FATIGUE CHARACTERISATION OF NATURAL FIBRE COMPOSITES FOR SMALL-SCALE WIND TURBINE BLADE APPLICATIONS

D. U. Shah[1*], P. J. Schubel[1], M. J. Clifford[1], P. Licence[2]

[1]*Division of Materials, Mechanics and Structures, Faculty of Engineering, The University of Nottingham, UK*
[2]*School of Chemistry, The University of Nottingham, UK*
**Corresponding author (eaxds1@nottingham.ac.uk)*

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Abstract
A noticeable lack of fatigue data of plant fibre composites (PFCs) limits their prospective use in fatigue critical components (like rotor blades) as component fatigue life prediction is not possible. This study has three aspects: i) evaluating the fatigue loads on a 3.5-meter study blade, ii) constructing S-N diagrams and constant-life diagrams of PFCs, and iii) predicting the design life of a hemp/polyester blade. In prediction of the fatigue life, it is confirmed that the PFC blade satisfies the 20-year design life criteria, inclusive of a 1.50 safety factor.

1 Introduction
Unprecedented growth in the global small wind industry (Figure 1) has stimulated a significant voice to suggest that small wind energy (<100 kW) can support the ambitious "20-20-20" climate targets set by the EU. Based on 2008 projections, it is estimated that by 2020, the total UK small wind capacity will exceed 1300 MW, through the installation of more than ~400,000 small wind turbine units [1]. Assuming these are 3-bladed horizontal axis systems, more than 1 million blades will need to be manufactured for installation [1].

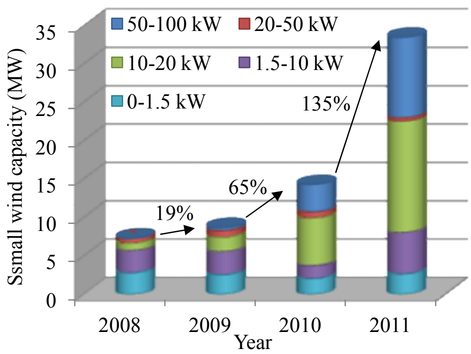

Figure 1. Annual deployed UK small wind capacity and the associated market growth rate. Adapted from [1].

Although blade materials have constantly evolved to achieve the stringent demands of the wind energy industry, E-glass/polyester (GFRP) has been the material of choice since the 1960s. Recently, plant fibre composites (PFCs) have proven to be eco-friendly substitutes to

GFRP in interior automotive applications [2-4]. PFCs have an impressive techno-ecological profile which includes low density and cost, high specific properties and reduced environmental impact [5, 6]. This makes them potential alternatives to GFRP, for even (semi-)structural applications (Figure 2).

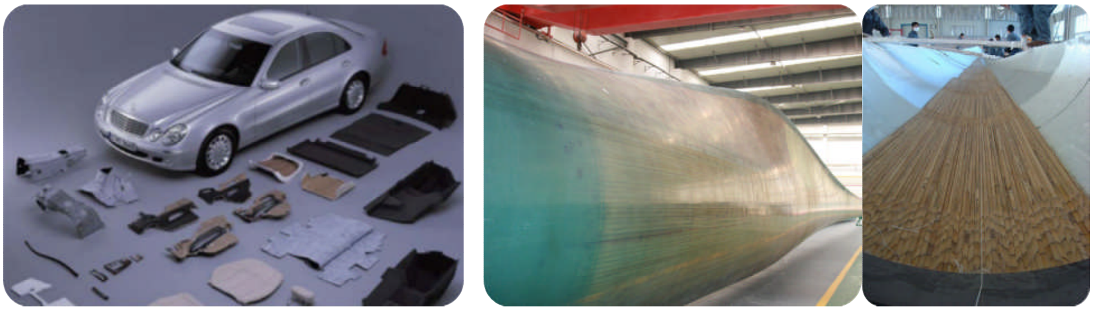

Figure 2. PFCs in automotive components (left, from [4]) and rotor blades (right, from [7]).

Wind turbine blades, a costly critical component of a wind turbine system, are designed to achieve operating life of 20 years. Small wind turbine blades (SWTBs) may cycle at up to 200 rpm, which amasses to a mammoth ~2.1×10^9 cycles over a 20-year design life. Over this period the blade materials need to sustain large 'normal operation' design loads which are fatigue loads. A fatigue assessment is thus a prerequisite for the design of a cost effective blade. However, a noticeable lack of fatigue data of PFCs [8-11] limits their prospective use in fatigue critical components (like SWTBs) as fatigue life prediction is not possible.

This study has three aspects: i) evaluating the fatigue loads on a 3.5-meter study blade, as per BS-EN61400-2:2006, ii) constructing S-N diagrams and constant-life diagrams of PFCs for varying parameters, and iii) predicting the design life of a hemp/polyester composite blade. In prediction of the fatigue life, it is confirmed that the PFC blade satisfies the 20-year design life criteria, inclusive of a 1.50 safety factor.

2 Blade fatigue load evaluation

2.1 Design summary of the PFC wind turbine blade

The study blade is a 3.5-meter hemp/polyester blade that is to be set-up on a 11 kW 3-bladed horizontal axis Class II small wind turbine at the University of Nottingham. The profile and lay-up of the blade is depicted in Figure 3. The blade will be manufactured through a single-shot VARTM process in an aluminium mould tool.

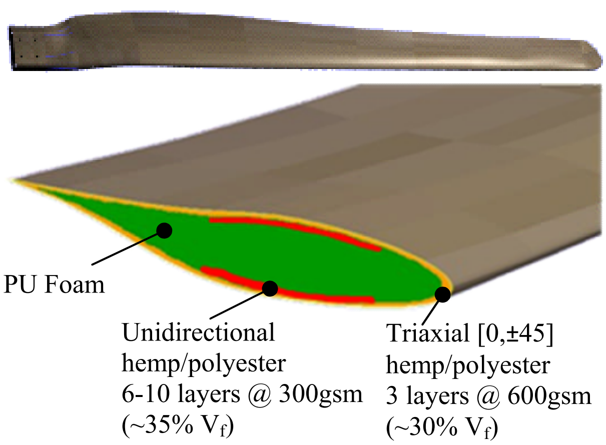

Figure 3. Profile and lay-up of the PFC blade.

2.2 Estimation of design fatigue loads

The fatigue loads on the blade are estimated using the *'Simplified load model' (Load case A)* in BS-EN61400-2:2006 [12]. The model states that the design load for 'normal operation' is a fatigue load and that fatigue loading is considered to occur at the airfoil-root junction or at the root-hub junction (whichever has the lowest strength). From static testing of a full-scale prototype GFRP blade, static failure is found to occur at the root-hub junction. The PFC blade is assumed to fail similarly.

Under Class II wind conditions (design wind speed = 11.9 ms^{-1}) and at a design rotor speed of 170 rpm, the fatigue loads at the root of a 25 kg hemp/polyester blade are found to be:

- Centrifugal load, ΔF_z = 25.3 kN
- Edgewise Bending Moment, ΔM_x = 1.03 kNm
- Flapwise Bending Moment, ΔM_y = 1.26 kNm

The loads include a material partial safety factor of 1.25. The resultant tension-tension and compression-compression fatigue stresses on the different constituents of the blade are then determined, as per BS-EN61400-2:2006 [12]. These are presented in Table 1. It is found that unidirectional (UD) hemp/polyester experiences the most severe stresses.

Tension-Tension	***Foam***	***Triax***	***UD***
Maximum [MPa]	1.3	21.1	57.6
Minimum [MPa]	0.4	6.2	16.5
Mean [MPa]	0.9	14.9	**41.1**
Amplitude [MPa]	0.5	7.5	**20.6**
Stress Ratio	0.29	0.29	**0.29**

Compression-Compression	***Foam***	***Triax***	***UD***
Minimum [MPa]	-1.1	-18.6	-44.1
Maximum [MPa]	-0.4	-7.1	-17.4
Mean [MPa]	-0.7	-11.6	**-26.7**
Amplitude [MPa]	0.3	5.8	**13.3**
Stress Ratio	2.6	2.6	**2.5**

Table 1. Fatigue stresses on different constituents at the blade root

3 Constant life-diagram for unidirectional hemp/polyester composites

2.1 Experimental

2.1.1 Manufacture of composites

3-3.3 mm thick unidirectional hemp yarn composites were manufactured through vacuum infusion in an aluminium mould tool. An orthophthalic unsaturated polyester (Reichhold Norpol type 420-100) matrix was used. The resin was mixed with 0.25 wt% NL49P accelerator and 1 wt% Butanox M50 MEKP initiator. Post-cure was carried out at 55°C for 6 h after ambient cure for 16 h. The density of the fibre, cured resin and composite were measured using helium pycnometry. The composite fiber volume fraction and void volume fraction were then determined to be 35.6 ± 3.3 % and 1.4 ± 0.4 %, respectively.

2.1.2 Static testing

Static tensile tests were conducted according to BS-EN527-4:1997 using an Instron 5985 testing machine equipped with an extensometer. Six test specimens (250 mm long, 15 mm wide) were tested. The tensile strength of the unidirectional hemp/polyester composites was measured to be 171.3 ± 6.5 MPa.

Static compression tests were conducted according to ASTM D3410 using an Instron 5581 testing machine equipped with a compression test fixture. The test specimens were speckle-coated prior to testing. Six test specimens (140 mm long, 15 mm wide) specimens were tested. A gauge length of 12.7 mm was used to prevent the specimen from buckling under compressive loads. The compressive strength of the unidirectional hemp/polyester composites was measured to be 95.1 ± 6.9 MPa.

2.1.2 Fatigue testing

Fatigue tests were conducted as per BS-EN13003:2003 using an Instron 8801 servohydrualic testing machine. Sinusoidal loads at a frequency of 10 Hz were applied. The test specimens were tested to failure to general data for S-N curves. Tests were carried out at 5 different stress ratios: R=0.1, 0.3, 0.5 in tension-tension (TT) mode, R=-1 in tension-compression (TC) mode, and R=2.5 in compression-compression (CC) mode. Tests were conducted for at least 6 different stress levels (% of the static tensile or compressive strength), up to at least 10^6 cycles.

For TT mode, test specimens were 250 mm long and 15 mm wide with a gauge length of 150 mm. For TC and CC modes, test specimens were 120 mm long and 15 mm wide with a gauge length of 115 mm. For all specimens, 50 mm long aluminium end-tabs were attached using Araldite 403, to protect the specimen surface from damage from the jaws of the test machine.

After plotting the S-N data, regression equations of the form $S = AN^b$ were determined, where b is the fatigue strength coefficient. The constant-life diagram was then plotted using data obtained from the regression lines of the various S-N plots.

2.2 Results and Discussion

2.2.1 S-N diagrams

The S-N data of hemp/polyester composites tested under TT mode is presented in Figure 4. It is observed that the power-law regression curves are a suitable fit to the data.

A gradual decline in fatigue strength with increase in the number of fatigue cycles is observed. The fatigue strength coefficient, b is a useful indicator of material fatigue behavior; the smaller it is, the steeper the slope of the curve is and hence the poorer the fatigue performance is. Commonly, S-N curves are presented in normalized form. Importantly, the fatigue strength coefficient remains the same, as can be seen in Figure 4.

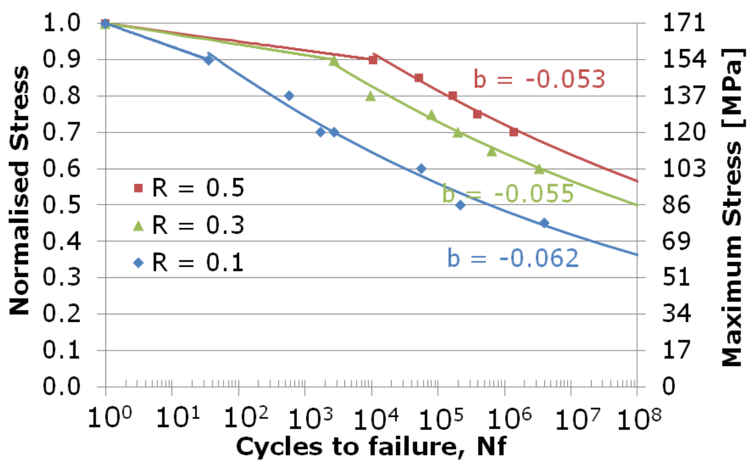

Figure 4. S-N data for hemp/polyester composites tested under TT mode.

For R=0.1, the value of b is found to be -0.062 for unidirectional hemp/polyester composites. Mandell and Samborsky find that b≈-0.074 for both chopped-strand and unidirectional E-glass/polyester composites tested at R=0.1 [13]. This suggests that the normalized fatigue performance (or 'fatigue sensitivity') of hemp fibre composites is better than or comparable to GFRP. UD carbon/epoxy composites, on the other hand, have a value of b≈-0.0292 (at R=0.1). Hence, they clearly outperform both GFRP and PFCs.

Figure 5 depicts the effect of stress ratio on the load spectrum; as the stress ratio increases the stress amplitude decreases. From Figure 4 and Figure 5, it is observed that increasing the stress ratio leads to improved normalised fatigue performance, since the value of b is observed to increase. Hence, it is possible that as R increases, b increases due to reduced crack growth rates; the latter is a result of reduced stress amplitudes and thus reduced stress/strain gradients at the fibre-matrix interface.

Figure 5 also shows the effect of stress ratio on the failure mode. Composites under fatigue and static loading usually fail in similar modes. While composites tested under TT mode fracture in a brittle catastrophic manner, composites tested under CC mode (R=2.5) TC mode (R = -1) display the typical wedge failure and single kink failure, respectively.

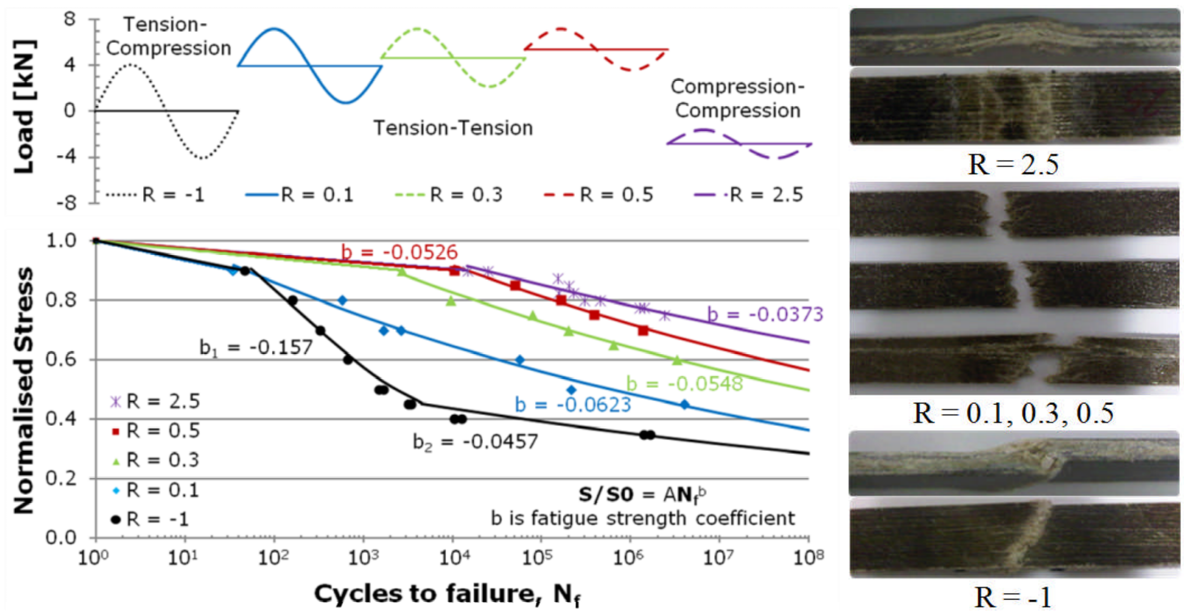

Figure 5. Effect of stress ratio on i) the applied load-spectrum (top), ii) the S-N curve (bottom), and iii) the failure mode (right).

3 Fatigue life prediction of the PFC blade

The constructed constant-life diagram for the unidirectional hemp/polyester composites is presented in Figure 6. From this diagram, the fatigue life for any combination of stress amplitude and mean stress can be determined. Clearly, the accuracy of this diagram can be improved by generating more fatigue data at further stress ratios. Nonetheless, this diagram can now be used to facilitate component fatigue life prediction.

The fatigue life of the study blade can now be determined. For a 20-year design life at a design rotor speed of 170 rpm, the blade needs to sustain the previously derived fatigue loads (inclusive of a 1.25 safety factor) for 1.8×10^9 cycles. Under the current stress regime (Table

1), the blade will survive the loads for ~10^{11} cycles (Figure 6). In fact, a higher safety factor of 1.50 can be used for the required life-span 20 years (Figure 6).

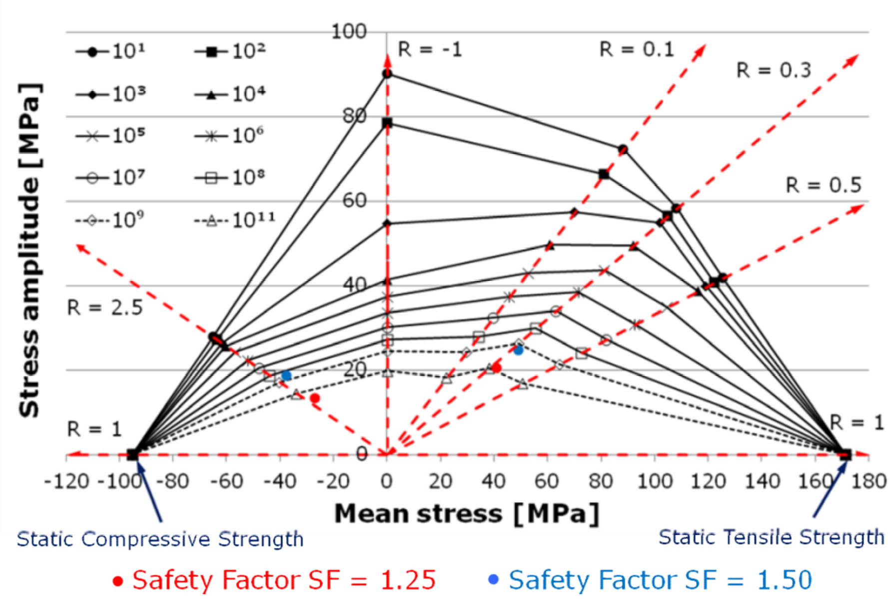

Figure 6. Constant-life diagram for unidirectional hemp/polyester composites.

4 Conclusions

The fatigue performance of unidirectional hemp/polyester has been captured through S-N diagrams. Constant-life diagrams have also been constructed; this will enable component fatigue life assessment. As part of the study, design fatigue loads on a 3.5-meter PFC blade have been determined. In prediction of the fatigue life, it is confirmed that the PFC blade satisfies the 20-year design life criteria, inclusive of a 1.50 safety factor.

References

1. *Small Wind Systems - UK Market Report*. 2011, RenewableUK (BWEA): London.
2. G. Mougin, M., Magnani, N. Eikelenberg *Natural-fibres composites for the automotive industry: challenges, solutions and applications.* International Journal of Materials and Product Technology, 2009. **36**: p. 176-188.
3. Bledzki, A., Faruk O, Sperber VE, *Cars from Bio-Fibres.* Macromolecular Materials and Engineering, 2006. **291**: p. 449-457.
4. Scarponi, C., *Industrial applications for natural fibre-reinforced composites*, in *JEC Magazine #46*. 2009.
5. Shah, D., Schubel PJ, Licence P, Clifford MJ *Hydroxyethylcellulose surface treatment of natural fibres: the new 'twist' in yarn preparation and optimization for composites applicability.* Journal of Materials Science, 2012. **47**: p. 2700-2711.
6. Wambua, P., Ivens J, Verpoest I, *Natural fibres: can they replace glass in fibre reinforced plastics?* Composites Science and Technology, 2003. **63**: p. 1259-1264.
7. *Zhongfu Lianzhong 5MW Composite Blade & 1.5MW Bamboo Fiber Blade Offline*. 2010 [cited 2012]; Available from: http://www.cnbm.com.cn/EN/c_000000160001/d_14806.html.
8. Gassan, J., *A study of fibre and interface parameters affecting the fatigue behaviour of natural fibre composites.* Composites Part A: Applied Science and Manufacturing, 2002. **33**: p. 369-374.
9. Yuanjian, T., Isaac, DH, *Impact and fatigue behaviour of hemp fibre composites.* Composites Science and Technology, 2007. **67**: p. 3300-3307.
10. Towo, A., Ansell, MP, *Fatigue of sisal fibre reinforced composites: Constant-life diagrams and hysteresis loop capture.* Composites Science and Technology, 2008. **68**: p. 915-924.
11. Liang, S., Gning, PB, Guillaumat, L, *A comparative study of fatigue behaviour of flax/epoxy and glass/epoxy composites.* Composites Science and Technology, 2012. **72**(5): p. 535-543.
12. *BS EN 61400-2:2006. Wind turbines - Part 2: Design requirements for small wind turbines*.

13. Mandell, J., Reed RM, Samborsky, DD, *Fatigue of fiberglass wind turbine blade materials (SAND92-7005)*. 1992, Sandia National Laboratories.