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The Effect of Ply Waviness for the Fatigue Life of Composite Wind Turbine Blades

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Abstract.

Wind turbine blade failure is one of the most prominent types of damage occurring in operating wind turbine systems. Glass fibre materials are mainly used for producing wind turbine blades and they consist of large tows, stitched fibres, which are prone to generate imperfections such as ply waviness. The primary objective of this research was to evaluate the effect of ply waviness on fatigue life of typical composites used in wind turbine blades. This study involves two main areas: Finite elements analysis (FEA) and experimental testing. The Finite element analysis was carried out using the commercial code from ESI group. The experimental work was carried out by manufacturing specimens from glass fibre with regular waviness and testing for static and fatigue failure. The tensile static test data was used to identify the effect of ply waviness for failure strength. Cycles to failure (S-N) curves were developed for two different wave profiles based on fatigue testing data. The long term aim of this ongoing research is to improve current fatigue life estimation methods applicable to composite wind turbine blades.

Key words

Wind turbine blades, composites, fatigue, ply waviness

1 Introduction

A wind turbine blade experiences a cyclic loading with every rotation of the rotor. This can produce more than 10^7 load cycles during 20 years life of a typical turbine blade (depending on the rotational speed and size of the turbine). Consequently, turbine blades are made from polymer composites due to their high specific stiffness and good fatigue performance. However, manufacturing defects are difficult to avoid and 64% of the turbine blades failures are reported to be caused by design and manufacturing errors [1]. Wind turbine blades are manufactured from large tow fabrics to build up thickness rapidly, but these are more likely to lead to defects such as waviness, dry patches, etc. Such defects will lead to local delaminations or ply failure, possibly causing overall structural strength or fatigue failure (Fig. 1.).

Waviness can be classified into two types; namely, in-plane waviness and out-of-plane waviness. In both cases waviness typically occurs during the laying of fabrics, or at discontinuities and shape changes in geometry of the part; an example of the laying up process is shown in Fig. 2.

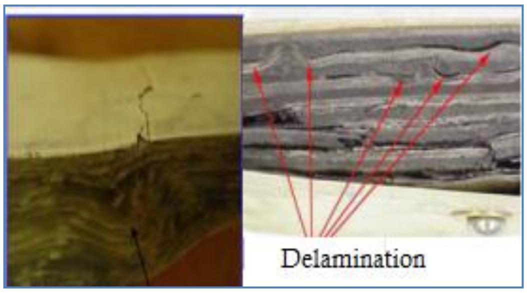

Fig. 1. Fibre Waviness Induced Delamination [2]

Fig. 2. Laying Up Glass Mat for Vacuum Resin Infusion [3]

Whereas surface waviness is relatively easy to detect, internal waviness is not and will be disguised by the top and bottom surfaces which will usually appear as normal or smooth [4].

Fig. 3. Inter-laminar Shear Failure under Tension

Composite waviness reduces stiffness, and creates internal stress concentrations that will lead to premature ply or inter-laminar (delamination) failure (Fig. 3.). In this context it is essential to identify the short and long term effects of fibre waviness on the strength and fatigue life of wind turbine blades.

1.1 Objectives of the study:

Determine the effect of ply waviness on ultimate strength reduction of composite glass fibre.

Development of S-N curves using manufactured specimens which have different wave profiles (A/L ratios where A is amplitude of the wave and L is wavelength), Fig. 4.

Create finite element models to evaluate the effect of ply waviness for ultimate strength reduction and experimental validation of numerical models.

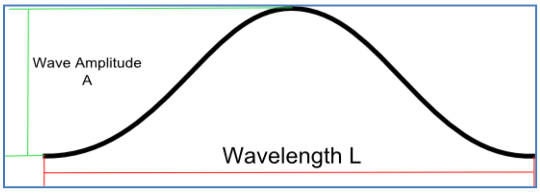

Fig. 4. Wave Profile as the Ratio of A/L

2 Experimental Methods

Two moulds with different waviness profiles were employed to produce specimens having the desired ply waviness ratios (Table 1).

Table 1: Geometrical Attributes of Moulds

	Length (mm)	Width (mm)	Wave amplitude (mm)	Wave length (mm)	Periods
Mould 1	300	90	1	12	2
Mould 2	300	150	1	24	**1**

A. *Material and Processing*

Specimens were manufactured by using the Vacuum Aided Resin Infusion (VARI) process (Fig. 5.). Bi-directional glass (0º-90º) fabrics (manufactured by Saertex), MOMENTIVE - Epikote MGS RIMR 235 resin and the curing agent MOMENTIVE - Epikure RIMH 236 were used to prepare samples. Three types of specimens were produced with layups $(0/90)_{4s}$ .The nominal thickness of each laminate was 2.6mm.

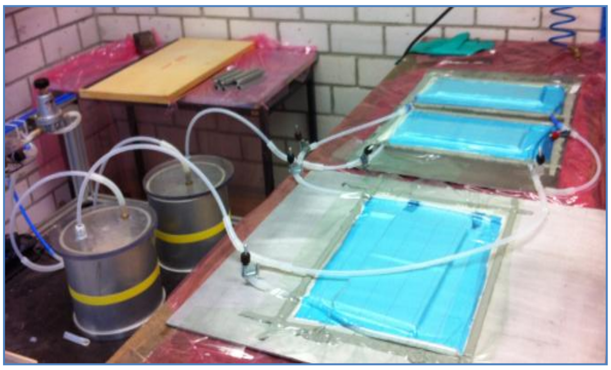

Fig. 5. Specimen Manufacturing Process

B. *Testing process*

1) *Tensile Testing*

The first phase of the experimental analysis was aimed to investigate the influence of ply waviness on damage initiation (delamination) and ultimate failure of the composite. Static tensile tests were carried out for the two different waviness profiles (A/L =0.043 and 0.082) and compared to identical (perfect) flat specimens.

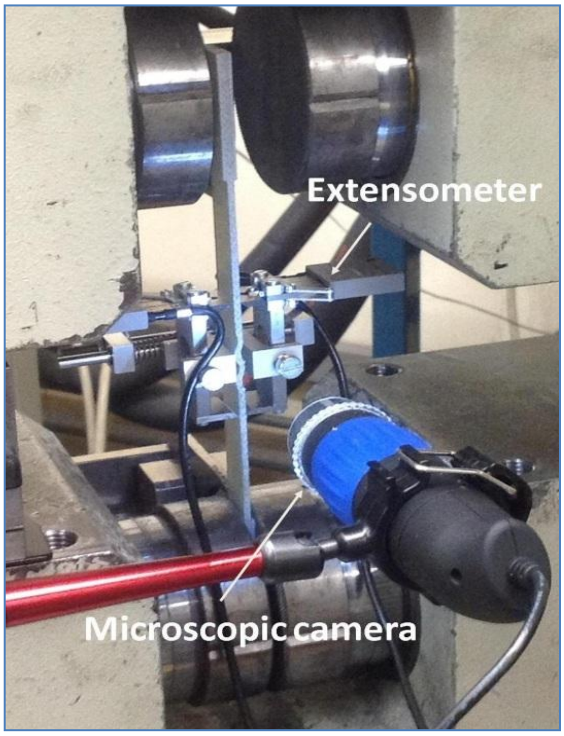

Fig. 6. Tensile Testing Fixture

An extensometer was used to identify displacement changes in the wave region (50mm length). Microscopic camera video images were also used to monitor failure mechanisms of laminates under tension loading. All tests were carried out until final failure and careful observations of the failure mechanism for both wave and flat specimens were noted.

2) *Fatigue testing*

The main objective of fatigue testing program was to identify the influence of ply waviness on fatigue life. An Instron 8502 machine was used to carry out all fatigue testing (Fig. 7.). The specimen was loaded with a sine curve and the ratio between maximum stress and minimum stress for one cycle was 0.1 (R = 0.1). These tests were carried out at a frequency of 5Hz to avoid autogenous heating of specimens. Fatigue testing data was used to develop S-N (stress versus number of cycles to failure) curves for both flat and wave specimens.

Fig. 7. Fatigue Testing Fixture

2 Experimental Results

The flat laminates and wave specimens undergo two different failure mechanisms. The failure of flat laminates was dominated by matrix cracking and ultimate fibre ply failure, whereas wave specimens exhibit matrix cracking, ply delamination, load redistribution and ultimately ply failure. Wave specimens started to delaminate at a lower tensile load and failed at a lower axial stress level compared to flat specimens. Typical photos of failure mechanisms for the flat and wave specimens are shown in Fig. 8. and Fig. 9. respectively.

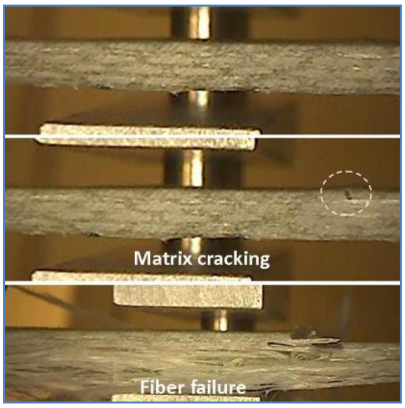

Fig 8. Failure of Flat Specimens

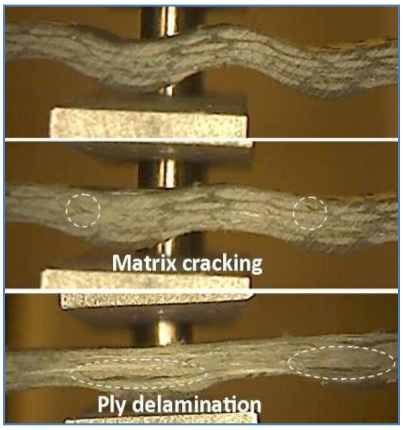

Fig. 9. Ply Waviness Induced Delamination

The single wave specimens had an A/L ratio between 0.04 to 0.043. Fig.10. shows the changes of displacement recorded by the extensometer for single wave specimen. Here S/S_{max} refers to the ratio between ultimate failure stress for flat laminates and axial stress of wave specimen. These results were compared with microscopic camera images taken at the static testing stage. The compared results suggest that single wave specimens (A/L=0.043) start to delaminate in the range of 0.37-0.38 of S/S_{max}. The rate of delamination propagation is initially less, but does keep increasing and becomes a maximum at S/S_{max} = 0.71.

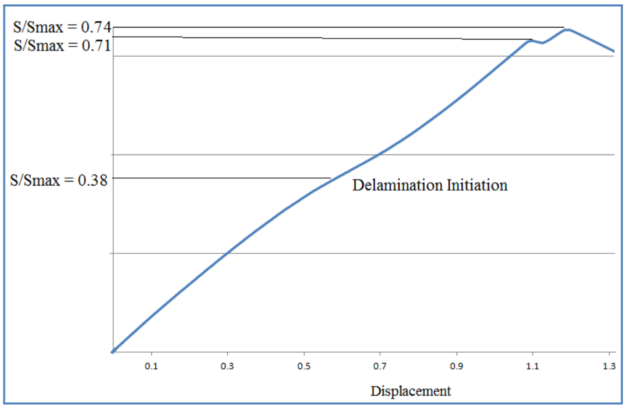

Fig. 10. Displacement Variation for Single Wave Specimen (A/L = 0.043)

Fig. 11. Illustrates the variation of displacement with axial load for the double wave specimen (A/L=0.082). The experimental results typically show that specimens delaminate at S/S_{max} ratios of about 0.32.

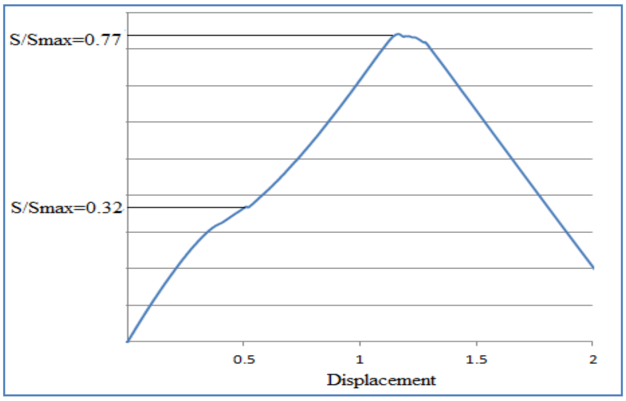

Fig. 11. Displacement Variation for Double Wave Specimen (A/L = 0.082)

The experiment results show degradation of delamination initiation stress with increased A/L ratio (here S_{max} is the failure stress of flat specimen under the same loading condition).

Table 2: Variation of Delamination Initiation with Waviness

A/L ratio	Delamination initiation (S/S_{max})
0.043	0.38
0.082	0.32

Analysis of the tensile testing data shows that wave specimens start to delaminate at 32%-38% of S_{max} and fail at 74%-77% of S_{max}. Fatigue life is drastically reduced after axial stress reaches 32% of S_{max} , as shown in Fig. 12. where a steeper curve for wave laminates occurs when S/S_{max} reaches 0.32. Consequently, analysis of tensile and fatigue testing data suggest that ply waviness induced delamination is the main cause of fatigue life reduction in this limited study.

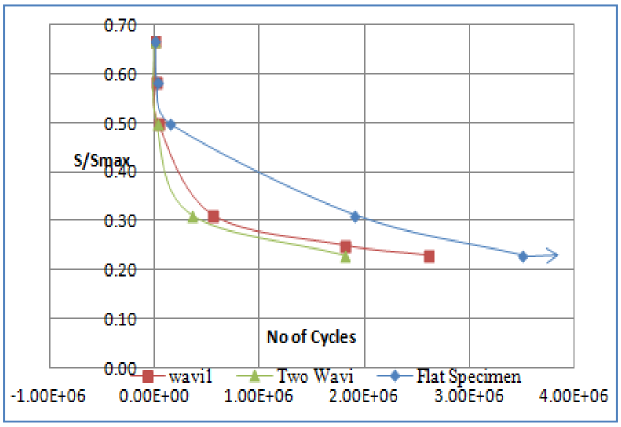

Fig. 12. The Effect of Ply Waviness on Fatigue Life

3 Finite Elements Analysis

Finite element analysis was carried out using the ESI commercial code - PAM-CRASH (Explicit) with Visual 7.5 post-processor [6] in order to compare with test results. Two material models are available in the PAM-CRASH finite element code to simulate composite delamination damage. In this case materials model 303, type 0 was used (The damage model which has used to simulate delamination is based on the Pickett-Payen Model [5].) This code is suitable for analysis composite components where material behaviour can be highly non-linear and large deformations are possible. Experimental test data and manufacturers published data were used to calibrate the delamination model. All models were defined using shell elements. The steps needed to generate and analyze the numerical model are shown in Fig.14.

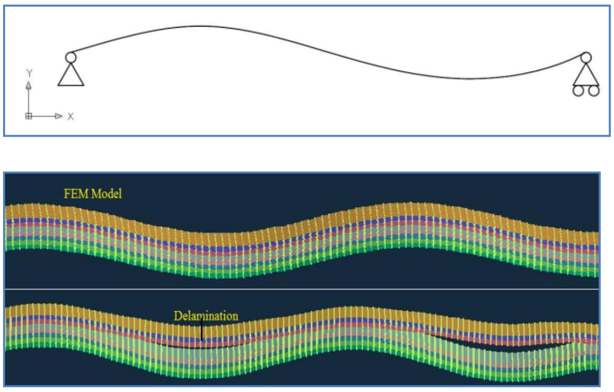

Fig. 13. FEA Boundary Constraints and PAM-Crash Model

The loading on the FE model was applied using constant in-plane displacements at one end of the model, with reaction force being computed at the other fixed support end.

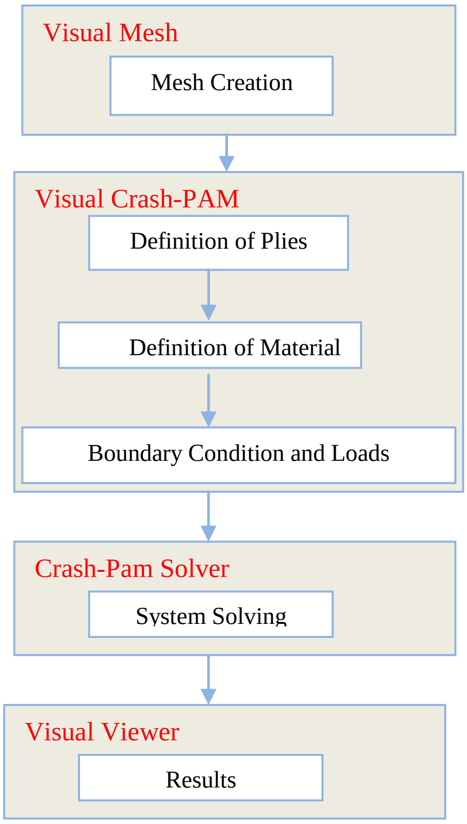

Fig. 14. Simulation Algorithm

Post processing was carried out using the PAM-CRASH Visual-Viewer software. After generating the results, it is possible to check stresses, strains and resultant forces at different points.

The results obtained in general agreed to those found in the experimental tests. The FEM model for the single wave specimen correctly shows delamination starts when the axial stress reach 0.36 of S_{max} with ultimate failure at 0.74 of S_{max}.

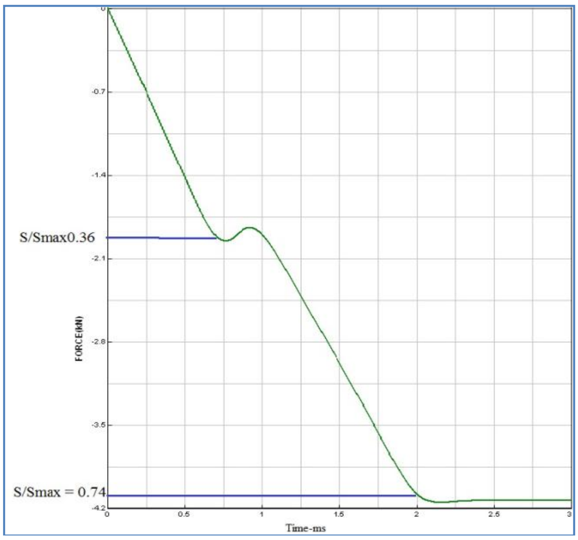

Fig. 15. Displacement Variation for Single Wave Specimen

4 Conclusions

Ply waviness is a critical manufacturing defect in wind turbine blades. Furthermore, wind turbine blades are fatigue critical structures. Therefore it is important to investigate the potential influence that defects such as ply waviness will have on fatigue life.

In this work real waviness imperfections have been idealised as regular waves using a profile that is expressed as the ratio of its height (A) to length (L) (A/L ratio, Fig. 4.). In this analysis two A/L ratios were considered; namely, a single wave with A/L ratio of 0.043 and a double wave with A/L ratio 0.082. The tensile static and fatigue testing results suggest that, flat laminates and wave specimens undergo two different failure mechanisms. Where the failure of flat laminates is dominated by matrix cracking and fibre failure. For wave specimens delamination is the main cause for failure and involves progressive matrix cracking, ply delamination, load redistribution and ultimately ply failure. Fibre waves reduce the ultimate failure stress of wave shapes to about 74%-77 of S_{max} (where S_{max} is the reference ultimate failure stress of flat laminates). Further fibre waviness creates delamination of structures under even lower stress levels (32%-38% of S_{max}).

Higher ply waviness (A/L ratio) increases the tendency for delamination. In this study, the single wave specimens (A/L ratio 0.043) starts to delaminate at 38% S_{max} and double wave specimens (A/L ratio 0.082) start at 32% S_{max}. Further, the microscopic camera images indicate the rate of delamination propagation is lower for single wave specimens compared to double wave specimens.

The analysis of S-N data suggests that fibre waviness induced delamination creates significant reduction of fatigue life when the axial stress of fatigue loading reaches the delamination initiation stress (32%-38% S_{max}). Finite element analyses and experimental results presented similar trends and failure values.

5 References

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