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Timber for High Efficiency Small Wind Turbine Blades

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ABSTRACT
This paper explores technical and other issues arising from using shaped timber for a 1 metre long high efficiency blade for a small 600 W wind turbine. Two readily available Australian grown softwood timber species, radiata pine and hoop pine, were selected. Reasons for selecting these timbers are detailed in the paper. The fatigue life of the both timbers was determined using four point flexural testing. Results show that hoop pine is 25% stronger and 6% more fatigue resistant than radiata pine. A fatigue test procedure for the 1 m blade has been created based on the aeroelastic response of a 2.5 m long composite wind turbine blade and wind data from the Australian Bureau of Meteorology. Blade fatigue-life predictions, using Miners rule for fatigue damage accumulation, indicated effectively unlimited fatigue-life for a blade constructed from hoop pine, with the turbine operating at design performance in wind speeds up to 20 m/s. The blade's life was reduced to a few months when it was constructed from radiata pine for the same operating conditions to 20 m/s. However for an upper wind speed of 17 m/s, the predicted blade fatigue-life is effectively unlimited for both species. Test blades were machined in both radiata pine and hoop pine on a 3-axis milling machine with tool paths created using Pro/Manufacture software. Some of the important issues with respect to creating the blades out of timber are discussed.

1. INTRODUCTION
The materials used to construct large wind turbine blades has changed over the years reflecting in part advances in technology, higher loads on the blades due to increase blade length as well as demands to reduce manufacturing costs without sacrificing performance. Currently glass fibre reinforced composites is the predominant construction material with some carbon fibre reinforce composites being used in very long blades of 40 m and more, Burton *et al.* (2001). However, construction materials for the blades of small turbines, that is for machines up to 50 kW rated output power and blades to about 10 m length, are more diverse than for the large machines. Construction materials include fiberglass skin with a foam core, carbon fibre, pultruded fiberglass and to a limited extent timber. All blade construction materials have at least one common attribute, namely a long fatigue-life. This is because wind turbine blades are subject to a combination of static and cyclic loading during operation, since the number of fatigue-inducing load cycles may exceed 10^8 cycles for a blade life of 20 years.

There are several important differences between the operation of large and small wind turbines which affect the loading on the blades. Blade rotational speed typically increases with decreasing blade length. Consequently for small blades, centrifugal forces are of more importance than on larger blades and the effects of fatigue loading more noticeable as fatigue cycles tend to be periodic with blade rotational speed. Lead-lag fatigue loading on blades is dominated by gravitational forces and is significant on large blades but not on smaller blades.

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During operation, the stress on small blades is mainly tensile in nature whereas on large blades the cyclic loads can induce stress reversal.

The Wind Energy Group at The University of Newcastle, Australia has been involved with the design, construction and testing of high efficiency blades for small wind turbines. To date, the smallest blade-type from the Group is 1 metre long blade, which is currently used on the Sun, Wind and Power Pty Ltd 600 Watt machine. The company presently has the blades manufactured from fibreglass reinforced composites, but, for a variety of reasons, we are investigating the suitability and feasibility of shaped timber blades (as distinct from wood laminates). Timber has excellent fatigue properties and for this size blade, knot and other defect-free lengths of timber in most species are readily available at a reasonable cost. Given the variety of both hardwood and softwood timber species available, it should be possible to find several species of timber that fulfil the latter two requirements. It is also desirable that the timber originates from a sustainable plantation, so improving the sustainable and "green" credentials of wind energy.

To assess whether timber can be successfully used as a material for small wind turbine blades, the following key issues need to be addressed: the fatigue life characteristics of the chosen species of timber; a suitable fatigue loading procedure to predict the lifetime of the blade, and the major constraints/problems associated with rapid and accurate machining of a complex 3D shape in timber. The latter issue is far from trivial, because it has a strong influence on the final cost of the blade and hence its success in the market place.

2. TIMBER FOR SMALL WIND TURBINE BLADES

Timber is a natural composite which has excellent fatigue properties - one of the important requirements for a material for blade construction. Timber is relatively lightweight, has excellent specific mechanical properties, easy to work, can have very low shrinkage and warpage, is relatively cheap and can be grown as a sustainable resource in plantations. Timber also has the advantage over fibre reinforced composites in that the fatigue life of different species is less variable and will depend mainly on its density, whereas each fibre reinforced system needs to be evaluated individually, Ansell *et al.* (1991). Their guide may be useful given the large variety of timber species available and the general lack of any published fatigue data.

Several timber species were investigated for blade construction with two softwood species. The final choices were, hoop pine (*Araucaria Cunninghamii)*, a native Australian pine, and radiata pine (*Pinus Radiata)*, an American pine. Both timber species are grown in plantations in Australia. Table 1 shows the general mechanical properties of both timbers with hoop pine stronger and slightly denser than radiata pine, with both having comparable shrinkage. Softwood was selected, rather than hardwood, because softwoods have a simple and uniform structure composed of fibres called tracheids which are 3-5mm long, Smith *et al.*

Table 1: Mechanical properties of Radiata and Hoop pine, Bootle (1971), AS/NZS 2878 - 2000

	Radiata Pine	Hoop Pine
Density (kg/m^3) 12% moisture content	500	545
Shrinkage %		
Radial	1.0 - 4.9	1.4 - 3.5
Tangential	2.4 - 5.9	2.4 - 5.0
Strength Group AS/NZS 2878-2000	SD6	SD5
Bending Strength (MPa)	65	78
Modulus of Elasticity (MPa)	10500	12100

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(2003). The structure of hardwood, however, is more complex, varied and contains pores, i.e. vessels containing sap, which can make it difficult to obtain a uniform machined surface. Fatigue properties of both hardwood and softwood appear to be similar. Interestingly the fibre to matrix volume ratio for timber is approximately 35:65, Dinwoodie (1989), which is similar to glass-fibre composites. Here the matrix material is the bonding material of the microfibril, which is essentially the load carrying component within the cell structure.

2.1. Radiata (also known as Monterey) Pine; *Pinus radiata*

Radiata pine is a native of North America, growing naturally in only three locations on a narrow stretch of coast in Southern California and two small islands off the coast of Mexico. The species is now one of the most widely grown exotic timber species in the world, with large areas of plantation in New Zealand, Chile, Australia and Spain. It is a cream to very light brown in colour, with a straight grain. Radiata pine is grown in every Australian state and the Capital Territory, with most timber from NSW, Victoria and South Australia. In Australia, radiata pine is the most widely used timber in the building and landscape industries. It can be readily sawn, peeled, or converted to pulp, has good nail holding ability, works well, can be easily stained, and when treated with preservatives, is suitable for long life applications in the ground.

In its native habitat around Monterey California, a radiate pine seldom grows any taller than 35 metres or reaches an age longer than 75 years. Many of the trees are misshaped or affected by disease. Yet other regions of the world, including Australia, favour improved growth and form than the native habitat. Early plantation trees in NSW grew up to 50 metres in 70 years while now in NSW a typical pine tree is harvested at 35 years when it is about 35 metres tall and half a metre across at the chest height. When grown as a plantation tree, radiata pine is a straight tree with small branches. Genetic modifications have improved growth rates and form (straightness and uniformity) of plantation grown radiata pine. Radiata pine was selected due to its availability and relatively low cost.

2.2. Hoop (also called Arakaria, Dorrigo or Colonial) Pine; *Araucaria Cunninghamii*

Hoop pine is a tall Australian native conifer with dark rough bark and small leaves. The timber has a texture that is plain, even and fine, without prominent grain or growth rings. The grain is straight and, because it peels easily, the timber is well utilised in the Australian plywood industry. Hoop pine grows to 60 m in height with diameters between 0.6 to 1.9 m. In its natural habitat the tree can be found in the lighter types of rainforest from Coffs Harbour in NSW to northern Queensland. Typically the tree is long and straight with little taper and is free of branches for up to two thirds of its height. Because it grows successfully in plantations, the timber has become widely available from sustainable managed plantations in Queensland and north eastern NSW. The planting to harvesting cycle of Hoop pine is about 50 years.

Hoop pine is currently used for the manufacture of veneers and plywood, match boxes, broom handles, cabinet work, furniture, flooring, mouldings, linings and boat building. It is now marketed as Arakaria MGP (Machine Graded Pine) for floor joists and other structural applications in the building industry where its light weight, easy working and structural ratings make it particularly popular. Hoop pine has been used for manufacture of propellers for ultra-light aircraft, making it a logical choice for small wind turbine blades.

3. FATIGUE PROPERTIES OF TIMBER

To determine the fatigue life of a blade requires the fatigue properties of the blade material to be known in detail. To the authors' knowledge there is no detailed data in the literature for

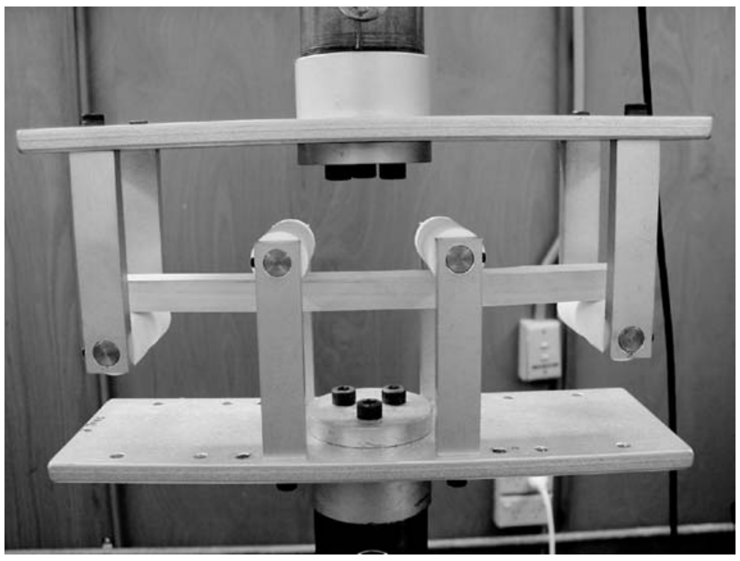

Figure 1: Timber sample in a four point test rig

radiata pine and hoop pine which could be used to generate a fatigue curve in the form of stress against logarithm of cycles - an S-N curve. As such these data need to be generated through fatigue testing of 'coupons', i.e. samples, of each selected timber species.

The blade in service is essentially undergoing flexural bending so it is appropriate to find the material's flexural fatigue properties. There appears to be no standard covering the testing for flexural fatigue in timber; the closest standard is related to fibre-reinforced composite materials. As a consequence, we followed the method of Tsai and Ansell (1990) who determined the fatigue properties of Khaya ivorensis laminates, Sitka spruce and beech laminates under load control in four point flexure. To undertake flexural tests, a four-point test rig was manufactured with support bars spaced at 240 mm and load bars at 80 mm to give a 1/3 load to support ratio, see figure 1. Load and support bars were manufactured from ϕ25 mm Teflon bar with a ϕ12 mm rod through its centre to provide a stiff support with a compliant surface to minimise damage to the timber samples. Tests were undertaken in a MTS model 810-03 fitted with a closed loop hydraulic system and controlled using MTS software package TestStar II version 4 running on a Pentium 200 personal computer.

All flexural fatigue experiments were undertaken at an R ratio of nominally 0, where R≡minimum stress/maximum stress, and loaded in ramp mode at a rate of 3 kN/sec for 90%, 80%, 70% and 60% (60 % for radiata pine only) of the timber's maximum stress level. An R ratio of 0 indicates the specimen is flexed between the unloaded position and the lateral displacement corresponding to the maximum stress position. Hoop pine tests were not done at the 60% level due to time restrictions on the use of the MTS machine. The coupons used for the tests were stored in an air-conditioned room that housed the MTS to ensure their moisture content remained the same during the testing period. The moisture content of radiata pine and hoop pine coupons were in the range of $12 \pm 1\%$.

Figure 2 shows the S-N data for both radiata and hoop pine along with the least square line of best fit through each data set. Samples of both timbers were carefully selected to ensure that the grain was even and parallel, there were no visible physical defects and the surface of all samples were smooth and flat. As can be clearly seen in Figure 2, the results for hoop pine show much less scatter than those of radiata pine, possibly indicating that hoop pine will generally have more consistent fatigue resistance properties than radiata pine. The scatter is the radiata pine results could be attributed to changes in the timber's density due to the

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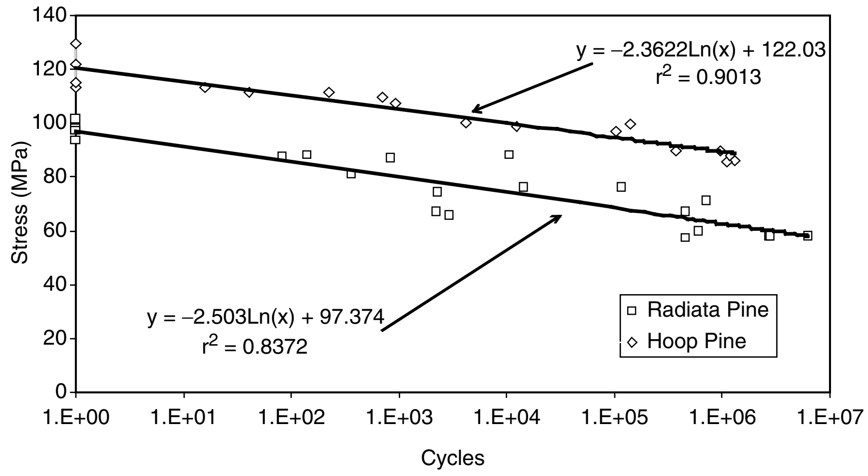

Figure 2: S-N curve for radiata pine at R = 0 with regression line of best fit. Correlation coefficient (r^2) for each line indicated in the figure.

presence of distinct growth rings. The results of Tsai and Ansell (1990) show similar scatter to those of radiata pine, with radiata pine appearing to be slightly stronger and slightly more fatigue resistant than Sitka spruce. The results of Figure 2 show that hoop pine is about 25% stronger and 6% more fatigue resistant than radiata pine (as shown by the difference in the slope of the lines of best fit), indicating it will be a much better blade construction material of the two, as long as they have similar machining characteristics.

4. FATIGUE LOADING PROCEDURE

A fatigue loading procedure consists of the loading cycles experienced by a blade at a "typical" site over its lifetime that will make a measurable contribution to fatigue damage of the blade structure. To create this procedure requires the following: the aeroelastic response of the blade and the number of cyclic variations in the wind speed hereinafter referred to as wind cycles, at the "typical" site. Wind cycles result in a cyclic variation in the load acting on the blade structure and, depending on the magnitude of these load variations, will lead to structural fatigue. The aeroelastic response was not available for a 1m long blade but was available for a 2.5 m long blade composite blade on a two-bladed 5 kW turbine operated at Fort Scratchley, Newcastle between 1998 and early 1999. Given the dearth of any other information, it was assumed that the aeroelastic response of the 1 m long blade would be the same as that of the 2.5 m blade. This assumption is likely to lead to a conservative fatigue procedure for the 1m long blade, as it is relatively much stiffer than the composite 2.5 m blade and therefore not likely to respond to all wind cycles experienced by the 2.5 m blade.

Wind data from a number of sites in Australia are available from the Australian Bureau of Meteorology. Unfortunately only the average and maximum wind speed is supplied for each 1/2 hour data sampling time with no wind cycles recorded. To account for any missing wind cycles, detailed wind data acquired over a 10 minute time period at 0.5 Hz from Fort Scratchley test site were rainflow counted, with the number of wind cycles correlated against both mean and maximum wind speeds in each 10 minute interval. This was used to account for the missing wind cycles from the Bureau's data. A comprehensive description of this process can be found in Epaarachchi (2002). Here it is sufficient to note that up to 30 fatigue cycles were predicted to occur in each 10 minute interval.

Blade stress cycles need to be determined from the wind cycles. Here the panel code of Wood (1991) was used to determine the aerodynamic pressures acting on the blade for the turbine

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operating at its design conditions. This pressure, when expressed as a pressure coefficient, remains essentially constant over all wind speeds as long as the turbine is operating at a constant tip speed ratio. This coefficient was converted to the equivalent point load acting through the aerodynamic centre of pressure of the blade at rated wind speed and appropriately scaled for all other wind speeds. This load was applied in a detailed finite element model of the blade, which was meshed from geometry imported from a Pro/Engineer solid model of the blade. This same solid model was used to manufacture the blade through a CNC machine.

The mechanical properties for each timber species were found from coupon testing undertaken on the MTS machine. To account for the variable nature of timber, static loading tests were done on a number of blades with strains and deflections recorded at several strategic locations along the blade. Predicted blade deflections and strains were compared with these measurements with the model's mechanical properties "fine-tuned" until good agreement was achieved. The degree of fine-tuning was generally very small only of the order of a few percent of the experimentally determined value of E, Youngs modulus of elasticity. Once done the largest stress in the blade was predicted for the design wind speed, and scaled appropriately for other wind speeds. The largest stress was found to occur close to the attachment block of the blade, which reduces the error between the actual stress and that determined by the equivalent point load. The wind cycles were then converted into equivalent stress cycles and binned into the 1 m/s bins for wind speed between 1 m/s and 20 m/s and for R between 0 and 0.9. These stress cycles are directly correlated to the blade's flapwise deflection, since the response is linear and elastic.

The turbine is designed to furl out of the wind at a wind speed of 15 m/s, which is technically the maximum wind speed experienced by the blade. However, to allow a significant margin of error, 17 m/s was used as the maximum experienced wind speed.

Table 2 shows the predicted number of wind cycles for the various R ratios and wind speeds up to 20m/s. Tabulated for each wind speed bin are (a) the maximum stress in the blade structure, (b) the predicted number of cycles, for each stress ratio R between 0 and 0.9 inclusive that the blade would experience per year, and (c) the total number of cycles at each wind speed for all R over 5 year period. As previously stated the fatigue life of the coupons was determined at R = 0 which is the most damaging stress ratio in our particular case. Consequently the computational assessment of the blade's life was done using the total number of cycles at each wind speed allocated to R = 0, which adds to the conservative nature of the results.

For each wind speed bin, the cycles to failure were determined using the least-squares fitted line through the fatigue data as shown in Figure 2. Damage accumulated was estimated using Miners rule. Miners rule sums the ratio across all stresses of the load cycles at a particular stress level (wind speed) to the total number of cycles to fatigue failure at that particular stress level. The structure is said to have failed by fatigue if this sum is greater than or equal to unity. For radiata pine a blade life of around 13,000 years was predicted for a maximum wind speed of 15 m/s, around 190 years for a maximum wind speed of 17 m/s and only 2 months for a maximum wind speed of 20 m/s. For Hoop pine the blade fatigue life is essentially unlimited up to a wind speed of 20 m/s. If the turbine were to operate at a wind speed of 20 m/s (i.e. if it did not furl at 15 m/s), it would produce in excess of 2 kW rotating at around 1500 rpm. If we consider the maximum operating wind speed to be 17 m/s, the blade life can be considered as effectively unlimited for both radiata pine and hoop pine.

5. BLADE MANUFACTURING ISSUES

A number of test blades were manufactured within the University on an Arix CNC 90 three-axis milling machine. This machine has not been specifically designed for working with timber, resulting in relatively long machining times due to the slower than optimal spindle

Table 2: Fatigue cycles at various R ratios for each wind speed bin and the maximum predicted stress on the blade. Bold bins (4 m/s to 17 m/s) indicate cycles considered in the fatigue analysis. For each wind speed, cycles were summed and testing undertaken at R = 0.

Max. Blade Stress (MPa)	U (m/s)	R: 0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Total 5yrs
0.22	1	0	79	372	1031	2080	3270	4014	3734	2500	1124	91020
0.87	2	0	292	1374	4354	7670	12055	14797	13766	9216	4145	338345
1.95	3	0	523	2690	6818	13761	22251	26546	24698	16535	7436	606290
3.5	4	0	823	3435	9713	19169	30125	37675	34402	23032	10358	843660
5.4	5	0	955	4260	11424	23276	36237	44480	41906	27705	12460	1013515
7.8	6	0	1007	4539	12547	24937	39581	48103	44754	30448	13475	1096955
10.7	7	68	1014	4428	12325	24842	38834	47909	44348	30218	13353	1086695
13.9	8	52	980	4134	11315	22664	35734	43932	40676	27730	12247	997320
17.6	9	58	842	3524	9652	19415	30510	37329	34934	23623	10457	851720
21.7	10	34	681	2848	7681	15434	24311	29846	27883	18544	8628	679450
26.3	11	26	538	2096	5730	11563	18154	22316	20910	14103	6225	508305
31.3	12	16	376	1490	4022	8084	12709	15613	14533	9905	4354	355510
36.7	13	42	237	959	2632	5347	8346	10246	9558	6350	3012	233645
42.6	14	40	157	610	1634	3273	5157	6327	5895	3906	1852	144255
48.9	15	20	81	354	939	1887	2959	3648	3408	2293	1073	83310
55.6	16	18	52	193	510	1022	1612	1971	1847	1247	586	45290
62.8	17	26	41	104	271	528	830	1030	953	660	310	23765
70.4	18	18	17	55	125	256	394	493	453	309	172	11460
78.5	19	20	6	27	61	114	175	226	199	154	84	5330
86.9	20	26	11	14	30	53	75	103	99	70	56	2685

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speeds as well as the need for some hand finishing of the blade's surface. Each blade took about 8 hours to create, which is not of any great concern for the tests, but it would be a major concern if the wooden blades are manufactured commercially.

The most likely way of producing the blades commercially is by a copying process. Here a 'master shape' of the blade would be created, possibly out of steel, by the process mentioned above, and through the use of a jig, copies of the master can be created in timber. The copying process will need to be done in two passes, because the trailing edge of the blade creates a singularity in the cutting process. Careful attention needs to be paid to how and where the timber blank is supported during the machining operation to minimise bending and twisting of the blank whilst it is being machined. To overcome these problems when machining the test blades, the blank was completely restrained against the table and ribs were left supporting the blade in the blank; the photograph in Figure 3 shows the blank bolted to the table with one side of the blade machined and part of the support ribs showing.

During the manufacture of the first hoop pine test blade, the blank was only secured at each corner to the table and it began to warp as the blade shape was being created. The magnitude of this warping was in the range of 1 mm-2 mm which is sufficiently large to result in significant changes to the blade's shape and therefore would affect its aerodynamic performance. On further investigation, it was found that this warping was a combination of cupping of the timber where it bends across the plank, and bowing, where it bends along the length of the plank. There are several reasons why a piece of timber may exhibit this behaviour whilst being machined and in this case it is not possible to identify the exact cause. It can depend on how the piece is cut from the log, here both the hoop pine and radiata pine had been back or plain sawn which gives planks with faces tangential to the growth rings, the size and shape of the piece, the presence of defects such as knots etc, the absence or presence of reaction wood and internal stresses from the original tree. The presence of reaction wood in timber can result in out of balance internal stresses occurring during the machining process which causes the timber to bend. In softwood, reaction wood is termed compression wood and causes regions of increased density, due to a higher proportion of lignin, but having reduced mechanical characteristics.

For optimal performance and durability, a timber blade will need a protective surface coating. A variety of surface coating materials are available for timber, with most being relatively cheap and easy to apply. This coating is required to perform several functions, including prevention of weathering, reduction of impact erosion and maintenance of optimum moisture content. For small wind turbines, leading edge tape is relatively thick compared to the boundary layer of a small blade and as such is likely to result in detrimental effects to the blade's aerodynamic performance. Weathering of the wood surface from the combined effect of sunlight and rain will give the surface a grey colour. This colour change, when confined to the surface layer, is due to the surface eventually being composed mainly of cellulose. The lignin (the matrix material) is degraded by long exposure to weather and is

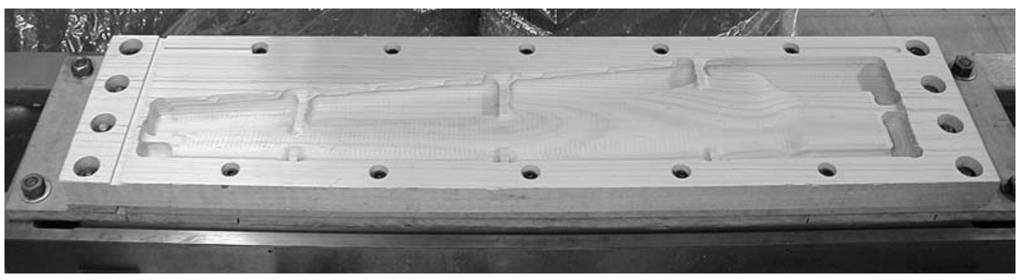

Figure 3. One side of the Test Blade Machined out of the Blank

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eventually removed from the surface from the effects of wind and rain. The weathering process raises the grain, separation of adjacent layers of wood along the grain known as checks and erosion of the surface layers. These may all have a detrimental effect on the aerodynamic performance of the blade similar to that experienced by machines due to 'insect roughness' near the blade leading edge.

The hardness of the timber, which is a measure of its resistance to indentation, is another important consideration when selecting a surface coating, because this has a direct contribution to the effects of impact erosion. Hardness data are available for timber, e.g. obtained using the Janka hardness test, Bootle (1971). Pine species generally have small hardness values (about 50% to those of eucalypts and other hardwoods); however, hoop pine is about 25% harder than radiata pine, as determined by the Janka method.

Timber is hygroscopic in nature and has anisotropic material properties (including shrinkage). To maintain the geometric attributes of the blade, chord, twist and cone etc, requires control of the timber moisture content in storage, during manufacture and in service. Most shrinkage occurs in the direction of the annual growth rings (tangentially), with approximately half as much across the rings (radially) and a small amount along the grain (longitudinally). Timber does not change shape at moisture content more than the fibre saturation point of between 25-30%t. At moisture content less than saturation, the physical and mechanical properties change as a function of moisture content, which itself is a function of both the ambient temperature and relative humidity. Timber's mechanical properties and flexural fatigue life both increase with decreasing moisture content, Tsai and Ansell (1985). Generally an average in service equilibrium moisture content of 12% is specified for most timber applications in Australia. An operating wind turbine, however, would experience a moisture range of between 6% and 18%, Bootle (1971), and therefore requires a protective coat to help maintain a constant moisture content and hence its geometric shape. Moisture change in timber is usually gradual, with short term fluctuations tending to only influence the surface wood. Generally protective coatings can only retard and not prevent moisture content changes. Nevertheless it is vital to have a surface coating to maximise the blade's lifespan.

6. DISCUSSION AND CONCLUSIONS

The work detailed in this paper indicates that both radiata and hoop pine have an adequate fatigue life to make them suitable for the construction of a 1 m long, high-performance wind turbine blades. Hoop pine appears to have better strength and fatigue resistance, and also less variability in fatigue resistance. Fatigue life, however, is not a major issue, because both materials produce blades with essentially unlimited lifespan for a maximum operating wind speed of 17 m/s. It is likely that blade machining issues will decide the most suitable type of timber for the commercial production of wooden blades. Both materials showed good machining characteristics, although some 8 hours were required to manufacture each test blade on a machine that was not specifically designed for machining timber. To manufacture these blades economically would require machining times to be significantly reduced without compromising both accuracy and surface finish. If this can be achieved, and the blade surface coated to minimize erosion, preserve the timber from changes in moisture content and damage from UV radiation, then it appears that timber is a viable material for these blades.

In practice, timber has many defects, with some unacceptable for blade manufacture. Obvious defects like knots and splits in a piece of timber can be easily detected and avoided in the selection process. However, defects like reaction wood in softwood are not obvious and may only become apparent during the blade machining process. If the volume of reaction wood in a blade is large, or located at a critical part of the blade, then this blade may be

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unacceptably warped and so fail quality assurance process. Further investigations may be needed to ensure a timber species is selected with a few critical defects to minimise the rejection rate and hence ensure manufacturing costs are as small as possible.

At this stage it maybe prudent to ask the following question – what is the longest blade that could be economically manufactured from solid timber? Consider a geometrically similar blade of 2.5 m in length which would suit a 5 kW wind turbine. The blade's mass would increase by 2.5^3 making it comparable in weight to a composite blade. The largest stress on the blade would essentially be the same as that on the smaller blade. The main issue is the availability of a suitable deflect-free plank of timber. It is likely that a suitable plank be available for this blade but any longer will require laminating which will add significantly to the cost of manufacturing these blades so making them economically unattractive.

7. ACKNOWLEDGEMENTS

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