Investigation of waviness in wind turbine blades: Structural health monitoring

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Abstract
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Keywords
blades, condition monitoring, fatigue testing, fracture, structural engineering, ultrasonics, wind turbines, nondestructive evaluation, QNDE, Aerospace Engineering

Disciplines
Aerospace Engineering | Materials Science and Engineering | Structures and Materials

Comments
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INVESTIGATION OF WAVINESS IN WIND TURBINE BLADES:
STRUCTURAL HEALTH MONITORING

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ABSTRACT: Waviness in composite wind turbine blades was detected and characterized with the help of air coupled ultrasonics. Based on the aspect ratio, the detected marcells are either accepted or rejected. A passive structural health monitoring approach has been presented here to monitor the accepted marcells above a threshold. The fatigue life of specimen is most affected in the presence of a marcel. Hence this study focused on the damage evaluation after fatigue testing. Wavy laminate was subjected to fatigue load to investigate the fracture mechanisms near the marcell. Different types of defects were identified from this study and were used to develop appropriate instrumentation for health monitoring of a wavy laminate using PVDF patches.

Keywords: Fiber Waviness, Structural Health Monitoring, Wind Turbine Blades
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INTRODUCTION

Research on the investigation of waviness is exhaustive. Different types of waviness based on their geometric form (uniform or discrete), position in the laminate (extrinsic or intrinsic), plane of distortion (in-plane or out-of-plane) has been dealt with before. The types of responses to wave propagation in wavy laminates has been studied and presented earlier [1][2][3][4]. This research extends this work and highlights the importance of structural health monitoring (SHM) for wavy laminates. SHM is a rapidly growing field which is taking the lime-light due to the importance placed on the need to know the status or health of a structure. SHM has been extensively used in large structures where local defects can affect the structural integrity and decrease the life span of the structure. SHM has been successfully implemented on bridges, dams, and other concrete structures. The technique has also been extended for aerospace applications for monitoring very vital structures of an aircraft or spacecraft. The objective of this work is to investigate the challenges that arise in implementing or extending these techniques for composite wind turbine applications. SHM is a very wide area which covers everything from instrumentation to understanding the mechanics of wave propagation due to multiple sources or transducers. In this paper we focus more on the instrumentation required to monitor a wavy laminate. As the first step the
fracture mechanism of a marcel in 4-point fatigue load was investigated. Based on the type of
defect that was formed from the fracture, instrumentation was chosen accordingly.

An extension of the previous work on characterization of marcels has also been
presented in this paper. Although the aspect ratio of the marcel can determined by the
changes in Rayleigh wave velocity, the depth remained a question, and plays an important
role in determining the aspect ratio as presented earlier [3][4]. Determination of depth of the
marcel with the help of contact transducers has been presented in this paper.

When a marcel or waviness is detected in a laminate, there are two possible solutions
for the inspection team. Depending on the aspect ratio and thickness of the structure at which
the marcel is present, the inspector can choose to remove the blade from service or monitor
the marcel periodically to extract some more of the life of the blade. The main objective is to
develop a series of techniques which will enable the NDT team to detect marcels using air
coupled transducers as shown earlier [3][4], and characterize them based on their depth, and
monitor the critical marcels using a health monitoring system.

MARCEL DEPTH DETERMINATION

The depth of the marcel plays a vital role in determining its aspect ratio. Changes in
Rayleigh wave velocity over a marcel depends on the depth at which the marcel is placed. To
determine the depth, contact ultrasonic transducers of 500 KHz frequency were used. A
schematic of the setup is shown in Fig.1.

The contact transducer is used in pulse echo mode to determine the depth of the
marcel. The transducer is placed at different locations on the wavy laminate, namely: (1)
outside the marcel, (2) 25% of the marcel width, and (3) 50% of the marcel width. A pulse
echo at location (1) gives “C” which is a reflection off the bottom surface. Location (2) gives
“C” and “B” which are the reflections from the bottom of the laminate and bottom of the
root-defect, where the root-defect is defined as the resin pocket found below the marcel.
Location (3) gives “C”, “B” and “A” which is the reflection from the top of the root-defect.
The A-Scans of the various reflections are shown in Fig.2.

The difference in time of flight between “A” and “B” gives the height of the marcel.
Knowing the velocity in the medium, the time of flight of “B” will help in determining the
depth of the marcel. But performing a B-Scan and collecting all the signals together, one can
map the contour of the marcel. This can be used as an alternative method to characterize the
marcel.

FIGURE 1: Contact transducer is used in Pulse-Echo mode to get the various reflections from the marcel. C:
represents the reflection from the bottom of the laminate. B: represents the reflection from the bottom side of
the root-defect. A: represents the reflection from the top of the root-defect.
FIGURE 2: (i) A-Scan of location (1) showing “C”, (ii) A-Scan of location (2) showing “B” and “C”, (iii) A-Scan of location (3) showing “A”, “B”, and “C”.

FAILURE MODES OF MARCELS

The first step in developing a monitoring system is to understand the failure mode of the structure. The modes of failure of marcel under tensile and compressive loads have been extensively studied earlier. But the effect of bending load has not been explored. As a preliminary study, the failure mode of marcel under bending load was performed. A wavy laminate was subjected to 4-point bending as shown in Fig.3 under linear and fatigue load criteria. The 4-point bend is used to generate a pure bending state over the marcel. The bending test was performed to determine the maximum failure load and 80% of this load was used to perform the fatigue test. Existing literature shows that the life of a wavy laminate is reduced by a factor of $10^2$ to $10^3$ [5]. This highlights the importance of performing a fatigue test.

The failure mode as observed after the fatigue testing is shown in Fig.4. The micrographs help in identifying the fractures in different regions of the marcel. Under bending load, the marcel tends to fracture at the wavy region above the root defect at $45^0$ to the principal axis or on the slope of the marcel. This extends to the root defect interface, and fractures the interface before extending on either direction of the marcel in the form of a delamination. A schematic of all the events is show in Fig. 5. This helps us to identify the defect which should be detected and the instrumentation can be developed accordingly. From the fatigue test results, delamination and fractured root-defect/fiber interface is chosen as the defect which has to be detected. These act as the failure initiation points and result in the

FIGURE 3: 4 point fixture used for testing. The marcel is places at the center which is the pure bending zone.
FIGURE 4: (a) Micrograph of root-defect/fiber interface (b) After fatigue failure, the root-defect/fiber interface fails and extends as delamination. Scale 4:1

FIGURE 5: Schematic of failure mode of marcel under 4-point bend. Event (i) corresponds to the fracture of the marcel at the slope of the marcel. Event (ii) represents the failure of the root-defect/fiber interface eventually resulting in a (iii) delamination extending outward.

failure of the entire structure. The objective of this study is not to study the fatigue behavior of the marcel but to detect the delamination failure after fatigue.

SHM EXPERIMENTAL SETUP

The objectives of health monitoring of a wavy laminate is to develop a system which is capable of both active and passive monitoring of the marcel in the wind turbine blade. The central idea of SHM in wind turbine blades revolves around cost analysis. By analyzing the cost of replacing a blade to monitoring a blade depending on the aspect ratio, massive cost savings can be achieved. For the preliminary work, commercially available [7] patch transducers were used for experimentation as shown in Fig. 6(a).

A schematic of the experimental setup is shown in Fig. 6(b). The patch transducer is a thin layer of Piezo film which is metallized on either side. PVDF is used for the construction of the Piezo film and the metal layer acts as electrode for the Piezo film. Excitation to transducer was a square wave pulse generated by a commercial available hand-held pulser receiver. Data was acquired using an oscilloscope which can be easily replaced by a data acquisition card and laptop for better field adaptability. The PVDF patch transducers were used in pulse-echo mode to generate longitudinal waves through the thickness of the.
laminate. A crack or delamination in the thickness will scatter the bulk waves and changes the amplitude.

RESULTS

For the preliminary study a single patch of PVDF was used as the transducer to record A-Scans. Data was collected in two regions of the fatigue fractured sample, namely the good region, where no fracture has occurred and in a region where delamination has occurred. The recorded A-Scans are shown in Fig. 7. In the absence of a delamination, a strong back wall echo can be observed as shown in Fig. 7(a). But in the presence of a delamination the backwall echo disappears. In general, for a delamination in the mid plane, a backwall should be observed earlier in the time domain compared to a no-delamination sample. But this phenomenon depends on the frequency and transducer characteristics. The frequency range for experimentation is from 500 KHz to 1.15 MHz and a dead band was observed in the transducer. Hence the backwall simply disappears instead of shifting earlier in time. This makes it a dark field technique, meaning when a defect is present, the signal disappears, contrary to bright field technique where the signal shifts in time. With better electronics the dead-band can be reduced and backwall can be obtained, depending on which technique is preferred. A dark field technique is easier to implement since an alarm can be set to monitor the amplitude of one signal, compared to monitoring a shift in time of flight of the signal.

The length of the transducer, along with frequency has to be optimized since a very long transducer on top of the marcel can cause averaging of the signal over the entire length of the marcel. This averaging effect can mask the effect of the delamination in a dark field technique. To avoid the averaging effect, small PVDF patches can be used instead of one long patch as shown in Fig. 6(b). This will also help in tracking crack growth patterns near the marcel. More study on the effect of multiple sources has to be done to effectively implement such a multi-element transducer technique.
DISCUSSION & CONCLUSIONS

The proposed system consists of a series of PVDF patch transducers which can be used to monitor crack and delamination initiation of a marcel in a wind turbine blade. As an extension of the previous work, depth of the marcel was determined by using contact ultrasonics in pulse/echo mode. This method can also be used alternatively to characterize the marcel. The dark field technique is robust and easily implementable in the field and can be used both as an active health monitoring system; by gating the backwall and monitoring it with an alarm, or as a passive health monitoring system; by collecting A-Scan data at selected intervals. This will help in extracting extra life out of the wind turbine blade and in a long term helps in cost savings of replacing a blade. The multi-element PVDF design will help in discounting the averaging issues and also help in determining crack growth pattern of the marcel.

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