Blade Manufacturing Processes

The structural design of a blade is closely linked to the manufacturing method as both have to be considered to enable the production of a cost effective and reliable blade. In the section on structural design two common approaches to blade design were discussed, namely the structural shell with shear webs, and the box spar with shell fairings. As with the structural design there are two main approaches to manufacturing blades, Prepreg and Infusion. Although either manufacturing method can be used to make the two common structural designs, prepreg is currently almost exclusively used to build the box spar design.

The choice of manufacturing process to provide the best all round performance and cost is a subject of much debate within the wind industry. The infusion process is commonly perceived to be the cheaper process due to the lower cost of the BOM (Bill of Materials). However, prepreg blades enable higher resin properties, a higher level of automation, and a more consistent process, thus enabling reduction in blade weight. A reduced blade weight reduces loading both on the blade and also on the generator providing possibilities for cost reductions and reduced wear on other components of the Wind turbine Generator (WTG). Therefore, the discussion on the performance and cost of a blade needs to consider many secondary considerations beyond the BOM.

One of the main considerations in the choice of material and manufacturing technology is the length of the blade. As blade length increases historical data has shown that the weight increases to the power of approximately 2.5. This is not sustainable for a number of reasons (transport limitations, loads on the bearings, loads on the blade structure, loads in the towers etc.) and therefore different materials technology, or new design concepts need to be adopted to enable the viability of large blades. One approach to reduce weight, whilst increasing length, is to replace glass fibres with stiffer and light materials like carbon fibre. Carbon ($E = 240$ GPa) is approximately 3 times stiffer than glass ($E = 80$ GPa) and also has a density of $1.8$ kg/m$^3$ versus 2.4 kg/m$^3$ for glass. Therefore the specific stiffness of carbon is approximately 4 x higher than glass. However, although carbon provides a solution to the weight of a blade, due to its high cost (7-8 times higher than glass), and the higher level of precision required in its application, designing and manufacturing with carbon provides some considerable challenges.
As blades become larger the failure mechanism within the composite structure also begins to change. On smaller blades 20-35m the design is primarily stiffness driven and therefore the material properties are dominated by the stiffness of the fibres. As blades become larger the design becomes much more sensitive to fatigue loads which are much more dependent on the resin in the composite. Furthermore, when the fatigue loads in compression become a design driver the quality of the laminate also becomes more critical. In compression the fibres need to be kept as straight as possible in the direction of the load and the resin also needs to prevent localized buckling of the fibres. Therefore, the load bearing laminate needs to be precisely aligned and as free of air as possible. To achieve these increasingly demanding requirements the material selection process becomes critical to the design, and as a consequence more favourable to prepreg technology for critical structural components like the spar caps. Prepreg provides accurate fibre alignment, high performance resin, and low void content.

**Resin Infusion Technology**

**Introduction**

The general principal of infusion is to “suck” a resin into the reinforcing fibres and fabrics using a vacuum. The vacuum reduces the pressure at one end of the fabric stack allowing atmospheric pressure to force the resin through the fibres. The speed and distance that you can infuse a fabric stack will be dependent on the following parameters:

- The viscosity of the resin system \( \eta \)
- The permeability of the fabric stack \( D \)
- The pressure gradient acting on the infused resin \( \Delta P \)

![Blade Weight vs Blade Length](image-url)

*Blade Weight vs Blade Length*

As blades become larger the failure mechanism within the composite structure also begins to change. On smaller blades 20-35m the design is primarily stiffness driven and therefore the material properties are dominated by the stiffness of the fibres. As blades become larger the design becomes much more sensitive to fatigue loads which are much more dependent on the resin in the composite. Furthermore, when the fatigue loads in compression become a design driver the quality of the laminate also becomes more critical. In compression the fibres need to be kept as straight as possible in the direction of the load and the resin also needs to prevent localized buckling of the fibres. Therefore, the load bearing laminate needs to be precisely aligned and as free of air as possible. To achieve these increasingly demanding requirements the material selection process becomes critical to the design, and as a consequence more favourable to prepreg technology for critical structural components like the spar caps. Prepreg provides accurate fibre alignment, high performance resin, and low void content.
The relationship between these can be simply defined using the following equation with respect to the speed of the infusion process $v$.

$$v \propto \frac{D \times \Delta P}{\eta}$$

Therefore the speed of an infusion is increased with increasing permeability of the fabric stack ($D$), increased with increasing pressure gradient ($\Delta P$), and decreased with increasing viscosity ($\eta$).

**Resin Viscosity**

From the equation above it is clear that to enable fast infusions you need a low viscosity resin system. A low viscosity resin will also allow the resin to travel further through the resin stack for a given pressure gradient as it will create less “drag” in the impregnated stack. This will reduce the number of injection points needed on a large component and decrease the complexity of the infusion.

The viscosity of a resin is determined by its chemical composition. In the case of epoxy resins, one of the most common infusion resins for wind turbine blades, formulators use diluents to reduce the viscosity of standard epoxy monomers. The skill of the formulator is required to ensure that the use of diluents does not reduce the mechanical and physical properties (eg thermal performance) of the epoxy resin.

Another way to improve the infusion speed is to increase the temperature of the resin. Viscosity is inversely proportional to temperature and as a rough rule of thumb the viscosity can be halved for every 10-15°C increase in temperature. Therefore, the benefits of infusing a heated resin into a heated tool are clear with respect to fast infusion speeds and reduced injection ports, as the resin will travel further for a given pressure gradient. However, temperature will also significantly increase the reactivity of the resin system accelerating the curing process.
As with viscosity the general rule is that for every 10-15°C increase the cure time halves. As a resin cures its viscosity will begin to increase exponentially until it forms a soft gel followed later by a glassy solid network. Increasing the viscosity is obviously counter productive to the infusion process, and when the resin gels it becomes immobile, which can lead to extensive repair if the part hasn’t completely infused by that point in time. As a consequence the formulator of the resin system needs to make sure the resin system is tailored to the requirements of the process both in terms of viscosity and reactivity.

Permeability
The permeability of a fabric or laminate stack is dependent on a number of factors:

- Fibre diameter
- Fibre sizing
- Fabric type

Glass and Carbon fibres have very different permeability with carbon being significantly more difficult to infuse with resin than glass. This is primarily due to the smaller fibre diameter of carbon compared to glass, at 5-10μm and 16-24μm respectively. As a consequence the carbon fibres can pack together more tightly reducing the permeability.

A chemical sizing is applied to a fibre to protect it during subsequent manufacturing operations like weaving, and to promote adhesion with the resin system to maximise mechanical performance of the laminate. One of the key requirements of adhesion is good surface wetting and therefore sizes are especially formulated to ensure good wetting characteristics. This is very important in the infusion process where fast fibre wetting is required to enable the resin to pass quickly through the fabric stack.

To enable easy handling of fibres and ensure fast deposition rates fibres are supplied in various different formats. The first stage is to combine thousands of fibres together to produce rovings or tows. These rovings or tows are held together by the sizing on the fibres and are subsequently stitched or woven together to form fabrics. More details on types of fabrics are given in the “Guide to Composites”. Fabrics are primarily selected for their mechanical performance and the orientation of the fibres, but for the infusion process careful consideration of their permeability is also required.

Pressure Gradient
The available pressure to infuse a resin stack is dependent on the atmospheric pressure at the time of infusion and the capacity of the vacuum pump, assuming that the tool and vacuum bag have no leaks. As the resin infuses into the fabric stack the effective drag on the resin front begins to increase. The amount of drag is directly proportional to the volume of infused fabric stack and its permeability, therefore once a given volume
of fabric stack is infused the drag will be equal to the original pressure gradient, and the infusion front will halt.

As the maximum pressure gradient available is limited by the atmospheric pressure, the pressure gradient must be maintained by selecting high permeability fabrics and/or placing additional inlet pipes at key positions across the component. As laminates and components vary in shape and thickness the determination of the location and number of injector points relative to the vacuum outlet can be complex, often requiring some form of computer modeling.

The Vacuum Stack and Tooling Requirements

Probably the most important process parameter for the infusion process is the vacuum integrity of the vacuum system and tooling. The smallest leaks will result in air being pulled into the laminate, and as there is a pressure gradient in the infusing laminate, the air will “bloom” across the laminate very rapidly. This can lead to reduced quality laminates due to high void contents or significant repairs. As a consequence great care is taken to check the vacuum integrity of tooling and that the vacuum bag has no leaks.

The tool vacuum integrity is checked by putting a vacuum bag over the surface of the tool together with a breathable layer to distribute the vacuum across the entire surface. A vacuum is pulled until the vacuum gauge stabilizes at a maximum value. The maximum vacuum pressure will be dependent on the atmospheric pressure on any given day and the altitude of the manufacturing site. The vacuum pump is then isolated and the “vacuum drop test” is performed to measure the integrity of the tool and the vacuum bag including all pipes and fittings. The typical requirement for an infusion process is to ensure that the drop in vacuum does not exceed 2.5% in 5 minutes, and it is critical that the vacuum pressure is measured at a point distant to the vacuum inlet.

In many blade manufacturing processes a priming gelcoat is applied to the mould before lay-up of the fabric stack. The primary function of the gelcoat is to provide a priming surface that can be lightly abraded before painting. However, the gelcoat also seals the tool providing a much higher vacuum integrity.
The vacuum stack or consumables in addition to providing a vacuum and pressure gradient within the laminate also provide some other functions. A nylon peel ply is often the first layer applied to the surface of the fabric stack which is subsequently removed “peeled” from the laminate surface after cure to remove the rest of the vacuum consumables and leave a clean surface ready for secondary manufacturing operations. On top of the peel ply is the infusion mesh which is used to accelerate the infusion speed. Different permeability meshes are available and are selected based on the laminate construction and the size of the component. Additional resin piping is then added to the infusion mesh to ensure that the required resin flow is achieved across the whole component. A tough impermeable vacuum bag is then placed over the entire assembly and fixed to the edges of the tooling with tacky tape. This process requires a certain amount of skill and training to ensure the system is completely air tight with very high vacuum integrity.

The Infusion Process

Putting resin infusion into practice is often not straightforward or appropriate for every component. The process has a reputation for potential unpredictability – mainly in the resin flow, and the susceptibility of the system to failure generally caused by vacuum integrity. The infusion methods detailed here refer to the side-to-side or centre-out sweep infusion. This is not the only working method and not necessarily the best method for some components but serves as a good working example of the methodology to develop a successful infusion process.

Fundamentals of the Infusion Process

The diagram below shows an infusion set-up for a flat monolithic (no core sandwich) laminate.
The key points in this infusion example are as follows:

- Multiple resin inlet feed lines and an infusion mesh are often used to achieve a faster fill time.
- Feed lines are arranged so that the flow does not isolate areas of the part. Often parallel feed lines, which sweep resin from one side to the other or parallel lines infusing from the middle out work well for simple parts.
- There is a flow lag between the top and bottom surfaces when infusing – this should be accounted for in the opening and ordering of the infusion lines to ensure the resin flow has completely saturated the laminate from top to bottom of the fabric stack.
- If the subsequent lines are opened too early (when the resin has wet the fabric layers on-top of the bag but has not yet wet the layers on the tool surface below) a dry spot underneath is created.
- Resin feed lines should first be first primed before the resin flow front arrives. This is achieved by opening the control valve to let the shot of resin fill the feed pipe and feed line on the part. This removes the air trapped between the control valve and the resin bucket. The valve should then be closed and not re-opened until the flow lag has been accounted for.

Controlling the Infusion Flow Rate

- The infusion mesh on the surface of the stack is used to accelerate infusion speeds but also creates a lag of infusion from the bag surface to the tool surface. This can be problematic if the lag is too great and a lower permeability mesh needs to be selected. Consideration also needs to be given to the end of the infusion process where the lag needs to be eliminated before the vacuum outlet is closed off by the resin preventing any further wet-out. Therefore, the infusion mesh needs to be stepped back on the top surface at the edge of the part to enable the lag to be removed.
- Low cost valves and pipes should be avoided as they can leak or collapse under vacuum pressure.

- If clamped pipes are used great care should be taken to ensure the ends are submerged in resin in the feed bucket to prevent air leaks.

- A vacuum integrity check is essential before starting the infusion. The vacuum is usually quantified by % of absolute pressure and typically this should be >95% for infusion. The leak rate or drop test should also be checked, whereby the vacuum pump is isolated and a vacuum gauge is use to determine how quickly the vacuum level decreases; for infusion a vacuum drop of <5mbar/min is usual.

- Time should be taken to ensure the vacuum bag is placed accurately over the fabric stack to prevent any bridging as this will cause “race tracking” of the resin and an uncontrolled flow front.

- The vacuum must be maintained until the resin in the laminate gels after the infusion process. After this point air can no longer penetrate the structure.

- The laminate then needs to be given a suitable cure, normally at above 50°C, to build the mechanical strength and thermal properties of the resin before the structure can withstand the loads during de-moulding.

**Fabric Lay-up**

Before starting fabric lay-up, the area to be used to locate the seal for the vacuum bag needs to be protected with masking tape. This is removed just before fitting the tacky to help prevent leaks from loose fibres between the tacky tape and the mould. During dry fabric lay-up, avoiding fibre bridging is critical to prevent areas of high permeability which would then race track the resin in female corners, and form ears on male corners. These issues can be avoided by good tailoring of fabrics and staggering joints and overlaps.

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*Female Corners before / after applying vacuum and bridging effects*
Infusion Vacuum Consumables

As with the fabrics it is essential that bridging is avoided during application of the peel ply, infusion mesh, and vacuum bag. To limit the possibility of bridging with the peel ply the layer should be divided into multiple tailored elements to allow movement during vacuum application and consolidation of the stack. The segmentation of the peel ply also allows easier removal after cure completion. The same approach applies to the infusion mesh. The vacuum bag however needs to be fitted as one continuous layer (if possible) to avoid the possibility of air leaks at joints. Therefore, the fitting of a vacuum bag becomes quite a skilled operation when the geometry of the component has a high level of complexity. One common approach is to apply 10-15% vacuum to begin to draw the bag into place but allows sufficient flexibility for movement and repositioning before full vacuum is applied.

In addition to the infusion mesh additional feed lines will be required to rapidly distribute larger volumes of resin across the component before infusion into the fabric stack. A number of products are available to distribute resin including spiral tubing. The tubing remains rigid at 1 atmosphere of pressure allowing resin to travel rapidly along its length but also flow out in a controlled manner through its side walls.

Resin Preparation

Before starting the infusion process some thought needs to be given to the resin mixing, the timings for the opening of sequential valves, and the consumption rate of the resin. Therefore, a plan needs to be created to ensure there are enough personnel for each operation and timings for each operation are correct.
Almost all resin systems (epoxy, polyester, vinyl ester) used for infusion are exothermic in nature, that is they give off heat during their reaction from a liquid to a solid matrix. To initiate the reaction the resin is mixed with a catalyst or a hardener. The speed of the catalyst or hardener or catalyst is chosen depending on the time of the infusion. For large components a long infusion time may be required and therefore a slow catalyst/hardener system is required to enable the liquid to infuse before its viscosity becomes too high to impregnate the fabric stack. However, wherever possible the infusion system is selected to minimize the infusion time to increase productivity and reduce risk of air leaks.

When the resin system is mixed it will begin to react slowly in the mixing container. If a large volume of resin is mixed at one time the heat given off from the reaction can’t escape increasing the temperature of the resin and accelerating the reaction time. Therefore, unless there is an automated mixing system, the resin needs to be infused into the part as soon as possible after mixing. This also creates the need to plan the supply chain of resin carefully as there won’t always be time to weigh and then mix resin in the quantities required for multiple resin inlets at the start of an infusion. Subsequent resin mixes should be poured into the original container to avoid removal of the resin inlet pipe increasing the possibility of air contamination.

The process of mixing can introduce air into the resin system which is undesirable for the mechanical performance of the resin. This can be resolved by allowing the mixed resin to stand for a few minutes, degassing the resin in a vacuum chamber, or by using an air free automated mixing system.

**Infusion**

Once the vacuum bag is under full pressure, bridges have been removed, and the final vacuum integrity checks have been completed the component is ready to be infused. If the resin is being mixed manually this is now initiated together with a short rest period to allow the majority of the air introduced during mixing to come to the surface. The valves on the inlet pipes are slowly opened to control the speed of the resin flow as this can be too rapid at the beginning of an infusion. This can lead to excessive lag on the infusion front creating dry spots and also exhaust the resin supply before subsequent batches can be mixed.

When the infusion process is running in a controlled manner more resin is mixed before opening the next set of valves. The next set of valves can only be opened when the entire resin front has passed the feed line at the top and bottom of the laminate stack. This will increase the resin flow speed again as the pressure gradient is increased significantly by removal of a significant volume of fabric/resin drag. This process is repeated until the entire component is infused with resin.
On completion of the infusion the resin inlet lines are clamped, with their end remaining submerged in resin, and the vacuum pressure reduced to prevent resin being drawn out of the laminate at the vacuum line. Any resin that does get drawn into the vacuum line is captured in a resin trap. The laminate now needs to gel and harden as quickly as possible to prevent the possibility of air inclusions. The gelation and curing process can be accelerated by increasing the component temperature but care needs to be taken that the vacuum stack retains its integrity.

Cure
To develop the optimum mechanical performance of the laminate the component will need to be given a heat treatment. Most resin systems used for infusion will give a high level of cure at room temperature but this can take up to 4 weeks. In many production environments the component needs to be removed from the mould as soon as possible for optimal productivity. Therefore, the cure process is accelerated by applying heat after the infusion process has been successfully completed. For a typical slow curing infusion system used for large components, a cure of 16hrs @ 50°C is commonly used. A temperature of 70°C could reduce the cure time to just 4 hrs but consideration of the capability of the mould to withstand these higher temperatures needs to be considered.

An alternative approach to fully curing a component in the mould is the application of a post cure. This is used where the mould is not designed to operate at temperatures above 25°C (Moulds become more expensive as the temperature requirements increase as they need to use more sophisticated materials in their construction, and more careful design is required to maintain the mould geometry at elevated temperatures). The component is left in the mould until the cure has progressed to a stage where the component is strong enough to be removed from the mould. The component is then placed in an oven where a very slow ramp rate is used to take the component up to the curing temperature. The slow ramp enables the resin to continue its cure and increase its thermal resistance, and as a consequence the oven temperature is always below the temperature at which the resin changes from a rigid glass like structure to a rubber called the glass transition temperature or Tg. If the temperature ramp rate is too high, and the thermal performance of the resin is exceeded, the component will distort under its own weight.
Wind Turbine Blade Infusion

The wind turbine blade is well suited to the infusion process as the geometry of the blade shells does not contain any complex structural details. However, the large size of the shell component, the inclusion of core in areas to form sandwich structures, the inherent difficulty in infusing the unidirectional fibres in the spar cap, and the demands on output from the mould, provide some additional challenges.

The main structural component of a blade is a spar cap consisting of many unidirectional fibres running from the root to the tip of the blade. By the inherent nature of unidirectional fibre layers the packing efficiency is very high and therefore permeability is low. To overcome this problem the unidirectional layers are interleaved with higher permeability layers to aid infusion, or manufactured in an off-line dedicated spar cap process. The cured spar cap is then included in the fabric stack assembly for the structural shell to provide a fully integrated structural shell. The shear webs are also manufactured in an off-line process and are integrated into the blade structure when the two shells are bonded together in the final assembly. A one-shot infusion process (i.e both shells & shear webs) is also possible and negates the need for a secondary bonding process, however the risk and complexity of infusion are greatly increased.

One of the main objectives of the manufacturer is to maximise the throughput of the factory by minimizing the time it takes to make a blade, and more specifically maximise the utilisation of the highest cost assets, the shell moulds. Therefore, reducing the complexity of the structural shell infusion by removal of the spar cap and shear webs to a parallel manufacturing process has been widely adopted for blade manufacture. As a consequence the focus of the blade infusion is directed at infusing the rest of the shell structure which is predominantly a sandwich structure.
**Sandwich Structures**

Single skin laminates, made from glass, carbon, aramid, or other fibers may be strong, but they can lack stiffness due to their relatively low thickness. Traditionally the stiffness of these panels has been increased by the addition of multiple frames and stiffeners, adding weight and construction complexity. More recently the addition of structural foams to increase thickness, and therefore stiffness, has been widely adopted within the composites industry.

A sandwich structure consists of two high strength skins separated by a light weight core material. Inserting a core into the laminate is a way of increasing its thickness without incurring the weight penalty that comes from adding extra laminate layers. In effect the core acts like the web in an I-beam, where the web provides the lightweight ‘separator’ between the load-bearing flanges. In an I-beam the flanges carry the main tensile and compressive loads and so the web can be relatively lightweight. Core materials in a sandwich structure are similarly low in weight compared to the materials in the skin laminates.

![Diagram of sandwich structure](image)

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.

**Infusing a Sandwich Structure**

One of the prominent advantages of resin infusion is that where a sandwich laminate is required, the core can be infused at the same time as the skins of the laminate. This can reduce processing time dramatically in many components where traditionally core
would be bonded to the first skin with a core adhesive before laminating the second skin. Infusion of a full sandwich component in one hit requires considerably more preparation than that of a simple single skin infusion, but this can be easily recouped once a successful infusion has been completed, and no further work is required to manufacture a full sandwich laminate. A fully infused sandwich laminate is also lighter than those made with conventional wet-laminating methods as the core bond used is exactly the right amount – the vacuum pressure ensures that the core will use exactly the right amount of resin to infuse a panel and fill the grooves and patterns between the core and the layers of fabric in the skins.

To aid infusion for sandwich construction, core can be modified to allow resin to flow more easily. A key parameter for succeeding in a cored infusion is allowing resin flow between the two skins of laminate on either side of the core. This can be done in many ways, and most cores can be bought in a variety of “infusion friendly” designs with features such as drilled holes, scored lines, grooves and scrims on each side, or a combination of these. Various core formats are available to allow flexibility in the speed and flow of the resin – some cores can infuse very quickly and others can reduce the flow to allow thicker laminates to be infused. It is very important to note that if a slow transfer mesh is used, the resin may use the core as the path of least resistance, meaning the mesh is made redundant.

By optimizing the core characteristics the infusion times can be significantly reduced and the requirements of a sacrificial infusion mesh are eliminated. The mesh will also contain a significant amount of resin which will be discarded at considerable cost. It must also be considered however, that grooves and holes in the core will also draw more resin, that will not be removed during de-moulding and therefore add to the final weight of the blade.

**Core Section with Infusion Score Lines**

**Structural Shell Infusion**

Having made many advances in the optimisation of the resin infusion process through core developments and infusion protocols, the infusion process is still susceptible to
significant variation due to changes in the environmental temperature and pressure. As discussed previously the rate of infusion is proportional to the viscosity of the resin and the pressure gradient. The viscosity of the resin is very sensitive to changes in temperature and therefore workshop temperatures need to be very consistent to ensure that the infusion process is not affected. In practice it is very expensive to air condition a very large factory due to the tolerances required especially in locations where seasonal fluctuations in temperature are high. To overcome this issue moulds are heated to a constant temperature before the infusion process is initiated. The mould temperature is typically around 30-35 °C, or at the highest seasonal peak temperature. This has the advantage of a constant resin viscosity and therefore stable process throughout the year, reducing the resin viscosity for accelerated infusion times, and reducing the cure time.

Unfortunately there are not many options available to control the atmospheric pressure and therefore regulate the pressure gradient. The increase in infusion temperature helps to minimize the affects of pressure variation as the viscosity is reduced creating less drag in the fabric stack and core. The atmospheric pressure will also determine the degree of consolidation of the laminate producing some variability in the laminate thickness and resin content.

The focus on the assembly of the fabric stack and core is also a key parameter in producing a blade of consistent quality and weight. The effects of fabric bridging on “race tracking” and subsequent dry spots has been discussed, but a secondary consequence of bridging is the additional resin that is required to fill these cavities. When you combine this variability with the resin fluctuation caused by changes in atmospheric pressure, the variability in overall blade weight can prove problematic. For individual turbines the three blades are matched in weight as closely as possible to reduce loads and wear on the generator, and therefore a large distribution of blade weights is undesirable.
**Structural Bonding of Infused Blades**

The final stage of the manufacturing process before finishing (painting) the blade is the bonding of the two structural shells and the shear webs. For this particular structural design (structural shells and shear webs), a significant amount of load needs to be transferred, from the spar cap in the shell into the shear webs, and between the shells at the leading and trailing edge. Therefore, a structural adhesive is required and is a critical component of this type of blade.

The first step in the bonding operation is to bond the shear webs into the bottom shell using jigs, and apply the adhesive around the perimeter of the shell and on the top of the shear webs. The upper shell is then lowered into position before the moulds are reheated to accelerate the cure of the adhesive and enable the blade to be demoulded. The shear web/spar cap adhesive joint is then over laminated to provide additional strength to the joint and to assist in the transfer of the loads from the shell into the shear web.

![Schematic of Adhesive Bonding Applications in Wind Turbine Blades](image)

To make a successful bond there are a number of critical material characteristics and process requirements that need to be considered. As is the case with all engineered structures the optimal solution is arrived at by considering the structural design, the materials, and the processing options.

**Joint Design**

The first step of creating an inherently strong joint is good design practice to minimize out of plain loading. The joint should also be designed to consider the bonding process and the surrounding structure to ensure that a high quality bond can be achieved repeatedly with the minimum amount of labour and time. The joint design should also minimise the volume of adhesive used to reduce weight and secondary effects such as exotherm and shrinkage which have the potential to weaken the joint.
Dispense rate
As with all other processes the bonding operation needs to be completed as quickly as possible whilst ensuring the highest build quality. With wind turbine blades the bond area is very large and therefore the adhesive needs to be applied very quickly and with a high level of precision. To enable rapid deposition of the adhesive it must be formulated for use in high dispense rate mixing equipment whilst maintaining its thixotropic properties (resistance to sagging and drainage). This can provide a significant challenge to the formulator as the mixing machines exert considerable shear forces on the material which can have detrimental effects on the thixotropic properties.

Thixotropy and Compressibility
Due to the size and geometry of the wind turbine blade, bond line thicknesses of up to 30mm are not uncommon. Therefore, the adhesive must be capable of maintaining a thickness of 30mm, even when unsupported on a vertical surface known as ‘sag-resistance’, and after passing through a high shear rate mixing machine, quantified by the shear-recovery time.

When the moulds are closed and the two shells are brought together in the bonding operation, there will be some requirement for the adhesive to move or “compress” to reduce the bond line to the minimum possible thickness. The “compressibility” of an adhesive will be closely linked to the viscosity and the thixotropy of the adhesive and is therefore carefully considered during the formulation process.

Exotherm and Cure Shrinkage
The adhesive is formulated to have the optimum processing properties for a period of time long enough for application and closure of the adhesive joint. Once the joint is closed the requirements of the adhesive then change as the joint then needs curing in the fastest possible time to allow the blade to be released ready for the next component. The formulation of the adhesive, and in particular its reactivity, is further complicated by the creation of an exotherm in thick bond line sections of the joint.

The exotherm is created by the volume of adhesive and the surrounding insulation provided by the laminates and core materials in the shells, preventing heat escape during the reaction. The high temperatures created by the exotherm can induce shrinkage in the adhesive and produce significant residual stress within the joint. Therefore, the adhesive must be formulated to limit the exotherm during cure and/or be formulated to be able to tolerate the resultant residual stresses.

Toughness
A common definition of toughness is the resilience of a material to crack formation and propagation, and therefore the capability to prevent brittle failure. This is an important characteristic of an adhesive as cracks can be initiated during the manufacturing process (from shrinkage stresses), due to impact stresses during transport, and from fatigue stresses during the day-to-day operation of the turbine. Therefore, adhesives for wind turbine blades are developed to have a certain level of toughness. This can be quantified by the measurement of the strain to failure, or elongation, of the adhesive as a load is
applied. This is illustrated in the diagram below for a brittle (red) and tough (blue) adhesive. The area under the curve is a measure of the energy absorbed during the failure of the joint and therefore gives an indication of the toughness of the adhesive.

Stress / Strain Curve for Tough & Brittle Adhesives

Even before adhesive has been applied to a manufactured components, the assembly joint design is a critical (and often overlooked) factor for success and blade design is no exception. It is well known that adhesives work best if peel stresses are avoided but this is not simple and localised joint design for leading edge, spar cap and other joints can have a dramatic effect.

Through careful design of the structure and its joint elements, and by giving consideration to the process of production, over-engineering can be avoided, material consumption reduced, and time and energy can be employed in the blade production as efficiently as possible.

Prepreg Technology

Introduction

Prepreg is an abbreviation for “pre impregnation” where a fibre layer or fabric is impregnated with a resin to form a homogenous precursor that is subsequently used to manufacture composite components. The resins used to manufacture prepregs have inherently high viscosities and are therefore semi-solid at room temperature allowing easy handling, cutting, and lay-up into the mould without any transfer or contamination from the resin. Once in the mould prepregs are then cured under vacuum at elevated temperatures, typically between 80 and 120 °C for industrial applications.
Prepregs are often supplied in roll format and provide the benefits of highly controlled resin content, higher performance resins than with infusion or wet systems, controlled fibre alignment in unidirectional products, and fast deposition rates and automation capability. However, as a consequence of the inclusion of higher performance resins, the requirement for chilled storage and shipping, and the additional processing step of “prepregging”, prepregs are more expensive per kg than the equivalent resin and reinforcement in an infusion process. Furthermore, the increased processing temperatures required for prepregs can also increase tooling costs.

**Prepreg Manufacture**

The manufacture of prepreg follows the same fundamental principals of resin infusion where the rate of infusion is proportional to the resin viscosity, the pressure applied, and the permeability of the fibres or fabric:

The viscosity of the resin system at the processing temperature $\eta$

The permeability of the fibre web/fabric $D$

The pressure acting on the web $P$

The relationship between these can be simply defined using the following equation with respect to the speed of the prepreg equipment PLS.

$$\text{Prepreg Line Speed (PLS)} \propto \frac{D \times P}{\eta}$$

Therefore, to impregnate a fabric or fibre web, the viscosity of the resin must be lowered, a degree of pressure must be applied, and the permeability of the fibres/fabric needs to be considered. As the viscosity of a typical prepreg resin is solid at room temperature, the prepreg line speed is directly proportional to the permeability of the fibres/fabric, and the pressure applied.
temperature the viscosity must be reduced significantly to enable impregnation. There are two fundamental approaches to achieve this: using solvents; and by applying heat. It is the second approach that is relevant to prepreg materials for wind energy.

To produce prepreg at viable industrial volumes and meet price targets, the prepreg line must run as fast as possible. This requires the viscosity to be reduced for a period of time whilst simultaneously applying pressure to the resin and fibre/fabric web. As a consequence prepreg machines can have large heating and consolidator zones to maximise impregnation potential even at high run speeds.

The illustration below is a schematic of the prepping process and can be summarised as follows:

**Step 1:** Filming of the resin onto a paper carrier.

**Step 2:** Resin film and fabric/fibres combined with a second paper carrier on the top.

**Step 3a:** Fibre/resin/paper web passes through heating zone to reduce resin viscosity.

**Step 3b:** Fibre/resin/paper web passes under impregnation rollers and fibre/fabric impregnated.

**Step 4:** Resin cooled to prevent staging or resin “spew” during wind-up onto roll.

**Step 5:** Paper carriers removed.

**Step 6:** Polyethylene/polypropylene backer(s) applied to protect prepreg from self adhering and from contamination prior to lay-up.

**Step 7:** The prepreg roll is taken to chilled storage to preserve its shelf life.

The accurate control of line-speed is important to prevent any detriment to the prepreg characteristics. Should the prepreg remain at a sufficiently high temperature for too long during manufacture then the resin matrix can partially react and the prepreg is said to be ‘staged’, affecting the performance of characteristics such as tack, drape and shelf-life.
Prepreg Characteristics

When defining the properties and characteristics of an infusion resin the main focus is around the viscosity and reactivity of the product as a function of temperature. Thermal and mechanical data is also provided on some standard fabrics at a range of cure temperatures to enable comparison to other resin systems. With prepregs the viscosity and reactivity during processing are also key characteristics, and mechanical and thermal properties can be easily defined for the specific prepreg, but there are also some additional handling parameters to consider.

Drape

The process of combining a high viscosity resin with the fibre/fabric makes a significant difference to the ability of the fabric/fibre to conform to a mould surface geometry. The ability of a prepreg to conform to a mould surface is known as drape and is dependent on the fabric/fibre architecture (fibre types, orientation, stitching pattern etc) and the resin chemistry. If there is insufficient drape in a prepreg problems can arise during lay-up as the prepreg plies will form bridges over details trapping large volumes of air in the laminate reducing the final part quality. Unlike the infusion process, these large voids won’t be filled in with additional resin as the volume of resin is predetermined in a prepreg laminate. Drape is also strongly dependent on temperature and therefore the minimum working temperature of a workshop needs to be considered when specifying the characteristics of the resin system.

Tack

Although the resin used in prepregs is generally semi-solid at room temperature, the surface of the prepreg will have some level of “stickiness.” The level of tack is somewhat subjective when measured by hand, but at the extremes a low tack prepreg would exhibit no stickiness even when applying considerable pressure, and a high tack prepreg would transfer resin to the finger on contact without significant pressure. The tack will vary considerably from one prepreg to another due to the resin content, the fibre and fabric type, to variations in resin formulation, and to variations in workshop temperature. In order to obtain a consistent tack level and subsequently a stable lay-up...
process, it is usual to air condition the production area where the prepreg will be laid into the moulds and consolidated under vacuum.

In general tack is beneficial to enable the prepreg to adhere to the mould surface and to subsequent plies during the lay-up process. If the mould has vertical surfaces a higher level of tack will be required to ensure the prepreg remains adhered to the mould. Excessive tack can lead to problems with removal of the protective PE/PP backers and repositioning of plies.

**Flow**

During the cure of the component the resin in the prepreg reduces in viscosity as the temperature increases. This enables the resin to flow creating seamless bonds between adjacent prepreg plies but also allows some air to be displaced from the laminate into the vacuum system. Resin flow is also essential to form good adhesive bonds with other materials such as gelcoats at the mould surface and the large volumes of core material in sandwich structures. Flow is primarily a function of viscosity and therefore the viscosity profile of a resin system is a key material characteristic of a prepreg. A typical viscosity profile as a function of temperature is shown in the Figure below.

![Prepreg Resin Viscosity Profile vs Temperature Increase @ 1°C/min](image)

**Out-life**

Prepreg resin systems use latent catalysts (requires temperature to activate them) so the prepreg retains the required level of tack and drape until the component is cured at high temperature. However, latent catalysts do react very slowly at room temperature building the viscosity of the resin until at some point there is no tack or drape left in the material. At this point the material becomes impracticable to use in most applications and is said to have reached the limit of its out-life. Prepregs used in the Wind Energy market typically have 60 days out-life at room temperature (20-23 °C) but this is significantly reduced at temperatures above 25 °C. Due to the nature of the catalysis used in these resins, prepregs are often stored and shipped in chilled storage to prevent the erosion of the outlife time.
Prepreg Processing

Prepreg is designed for the manufacture of monolithic (prepreg only) and sandwich (prepreg and core) composite structures and is generally processed using either atmospheric vacuum bag technology or by autoclave. The autoclave (pressured oven running at 6 atmospheres) approach is used extensively in the aerospace industry but is expensive due to the capital intensity of the autoclave equipment. Autoclaves also become prohibitively expensive for very large components. In recent years there has been significant progress in achieving very high quality laminates in large structures without the use of autoclaves and this has been primarily due to advances in prepreg technology such as SPRINT® and SparPreg™. For most industrial applications prepreg is processed using standard vacuum bag techniques and 1 atmosphere of pressure to enable rapid cycle times on relatively low cost moulds.

Prepreg Lay-up

Prepregs are transported and stored at low temperatures to preserve their outlife. Therefore, before application the prepreg rolls have to be conditioned or ‘tempered’ to return the whole roll to room temperature. This has to be done with the protective packaging in place as condensation can contaminate the material. The prepreg is then cut to shape, with its protective backers intact.

The prepreg is then transferred to the mould and the first backer removed before being tacked against the mould surface. The ply can be moved if required as the tack is designed to allow replacement and small adjustments. The second backer on the first ply is only removed when the second ply is ready for application to prevent contamination. Special attention is required to ensure that each ply of material goes down as flat as possible without any bumps or creases, and that there are no bridges formed around details like core edges.

For sandwich structures core kits are tacked onto the first layers of prepreg before additional prepreg plies are applied over the top of the core to create the second skin.

The Vacuum Stack

On completion of the lay-up of the prepreg (and core for sandwich structures) a nylon peel ply is immediately placed across the entire surface of the laminate to prevent any contamination of the prepreg. The peel ply is used to remove the vacuum stack from the laminate after cure and also provides a suitable laminate surface for subsequent bonding operations.

The peel ply is followed by a perforated release film that is used to control the flow of the resin during the early stages of the component cure. The size and frequency of the holes in the film are selected to match the flow characteristics of the resin system. A degree of flow is required to create a high quality laminate and ensure secondary elements such as core and surface gelcoats are well bonded to the prepreg. However, excessive flow can be detrimental to the quality of the component as too much resin is removed from the laminate creating dry areas.
To provide a vacuum distribution across the entire surface of the component, a polyester breather is applied on top of the release film. The breather when under vacuum provides the pressure to consolidate the laminate and allows the resin to flow up through the perforated release film. If the perforated release film has too many holes at the wrong frequency, the resin can saturate the breather which prematurely removes the consolidation pressure and drains the laminate of resin. The degree of flow can also be controlled by the cure profile and the temperature/viscosity of the resin.

The final layer of the vacuum stack is the vacuum bag which covers the entire laminate and vacuum stack. The vacuum bag is attached to the mould around the periphery using temperature resistance tacky tape to prevent air leaks during the elevated temperature curing process.

**Vacuum Application and Component Curing**

When the lay-up and vacuum stack process is completed the vacuum is applied to remove air from the component and consolidate the prepreg. The vacuum integrity of the system is not as critical as is the case for infusion processing as the resin viscosity is significantly higher, and therefore resistant to air permeation. However, a minimum of 85% vacuum pressure is still required to ensure sufficient consolidation of the laminate to produce a high quality component. For prepreg components, a leak rate of 50mbar/min is not unusual, although higher “leak rate” may result in a whitening of the laminate due to air inclusions.

The cure cycle is designed to cure the component in the fastest possible time without compromising the quality of the component or damaging the mould by exceeding its thermal capability. Cure cycles are quite straight forward for thin laminates (1-5mm) where the mould temperature or oven can be taken straight up to the maximum curing temperature for fast curing. However, if the laminate is thicker than 5 mm, or there is core in the structure, the curing process becomes more complex.
Epoxy resin systems are exothermic in nature and therefore generate heat during the cure reaction. For thicker laminates, the dissipation of the heat becomes more difficult and the temperature at the centre of the laminate increases. The localized increase in temperature accelerates the reaction speed which in turn creates more heat, creating an exotherm or temperature spike. If exotherm temperatures become too high, the properties of the laminate can be degraded or the mould can be severely damaged. To avoid or control the peak exotherms within a laminate, the cure schedule can be modified with a low temperature dwell. The dwell must be at a temperature above the activation temperature of the catalyst but low enough to keep the reaction rate slow and allow heat removal from the laminate as the cure progresses. Knowing how long the dwell should be, is usually determined by the thickest part of the laminates which tends to exhibit the highest exotherm temperature. This area is monitored during the cure cycle and when the peak exotherm temperature has been achieved, it is then safe to proceed to the final cure temperature.

The inclusion of core in the laminate structure can increase local exotherms due to core’s excellent insulating properties, but in general, the laminate skins are relatively thin in sandwich structures reducing the likelihood of an exotherm. However, cores can provide another problem if the cure schedule is not controlled correctly.

Most core types produce gas when they are heated either from chemicals used in their manufacture or from water absorbed from the atmosphere during transport and preprocessing operations (kitting). Out-gassing can result in a significant pressure building up between the core and the laminate skin, and when this exceeds the consolidation pressure from the vacuum bag, the skin will be lifted from the core providing a large defect. Even if cores are treated to minimise out-gassing prior to application, there is still the potential to have a problem if an intermediate dwell is not introduced to the cure schedule. The intermediate dwell limits the rate of out-gassing and allows the resin to cure and form a strong adhesive bond with the core, before raising the cure temperature to complete the cure of the component.
Once the component has been cured the temperature is reduced as quickly as possible to enable demoulding. Cooling too quickly can cause problems in thick laminates as large temperature gradients can cause internal stresses to develop. Therefore, care is taken to ensure that cooling is achieved in a controlled and considered manner.

**SPRINT® Technology**

**Introduction**

SPRINT® is a prepreg product group that was developed specifically for large structures. As laminate thickness began to increase with increasing component size, the problem of removing entrapped air between prepreg plies became significant. The figure below shows how the inter-ply voiding can increase in a simple UD laminate constructed of individual plies of 1600g UD glass prepreg.
This could be overcome by debulking the laminate after the application of every 3-4 plies, i.e. applying a vacuum bag and increasing the temperature to around 40 °C. However, this approach is prohibitively expensive and time consuming for a component that is manufactured in high volumes and at minimal cost. Therefore, to overcome the issue of removing inter-ply air between adjacent layers of prepreg, SPRINT® materials were developed.

SPRINT® differs from conventional prepreg in the way the fibres and resin are combined. In a conventional prepreg the fibre is fully impregnated by the resin, but SPRINT® keeps the fibres as dry as possible especially the outer surfaces. SPRINT® can come in a number of formats but the most common are the “double sided” (two dry fabrics on either side of a resin film), and the “single-sided” (one dry fabric joined to a resin film).

The SPRINT® Concept

SPRINT® is a product group that combines the advantages of both infusion and prepreg technology. The infusion process is capable of producing very thick, high quality laminates (air free), in a single operation. However, the process variability can become a major problem for large structures as the resin has to be moved over considerable distances. The prepreg process utilizes higher performance resin systems, allows accurate fibre alignment, provides accurate resin content in the final component, but is limited by its ability to remove the air in thick laminates. SPRINT® is an acronym for SP Resin INfusion Technology as it uses advanced prepreg resin technology to infuse laminates structures.

As the resin is supplied within the reinforcing material the infusion process occurs primarily in the z-coordinate direction (perpendicular to the mould surface), enabling large structures to be infused almost instantaneously. The infusion is facilitated by the application of a vacuum which is connected directly to the laminate. The vacuum evacuates the air from within the reinforcing fabric, and care is taken to ensure all SPRINT® plies are properly interconnected. With the vast majority of the air removed from the laminate stack, the temperature is then increased to enable the resin to flow and infuse the reinforcing fibres.
SPRINT® Manufacture
The manufacture of SPRINT® uses the same building blocks as conventional prepreg; high performance resins with latent catalysis, reinforced fabrics, paper carriers, and polyethylene protective films. The fundamental difference between the manufacture of conventional prepregs and SPRINT® is that the SPRINT® product does not undergo the impregnation process. The resin film and fabrics are joined together using a small amount of contact pressure ensuring that wet-out of the fabric is minimised.

SPRINT® Characteristics
Many of the characteristics of SPRINT® materials are comparable to those of prepreg as they use the same fundamental building blocks. However, as the fibres are not impregnated there are some significant differences in the storage and handling of these materials.

Drape
The SPRINT® format provides a significant increase in the drape capability compared to its prepreg counterpart (drape definition is provided in Prepreg Characteristics section). This is because the resin and fibre interactions are limited to the interface between the resin and the fabrics. The increased drape allows for improved conformance to the mould surface and reduces laminate defects like bridging.

Tack
In principal SPRINT® products have no tack as the resin is concealed at the centre of a 3 layer sandwich. However, for some lower areal weight fabrics there will be gaps through which the resin can pass to provide some small amount of tack. However, this does not affect the performance or functionality of the SPRINT® as the fabrics are still dry enabling air connections and subsequent air evacuation during processing. For some SPRINT® applications, some level of tack is desirable and in this instance a light weight tack film is applied to the surface of the SPRINT®.

In the case of single-sided SPRINT® products (one fabric layer, one film layer) the resin layer is exposed and therefore the tack must be carefully formulated to enable easy handling and lay-up.

Flow
Flow is a very important characteristic of a SPRINT® material as its air breathing functionality is directly affected by the flow characteristics of the resin, especially at room temperature. The relevance of flow at room temperature is defined in a separate “SPRINT® Life” characteristic below.

Once the SPRINT® material has been infused, typically at temperatures from 30-50 °C, the flow characteristics of the resin are very similar to those of a prepreg.
**SPRINT®-life**

The functionality of the SPRINT® product is provided by the dry fibres in the fabric. Therefore it is essential that the fabrics are maintained in the dry state prior to processing to provide the desired high quality laminates. Standard prepreg resins are not designed to resist small amounts of flow at room temperature and therefore SPRINT® resins are modified to ensure that fibre wet-out does not occur. However, even at room temperature the SPRINT® materials will begin to wet-out due to the pressure exerted on each layer of SPRINT® within a roll. Therefore, for long term storage of SPRINT® materials, chilled transport and storage is required as the SPRINT®-life at ambient can be expected vary between 5 and 28 days depending on ambient conditions and product format.

**Out-life**

SPRINT® resin systems are catalysed in a very similar way to resins used in prepregs and therefore the out-life requirements of SPRINT® are the same as those for prepreg.

**SPRINT® Processing**

SPRINT® was specifically developed to enable the manufacture of high quality large scale components without the use of autoclaves. As the SPRINT® product uses a combination of prepreg and infusion technology the processing route by implication uses techniques from infusion and prepreg processes.

As the product undergoes a film infusion step a high quality vacuum system is required. The SPRINT® resin has a significantly higher viscosity than an infusion resin and is therefore much more tolerant to vacuum leaks. However, to ensure the optimum quality of component the vacuum integrity of the tool is very important (see INFUSION: Vacuum Stack and Tooling requirements).

Once the SPRINT® has been infused the processing then follows the same route as that as a vacuum cured prepreg. The only significant difference is the SPRINT® vacuum stack does not use a perforated release film and therefore there is no resin flow into the breather. This provides an additional benefit of re-useable vacuum consumables and no wastage of resin.

**SPRINT® Lay-up**

SPRINT products are transported and stored at low temperatures to preserve their out-life and SPRINT®-life. Therefore, before application the SPRINT® rolls have to be conditioned to return the whole roll to room temperature. This has to be done with the protective packaging in place as condensation can contaminate the material. Once SPRINT® materials reach room temperature they need to be used within a defined period of time before the fabrics within the roll begin to wet-out and lose their breathing properties.
Where appropriate the SPRINT® materials may be cut to shape, with its protective backers intact. SPRINT® is also commonly used in winding applications for thick section conical components.

When SPRINT® is applied to the mould or mandrel, consideration of the air paths between each ply and then to the vacuum manifold is required. It is essential that these connections are maintained at every level of the laminate to ensure air pockets are not trapped in the final component.

**Air paths in a SPRINT® Laminate**

**The Vacuum Stack**

On completion of the lay-up of the SPRINT® a nylon peel ply is immediately placed across the entire surface of the laminate to prevent any contamination. The peel ply can also be used to provide air path connections from the laminate stack to the vacuum manifold.

Unlike prepreg perforated release film is not required for SPRINT® products. A non perforated film is used to ensure that there is no resin flow into the breather or vacuum channels. This has the advantage of enabling reuse of the vacuum distribution system on numerous components reducing cost and waste.
To provide a vacuum distribution across the entire surface of the component a polyester breather is applied on top of the release film. The breather when under vacuum provides the pressure to consolidate the laminate once the SPRINT® fabrics have been infused and maintain the component geometry until the resin solidifies.

The final layer of the vacuum stack is the vacuum bag which covers the entire laminate and vacuum stack. The vacuum bag is attached to the mould around the periphery using temperature resistance tacky tape to prevent major air leaks during the elevated temperature curing process.

**Vacuum Application and Component Curing**

When the lay-up and vacuum stack process is completed the vacuum is applied to remove air from the component. As the SPRINT® material provides numerous air channels consolidation pressure is achieved in every ply (prepreg consolidation comes only from the breather on the outer surface). The vacuum integrity of the system is more critical than is the case for prepreg processing, but not as critical as for infusion processing as the resin viscosity is significantly higher, and therefore more resistant to air permeation. However, a minimum of 85% vacuum pressure is still required to ensure sufficient consolidation of the laminate to produce a high quality component and ideally a leak rate of less than 50mbar/min.

It is also important to consider the air connection between the SPRINT® materials and the breather materials to ensure that the air can be removed efficiently. This is normally quite simple, but sometimes care must be taken not to isolate SPRINT® materials, particularly when co-curing with prepreg.

Because SPRINT® resin systems are catalysed in a very similar way to resins used in prepregs the cure behaviour and requirements of SPRINT® are the same as those for prepreg.

**Prepreg/SPRINT® Blade Manufacture**

Manufacturing of wind turbine blades with prepreg technology is well established. Due to the fundamental differences between infusion and prepreg materials a different manufacturing approach is adopted for prepregs. Prepreg and SPRINT® materials are well suited to automation and as a consequence the manufacturing processes have evolved to maximize this benefit. The outcome is often a blade design that utilizes a structural box spar component and a non-structural shell.
**Structural Spar**

The structural spar component can be manufactured either on a male mandrel or in a split female mould, which is subsequently bonded together prior to insertion between the shells. Both approaches require two spar caps which are connected by two shear webs.

![Structural Spar Diagram](image)

**Structural Box Spar**

Where a male mandrel is used a high degree of automation can be used to wind on the bi-axial materials to create the shear webs. The biax is interleaved with the continuous uni-directional prepreg material in the spar caps to ensure load is transferred between the two spar caps when the blade is in operation. In addition to the biax material, foam inserts will also be included in the shear webs to provide the required thickness and buckling stability.

The application of the materials to the mandrel ensures correct fibre placement and alignment. The air within the laminate then needs to be efficiently removed before and during the initial stages of the curing process. To enable the air removal the laminate has to be carefully designed to ensure available air paths are created to ensure that low void contents are achieved in all sections of the spar. As blades have increased in size, the removal of this air has become more critical, and as a consequence more specialised materials like SPRINT® biax have been adopted.

After the vacuum has been applied to the component the curing process begins by increasing the temperature to an initial dwell. The first dwell is used to allow SPRINT® materials to impregnate and remove any remaining trapped air from the laminate. The temperature is then increased to a second dwell temperature to activate the curing mechanism within the resin, and to control the high temperature exotherm in the thickest laminate sections. Once the peak exotherm temperature is achieved the component can be safely cured at higher temperatures for the short period of time required to complete the resin reaction.
Root Joint

The root joint is a critical component of the blade structure as it transfers all of the loads from the blade into the turbine. Therefore, the root design and manufacturing process are often separated from the spar to create a separate component which is subsequently integrated into the blade during the spar manufacturing process. The separation of the root section from the main structural spar reduces manufacturing risk and enables full quality inspection of the root before integration with the high value spar component.

The root joint is attached to the hub of the turbine rotor using metal studs which have to be either bonded or mechanically fastened (T-bolt) to the root laminate. To accommodate the bolts and the local stresses the laminate has to be of substantial thickness, which can be up to 100mm for large blades. The laminate also has to be of very high quality in this area as defects can lead to premature failure of the root joint and catastrophic failure of the blade.

The requirement of a high quality (low void content) thick section laminate provides some difficult challenges for conventional prepregs due to their limited air breathing properties, and as a consequence SPRINT® materials are more suited to these applications. The thickness of the laminate also demands that fast material deposition rates are required and therefore rapid automated winding techniques are often adopted for root components.

Blade Shells

For a structural spar design the primary function of the shell is to transfer the aerodynamic loads from the shell to the spar. Therefore, the shell is typically designed as a sandwich structure using tri-axial and bi-axial glass prepregs or SPRINT®. The shell laminate surface also provides the aerodynamic profile of the blade which needs to be maintained using an aesthetically appropriate surface coating in the form of a gelcoat or paint. The provision of a suitable laminate surface for paint application, or the use of an in-mould gelcoat, creates some additional technical challenges in shell manufacture.
The first step in the manufacture of a prepreg or SPRINT® shell is the application of a gelcoat or primer to the mould surface. The coating is then allowed to reach a level of cure that enables the laminators to walk on its surface to apply the first prepreg layer. The interface between the coating and the prepreg needs to be carefully controlled to ensure optimum bonding is achieved, and a number of specialist products have been developed for this purpose.

For the rapid deposition of material into the shell mould the prepreg is cut into kits in an off-line process. Kits are designed to facilitate ease of lay-up and to minimise waste. The same approach is taken with the structural foam where blade foam kits are supplied ready for direct application to the mould. The final layers of prepreg are then applied over the surface of the foam before creation of the vacuum stack.

Although the shell laminates are typically thinner in section than those in the spar or root joint, the exotherm during cure can still be a problem if appropriate temperature dwells are not implemented. The intermediate dwell also serves to reduce outgassing effects from the foam which can lead to large defects between the core and the laminate skins (blow off). The resin flow is also more critical in shell manufacture as the interface with the gelcoat or primer has to be considered. As the flow can be influenced by the cure process, an appropriate cure cycle is selected to ensure good wetting behaviour of the prepreg resin is achieved.

**Bonding of Prepreg Blades**

The final stage of the manufacturing process before finishing (painting) the blade is the bonding of the two structural shells and the structural spar. For this particular structural design (non-structural shells and structural spar) the loads in the adhesive are significantly lower than those observed in the structural shell/shear web arrangement. This enables the use of a lower performance, low cost adhesive. The bonding process is also less complex than is the case for the shear web design as the shells and spar can be bonded in a single operation without the use of jigs.

**Prepreg vs Infusion**

Prepreg and Infusion processes are both used widely in the manufacture of wind turbine blades and both processes have their advantages and limitations. Prepregs are generally perceived as higher cost due to; higher material costs, higher temperature tooling, and more demanding environmental control and storage conditions. However,
prepregs provide some benefits with respect to process reliability and repeatability, higher levels of automation, higher mechanical performance, and carbon utilization (infusion of carbon fibre is very difficult).

The higher mechanical performance of prepreg materials allows the design of lighter blades, but the benefit can only be realized if an integrated design approach is followed for the entire turbine. Weight also becomes a more significant factor with increasing blade size, but the point at which prepreg becomes more viable than infusion is still not well defined.

The relative merits of prepreg and infusion technology are presented in a later chapter where a parametric study of a 35m blade is undertaken. The study considers a standard box spar design with a fixed tip deflection. The blade cost is then developed from consideration of materials, direct labour, mould utilization, indirect labour, tooling costs and depreciation, and overall plant CAPEX. The results are analysed using standard financial ratios and provides a good general financial overview of these two technologies.