics of PVC foams fit the needs of the marine industry well. PVC foams are closed-cell, moisture resistant, and have good physical properties when compared to other foams of similar density.

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PVC foam is technically an Interpenetrating Polymer Network (IPN) of PVC and polyurea. The interaction of these polymers gives the foam its unique characteristics. Although, the foam is a thermoset, it can still be thermoformed. In addition, it is resistant to many solvents including styrene and most fuels, yet is compatible with most adhesives and laminating resins. PVC foam is closed-cell and has very low moisture absorption. It is self-extinguishing and will not rot. Other inherent properties are excellent fatigue life and good bond strength with common adhesives and resins.

PVC foams are available in a variety of densities from 3pcf to 25 pcf (45kg/m3 to 400kg/m3). Unlike polyurethane foam, PVC foam is not a two-component pour in place type of foam. The manufacturing process is much more involved. The raw ingredients are mixed together under controlled conditions and dispensed into a mould. The filled mould is then sealed, placed in a large press and heated while remaining clamped shut. After this process is completed, a slab of solid material emerges from the mould. The material is then expanded in a hot water bath to final density and cured. The cured blocks are then cut into sheets of a varying thickness, depending on customer requirements. The process and formulation combine to give the foams their closed-cell nature and excellent physical properties.

PVC foams can be formulated in rigid or ductile versions. Rigid PVC foams, sometimes referred to as cross linked, have higher heat and solvent
resistance than ductile foams. In addition, the physical properties are generally 20-40% higher. Shear strain to failure for rigid PVC foams varies with density between 12-30%. Ductile PVC foams, sometimes referred to as linear, have higher shear elongation to break, typically in excess of 40%. However, ductile foams have lower physical properties, heat and solvent resistance for a given density.

Marine grade rigid PVC foams can be processed up to 180F and used continuously up to 160F. They do not get brittle at cold temperatures and can even be used in cryogenic applications. Specialized grades of PVC foams can be processed up to 250F and used continuously up to 190F. Ductile PVC foams can be processed up to 150F and used continuously at 120F.

PVC foams are widely used core materials in the marine, surface transport, aerospace, and wind energy industries due to their consistent density, high moisture resistance, and excellent physical properties.

Other Foam Cores

Foams are one of the most common forms of core material. They can be manufactured from a variety of synthetic polymers including polyvinyl chloride (PVC), polystyrene (PS), polyurethane (PU), polymethacrylamide, polyetherimide (PEI) and styreneacrylonitrile (SAN). They can be supplied in densities ranging from less than 30kg/m3 to more than 300kg/m3, although the most used densities for composite structures range from 40 to 200 kg/m3. They are also available in a variety of thicknesses, typically from 5mm to 50mm.

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PVC Foam

Closed-cell polyvinyl chloride (PVC) foams are one of the most commonly used core materials for the construction of high performance sandwich structures. Although strictly they are a chemical hybrid of PVC and polyurethane, they tend to be referred to simply as 'PVC foams'.

PVC foams offer a balanced combination of static and dynamic properties and good resistance to water absorption. They also have a large operating temperature range of typically -240°C to +80°C (-400°F to +180°F), and are resistant to many chemicals. Although PVC foams are generally flammable, there are fire-retardant grades that can be used in many fire-critical applications, such as train components. When used as a core for sandwich construction with FRP skins, its reasonable resistance to styrene means that it can be used safely with polyester resins and it is therefore popular in many industries. It is normally supplied in sheet form, either plain, or grid-scored to allow easy forming to shape.

There are two main types of PVC foam: cross linked and uncross linked with the uncross linked foams sometimes being referred to as 'linear'. The uncross linked foams (such as Airex R63.80) are tougher and more flexible, and are easier to heat-form around curves. However, they have some lower mechanical properties than an equivalent density of cross-linked PVC, and a lower resistance to elevated temperatures and styrene. Their cross-linked counterparts are harder but more brittle and will produce a stiffer panel, less susceptible to softening or creeping in hot climates. Typical cross-linked PVC products include the Herex C-series of foams, Divinycell H and HT grades and Polimex Klegecell and Termanto products.

A new generation of toughened PVC foams is now also becoming available which trade some of the basic mechanical properties of the cross-linked PVC foams for some of the improved toughness of the linear foams. Typical products include Divincell HD grade.

Owing to the nature of the PVC/polyurethane chemistry in cross-linked PVC foams, these materials need to be thoroughly sealed with a resin coating before they can be safely used with low-temperature curing prepregs. Although special heat stabilisation treatments are available for these foams, these treatments are primarily designed to improve the dimensional stability of the foam, and reduce the amount of gassing that is given off during elevated temperature processing.

Polystyrene Foams

Although polystyrene foams are used extensively in sail and surf board manufacture, where their light weight (40kg/m3), low cost and easy to sand characteristics are of prime importance, they are rarely employed in high performance component construction because of their low mechanical properties. They cannot be used in conjunction with polyester resin systems because they will be dissolved by the styrene present in the resin.

PMI (Polymethacrylimide) Foams

For a given density, PMI (polymethacrylimide) foams such as ROHACELL® offer some of the highest overall strengths and stiffnesses of foam cores. Their characteristics also include high dimensional stability, a closed cell structure and high fatigue life, and they can be cured and used at elevated temperatures. Their overall cost and performance characteristics mean that, to date, their use has mainly been in higher performance composite parts such as helicopter rotor blades, ailerons and stringer profiles in pressure bulkheads.

Styrene acrylonitrile (SAN) co-polymer Foams

SAN foams behave in a similar way to toughened cross-linked PVC foams. They have most of the static properties of cross-linked PVC cores, yet have much higher elongations and toughness. They are therefore able to absorb impact levels that would fracture b

SAN foams are replacing linear PVC foams in many applications since they have much of the linear PVC's toughness and elongation, yet have a higher temperature performance and better static properties. However, they are still thermo formable, which helps in the manufacture of curved parts. Heatstabilised grades of SAN foams can also be more simply used with low-temperature curing prepregs, since they do not have the interfering chemistry inherent in the PVC's. Typical SAN products include ATC Core-Cell's A-series foams.

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Other thermoplastics

As new techniques develop for the blowing of foams from thermoplastics, the range of expanded materials of this type continues to increase. Typical is PEI foam, an expanded polyetherimide/polyether sulphone, which combines outstanding fire performance wit

Honeycomb Cores

Honeycomb cores are available in a variety of materials for sandwich structures. These range from paper and card for low strength and stiffness, low load applications (such as domestic internal doors) to high strength and stiffness, extremely lightweight components for aircraft structures. Honeycombs can be processed into both flat and curved composite structures, and can be made to conform to compound curves without excessive mechanical force or heating.



Thermoplastic honeycombs are usually produced by extrusion, followed by slicing to thickness. Other honeycombs (such as those made of paper and aluminium) are made by a multi-stage process. In these cases large thin sheets of the material (usually 1.2x2.4m) are printed with alternating, parallel, thin stripes of adhesive and the sheets are then stacked in a heated press while the adhesive cures. In the case of aluminium honeycomb the stack of sheets is then sliced through its thickness. The slices (known as 'block form') are later gently stretched and expanded to form the sheet of continuous hexagonal cell shapes.
In the case of paper honeycombs, the stack of bonded paper sheets is gently expanded to form a large block of honeycomb, several feet thick. Held in its expanded form, this fragile paper honeycomb block is then dipped in a tank of resin, drained and cured in an oven. Once this dipping resin has cured, the block has sufficient strength to be sliced into the final thicknesses required.

In both cases, by varying the degree of pull in the expansion process, regular hexagon-shaped cells or over-expanded (elongated) cells can be produced, each with different mechanical and handling/drape properties. Due to this bonded method of construction, a honeycomb will have different mechanical properties in the 0° and 90° directions of the sheet.

While skins are usually of FRP, they may be almost any sheet material with the appropriate properties, including wood, thermoplastics (e.g. melamine) and sheet metals, such as aluminium or steel. The cells of the honeycomb structure can also be filled with a rigid foam. This provides a greater bond area for the skins, increases the mechanical properties of the core by stabilising the cell walls and increases thermal and acoustic insulation properties.

Properties of honeycomb materials depend on the size (and therefore frequency) of the cells and the thickness and strength of the web material. Sheets can range from typically 3-50 mm in thickness and panel dimensions are typically 1200 x 2400mm, although it is possible to produce sheets up to 3m x 3m.

Honeycomb cores can give stiff and very light laminates but due to their very small bonding area they are almost exclusively used with high-performance resin systems such as epoxies so that the necessary adhesion to the laminate skins can be achieved.

Aluminium honeycomb

Aluminium honeycomb produces one of the highest strength/weight ratios of any structural material. There are various configurations of the adhesive bonding of the aluminium foil which can lead to a variety of geometric cell shapes (usually hexagonal). Properties can also be controlled by varying the foil thickness and cell size. The honeycomb is usually supplied in the unexpanded block form and is stretched out into a sheet on-site.

Despite its good mechanical properties and relatively low price, aluminium honeycomb has to be used with caution in some applications, such as large marine structures, because of the potential corrosion problems in a salt-water environment. In this situation care also has to be exercised to ensure that the honeycomb does not come into direct contact with carbon skins since the conductivity can aggravate galvanic corrosion. Aluminium honeycomb also has the problem that it has no 'mechanical memory'. On impact of a cored laminate, the honeycomb will deform irreversibly whereas the FRP skins, being resilient, will move back to their original position. This can result in an area with an unbonded skin with much reduced mechanical properties.

Nomex honeycomb

Nomex honeycomb is made from Nomex paper - a form of paper based on Kevlar, rather than cellulose fibres. The initial paper honeycomb is usually dipped in a phenolic resin to produce a honeycomb core with high strength and very good fire resistance. It is widely used for lightweight interior panels for aircraft in conjunction with phenolic resins in the skins. Special grades for use in fire retardant applications (e.g. public transport interiors) can also be made which have the honeycomb cells filled with phenolic foam for added bond area and insulation.

Nomex honeycomb is becoming increasingly used in high-performance non-aerospace components due to its high mechanical properties, low density and good long-term stability. However, it is considerably more expensive than other core materials.

Thermoplastic honeycomb

Core materials made of other thermoplastics are light in weight, offering some useful properties and possibly also making for easier recycling.

Their main disadvantage is the difficulty of achieving a good interfacial bond between the honeycomb and the skin.

ABS - for rigidity, impact strength, toughness, surface hardness and dimensional stability Polycarbonate - for UV-stability, excellent light transmission, good heat resistance & self-extinguishing properties Polypropylene - for good chemical resistance Polyethylene - a general-purpose low-cost core material

Wood Cores

Wood can be described as 'nature's honeycomb', as it has a structure that, on a microscopic scale, is similar to the cellular hexagonal structure of synthetic honeycomb. When used in a sandwich structure with the grain running perpendicular to the plane of the skins, the resulting component shows properties similar to those made with man-made honeycombs. However, despite various chemical treatments being available, all wood cores are susceptible to moisture attack and will rot if not well surrounded by laminate or resin.

Balsa

The most commonly used wood core is end-grain balsa. Balsa wood cores first appeared in the 1940's in flying boat hulls, which were aluminium skinned and balsa-cored to withstand the repeated impact of landing on water. This performance led the marine industry to begin using end-grain balsa as a core material in FRP construction. Apart from its high compressive properties, its advantages include being a good thermal insulator offering good acoustic absorption. The material will not deform when heated and acts as an insulating and ablative layer in a fire, with the core charring slowly, allowing the non-exposed skin to remain structurally sound. It also offers positive flotation and is easily worked with simple tools and equipment.

Balsa core is available as contoured end-grain sheets 3 to 50mm thick on a backing fabric, and rigid end-grain sheets up to 100mm thick. These sheets can be provided ready resin-coated for vacuum-bagging, prepreg or pressure-based manufacturing processes such as RTM. One of the disadvantages of balsa is its high minimum density, with 100kg/m3 being a typical minimum. This problem is exacerbated by the fact that balsa can absorb large quantities of resin during lamination, although pre-sealing the foam can reduce this. Its use is therefore normally restricted to projects where optimum weight saving is not required or in locally highly stressed areas.

Cedar

Another wood that is used sometimes as a core material is cedar. In marine construction it is often the material used as the 'core' in strip-plank construction, with a composite skin on each side and the grain of the cedar running parallel to the laminate faces. The cedar fibres run along the length of the boat giving fore and aft stiffness while the fibres in the FRP skins are laid at ±45° giving torsional rigidity, and protecting the wood.

Other Core Materials

Although not usually regarded as true sandwich cores, there are a number of thin, low-density 'fabric-like' materials which can be used to slightly lower the density of a single-skin laminate. Materials such as Coremat and Spheretex consist of a non-woven 'felt-like' fabric full of density-reducing hollow spheres. They are usually only 1-3mm in thickness and are used like another layer of reinforcement in

the middle of a laminate, being designed to 'wet out' with the laminating resin during construction. However, the hollow spheres displace resin and so the resultant middle layer, although much heavier than a foam or honeycomb core, is lower in density than the equivalent thickness of glass fibre laminate. Being so thin they can also conform easily to 2-D curvature, and so are quick and easy to use.

Comparison of Core Mechanical Properties

The figures below give the shear strength and compressive strength of some of the core materials described, plotted against their densities. All the figures have been obtained from manufacturers' data sheets.
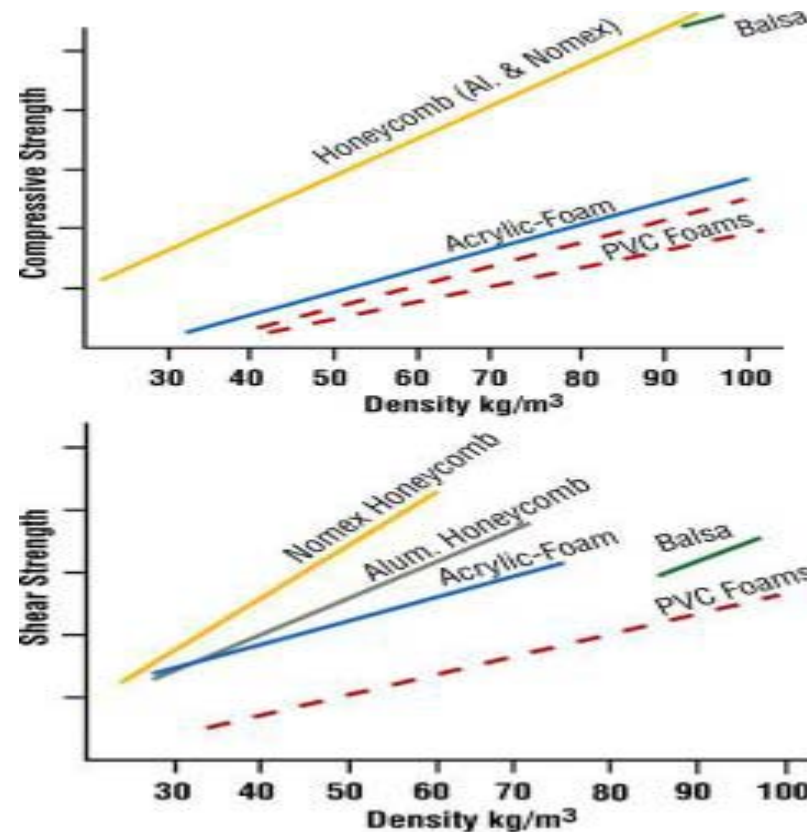
As might be expected, all the cores show an increase in properties with increasing density. However, other factors, besides density, also come into play when looking at the weight of a core in a sandwich structure. For example, low density foam materials, while contributing very little to the weight of a sandwich laminate, often have a very open surface cell structure which can mean that a large mass of resin is absorbed in their bond lines. The lower the density of the foam, the larger are the cells and the worse is the problem. Honeycombs, on the other hand, can be very good in this respect since a well-formulated adhesive will form a small bonding fillet only around the cell walls.

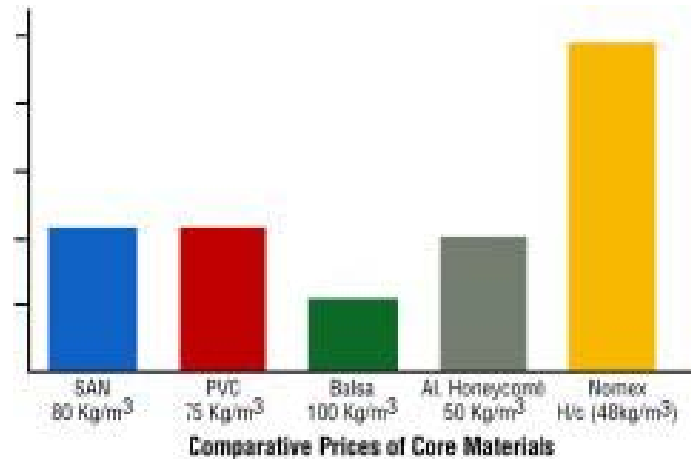**PRO-LITE Technical Information**
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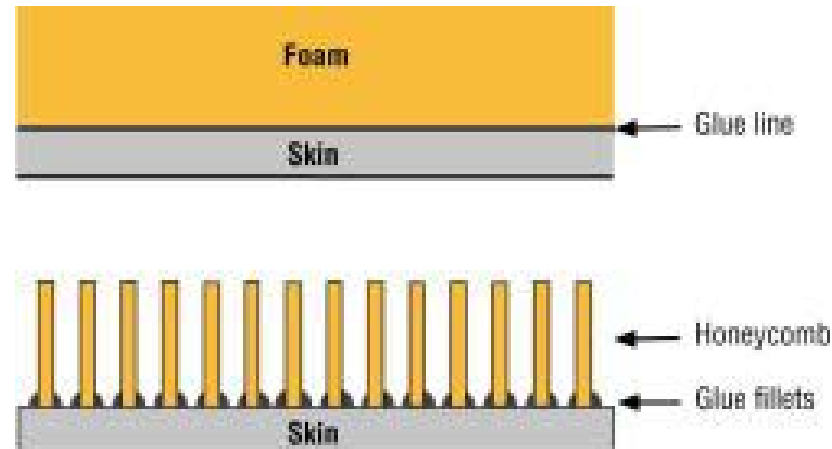


Finally, consideration needs to be given to the form a core is used in to ensure that it fits the component well. The weight savings that cores can offer can quickly be used up if cores fit badly, leaving large gaps that require filling with adhesive. Scrim-backed foam or balsa, where little squares of the core are supported on a lightweight scrim cloth, can be used to help cores conform better to a curved surface. Contour-cut foam, where slots are cut partway through the core from opposite sides achieves a similar effect. However, both these cores still tend to use quite large amounts of adhesive since the slots between each foam square need filling with resin to produce a good structure.

In weight-critical components the use of foam cores which are thermo formable should be considered. These include the linear PVC's and the SAN foams which can all be heated to above their softening points and pre-curved to fit a mould shape. For honeycombs, over-expanded forms are the most widely used when fitting the core to a compound curve, since with different expansion patterns a wide range of conformability can be achieved.

**Comparative Prices of Core Materials**

| SAN 80 Kg/m³ | PVC 75 Kg/m³ | Balsa 100 Kg/m³ | Al. Honeycomb 50 Kg/m³ | Nomex H/c (48kg/m³) |

Manufacturing Processes

Taking composite materials as a whole, there are many different material options to choose from in the areas of resins, fibres and cores, all with their own unique set of properties such as strength, stiffness, toughness, heat resistance, cost, production rate etc.. However, the end properties of a composite part produced from these different materials is not only a function of the individual properties of the resin matrix and fibre (and in sandwich structures, the core as well), but is also a function of the way in which the materials themselves are designed into the part and also the way in which they are processed. This section compares a few of the commonly used composite production methods and presents some of the factors to be borne in mind with each different process, including the influence of each process on materials selection.

Spray Lay-up

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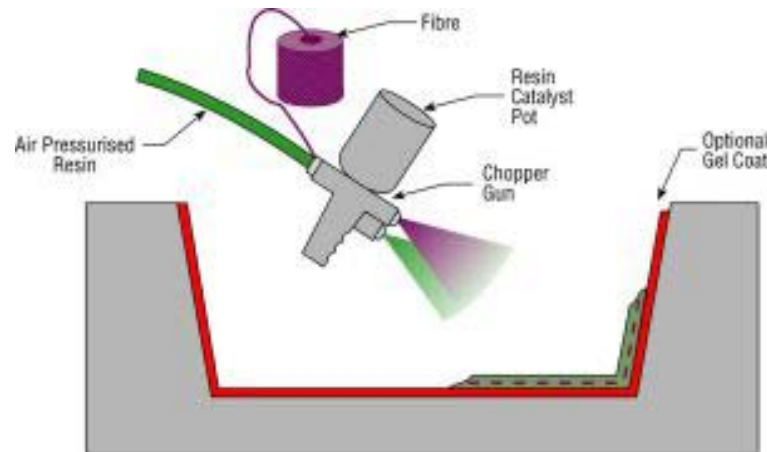


Description
Fibre is chopped in a hand-held gun and fed into a spray of catalysed resin directed at the mould. The deposited materials are left to cure under standard atmospheric conditions.

Materials Options:
Resins: Primarily polyester.
Fibres: Glass roving only.
Cores: None. These have to be incorporated separately.

Main Advantages:
i) Widely used for many years.
ii) Low cost way of quickly depositing fibre and resin.

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iii) Low cost tooling.

Main Disadvantages: i) Laminates tend to be very resin-rich and therefore excessively heavy.  ii) Only short fibres are incorporated which severely limits the mechanical properties of the laminate. iii) Resins need to be low in viscosity to be sprayable. This generally compromises their mechanical/thermal properties. iv) The high styrene contents of spray lay-up resins generally means that they have the potential to be more harmful and their lower viscosity means that they have an increased tendency to penetrate clothing etc. (v) Limiting airborne styrene concentrations to legislated levels is becoming increasingly difficult.

Typical Applications:
Simple enclosures, lightly loaded structural panels, e.g. caravan bodies, truck
fairings, bathtubs, shower trays, some small dinghies.

Wet lay-up/Hand Lay-up
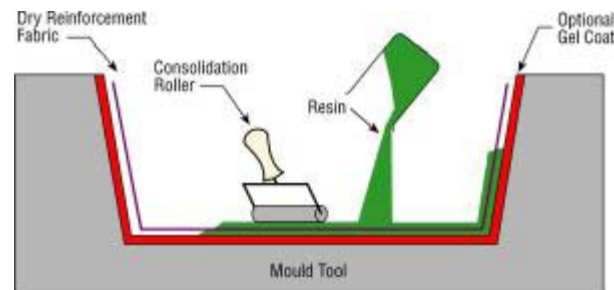


Description
Resins are impregnated by hand into fibres which are in the form of woven, knitted, stitched or bonded fabrics. This is usually accomplished by rollers or brushes, with an increasing use of nip-roller type impregnators for forcing resin into the fabrics by means of rotating rollers and a bath of resin. Laminates are left to cure under standard atmospheric conditions.

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Materials Options:
Resins: Any, e.g. epoxy, polyester, vinylester, phenolic.

Fibres: Any, although heavy aramid fabrics can be hard to wet-out by hand.
Cores: Any.

Main Advantages: i) Widely used for many years. ii) Simple principles to teach. iii) Low cost tooling, if room-temperature cure resins are used.   iv) Wide choice of suppliers and material types. v) Higher fibre contents, and longer fibres than with spray lay-up.

Main Disadvantages: i) Resin mixing, laminate resin contents, and laminate quality are very dependent on the skills of laminators. Low resin content laminates cannot usually be achieved without the incorporation of excessive quantities of voids.   ii) Health and safety considerations of resins. The lower molecular weights of hand lay-up resins generally means that they have the potential to be more harmful than higher molecular weight products. The lower viscosity of the resins also means that they have an increased tendency to penetrate clothing etc. iii) Limiting airborne styrene concentrations to legislated levels from polyesters and vinylesters is becoming increasingly hard without expensive extraction systems. iv) Resins need to be low in viscosity to be workable by hand. This generally compromises their mechanical/thermal properties due to the need for high diluent/styrene levels.

Typical Applications:
Standard wind-turbine blades, production boats, architectural mouldings

Vacuum Bagging
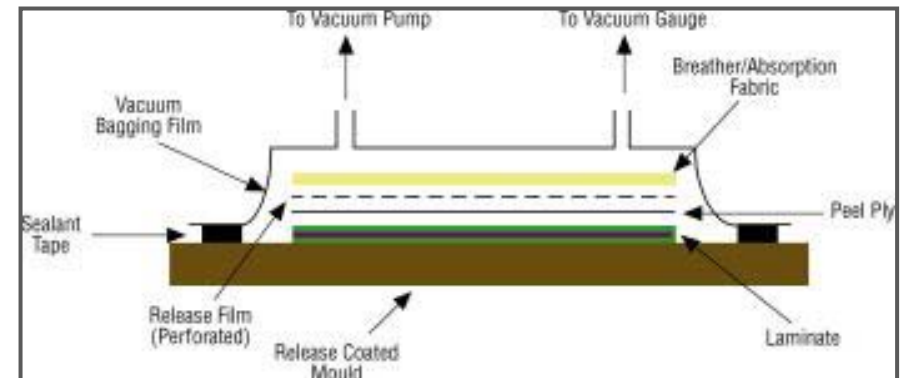
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Description
This is basically an extension of the wet lay-up process described above where pressure is applied to the laminate once laid-up in order to improve its consolidation. This is achieved by sealing a plastic film over the wet laid-up laminate and onto the tool. The air under the bag is extracted by a vacuum pump and thus up to one atmosphere of pressure can be applied to the laminate to consolidate it.

Materials Options:
Resins: Primarily epoxy and phenolic. Polyesters and vinylesters may have

problems due to excessive extraction of styrene from the resin by the vacuum pump. Fibres: The consolidation pressures mean that a variety of heavy fabrics can be wet-out. Cores: Any.

Main Advantages: i) Higher fibre content laminates can usually be achieved than with standard wet lay-up techniques. ii) Lower void contents are achieved than with wet lay-up.   iii) Better fibre wet-out due to pressure and resin flow throughout structural fibres, with excess into bagging materials. iv) Health and safety: The vacuum bag reduces the amount of volatiles emitted during cure.

Main Disadvantages: i) The extra process adds cost both in labour and in disposable bagging materials ii) A higher level of skill is required by the operators   iii) Mixing and control of resin content still largely determined by operator skill

Typical Applications:
Large, one-off cruising boats, racing car components, core-bonding in production boats.

Filament Winding
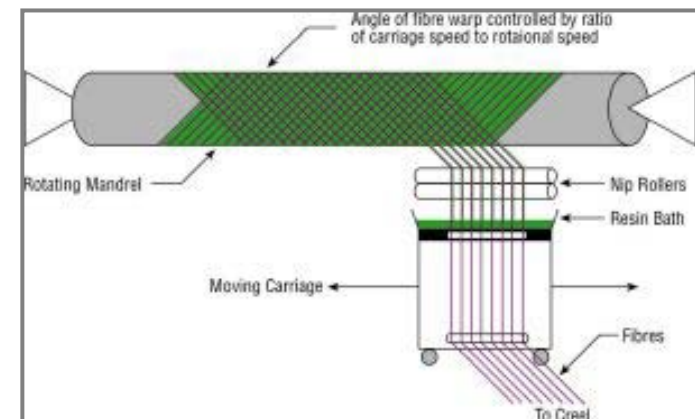
Description
This process is primarily used for hollow, generally circular or oval sectioned components, such as pipes and tanks. Fibre tows are passed through a resin bath before being wound onto a mandrel in a variety of orientations, controlled by the fibre feeding mechanism, and rate of rotation of the mandrel.

Materials Options:
Resins: Any, e.g. epoxy, polyester, vinylester, phenolic.
Fibres: Any. The fibres are used straight from a creel and not woven or
stitched into a fabric form.
Cores: Any, although components are usually single skin.

Main Advantages: i) This can be a very fast and therefore economic method of laying material down. ii) Resin content can be controlled by metering the resin onto each fibre tow through nips or dies. iii) Fibre cost is minimised since there is no secondary process to convert fibre into fabric prior to use. iv) Structural properties of laminates can be very good since straight fibres can be laid in a complex pattern to match the applied loads.

Main Disadvantages: i) The process is limited to convex shaped components. ii) Fibre cannot easily be laid exactly along the length of a component.   iii) Mandrel costs for large components can be high. iv) The external surface of the component is unmoulded, and therefore cosmetically unattractive. v) Low viscosity resins usually need to be used with their attendant lower mechanical and health and safety properties.
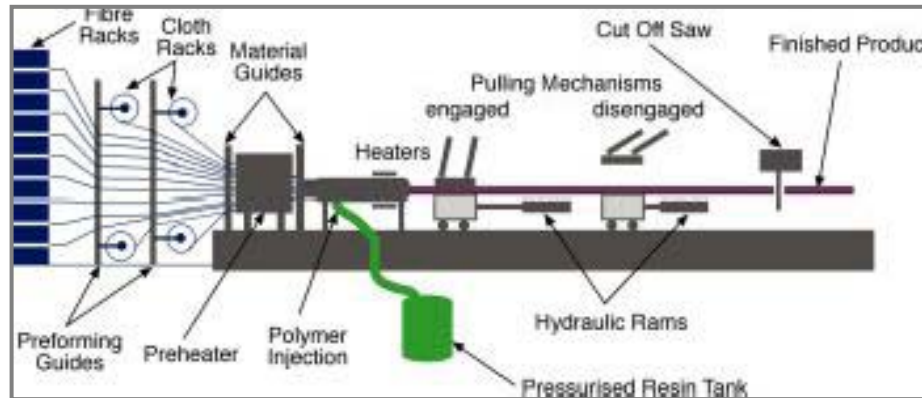
Typical Applications:
Chemical storage tanks and pipelines, gas cylinders, fire-fighters' breathing
tanks.

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Pultrusion



Description
Fibres are pulled from a creel through a resin bath and then on through a heated die. The die completes the impregnation of the fibre, controls the resin content and cures the material into its final shape as it passes through the die. This cured profile is then automatically cut to length. Fabrics may also be introduced into the die to provide fibre direction other than at 0°. Although pultrusion is a continuous process, producing a profile of constant cross-section, a variant known as 'pulforming' allows for some variation to be introduced into the cross-section. The process pulls the materials through the die for impregnation, and then clamps them in a mould for curing. This makes the process non-continuous, but accommodating of small changes in cross-section.

Materials Options:
Resins: Generally epoxy, polyester, vinylester and phenolic.

Fibres: Any.
Cores: Not generally used.

Main Advantages: i) This can be a very fast, and therefore economic, way of impregnating and curing materials. ii) Resin content can be accurately controlled. iii) Fibre cost is minimised since the majority is taken from a creel. iv) Structural properties of laminates can be very good since the profiles have very straight fibres and high fibre volume fractions can be obtained. v) Resin impregnation area can be enclosed thus limiting volatile emissions.
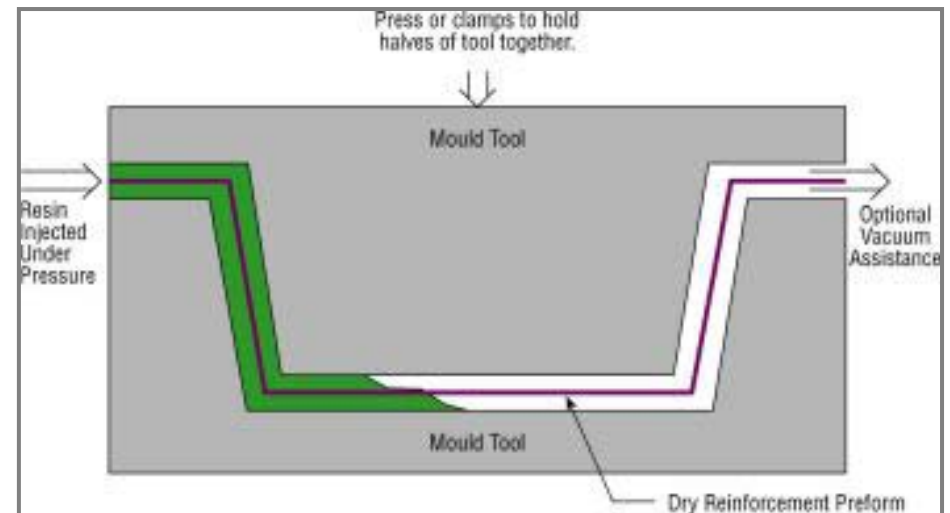
Main Disadvantages:

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i) Limited to constant or near constant cross-section components
ii) Heated die costs can be high.

Typical Applications:
Beams and girders used in roof structures, bridges, ladders, frameworks.

Resin Transfer Moulding (RTM)



Description
Fabrics are laid up as a dry stack of materials. These fabrics are sometimes pre-pressed to the mould shape, and held together by a binder. These 'preforms' are then more easily laid into the mould tool. A second mould tool is then clamped over the first, and resin is injected into the cavity. Vacuum can also be applied to the mould cavity to assist resin in being drawn into the fabrics. This is known as Vacuum Assisted Resin Injection (VARI). Once all the fabric is wet out, the resin inlets are closed, and the laminate is allowed to cure. Both injection and cure can take place at either ambient or elevated temperature.

Materials Options: Resins: Generally epoxy, polyester, vinylester and phenolic, although high temperature resins such as bismaleimides can be used at elevated process temperatures. Fibres: Any. Stitched materials work well in this process since the gaps allow rapid resin transport. Some specially developed fabrics can assist with resin flow.
Cores: Not honeycombs, since cells would fill with resin, and pressures

involved can crush some foams.

Main Advantages:
i) High fibre volume laminates can be obtained with very low void contents.
ii) Good health and safety, and environmental control due to enclosure of resin.
iii) Possible labour reductions.
iv) Both sides of the component have a moulded surface.

Main Disadvantages: i) Matched tooling is expensive, and heavy in order to withstand pressures.   ii) Generally limited to smaller components. iii) Unimpregnated areas can occur resulting in very expensive scrap parts.

Typical Applications:
Small complex aircraft and automotive components, train seats.

Other Infusion Processes - SCRIMP, RIFT, VARTM

Description
Fabrics are laid up as a dry stack of materials as in RTM. The fibre stack is then covered with peel ply and a knitted type of non-structural fabric. The whole dry stack is then vacuum bagged, and once bag leaks have been eliminated, resin is allowed to flow into the laminate. The resin distribution over the whole laminate is aided by resin flowing easily through the non-structural fabric, and
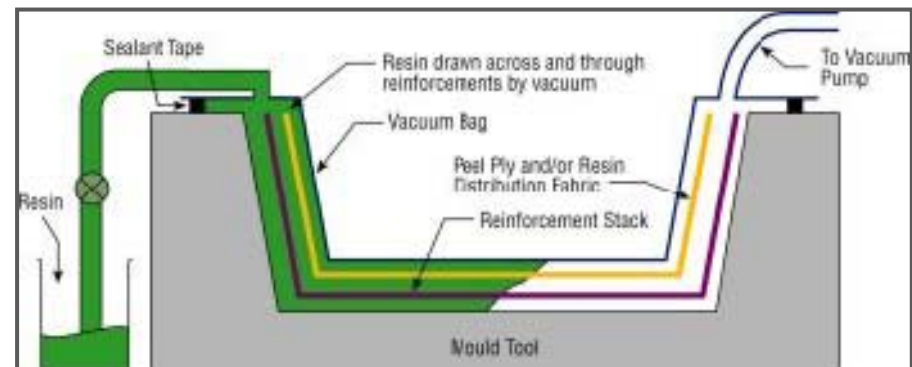
wetting the fabric out from above.

Materials Options:
Resins: Generally epoxy, polyester and vinylester.
Fibres: Any conventional fabrics. Stitched materials work well in this process
since the gaps allow rapid resin transport.
Cores: Any except honeycombs.

Main Advantages:
i) As RTM above, except only one side of the component has a moulded
finish.
ii) Much lower tooling cost due to one half of the tool being a vacuum bag, and
less strength being required in the main tool.
iii) Large components can be fabricated.

iv) Standard wet lay-up tools may be able to be modified for this process.
v) Cored structures can be produced in one operation.

Main Disadvantages: i) Relatively complex process to perform well. ii) Resins must be very low in viscosity, thus comprising mechanical properties. iii) Unimpregnated areas can occur resulting in very expensive scrap parts.   iv) Some elements of this process are covered by patents (SCRIMP).
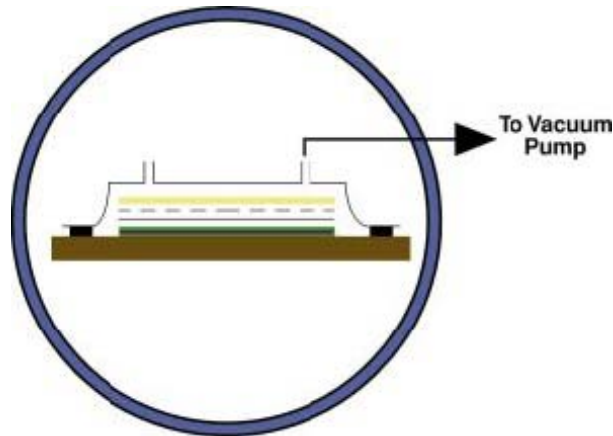
Typical Applications:
Semi-production small yachts, train and truck body panels.

Prepreg Moulding

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To Vacuum Pump

Description
Fabrics and fibres are pre-impregnated by the materials manufacturer, under heat and pressure or with solvent, with a pre-catalysed resin. The catalyst is largely latent at ambient temperatures giving the materials several weeks, or sometimes months, of useful life when defrosted. However to prolong storage life the materials are stored frozen. The resin is usually a near-solid at ambient temperatures, and so the pre-impregnated materials (prepregs) have a light sticky feel to them, such as that of adhesive tape. Unidirectional materials take fibre direct from a creel, and are held together by the resin alone. The prepregs are laid up by hand or machine onto a mould surface, vacuum bagged and then heated to typically 120-180°C. This allows the resin to initially reflow and eventually to cure. Additional pressure for the moulding is usually provided by an autoclave (effectively a pressurised oven) which can apply up to 5 atmospheres to the laminate.

Materials Options: Resins: Generally epoxy, polyester, phenolic and high temperature resins such as polyimides, cyanate esters and bismaleimides. Fibres: Any. Used either direct from a creel or as any type of fabric.   Cores: Any, although special types of foam need to be used due to the elevated temperatures involved in the process.
Main Advantages: i) Resin/catalyst levels and the resin content in the fibre are accurately set by the materials manufacturer. High fibre contents can be safely achieved. ii) The materials have excellent health and safety characteristics and are clean to work with. iii) Fibre cost is minimised in unidirectional tapes since there is no secondary process to convert fibre into fabric prior to use. iv) Resin chemistry can be optimised for mechanical and thermal performance, with the high viscosity resins being impregnable due to the manufacturing

process. v) The extended working times (of up to several months at room temperatures) means that structurally optimised, complex lay-ups can be readily achieved. vi) Potential for automation and labour saving.

Main Disadvantages:
i) Materials cost is higher for preimpregnated fabrics.
ii) Autoclaves are usually required to cure the component. These are
expensive, slow to operate and limited in size.
iii) Tooling needs to be able to withstand the process temperatures involved
iv) Core materials need to be able to withstand the process temperatures and
pressures.

Typical Applications:
Aircraft structural components (e.g. wings and tail sections), F1 racing cars,
sporting goods such as tennis racquets and skis.

Autoclave Design and Construction

Maximising performance of thermoset composite materials, requires, amongst other things, an increase in the fibre to resin ratio and removal of all air voids. This can be achieved by subjecting the material to elevated pressures and temperatures. As described in the vacuum bagging section, some pressure can be exerted by applying a vacuum to a sealed bag containing the resin/fibre lay-up. However, to achieve three dimensional, uniform pressures of greater than 1 bar, additional external pressure is required. The most controllable method of achieving this for an infinite variety of different shapes and sizes is by applying a compressed gas into a pressure vessel containing the composite lay-up. In practice, this is achieved in an autoclave.

Autoclaves - A Brief History

Autoclaves have been used in industry for many decades. As technology has progressed so has autoclave design, initially from basic

riveted steam heated vessels to vessels fabricated utilising the latest welding techniques with highly sophisticated computerised control systems.



The industries that make use of autoclaves have also evolved over the years. Initially used in the textile, timber, food, sterilising and rubber industries, autoclaves are now essential items in the advanced composites and investment casting industries.



For use in the production of advanced composite materials, a hot atmosphere autoclave has to achieve the following criteria:

        Fail to safety, safety systems
        Achieve the required internal environment (i.e. heat and pressure)
        Programmable temperature control and uniform temperature
distribution

Programmable pressure control
Computerised process control, monitoring and data logging
Achieve the required internal environment (i.e. heat and pressure)

Safety Systems

Safety is of paramount importance when working with autoclaves. They are generally situated in an area where personnel are present. To put it in perspective, standing in front of a 1m diameter autoclave pressurised to just 0.5bar (typical working pressures are 5-7bar), is like standing underneath a 4 ton weight.
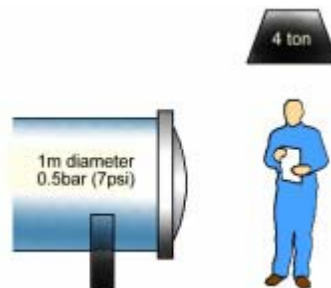


The UK Health and Safety Executive has produced a Guidance Note PM73 'Safety at Autoclaves' so that safety devices are fitted to:

Ensure the autoclave cannot be pressurised without the door being fully locked
Ensure the autoclave door cannot be opened until the pressure has safely vented
Warn the operator of any residual pressure, prior to door opening
Prevent the autoclave from opening violently due to residual low
pressure

Prevent the door from opening until the atmosphere and temperature are at a safe level

Due to the critical nature of these devices, all must be designed to 'fail to safety'. They can be of mechanical or electrical design, but any electrical devices should be 'dual circuit cross monitored'.
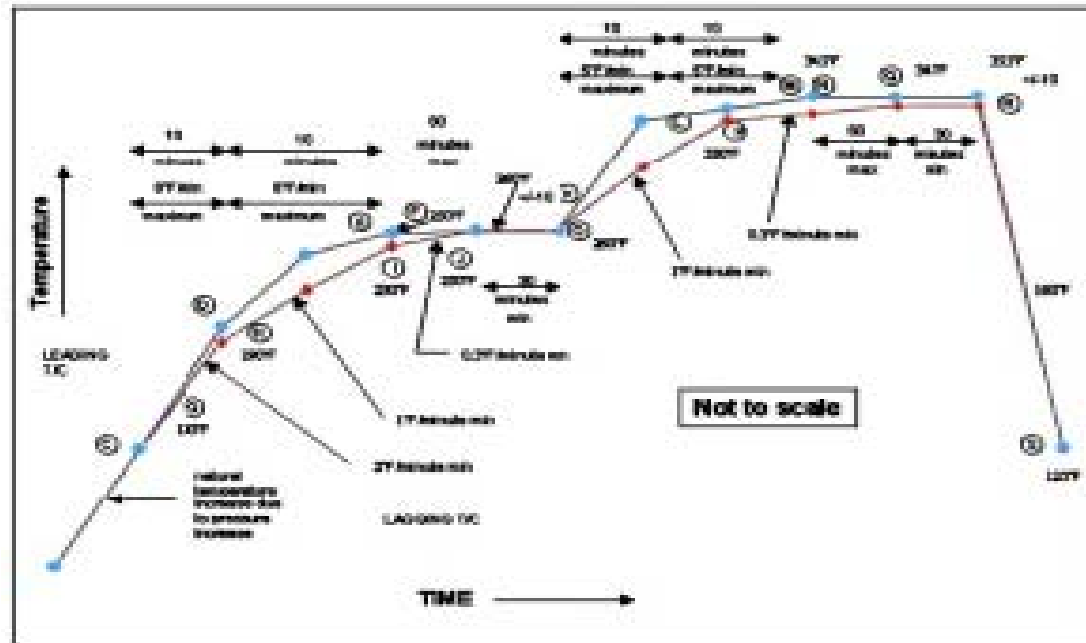
Temperature Control

Temperature control is of critical importance where resin systems are involved and the ability to achieve a uniform temperature inside the autoclave, within the tight tolerances stipulated by the aerospace industry, is of paramount importance. There are several systems employed by autoclave manufacturers to achieve this, these fall into two main categories, direct and indirect heating systems. Indirect heating systems have the heat source outside the autoclave and transfer heat into the working envelope by means of a heat exchanger. Direct heating systems have their heat source within the autoclave and aim to maximise the heat transfer from the elements to the pressure medium.

Electrically heated and gas heated systems are available. The choice of heating system is influenced by various factors such as controllability, cleanliness, efficiency, maintenance requirements and running costs. When considering running costs, it is important to evaluate the system as a whole.

Control systems are designed to manage cure cycle temperature strategies in accordance with the desired criteria. Temperature profiles are generally made up of a series of heating gradients, dwells and cooling gradients. The graph below shows a typical temperature profile specification.

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Pressurisation Control

Autoclave systems are designed to allow the user to set the internal pressure conditions to the required level at any time during the cure cycle. As in the temperature control, this generally takes the form of a series of pressurisation gradients, dwells and de-pressurisation gradients. Accurate control is achieved through the use of modulating valves on the inlet and exhaust pipe work systems of the autoclave.

Safety is of paramount importance, when working with pressurised systems. Strict design codes (e.g. PD5500, ASME) are specified to ensure the necessary safety margins are in place. All new autoclaves undergo a hydro test, pressurising the vessel with water, up to a pressure of 1.5 times the stipulated maximum working pressure, prior to gaining certification for use. In addition to this all vessels are

fitted with a relief valve, typically set to 10% above the stipulated maximum working pressure, which will release in the event of a pressure overload. This safety valve is a mechanical device ensuring that a dangerous situation is avoided even if the electronic control system devices fail.

Vacuum Control

The bagged composite lay-up arrives at the autoclave with a vacuum already drawn. The bag is then connected to the autoclave vacuum system via flexible umbilical hoses fitted inside the autoclave. During the cure cycle the vacuum level in each bagged component is monitored and in the event that a leak or burst condition occurs, the offending bag is automatically isolated from the rest of the vacuum system, thus preventing positive pressure from entering other bags via a common manifold. During the cure process, volatile substances are created within the bag. These are drawn away by the vacuum system and filtered out by a resin trap fitted in the main vacuum draw line. Systems are available with the facility to vary the level of vacuum drawn within the bag. This is of particular relevance when honeycomb structures are produced.

Computerised Process Control, Monitoring and Data Logging

The most significant advances in autoclave technology over the last 10 years have been in the field of electronic control systems. The sophisticated systems of today are a far cry from the manually controlled systems of yesteryear. Due to ever increasing pressures on productivity, there is a constant drive to achieve reduced cure cycle times, while maintaining product quality and repeatability. The majority of today's autoclaves, supplied to the advanced composites industry, are supplied with a PC and SCADA software. These enable the user to monitor the cure parameters in real-time both for data-logging purposes and also for cure optimisation.

The Future

It has been said for years that with the development of modern thermoplastic composites and resin transfer moulding manufacturing processes that the future for composite curing autoclaves is uncertain.



The quest however for lighter, faster and more agile fighter aircraft, larger passenger aircraft and increasingly higher performance

motor sport vehicles, has lead to an increase both in the size and sophistication of the modern day autoclave in increasing numbers. Whilst the search is still on for alternative curing techniques and increased performance from RTM manufactured components, the autoclave still serves as the every day workhorse for the world's aerospace and motor sport industries and would appear to still have an exciting future.

Low Temperature Prepreg Moulding
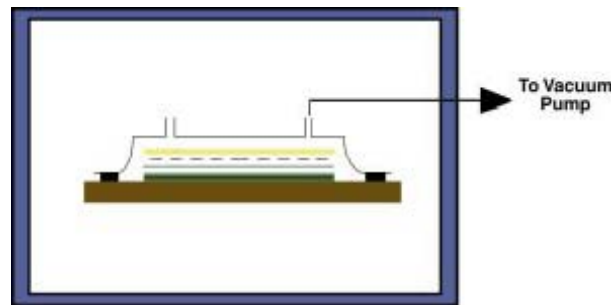


Description

Low Temperature Curing prepregs are made exactly as conventional prepregs but have resin chemistries that allow cure to be achieved at temperatures from 60-100°C. At 60°C, the working life of the material may be limited to as little as a week, but above this working times can be as long as several months. The flow profiles of the resin systems allow for the use of vacuum bag pressures alone, avoiding the need for autoclaves.

Materials Options:
Resins: Generally only epoxy.
Fibres: Any. As for conventional prepregs.
Cores: Any, although standard PVC foam needs special care.


Main Advantages: i) All of the advantages ((i)-(vi)) associated with the use of conventional prepregs are incorporated in low-temperature curing prepregs.   ii) Cheaper tooling materials, such as wood, can be used due to the lower cure temperatures

involved. iii) Large structures can be readily made since only vacuum bag pressure is required, and heating to these lower temperatures can be achieved with simple hot-air circulated ovens, often built in-situ over the component.   iv) Conventional PVC foam core materials can be used, providing certain procedures are followed. v) Lower energy cost.

Main Disadvantages: i) Materials cost is still higher than for non-preimpregnated fabrics.   ii) An oven and vacuum bagging system is required to cure the component. iii) Tooling needs to be able to withstand above-ambient temperatures involved (typically 60-100°C). iv) Still an energy cost associated with above-ambient cure temperature.

Typical Applications:
High-performance wind-turbine blades, large racing and cruising yachts,
rescue craft, train components.

Resin Film Infusion (RFI)
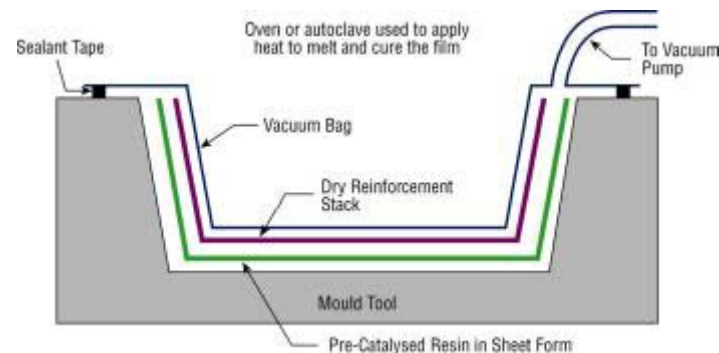


Description
Dry fabrics are laid up interleaved with layers of semi-solid resin film supplied on a release paper. The lay-up is vacuum bagged to remove air through the dry fabrics, and then heated to allow the resin to first melt and flow into the

air-free fabrics, and then after a certain time, to cure.

Materials Options:
Resins: Generally epoxy only.
Fibres: Any.
Cores: Most, although PVC foam needs special procedures due to the
elevated temperatures involved in the process.

Main Advantages: i) High fibre volumes can be accurately achieved with low void contents. ii) Good health and safety and a clean lay-up, like prepreg. iii) High resin mechanical properties due to solid state of initial polymer material and elevated temperature cure. iv) Potentially lower cost than prepreg, with most of the advantages.

Main Disadvantages: i) Not widely proven outside the aerospace industry. ii) An oven and vacuum bagging system is required to cure the component as for prepreg, although the autoclave systems used by the aerospace industry are not always required. iii) Tooling needs to be able to withstand the process temperatures of the resin film ( which if using similar resin to those in low-temperature curing prepregs, is typically 60-100°C). iv) Core materials need to be able to withstand the process temperatures and pressures.

Typical Applications:
Aircraft radomes and submarine sonar domes.

Cure Monitoring

The process by which a liquid thermosetting pre-polymer is turned into a rigid solid is called 'cure'. Cure comprises a complex set of chemical reactions, usually heat activated, which gradually elongate and cross link the original pre-polymer molecules. This process is accompanied by a gradual and then sudden rise in the viscosity of the resin. The time at which this sudden viscosity rise is noted coincides with gelation of the resin and indicates the formation of a 3D molecular network. Further reactions tighten up this network,

increasing its stiffness up to a point where no more reactions can take place (at a given temperature). The network is then said to have vitrified. The regions of gelation and vitrification in the resin are of great practical significance in the processing of fibre reinforced composites in which the thermosetting resin is used as the matrix separating and supporting the fibres.

Many techniques can be considered for monitoring these changes in the resin state, such as DSC, DMA, ultrasound, NMR or mechanical impedance. However, at present, only two types of micro sensors are used reasonably widely in both academic research and industrial R&D to monitor the state of cure in real time : dielectric sensors and optical fibre sensors. Both types of sensors can be embedded in selected locations of a composite prior to cure.

Composite Damage Repair

Introduction

Damaged composite structures are definitely repairable, shown clearly in the before and after images below.
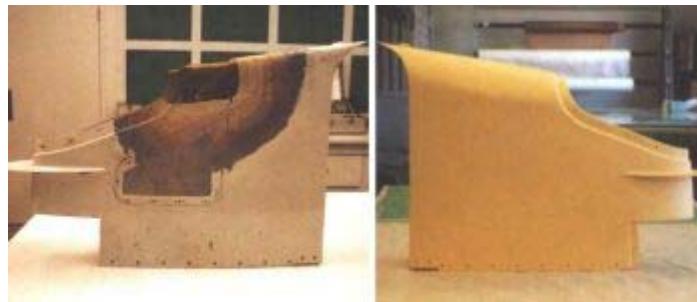


However, there are challenges:

Hidden damage issues, including manufacturing defects. (for example, a low velocity impact, which normally wouldn't cause much damage may cause a sandwich structure to disbond between the skin and core due to poor adhesion during manufacture. If this disbond is the only damage, there may be no visible trace of it from the surface.)

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Unexpected damage sources. (for example, an aircraft vertical tail part may be designed to withstand hailstone impact but not able to resist damage from being dropped during shipping or removal for inspection)

"Best" repair techniques are heavily dependent on details of the structure. In other words, because composites excel at being tailored to meet very specific needs, there are few "universal" materials and methods that can be used to achieve successful results. Composite repair specifics really have to be determined on a case-by-case basis.
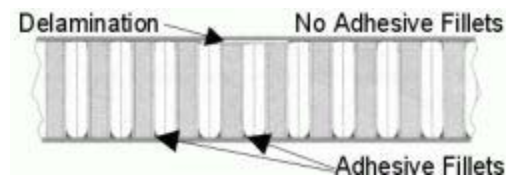


Basic Repair Process

The very basic fundamentals of composite repair include the following steps:

    Inspect to assess damage (extent and degree)
    Remove damaged material
    Treat contaminated material
    Prepare repair area
    Complete composite repair
    Inspect repair for quality assurance (e.g. delaminations, inclusions, proper cure, etc.)
    Restore surface finish
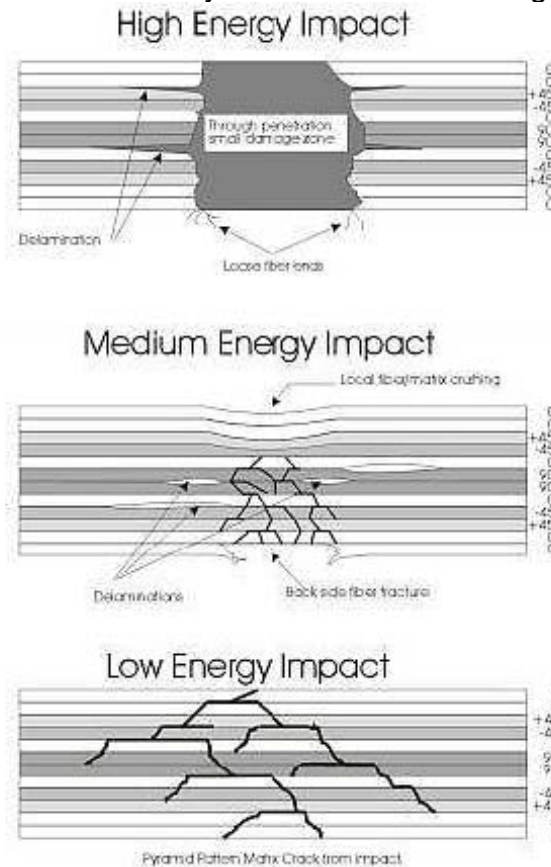
Damage Assessment

Damage to composites is often hidden to the eye. Where a metal structure will show a "dent" or "ding" after being damaged, a composite structure may show no visible signs of damage, and yet may have delaminated plies or other damage within

Impact energy affects the visibility, as well as the severity, of damage in composite structures. High and medium energy impacts,

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while severe, are easy to detect. Low energy impacts can easily cause "hidden" damage.



There are a variety of non-destructive inspection techniques available to help determine the extent and degree of damage. Each has its own strengths and weaknesses, and more than one method may be needed to produce the exact damage assessment required. The following table provides a basic comparison between the non-destructive inspection techniques. 'A' indicates damage where the technique scores well, and 'C' indicates damage where the technique is not so good.

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| | Visual | Tap Test | A-Scan | C-Scan | X-Rays | Thermal | Dye Penet |
|---|---|---|---|---|---|---|---|
| Surface Delams | B | A | B | A | B | A | N/A |
| Deep Delams | N/A | C | A | A | B | B | N/A |
| Full Disbond | B | B | A | A | B | A | N/A |
| Kissing Disbond | N/A | C | C | C | N/A | N/A | N/A |
| Core Damage | B | B | C | A | A | B | N/A |
| Inclusions | B | B | A | A | A | A | N/A |
| Porosity | B | N/A | B | A | N/A | N/A | B |
| Voids | B | B | B | B | B | B | B |
| Backing Film | N/A | B | B | B | B | B | N/A |
| Edge Damage | A | B | B | A | A | B | A |
| Heat Damage | B | B | B | B | N/A | B | N/A |
| Severe Impact | A | A | A | A | C | A | A |
| Medium Impact | A | A | A | A | N/A | C | C |
| Minor Impact | C | C | C | C | N/A | C | N/A |
| Uneven Bondline | C | N/A | C | C | C | C | N/A |
| Weak Bond | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Water in Core | N/A | B | C | A | B | A | N/A |

Damage Removal

The first step is to remove paint and/or outer coatings. Chemical paint strippers must NOT be used, unless you know for sure they are specifically designed for composite structures. Most paint strippers are based on Methylene Chloride, and will attack cured epoxy resin (which is a common basis, or matrix material, for composite structures). Paint and coatings may be removed by:

    Hand sanding — do NOT sand through any fibres of the undamaged structure
    Wheat starch blasting
    CAREFUL grit blasting or plastic media blasting.

It is important to check any repair manuals—such as structural repair manuals (SRM's) for aircraft—or guidelines offered by manufacturers, and also to make sure all health and safety requirements are met.

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After paint removal, additional damage assessment is performed, as hidden damage now becomes more apparent. Damaged composite skin may be removed by careful routing or grinding through the damaged surface. Note the following guidelines:

   Routing is usually the method of choice for a solid laminate with through damage. However, for a thick solid laminate with damage only on surface plies, use careful sanding until undamaged plies are reached.
   Routing also works well for a sandwich structure with damage into the core. Damaged cored should also be removed and can be routed out or cut & scraped out using a knife or other cutting tool.
   Remove damage in circular or oval shapes, and do not use sharp corners. If an irregular shape must be used, then round off each corner to as large a radius as practical.
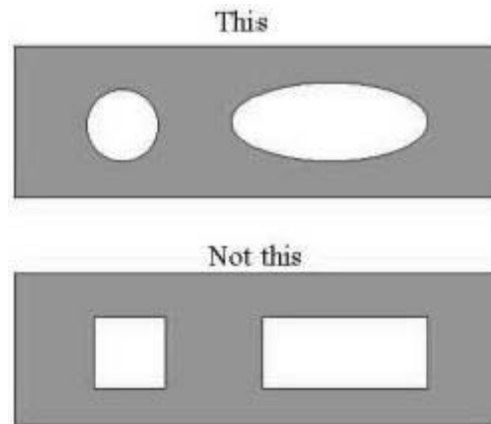


Contamination Treatment

Damaged composite structures may be contaminated by fuel, oil, hydraulic fluid, etc. Damaged areas may also absorb moisture, which will prevent achieving a successful composite repair. Solid laminates contaminated with fuel, oil, etc. may be treated by wiping THOROUGHLY with a solvent, using reagent grade solvents for the final wipe. It is important to know what the composite is made of, what the contaminant is, and to check any and all suggested procedures to ensure the solvent being used is capable of dissolving the foreign fluid without further damaging the composite structure.

If the core in a sandwich structure is contaminated, replacement of the affected material is the best answer. Solvent cleaning may be possible via a vapour degreasing process.

All affected composite materials must be dried before an effective repair can be achieved. Cured resin as well as fibres will absorb moisture from the environment, and honeycomb cores can hold large quantities of fluid. If performing a repair using high-temperature curing resin or prepreg, all moisture must be removed to prevent steam from forming and disbanding the repair.

When repairing a structure with honeycomb core, the core is almost always moisture contaminated. Refer to the drying cycles specified in repair manuals and guidelines, but note that one hour is usually not enough and sometimes 4 days of drying time is required. Drying is typically done with a heat blanket and vacuum bag, using heat to convert the moisture to steam and vacuum to draw it out. One trick for telling when the structure is dry is to exhaust the vacuum pump through a desiccant which will change colour with change in moisture content.

Repair Design

The following table lists some of the considerations, practicalities and parameters of composite repair:

| Design Considerations | Practicalities | Parameters |
|---|---|---|
| Temporary or permanent | Time | Strength |
| Bonded or bolted | Environment | Stiffness |
| Flush or external doublers | Equipment | Weight |
| Single-sided or double-sided | Skills | |
| Wet lay-up or prepreg | Materials | Shape / Contours |
| Appearance desired | Regulatory and organizational | Appearance / Surface finish |
| Access to part and/or damaged area | requirements | |
| Details (shape, heat sinks, etc.) | Failure consequences (cosmetic fairing or primary structure?) | |

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The PERFECT repair is to replace the damaged part with a new one. If replacement is not possible, then the ideal repair is to match all original design parameters exactly (e.g. materials, fiber orientation, curing temperature, etc.). In reality, this is rarely possible and compromises are inevitable. However, the goal remains to return the structure, as much as possible, to its original strength, stiffness, shape and surface finish, etc.

Note: If the extent of damage or overall damaged area exceeds allowable repair limits in applicable repair manuals, then specific engineering support is required in order to proceed with the repair. An individually designed repair is necessary. Repair design is quite a complex subject, and specific training in composite repair design is a must!

Types of Repair

Basic types of composite repair include the following:

Cosmetic

A superficial, non-structural filler is used to restore a surface to keep fluids out until a more permanent repair is made. This type of repair will not regain any strength and is used only where strength is unimportant. Due to high shrinkage, cosmetic repairs may start to crack after a relatively short time in service.
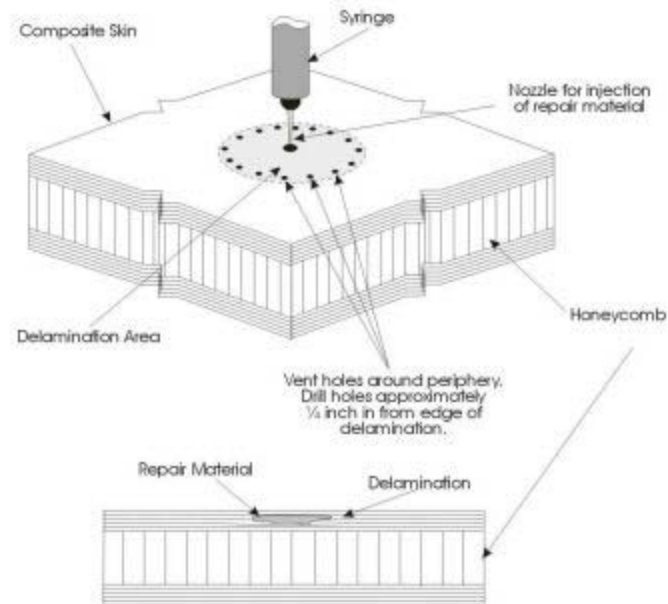


Cosmetic Repair (Non-Structural)
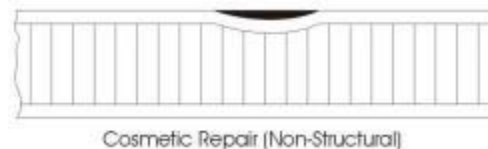
Resin Injection

This type of repair can be effective in limited instances, where the delamination is restricted to one ply. However, not much strength is regained, and the primary benefit is that it is quick and cheap. At best, this type of repair can hope to slow the spread of delamination and is generally considered a temporary measure.
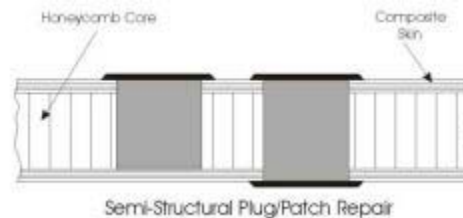
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Composite Skin

Syringe

Nozzle for injection of repair material

Delamination Area

Honeycomb

Vent holes around periphery. Drill holes approximately ¼ inch in from edge of delamination.

Repair Material

Delamination

Semi-structural Plug / Patch

This type of repair can regain some strength. The mechanically-fastened plug
(i.e. core plug) and patch repair can be especially effective where thick solid laminates are used, since they take bolt loads well.



Honeycomb Core

Composite Skin

Semi-Structural Plug/Patch Repair

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Structural Mechanically–fastened Doubler

Full structural repairs using bolted doublers can be used in heavily loaded solid laminates. This is often the only practical means of repairing such structures. However, such repairs are not aerodynamically smooth, and may cause "signature" problems in structures where low-observability by radar is required. They also leave the original damage and simply attempt to transfer loads around the damage. Finally, they can create stress concentrations at their corners and edges.



Bolted Patch Repair
(Thick Skin)
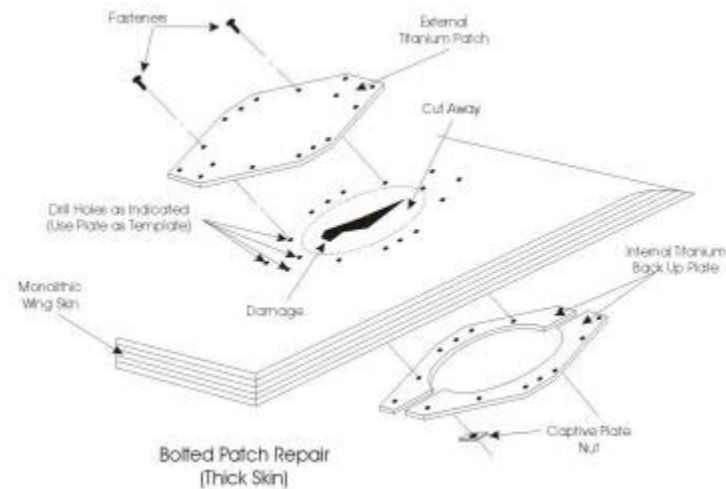
A doubler is a localized area of extra layers of reinforcement, usually to provide stiffness or strength for fastening, or other abrupt load transfers, such as repairs.

Structural Bonded External Doubler

Bonded external doublers are often used to perform repairs to lightly loaded thin laminate structures. This type of repair is especially common using wet lay-up materials. They may be room-temp or high-temperature cured, depending on the matrix resin system used. These repairs can regain a significant portion of the original strength of the structure—or even full strength—although with a

significant stiffness and weight penalty in many cases. This type of repair is generally easy , relatively quick and does not require the highly developed skills of flush structural repairs.

Structural Flush Repair

This repair restores full structural properties by forming a joint between the prepared repair area and the repair patch. The repair patch is made by replacing each ply of the composite laminate that has been removed from the damage area. The size of the repair patch should fit exactly the area prepared for repair, except for a final cosmetic or sanding layer, which is often slightly larger to allow for sanding down to achieve a smooth and/or cosmetic surface.
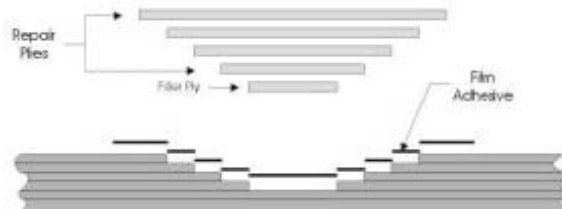


Bolted vs. Bonded Repairs

Which is better? This depends on the definition of "better" for each specific case. For example, "better" for some repairs may be lighter, while for others it may be heavier but longer lasting. In some cases cheaper is "better", while in others producing the repair quickly is the goal.

Bonding usually excels with very thin structures—bonding two thin pieces of aluminium is much stronger than bolting them—and with dissimilar structures—one can glue a piece of paper to a steel plate which isn't feasible with mechanical fasteners like bolts or screws. Other advantages to bonding include:

    Bonding minimizes corrosion.
    Adhesives also make good sealants.

No fastener holes to weaken structure.
No point stress concentrations.
Smooth surface finish.

Bolted joint and repair strengths increase as the substrates get thicker. This isn't true for bonding, except for very flexible materials. Other advantages of bolting include:

Doesn't require meticulous surface preparation
Easy to inspect for quality
Easily disassembled

Therefore, a basic rule for achieving the highest strength composite repair is to use bonding for thin laminates and bolting for thick laminates. Thickness here refers to the original laminate or skins, excluding any core materials. The crossover point varies tremendously with the specific details of each case, but in general 1/64inch (0.4mm) is considered thin and 1/2inch (12.5mm) is somewhat thick.

Note that parts with an aerodynamic or cosmetic surface usually require a flush repair, which almost necessitates bonding. However, when bonding is not possible, a bolted temporary or permanent repair may be necessary

Scarfing

After completing initial damage removal, the area around the repair must be prepared. The corners of the repair hole must be rounded off and the hole itself should be tapered to provide the best load transfer when the repair patch is bonded in. Scarfing, or taper sanding, is usually achieved using a compressed-air powered high-speed grinder. This is a gentle process, which prepares the damaged area for application of a repair patch. It is imperative to follow all repair manual guidelines, and significant skill and practice on the part of the repair technician is mandatory.
Note: If the damaged area exceeds allowable repair limits in applicable repair manuals, then specific engineering support is required in order to proceed with the repair.

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Ply Determination
For scarfing, it is important to know the number of plies in the composite laminate. The ply orientations are not needed for preparing the damaged area but will be needed for cutting repair materials and fabricating the repair patch.

Scarf Angles
A crude rule of thumb for the amount of material to remove during scarfing is to taper sand approximately 1/2 inch (12.5mm) of area per ply of composite laminate. Typical scarf distances are from 20 to 120 times the thickness of the laminate being scarfed.

Scarf distance

Double-sided

Scarf distance

Single-sided
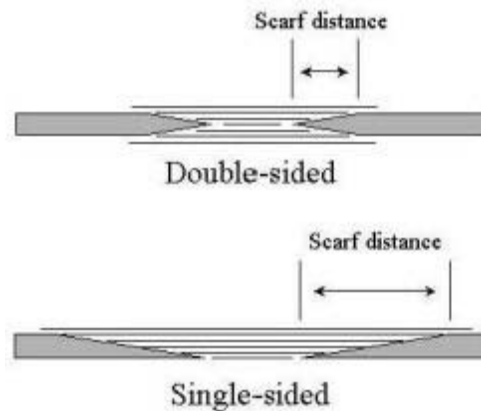
The material removed during scarfing is often referred to by angles, rather than distance per ply. The flatter the scarf (more area per ply), the larger the adhesive bond, and the lower the load on the bond. The steeper the scarf, the less undamaged material is removed. Lightly loaded structures may be able to tolerate a smaller, steeper scarf. Heavily loaded structures usually require a larger, more gentle scarf, such as 20:1 up to as much as 100:1.

Scarfing vs. Stepping

Stepping is an alternate method for removing material in preparation for applying a repair patch. In stepping, the overall angle is

achieved by removing a precise area of material per ply of composite laminate. Both methods work. Most consider scarfing to be easier, and it is generally considered to be better. Stepping leaves abrupt edges and butt joints in each repaired ply. It is also hard to do without cutting through and damaging the underlying plies.

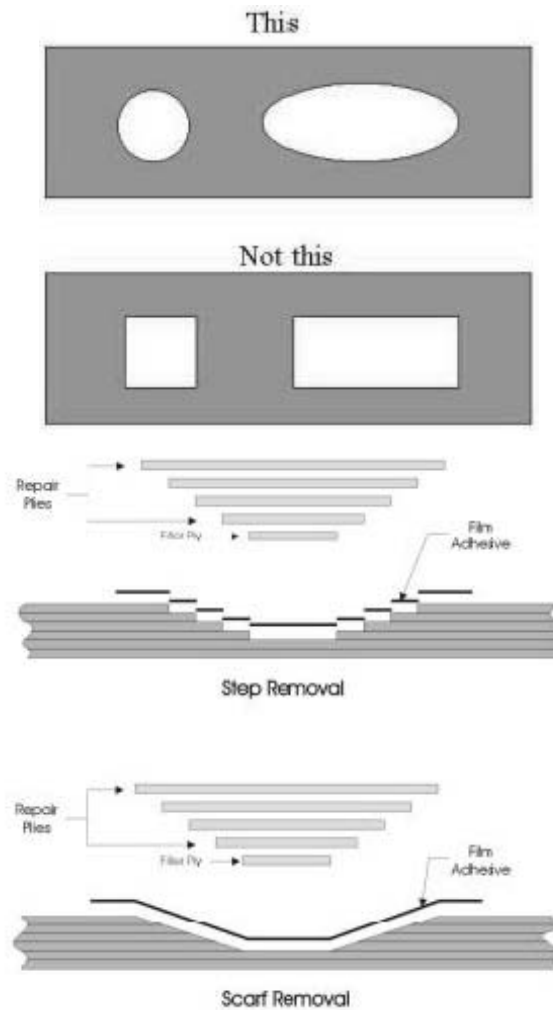

Step Removal



Scarf Removal
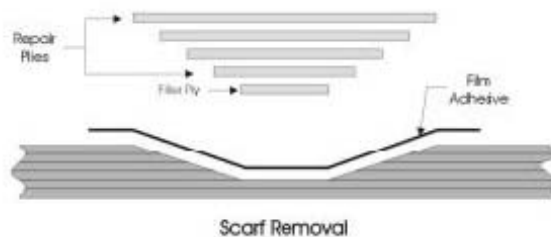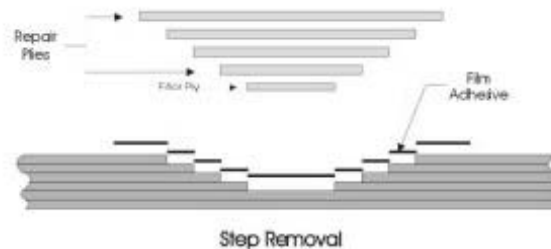
The Repair Patch

The edges of the repair patch should be tapered and all plies should have rounded corners. The repair patch is attempting to replace the damaged area in the composite laminate exactly, restoring it as much as possible to original. Thus, the number of plies and orientations of each ply must match, layer for layer, that of the original structure.

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This

Not this

Repair
Plies

Filler Ply    Film
Adhesive

Step Removal

Repair
Plies

Filler Ply    Film
Adhesive

Scarf Removal

So, in an exact ply-by-ply replacement, will the repaired structure be as strong as the original? No. Depending on many details, the

repaired structure is typically about 60-80% as strong as the original undamaged structure.

Is it possible to make a repaired structure as strong as the original? Yes. However, extra repair plies must be added to compensate for the loss of strength caused by the repair. This means the repair will not be perfectly flush, and also that the repaired structure will be stiffer than the original.

Is the extra stiffness a problem? If the original structure is not stiffness critical but is primarily loaded in straight tension or compression, then a stiffer repair will most likely be fine. However, if the structure flexes significantly under load, the "stiff spots" caused by a full-strength repair can cause failure at the edges of the repair. Some repairs may therefore need to be deliberately under-strength, in order to match the stiffness of that original area in the structure.

Repair Sequence for a Scarfed Repair

Below is a review of the general outline for steps in performing composite repair, but with detail added specifically for a scarfed repair with flush bonded repair patch.

1. Inspect for extent of damage:

   Visual
   Tap, Ultrasonic, and/or X-rays

1      Get best access possible, both sides if feasible.
       3. Remove all damaged and delaminated material.
       • Circular or rounded corners
       4. Grind away scarf angle taper:
       • Smooth, flat ground surface
2      Determine ply orientations and materials of original structure.
       6. Replace plies:
       Adhesive layer first

One or more filler plies, orientation not important
Repair plies - match orientations with original structure
Extra plies - usually orientation matches original outer ply
Often an outer adhesive layer

3   Vacuum-bag and cure repair plies as required
4   Trim to net edge dimensions after cure, if necessary.
5   Inspect repair for delaminations, inclusions, proper cure documentation, etc.
6   Sand and finish as required.

• Do not sand into fibres of repair plies.

Portable Repair Systems

Portable repair systems (sometimes called "Hot Bonders") are suitcase-sized or smaller units designed to allow for the accurate application of controlled hear (temperature) and vacuum to a composite repair. They are especially useful for field repairs, in situations where it is not possible to remove the damaged part for repair. Portable repair systems are most commonly used to control heat blankets, but can also be used to control heat lamps, hot air guns, or even ovens. They require an electrical power source, and many also require a clean compressed air source. They rely fundamentally on accurate readings from thermocouples.

A thermocouple is a device that uses a circuit of two wires of dissimilar metals or alloys, the two junctions of which are at different temperatures. A net electromotive force (emf), or current, occurs as a result of this temperature difference. This current can be read by various instruments (galvanometer, potentiometer) or by control units such as portable repair systems.

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Large prong is negative ⊖ or ⊕ prong. Connected to Constantan Wire (RED or NON-MAGNETIC wire).

Small prong is positive ⊕ Connected to Iron wire (WHITE or MAGNETIC wire).

Bare thermocouple wire is twisted and welded at the end to complete a circuit.

Heat Blankets and Other Heating Methods

Accurate temperature control and uniformity are difficult with heat lamps and hot air guns. Temporary ovens and heat blankets offer better control of curing temperature and even distribution of heating.

A heat blanket the same size as the repair area is too small. Heat blankets must be considerably larger than the area being cured. For example, an 8inch (200mm) diameter circular repair will require at least a 12inch (300mm) diameter heat blanket. Using this size of blanket allows for thermocouple placement well inside the blanket edges. Controlling thermocouples placed near the edge will make the blanket overheat, causing a very real fire risk and a damage risk to the component. Also, temperatures drop within 2 inches of the blanket's edge. At the very edge of the blanket, the temperature is easily 100ºF (55ºC) colder than at its centre.

Cure Temperature Considerations

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There are 4 common choices, with variations:

| Curing Temperature | Mfg. Method |
| --- | --- |
| Room temp – 77°F (25°C) | wet lay-up |
| Room temp with post-cure at 150°F (65°C) – 200° (95°C) | wet lay-up |
| 250°F (120°C) | prepregs |
| 350°F (180°C) | prepregs |

Which is best? It depends. Post-cures are very often required for room-temperature laminating resins, in order to develop full strength in a reasonable time. Often, but not always, the prepregs cured at higher temperatures are stronger than room temperature cured materials. However, high curing temperatures can induce problems:

Steam creation in laminates and over cores (Blown skins; Excessive porosity in bond lines)
Uneven heating problems
Overheating/fire risks
Increased documentation, often with expensive equipment
More training required

Often the applicable repair manuals will offer a choice, especially with smaller repairs. In this situation, go with the lowest-temperature repair allowed by the manual or guidelines. It will offer an easier repair with less ways for things to go wrong. If there is no choice, then it is imperative to do exactly what is proscribed in the manual or guidelines.

Thermocouple Placement

Proper thermocouple placement is crucial for proper high-temperature repairs using portable heating systems. When heat blankets are used, multiple thermocouples are required. In general, the more thermocouples the better. This is because thermocouple failures are common and replacement during a running cure is virtually impossible. Also, temperatures can easily vary widely across a repair area during cure: 60–80ºF (35–45ºC) spreads are not uncommon. Most composite parts contain variances in thickness and/or temperature conductivity of the materials which will create this temperature variation during cure. There may also be heat sinks in the

part or underlying tooling and non-uniformity in the heat blankets being used.

Do not place thermocouples directly over the repair area, due to possible thermocouple mark off. The thermocouples may "print" through the bagging schedule and even thin metal top caul plates, leaving an undesirable groove through the repair area. Even more important – thermocouples MUST be placed well inside the edge of any heating blanket. These blankets are cooler within about 5cm (2")of the edge, and are quite cool very near the edge, within about 2cm (1"). Thermocouples placed here will naturally read cooler than they will near the middle of the heating blanket. Since the heating equipment is programmed to go to a desired temperature, it will apply too much power to the blanket in an attempt to being up these cool thermocouples to the desired temperature, and thereby overheat the repair area itself. This can burn the repair area, and even start a fire in some instances.

Repair Tooling and Caul Plates

Caul Plates

Caul plates are smooth metal plates, free of surface defects, the same size and shape as a composite lay-up, used immediately in contact with the lay-up during the curing process. They transmit normal pressure and temperature, and provide a smooth surface on the finished laminate. Used in conjunction with heat blankets for composite repair, caul plates prevent the heater blanket wires from making impressions in the repair. They provide a smoother, more aerodynamic surface and allow for more uniform distribution of heat. They also enable placement of thermocouples closer to the centre of the repair.

Caul plates can be difficult to form to complex contours. Also, metal caul plates can cause thermocouple calibration problems. One solution to this problem is to use flash breaker tape. Silicone rubber caul plates can act as insulators, if thick enough to prevent thermocouple mark-off.

Repair Tooling

For complex shapes, repair tooling is sometimes required. Repair plies can be laid up and debulked in the repair tool, or even partially cured (a process known as "staging"). The repairs can then be bonded to the original structure. This is not usually practical for quick field repairs, but is more useful for heavy maintenance type of repairs performed in a dedicated facility with specific repair equipment.
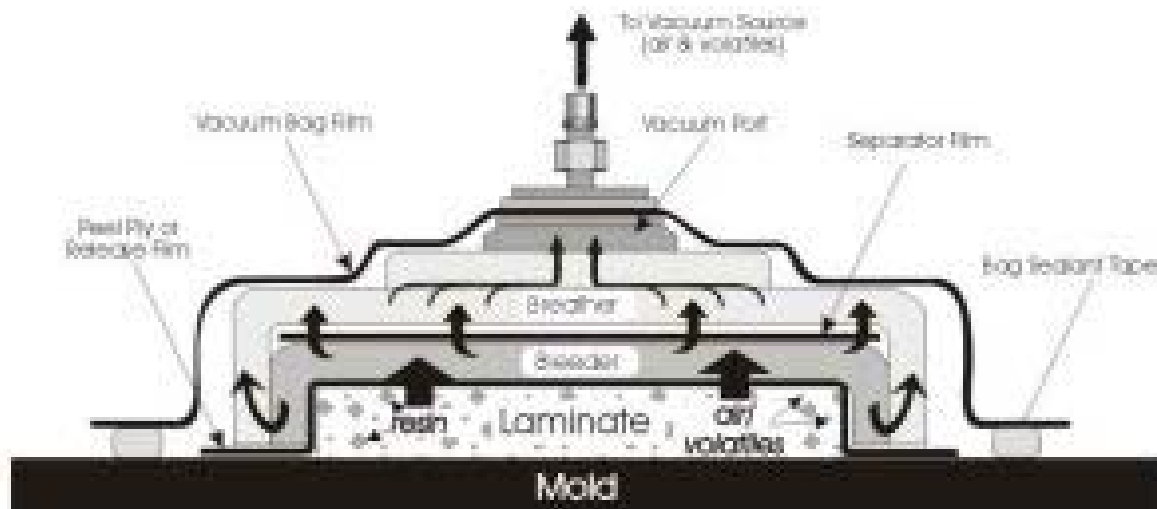
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Vacuum Bagging Schedules

There are three main purposes for vacuum bagging:

      Application of compaction pressure to consolidate plies
      Extraction of moisture, solvents, and volatiles from curing composite
      Allow resin to flow and be absorbed without hydraulic lock

The maximum compaction pressure available at sea level with a perfect vacuum bag is 14.7 psi (29.92 inches or 760 mm of mercury.) This maximum available pressure drops approximately 0.5 psi (1 inch or 25.4 mm of mercury) for each 1,000 foot gain in altitude. The routes for extraction of gases and resins is shown in the figure below:

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The compaction pressure provided by a vacuum bag is crucial for good quality parts, when they are cured in a vacuum bag only. However, in an autoclave cure, much higher pressures are routinely available, up to several hundred psi for some types of solid laminates. However, the vacuum bag is still required in these circumstances, to extract the gases and reduce porosity.

How to sequence and use the variety of materials used in vacuum bagging can be one of the most confusing aspects in performing composite repair. The sequence of materials used is called the bagging schedule.
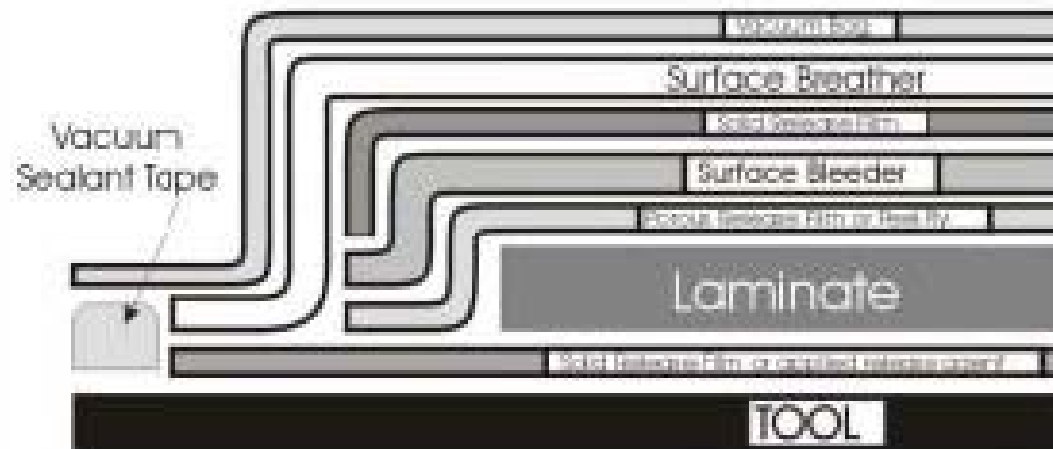


Release film or peel ply

The first layer that goes against the uncured laminate is a release film or a peel ply that is used as a barrier between the laminate and the subsequent bleeder or breather layers. This layer can be non-porous or porous material depending on whether or not resin bleed is necessary. Often a perforated release film is used for a controlled resin bleed. The diameter and the spacing of the holes can vary

depending on the amount of resin flow desired. A porous peel ply is used when you do not wish to restrict the resin bleed and/or a peel ply surface texture is required. A non-porous peel ply (commonly known as FEP, fluorinated ethylene propylene, or Teflon®) is used when no resin bleed is required, but evacuation of the volatiles and solvents is desired. This layer usually extends beyond the edge of the lay-up and can be sealed and/or secured with flash breaker (FB) tape as required.

Bleeder layer

The bleeder layer is used to absorb resin from the laminate either through a porous peel ply or a perforated release film as described above. The bleeder layer is usually a non-woven synthetic fiber material that comes in a variety of different thicknesses and/or weights that range from between 2 oz./yd2 to 20 oz./yd2. Multiple layers can also be utilized for heavy resin bleed requirements. This layer usually extends beyond the edge of the lay-up and is secured in place with FB tape as required.

Separator film layer

The separator layer is used between the bleeder layer and the subsequent breather layer to restrict or prevent resin flow. This is usually a solid or perforated release film that extends to the edge of the lay-up, but stops slightly inside the edge of the bleeder layer, to allow as gas path to the vacuum ports. Non-porous FEP can also be used as a separator layer.

Breather layer

The breather layer is used to maintain a "breather" path throughout the bag to the vacuum source, so that air and volatile can escape, and so continuous pressure can be applied to the laminate. Typically synthetic fiber materials and/or heavy fibreglass fabric is used for this purpose. The breather layer usually extends past the edges of the lay-up so that the edge-band makes contact with the bleeder ply around the separator film. The vacuum ports are connected to the breather layer either directly or with strips that run up into the pleats of the bag. It is especially important that adequate breather material be used in the autoclave at pressure.

Bag film and sealant tape

The bag film is used as the vacuum membrane that is sealed at the edges to either the mould surface or to itself if an envelope bag is

used. A rubberised sealant tape or putty is used to provide the seal at the periphery. The bag film layer is generally much larger than the area being bagged as extra material is required to form pleats at all of the inside corners and about the periphery of the bag as required to prevent bridging. Bag films are made of Nylon®, Kapton®, or P.V.A. (polyvinyl alcohol) materials.

In addition to bagging schedules, there are other issues in vacuum bagging:

Thermocouple quantity and placement
Caul plates
Heat blanket issues
Heat sinks
Extra adhesive layers
Vacuum port quantity and placement
Bagging "pleats"
How much vacuum to draw

There are no quick and easy answers here. The bagging schedules used with wet lay-up repairs are affected by the ambient temperature as well as the pot life and amount of resin used. With prepreg repairs, the shelf life of the prepreg as well as its out-time "B-stage" affect the bagging schedule. Also, older but still certified prepreg may require a different schedule than fresh prepreg. The best practice is to test first whenever in doubt.

Common Vacuum Bagging Terms

Bleeder: A non-structural layer of material used in the manufacturing of composite parts to allow the escape of excess gas and resin during cure. The bleeder material is removed after the curing process is completed and the excess resin taken with it.

Breather: A loosely woven or nonwoven material that acts as a continuous vacuum path over a part but does not come in contact with the resin.

Mould Release Agent: A material applied to mould surfaces to facilitate the release of the moulded article. Liquid, paste, spray and

solid release materials are all common in composite fabrication.

Peel Ply: A sacrificial nylon, polyester or non-porous Teflon ply that is placed over the outer plies of a laminate during lay-up. When the resin has cured the peel ply is removed. The results are a smooth surface that is easily prepared for subsequent bonding or painting.

Perforated Release Film: A solid release film that has been perforated with a uniform hole pattern comprised of usually 0.015" or 0.045". Hole spacing ranges from 0.25" to 8" spacing. The effect is to restrict the amount of resin bleed that is able to pass through the film.

Solid Film: A barrier between the bleeder and breather layer to prevent the excess resin absorbed into the bleeder from soaking into the breather. The solid film is sized smaller than the bleeder and breather to allow an air path connecting both.

Tool: A structure, also referred to as a mould, that provides a specific size and shape in or over which a lay-up is formed, shaped and cured.

Vacuum Bagging Film: An airtight flexible sheet placed over a lay-up and sealed along its edges. The bag is fitted with vacuum ports and connected to a vacuum source. During the cure the bag is evacuated and the lay-up is compacted under atmospheric or autoclave pressure. Vacuum is applied to the bag during the entire cure cycle.

Vacuum Port: A machined or cast metal fitting that connects the vacuum bag to the vacuum source. The vacuum source can be a vacuum pump or a compressed air venturi. The port is connected to the vacuum source with a reinforced hose. Both the hoses and ports typically incorporate fittings that allow the hoses to be removed without losing the vacuum.

Vacuum Sealant Tape: A thick rubber based adhesive tape that is sticky on sides and used to form a seal between the vacuum bag and the tool surface. It has the ability to remain soft and pliable at temperatures in excess of 350ºF.

Repair Summary

The more primary a structure is, and the closer it operates to its design limits, the more difficult the repair. However, even heavily-loaded primary structural composites have been successfully repaired for many years. Heavily loaded, oriented-fiber,

advanced composite structures require careful engineering design of major repairs—it is not simply a matter of slapping on a patch.

Given a good repair design, the skill and quality attitude of the repair technician becomes critical. Vacuum-bagging becomes virtually mandatory for advanced composite repairs, in order to achieve the required compaction and proper consolidation of the repair plies.

Prepreg can sometimes be repaired with either prepreg or wet materials in field conditions—autoclaves for repairs are rarely necessary.

Composite repairs can be quite time-consuming, and require careful attention to lots of picky details. Most of these repairs rely fundamentally on high-quality adhesive bonding. The strength of an adhesive bond cannot be measured without destroying it! Therefore, careful control of the repair process, especially regarding cleanliness, fit of the repair patch, and meticulous surface preparation of the bonding surfaces, becomes crucial. It all goes back to the skill, training, and integrity of the person doing the repair.

In spite of all these obstacles, successful repairs of complex composite structures are being done every day. There is no "black art" to composite repair—just a good attitude, training, and practice. Experimentation will always help to prove-out the best practices and clear-up uncertainties. Finally, quality assurance is an absolute must, requiring a thorough understanding and dedication to underlying principles and the testing required to ensure the repair will be successful long-term.