FATIGUE LOADING IN WIND TURBINES

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INTRODUCTION

Because of the complex systems of variable loads that wind turbines are subjected to, they are particularly susceptible to fatigue damage. The rotor blades are mostly at risk. Research efforts have been directed into assessing the potential for blade fatigue damage during operation.

Some drive train failures have also been due to fatigue, and efforts have devoted into alleviating the effects of variable loads on them

Fig. 1: Inspection of rotor blade tips for possible cracks. They are subjected to wind speeds reaching 250 km/hr. Source: Nordex.

FATIGUE LOADING AND FAILURE

The cyclic loading of the structure of a wind turbine could cause failure if some critical level of damage is exceeded. Once initiated, the damage will grow with the load cycling until failure occurs. The failure process would occur because of one of the following reasons

1. The net section stress, accounting for the loss of section caused by the damage, exceeds the ultimate strength of the material.
2. A critical crack forms by the accumulation of damage.

If the damage growth rate in a component depends on the cyclic stress range, the load ratio *R*, is defined as:

$$R = Load\ Ratio = \frac{Maximum\ applied\ cyclic\ load}{Material\ Tensile\ Strength} \qquad (1)$$

and the current value of damage *D*, then:

$$\frac{dD}{dN} = f(\Delta\sigma, R, D) \qquad (2)$$

where:

$\Delta\sigma$ is the cyclic stress range

R is the ratio of maximum applied cyclic stress to the material's tensile strength

D is the current value of damage as a percent of section subject to fracture

N is the number of loading cycles

The fatigue lifetime or the number of cycles at failure N_f is defined as the number of load cycles that are necessary to raise the initial damage state D_i to the final or critical level of damage D_f, where failure occurs.

By integration the inverse of Eqn, 2, we can write:

$$N_f = \frac{dD}{f(\Delta\sigma, R, D_f)} \qquad (3)$$

It is necessary to define the function *f* in order to quantify N_f. This is carried out empirically by the use of the Stress versus Number of cycles or S-N curves.

An alternating stress is applied to the material being tested and the number of cycles to failure N_f is determined as a function of the stress amplitude *S*.

The slope of the S-N curve is a measure of the resistance of the material to fatigue, and the actual shape of the curve varies from one material to another.

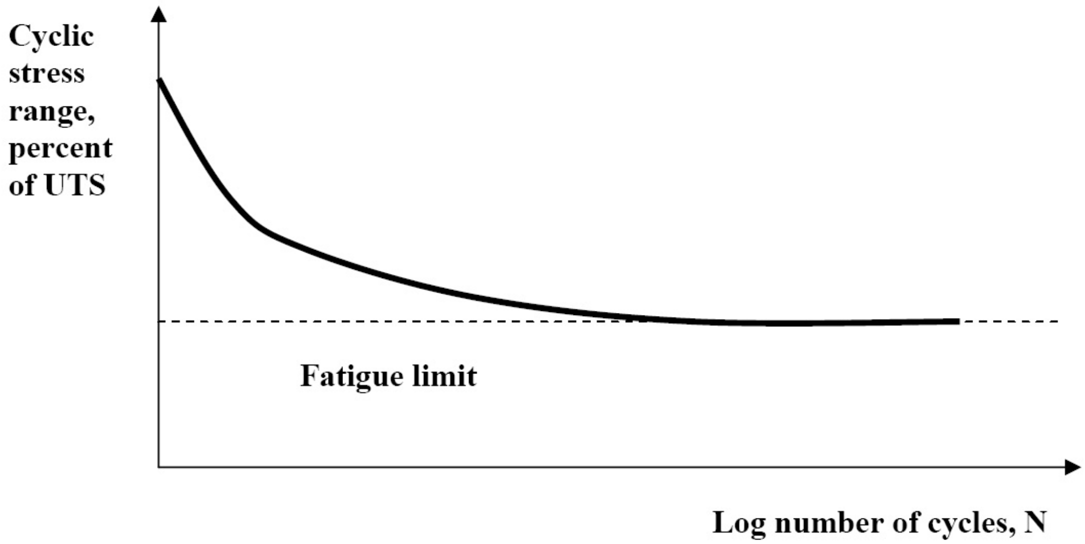

Fig. 2: Shape of the S-N curve for a given material. The y axis is the cyclic stress range as a percent of the Ultimate Tensile Stregth (UTS) and the y axis is the logarithm of the number of cycles N.

FORCES RELEVANT TO FATIGUE

Even though the S-N curves provide an indication of the relative fatigue properties, they do not take into account the complex effect of the large number of different cyclic forces which act on a wind turbine blade during operation.

These forces arise due to the blade's own mass and the force of the wind acting upon it and include:

1. The gravitational force caused by the pull of the Earth on the mass of the blade. This leads to compression and tension in each cycle.
2. The centrifugal force due to the rotation of the rotor blade.
3. The wind thrust which is a force that is perpendicular to the plane of the rotor blade. It varies relatively slowly.
4. Other rapidly varying forces arising from wind turbulence which increase as the stall conditions are approached.

Research indicates that the relatively low frequency high amplitude wind thrust forces primarily contribute to fatigue damage.

ENVIRONMENTAL FACTORS AFFECTING FATIGUE

For a chosen fatigue resistant material, environmental attack can rapidly reduce its fatigue strength. This could occur in two ways:

a) Blade Topography:

The topography of the blade surface may be modified by minute erosive and corrosive pits from sand or rain impingement. These would act as stress concentrators during cyclic loading, causing localized cracking to be initiated. The corrosive attack along the grain boundaries in metals acts in a similar way; setting up crack initiation sites for intergranular fracture. For larger Glass Reinforced Composites (GRP) and wood laminate blades, the erosion attack can occur near the blade tips where the rotational velocities can reach the equivalent of 100 m/sec.

b) Bulk material properties:

The bulk material properties may be altered, thus reducing fatigue strength throughout the blade wall thickness or through the surface layers. An example would be a moisture intrusion into the wood laminate blades in poorly protected regions or at the trailing edge where a loss of bonding of the laminates can happen.

The remedy is the use of protective coatings that are applied initially at the manufacturing stage and then regularly checked during the maintenance process. The wood laminate blades are usually coated with an epoxy skin for environmental protection, in a similar technique to that used in the manufacture of helicopter blades. The leading edge of wind turbine blades always requires a special finish and care.

ROTOR BLADE DESIGN CONSIDERATIONS

The rotor blade design should not exacerbate the effect of the cyclic forces it is subjected to. Some blade geometries should be avoided in order to reduce the prospect of early fatigue failure. Sharp changes in the blade profile at the blade root and hub junction can act as stress concentration regions, causing the yield stress of the blade material to be locally exceeded and leading to crack initiation. As an example of this process is the British Comet passenger plane disasters in the early 1960's which were due to such a design error. It was caused from the use of a sharp radius of curvature at the corners of the fuselage window openings.

The design of the connecting joints is important in rotor blade construction. The veneer butt joints in wood laminate rotor blades are particularly susceptible to fatigue failure. Using a simple modification by substituting scarf or angled joints at the veneer junctions would significantly reduce the failure rates.

CHOICE OF ROTOR BLADE MATERIALS

The S-N graphs for some turbine rotor blade materials are shown in Fig. 2. The data about the fatigue life of materials must be considered with care. In the case of a composite the materials differences in the fiber or mat type, the matrix and reinforcement bond strength or the construction methods can introduce significant uncertainties.

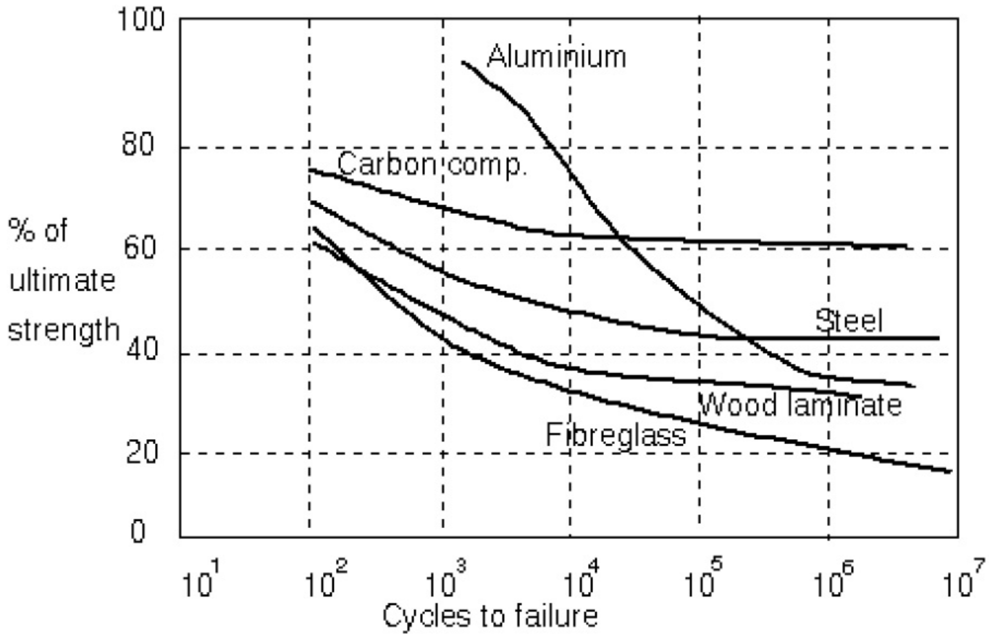

Fig. 3: S-N diagrams of some rotor blade materials.

The turbine rotor blade materials may be classified into the following groups:

METALS

Some metals such as mild steel are relatively fatigue resistant; provided it is subjected to a cyclic stress below its fatigue threshold. This is usually less than 1/2 its Ultimate Tensile Strength (UTS). Mild steel can be used for long periods if the component is designed, fabricated and maintained correctly.

Some light alloys like aluminum have an S-N curve which falls continuously with time. Failure becomes increasingly likely if the material remains in service under cyclic stress conditions long enough.

This suggests in the concept of a limited service life for the component after which it must be discarded, regardless of whether any damage is apparent. Such an approach is used in the maintenance of some civilian and most military aircraft.

WOOD LAMINATES

A number of wind rotors manufacturers produce wood laminate blades up to 25 meters in length. Wood laminate offers good strength to weight properties when compared to Glass Reinforced Composites (GRP). A favorite wood laminate material from the perspective of fatigue response is Khaya, or African Mahogany.

COMPOSITE MATERIALS

The fatigue properties of composite materials depend on the inherent strength and stiffness of their component materials as well as on their structure. Composite materials are common such as in automobile tires, airplane wings and fuselage and reinforced concrete. The steel reinforcement in concrete carries out the tensile loading, while the concrete matrix carries the compressive load.

Glass Reinforced Composites (GRP) are the most commonly used turbine rotor blade material. Experimental full scale simulations have been conducted and indicate a satisfactory service life under normal conditions.

Laboratory testing data show a steadily decreasing S-N curve for GRP, indicating a finite service life. A careful monitoring of GRP rotor blades under operational conditions should be undertaken.

Composite materials containing higher modulus or stiffer fibers such as possess better fatigue properties, if cyclic stress is applied parallel to the fiber orientation. This is because the matrix epoxy material is constrained by the reinforcing fibers during cyclic loading, subjecting the composite to relatively low strains which do not approach the cracking strain of the matrix. The second phase, such as the glass fiber in GRPs can also act as a crack arresting zone, effectively pinning the growth of fatigue cracks.

Carbon fiber reinforced composites exhibit outstanding fatigue performance when compared with metals and other composites, especially when subjected to tension fatigue in the fiber direction. Their advantage is reduced when the matrix material becomes the predominant load bearer, but they nevertheless offer many times the performance of other composites or metals. Cost constraints cause carbon fiber composites to be rarely used in turbine rotor blade construction.