Wind Turbine Blade Structural Engineering

As we saw in the discussion on aerodynamics the blade design process starts with a “best guess” compromise between aerodynamic and structural efficiency. The choice of materials and manufacturing process will also have an influence on how thin (hence aerodynamically ideal) the blade can be built, and at what cost. Therefore, the structural engineering process has a critical role in bringing all the disciplines of design and manufacture together and producing the optimum solution in terms of performance and cost.

The blade as a structural beam

The lift force on the blade, which drives the turbine round, is distributed along the blade approximately in proportion to the local radius, i.e. there is more lift force close to the tip than there is near the hub. The reasons why this is so, and why it is desirable, are explained in the preceding chapter.

The lift force tends to make the blade bend. If we look at a section of the blade at some point along its length, all the lift forces outboard of that point will have a cumulative effect on the tendency to bend, with those furthest away having the greatest effect as they have the greatest leverage. The effect is called bending moment. The bending moment is greatest at the root of the blade: at this point there is more blade outboard (contributing to bending moment) than at any other point along the blade. At the tip the bending moment drops to zero.

Bending moment against radius in a large turbine blade
So it is intuitive that the blade must be thickest, i.e. strongest, at the root and can taper in thickness towards the tip where the bending moment is less. As it happens, that suits the aerodynamics too: the blade needs a thinner section at the tip where drag is most critical and the local chord (width) of the blade is small. Also for turbines that rely on stall for power regulation in strong winds, a thin section stalls more easily so is beneficial at the tip. Closer to the root the chord is wider, but to avoid making it very wide (hence expensive) the blade needs to be thicker to generate enough lift given the lower wind speed close to the hub (thicker aerofoils can generate a greater maximum lift before they stall).

Unfortunately the thickness needed to make the blade stiff and strong enough is greater than that required for aerodynamic efficiency, so a compromise must be found between structural weight (= cost) and loss of aerodynamic efficiency.

**Internal beam structure**

If the blade was solid rather than hollow, the required thickness at each point along the blade would simply be determined by the bending moment at that point. But considering how the material in this hypothetical solid blade is working, as the blade bends downwind, the material on the upwind face of the blade stretches, carrying tension, and the material on the downwind face compresses. The material mid-way between the two faces, i.e. in the middle of the blade, is neither in tension nor compression – i.e. it does not do much work. So to reduce the cost of the blade it makes sense to take out some of that material in the middle, and make the blade hollow.

In the extreme case you would be left with two strips of material, one on the upwind face and one on the downwind face. This would not work for two reasons: shear strength and aerodynamics. The aerodynamics is obvious: there must be a continuous shell to give the aerodynamic shape. Shear strength is less obvious but is most easily visualised by thinking about what would happen to the two strips of material if they were not joined by anything: they would slide relative to each other and act like two separate, very thin, blades. They would lose all the bending strength that we are trying to maintain. So to work properly they must be structurally joined together; this connection is called a shear web. The classic embodiment of this concept is the steel I-beam.
The key thing to understand about structural beams is that the material carrying bending loads (the spar caps) should be separated as far apart as possible but joined together by a shear web. The wind turbine blade works in much the same way as the steel I-beam except that there are shells around the outside that form the aerodynamic shape. The shells contribute some bending strength but the majority comes from the spar caps, equivalent to the flanges of the I-beam. There are two common ways to achieve the shear web connection: either the spar caps are built as part of the shell and a separate shear web is bonded between them, or the shear webs and spar caps are built together as a box spar and glued into the shell.

**Laminate orientation**

Modern wind turbine blades are made from fibre-reinforced plastics (FRP) owing to the materials’ superior strength-to-weight ratio compared to wood and metals. FRP is particularly suited to long, slender structures like wind turbine blades because most of the stresses are in one direction and the fibres can be aligned to suit. It is fairly evident that most of the fibres in the spar caps should be oriented along the blade, since that is the direction of the bending loads (tension on the upwind side and compression on the downwind side).

It is perhaps less obvious that the fibres in the shear webs should be laid diagonally, so that they meet the spar caps at 45 degrees in either direction.

Consider a framework made of three bars, pin-jointed at their ends as shown in the diagram below.

![Diagram of a framework with hinges and loads](image)

**Shearing and reinforcement of a simple frame**

If a load is applied to the framework, it will deform to a rhombus shape (“shearing”). The key thing to note here is that the bars are still the same length but the (imaginary) diagonal lines are not; one is now shorter and the other longer. So the best way to stiffen the framework would be to add diagonal bars.
The framework could be extended by adding more bars to form a longer beam. Each section would need a pair of diagonals to give it shear stiffness. Both diagonals are needed (rather than just one); one set works in tension and the other in compression. These forces balance out transversely to keep the spar caps a constant distance apart. Longitudinally their cumulative effect is to prevent the spar caps from sliding (shearing) relative to one another.

To make the spar caps and shear webs, two different fabric styles are typically used: unidirectional are the best way to achieve the high axial fibre content of the spar caps, while ±45° stitched biaxial fabric is used for the shear webs. The spar caps usually incorporate some biaxial to transfer load between the unidirectional fibres, either by interleaving the shear web plies (in the case of a blade with a box spar) or by including extra plies (in the case of a blade with a separate shear web). In the latter case, care needs to be taken to ensure sufficient overlap of the shear web with the spar cap to transfer all the load through the relatively weak adhesive that bonds them together.

**Optimum geometry**

The ability to vary the strength of the blade without changing the outside shape (by making the spar caps thicker or thinner) gives us some freedom to optimise the design for minimum cost. If the blade is made thinner, it may perform better aerodynamically but thicker spar caps will be needed, making the blade more expensive. [The shear web must also be stronger but it will be narrower too, so the total amount of shear material is similar]. Optimum geometry is arrived at iteratively by considering turbine design, loads, structural design, and manufacturing costs.
Fatigue

It is well known that structures loaded repeatedly tend to fail at a lower load than expected. For metal structures the expression “metal fatigue” is well known and understood and is easily demonstrated by bending a spoon back and forth until it breaks. The same effect occurs in other materials, to a greater or lesser extent, including FRP. Wood is relatively good at resisting fatigue, which is why it has been a popular choice for smaller wind turbine blades, but wood’s lower strength-to-weight ratio compared to FRP precludes its use in larger blades.

Wind turbine blades are subjected to varying lift force due to wind gusts, wind shear (blades see more wind at the top of their rotation than at the bottom), up-draught and yaw error (if the turbine isn’t pointed straight into the wind, the blades’ angle of attack, hence lift force, will vary as they rotate), and turbulence. The lifting force acts in the “flapwise” direction (like a bird’s wing). The blades are also loaded in the “edgewise” direction, by their own weight, which causes reversing bending moments as the blades rotate from one side of the turbine to the other.

Fatigue can be accounted for at a simple level by designing for a lower allowable stress in the material. Fatigue testing of small samples of material by loading and unloading them thousands or millions of times allows a relationship to be plotted between the stress and the number of cycles to failure. The result is called an S-N curve:

![S-N curve for a typical wind turbine blade unidirectional material](image)

So for 10 million cycles, which corresponds roughly to 20 years’ use of a wind turbine, the allowable stress might be around 30% of the ultimate (once-only) strength. This depends heavily on the material: carbon fibres in epoxy prepreg resin may withstand
50% of their ultimate load for 10 million cycles, whereas a lower quality glass fibre laminate with vinylester resin might take less than 20% of its ultimate load.

Simply designing for a lower maximum stress is fine as a first check but if fatigue is driving the design, it will not provide enough certainty. Overcoming the uncertainty by using a larger safety factor (i.e. designing so the structure only sees very low stresses) will then result in significant extra material cost (see safety factors section).

More sophisticated design approaches look at the anticipated variation of load over time (the load spectrum) and use statistical methods to calculate an equivalent number of load cycles at each of several different stress values. Usually this is done using an algorithm called “rainflow counting.” The damage caused by each set of load cycles can then be calculated by seeing how much of the blade’s lifetime has been used up on the S-N curve at each value of stress. For instance if that stress would normally cause failure after 1000 cycles and the load spectrum predicts 200 cycles at that stress, 20% has been used up. If we make the assumption that the damage at each stress level can be added together to get a cumulative damage then we can see how much of the blade’s total fatigue life will be used up when it has been subjected to that load spectrum (this is called Palmgren-Miner’s law, after the engineers who proposed it). So there might be 20% used up by loads at one stress level, 35% used up by more cycles at a lower load, and so on; if the total exceeds 100% the blade will fail before its design life is reached.

**Blade shells**

Whilst the primary function of the shells is to provide the aerodynamic shape, they also play a structural role in stiffening and strengthening the spar, particularly to resist torsion (twisting) loads. Just as for bending, a bigger section resists torsion better than a small one, and the blade shells are of course significantly larger in cross-sectional area than the box spar so are very useful in this respect. Structures loaded in torsion experience pure shear loading, so just like the spar shear webs, the shells have a high proportion of fibres running diagonally.

The shells also have fibres running along the length of the blade. To an extent this assists the spar caps in flapwise bending but the main reason is to give the blade more strength in edgewise bending as structural beams work best with the load-carrying material separated as far apart as possible (like the spar caps in flapwise bending). Looking at the cross-section below, the shells are significantly wider than the spar so are the most efficient way to provide edgewise bending stiffness.

Edgewise bending is primarily due to the blade’s own weight. Since the centre of gravity of the blade is not very far outboard, by far the biggest edgewise bending moment is at the root. What this means is that, whilst the shells can support the edgewise bending stresses for most of the length of the blade, often some extra reinforcement of the trailing edge is needed near the root.
If the blade shells were made just of FRP the thickness required to make them strong enough would be very small, only a few millimetres. However, since there can be a metre or more of shell between the spar cap and the trailing edge, the shell would be too flexible if it was that thin. The flexibility would be a problem both for keeping the aerodynamic shape and to resist buckling (the tendency of flexible structures to deflect sideways under compressive loading).

To make it thicker with more FRP would add considerable weight (and cost) so instead the shells are made as a “sandwich” construction of FRP skins either side of a low density core, usually rigid foam or balsa wood. This works along the same lines as the I-beam or box spar, with the core carrying shear loads and the skins providing bending stiffness. The foam core can be omitted where the spar caps support the shell, indeed it is advantageous to do this as it allows the spar caps to be better separated to carry the bending loads, which as we have already shown, is beneficial.

**Root design**

The blade root, as mentioned in the previous chapter on aerodynamics, generally needs to be circular in section to connect to the circular pitch bearing in the hub. Since the blade needs to be removable for maintenance, this is invariably a bolted connection. If the spar was metal, it could have a flange welded to it but the same approach would be inefficient in FRP as the resin would have to support high stresses around the flange corner.

Instead most blade roots consist of a thick tube of solid laminate with studs or T-bolts screwed in or set into it in adhesive. The load can be transferred into the studs over their whole length, which suits the limited load capacity of the adhesive or threaded hole.

*Section through blade near root showing TE tapes and cored/uncored area of shells*
Somehow in the manufacture of the blade, the I-section or box section spar must be joined to the cylindrical laminate at the root. For a box spar it is possible to laminate the spar on a mandrel that blended smoothly from circular at the root to rectangular further out, so that the thick root laminate could be interleaved seamlessly with the box spar. In practice this can lengthen the time taken to make the spar, owing to the large number of plies that must be laid down to make the root. The high thickness also poses some manufacturing issues with respect to high exothermic temperatures that can occur in thick laminate sections, and the high quality of laminate that is required in this critical area of the structure. As a consequence many manufacturers make the root as a separate component and bond it into the structure. Naturally if the adhesive failed, the consequences would be terminal: in short, the joint requires careful design and a strong, fatigue-resistant adhesive. In particular, great care must be taken to avoid a concentration of stress in the adhesive at either end of the joint.

**Stiffness**

So far we have looked at the strength of the blade, but it needs to be stiff enough too. (Strength and stiffness have distinctly different meanings in engineering which can be visualised with a simple example: a rubber bungee is easy to stretch but hard to break, so is strong but not stiff; an eggshell by comparison is stiff but not strong).

If the blade is not stiff enough it might suffer one of two problems, both due to the tower. If the tower is round, as most are, the wind forms a turbulent wake downwind of it. A turbine placed downwind of the tower would suffer big variations in lift force as the blades passed through the wake, leading to reduced power and high fatigue loading. So most designs put the turbine upwind of the tower. However this means that as the blades bend, they get closer to the tower, so must be made sufficiently stiff not to hit it. Designers typically aim for a minimum clearance between the blade tips and the tower of 30% of the unloaded clearance under the worst-case loading.
It might seem that a simple solution would be to increase the initial tip clearance, either by putting the rotor further upwind of the tower, tilting it out at the bottom, pre-bending the blades or “coning” (angling all the blades upwind relative to the flat rotor plane). All of these approaches are adopted to an extent but each has a cost associated with it, either in aerodynamic losses or greater manufacturing cost (for instance a greater overhang of the rotor from the tower means the nacelle yaw bearing must be stronger).

The other problem is that the blades still experience a pressure pulse from the air flowing around the tower even if they are upwind of it. This not only contributes to the fatigue loading (though less so than if the blades were downwind) but more significantly can cause the blades to resonate. Resonance can be likened to pushing a child on a swing: if you push at the same frequency as the swing moves, the amplitude of the motion gets greater and greater; pushing out of sync with the swing reduces the motion. Resonance caused by tower passing greatly increases the vibration of the blade, hence the fatigue stresses on the blade, hub and bearings. So the blade must be stiff and light enough to keep the natural frequency of vibration well above the tower passing frequency. Unfortunately adding material to stiffen the blade increases the blade weight, and consequently it may be necessary to thicken the shape of the blade to address natural frequency issues.
Since the blades are joined together at the hub, vibrations of one blade affect the others too. So their natural frequencies must not coincide with the frequency at which they or their neighbours pass the tower (called the 1P and 3P frequencies). For example, if one blade of a three-blade turbine passes the tower every second, the natural period of oscillation of the blades must be neither one second nor three seconds. For turbines that operate at variable speed (hence a range of blade passing frequencies) this requirement becomes even harder to satisfy.

Fibre types

The most popular fibres to use in FRP are glass and carbon. Carbon fibres are about twice as strong as glass and three times stiffer. Their extra stiffness also allows the surrounding resin to withstand fatigue better by reducing the strain in the resin. Unfortunately carbon fibres are much more expensive, so they tend to be used only where their properties are essential for the performance of the blade.

In general this means carbon is used only on some of the largest turbines (over about 80m diameter), and even then only on the spar caps. The reason why larger blades need carbon more than smaller ones is that it is much harder to achieve sufficient stiffness on a long blade without adding excessive weight. The extra weight not only means greater cost of material but also lower natural frequency (so the tower passing frequency can be a problem) and higher fatigue loading due to edgewise bending (which it will be remembered is caused by the weight of the blade flexing it one way then the other as it rotates). For these reasons the extra cost per kilogramme of carbon can be economically justified if it allows the global weight of a blade to be reduced significantly.

Indeed the weight of the blade theoretically increases with the cube of its length, while the power output only increases with the square of the length. If we accept the approximation that cost of manufacture is proportional to weight, this means that it becomes hard to justify making turbines larger unless the savings on cost per kilowatt due to having less towers, less generators etc can offset the additional blade cost. To get past this hurdle it is necessary to make blades lighter, which either means making them thicker (and therefore less aerodynamically efficient) or using carbon.

The structural design process

Flapwise bending, due to the lift forces, is usually the most dominant loading and is known most accurately at the outset, so the design starts by considering the spar cap and shear web laminates needed to withstand it. As we stated at the beginning of this chapter, there is a trade-off between aerodynamic efficiency (thin blades) and structural efficiency (thick blades), both of which have a strong effect on the cost of electricity generated. The design process therefore requires the optimum thickness distribution to be found, by finding the effect of varying thickness on both the power output and the structural weight.
There is then an iterative loop to be followed in the structural design because the edgewise fatigue loading depends on the blade’s mass. Until the blade is designed, its mass is not known so must be assumed. Once the mass is known more accurately the blade laminates may need to be re-designed to account for the new loading (derived from the mass). At this stage fatigue may be dealt with by simply lowering the allowable stress of the material. Design codes such as Germanisher Lloyds provide conservative default knock-down factors on strength to be used if fatigue data is unavailable, typically about 5 for glass fibre and 3 for carbon at 10 million cycles.

With the basic bending parameters (flapwise and edgewise) of the blade determined, the shells can be checked for torsional stiffness and resistance to buckling. The root can be designed to carry the bolt loads from the blade to the hub and the adhesive joint analysed to keep stresses in the adhesive down to an acceptable level.

Gurit’s Blade Design Tool enables the shape to be matched with the mathematical approximation

Up to this point in the design, the analysis will usually have been done using a spreadsheet or other simple analytical method, which gives only an approximate answer but allows rapid iterations of the design towards the optimum. For the final analysis, a more accurate answer can be provided by Finite Element Analysis (FEA). This uses a three-dimensional virtual model of the blade which is broken up into thousands of square elements, like tiles. Because the computer can model accurately the behaviour of each element and knows how the elements are joined together, it can simulate the structural response of the whole blade to any load scenario.
If fatigue has been identified as potentially critical in any areas, it can be considered in more detail once the design is close to finalised. The stress at the worst locations can be analysed under the anticipated loading spectrum to calculate the cumulative damage over the lifetime of the blade, and check that this will not cause premature failure.

The flowchart overleaf shows the structural design process and the interaction of the aerodynamic design with the static and dynamic load calculations:
Blade Structural Design Process

Design requirements (power, site conditions)

Initial aerodynamic design

Flapwise loads

Initial Structural Design
- Strength
- Basic fatigue check
- Stiffness check

Thickness optimisation
(for cost of electricity)

Weights

Natural frequencies check

Edgewise loads check (fatigue)

Root design including adhesive bond

Buckling check

Final weight

Finite element analysis
- Ultimate stresses
- Fatigue
- Deflection
- Natural frequencies

Build & test prototypes
Safety Factors

As for other engineered structures, the structural design of a wind turbine blade relies on safety factors to account for the unknowns: inaccuracies of the assumptions made in analysis, variations of geometry, loading and material behaviour – in essence all the “real world” effects. At its simplest, a safety factor multiplies up the design load or reduces the design stress to achieve sufficiently low probability of failure.

Wind turbine design codes use the (more precise) method of “partial safety factors,” that is to say the overall safety factor consists of several partial factors multiplied together. Each of the partial factors accounts for one effect, e.g. uncertainty of loading, ageing of the material, manufacturing variations or material type. By using partial factors, the differences between (for instance) one manufacturing method or another can be taken into account more accurately than with a simple global factor. A further factor may be added for the “consequence of failure”; thus if the integrity of a particular part is essential for the turbine’s survival, that part’s factor will be higher to reduce the probability of failure of the whole machine.

Testing

To achieve an acceptable (in)frequency of failures, the partial safety factors on material strength would have to be very large if no testing was done. The cheapest and simplest tests performed are on small samples ( coupons) of the material, to establish the material properties, both the ultimate strength and the resistance to fatigue (the S-N curve). From these coupon tests, statistical calculations can be used to determine the lowest likely strength of the material used in the real structure (called the “characteristic value” of strength). Several repeats of the same test are needed, on coupons taken from different batches of material, because of the natural variability of materials. By taking up to twenty test values for each material property, the characteristic values can be calculated with reasonable confidence. Normally the characteristic value is chosen so that 95% of material will be at least that strong, with 95% confidence.

The partial safety factors are then applied to the characteristic value to give a design allowable value of strength. So the process is:

Coupon testing → mean & standard deviation → characteristic value → partial factors → design allowable

Note that in composites the strength is normally given in terms of strain (the maximum elongation that the material can withstand) rather than stress (the maximum force per unit area). This is because laminated composites have varying stress through the thickness of the material, depending on fibre orientation, which makes calculation of the failure load complicated. The strain however is constant or varies linearly, so analysis using strains is more straightforward.

After the design is completed, a prototype is built and tested to simulate the real blade in service. One blade will be tested to the once-only ultimate flapwise load and another loaded repeatedly to check the fatigue strength.
Since the design life of a blade is usually 20 years, a fatigue test over the same timescale would be prohibitively lengthy. Instead the S-N curves obtained for the basic materials are used to calculate an amplified loading that could be expected to cause equivalent fatigue damage to the full design life after fewer load cycles. By doing this, and by loading the blade faster, the test can be accelerated to take only a few months.

Summary of structural design
The structural design process must take into account the aerodynamic shape, material properties under extreme and fatigue loading, and the manufacturing method.

Spar: Primarily the blade is loaded in bending, due to the aerodynamic lift forces (flapwise) and to a lesser extent the blade’s own weight (edgewise). To resist bending, unidirectional fibres running along the length of the blade are placed as far apart as possible in the flapwise direction. These are called spar caps and to be effective they must be joined by a shear web comprised of diagonal fibres.

Shells: The aerodynamic shape is formed by shells which are stiffened by using a sandwich construction. Thin skins, usually of glass reinforced plastic, are placed either side of a light weight foam core. The resulting sandwich construction is stiff enough to resist bending due to aerodynamic pressures and buckling. With diagonal fibres in the laminate, the shell provides the blade with the necessary torsional stiffness.

Root: Where the blade is bolted to the rotor hub, the spar must be circular and the laminate is locally thickened. For ease of manufacture, this part is often made separately and bonded to the spar and shells as a secondary operation.
Strength and Stiffness: The blade must be both strong enough not to break and stiff enough not to strike the tower. It must also be stiff and light enough so that its natural frequency of vibration does not coincide with the frequency at which the blades pass the tower, or resonance will occur, amplifying the vibrations until tower strike or fatigue failure occurs.

Fatigue: With a typical 20 year design life, the blades will flex about ten million times. This weakens the material (fatigue) so for normal operating loads, the blade must be designed to a lower stress than for extreme, one-off loading situations (e.g. a 50-year gust). Fatigue testing of small coupons of material is used to establish an “S-N” curve that shows how many cycles the material can withstand at a given stress.

Fibre type: Glass fibre reinforced laminates offer good strength to weight ratio. Carbon fibre is more expensive but much stiffer and stronger, so tends to be used for the spar caps of longer blades.

Structural design process:

- Material properties are generated by coupon testing and reduced by partial safety factors appropriate to the material and manufacturing method.
- On provision of the preliminary aerodynamic profile flapwise loads due to aerodynamic lift are used to calculate the preliminary laminate design, hence confirm that the design can be made to work structurally within the chosen aerodynamic shape.
- Given the preliminary laminates, the mass of the blade can be used to estimate edgewise fatigue loading.
- Blade shells are checked for buckling resistance and torsional stiffness.
- Manufacturing processes and material selection are defined with the implications on weight and cost.
- Further loading/laminate iterations converge on a final design which is then checked by Finite Element Analysis for stiffness, buckling stability and strength including fatigue.
- Finally a prototype blade is built and tested, both for extreme flapwise loading and fatigue loading to validate the design.