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Analysis of the Effect of Defects for Fatigue Life of Composite Wind Turbine Blades Using FEM Data

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Abstract

One of the main global engineering challenges for wind energy sector is to develop efficient wind turbine blades with high fatigue life. Large wind turbine blades made out of polymer composites to delivering high specific stiffness and strength, and good fatigue performance. The arbitrary nature of wind flow and extreme weather conditions render wind turbine blades as fatigue critical elements. Therefore, reliable fatigue damage models need to be developed. Numerous studies were carried out in the past to identify the effect of various materials and loading conditions for fatigue life of wind turbine blades. However, these models do not consider the effect of manufacturing defects and in-service damages for fatigue life of wind turbine blades. This paper discusses the available fatigue life estimation models for wind turbine blades and their limitations. The paper, propose a framework for developing fatigue life estimation technique for wind turbine blades based on finite element analysis (FEM) stress and strain data.

Key words

Wind turbine blades, polymer composites, fatigue, manufacturing defects, in-service damages

1. Introduction

The volume of wind turbine rotors has amplified in the past decade, from 40 m to more than 120 m diameter. The resulting mass of about 18 tons per rotor blade causes high bending moments at the inner part of a blade due to the gravitational loads. More than 108 load cycles will happen in the expected lifetime of 20 years of a turbine [1]. During this time the rotor blades are exposed to various hostile conditions such as extreme temperatures, humidity, rain, hail impact, snow, ice, solar radiation, lightning and salinity. In order to endure these external conditions a sound knowledge about fatigue behaviour of the material and structural properties is important. Further, it is required to analyze how different factors manipulate the fatigue failure of wind turbine blades. Manufacturing defects and poor maintenance issues are other factors affecting the fatigue failure of wind turbine blades.

In a normal blade design, the influences of variations in the material properties are taken into account by applying a partial safety factor. However there is still variation in the load carrying capacity which to some extent can be caused by physical variations in the material properties during service life and local manufacturing defects in the blades which are due to minor or gross variations in the manufacturing process [2]. Consequently, it is need to identify the influence of manufacturing defects and in-service damages for fatigue life of wind turbine blades and develop method to discover the effect of these defects for fatigue life in wind turbine blades. The results of this analysis are imperative for wind turbine design, repair, and preventive maintenance processes.

1.1 Objective of the study

- To discuss fatigue life estimation methods for wind turbine blades and their limitations.
- To discuss the effect of manufacturing defects and in-service damages for fatigue life of wind turbine blades.
- Evaluate the effect of defects for fatigue life of wind turbine blades.
- Introduce framework to analyse the effect of defects for fatigue life of wind turbine blades.

2. Fatigue Life Prediction

Design constraints for wind turbine structures fall into either extreme load or fatigue categories. For the case of extreme load design, the load estimation problem is limited to finding a single maximum load level that the structure can bear. For design fatigue, however, loads must be defined for all input conditions and then summed over the distributed of input conditions weighed by the relative frequency of occurrence [3].

Most ongoing research on fatigue phenomena uses load spectra obtained by digital sampling of a specific configuration of strain gages which read the strain at a specific location near the root of the blade. Then, the representative sample of each load spectrum is weighted by its rate of occurrence that can be obtained from the statistical study of the wind pattern, finally, all the weighted load spectra are summed and the total load spectrum is derived. Figure-1 illustrates the different stages of fatigue investigations on wind turbine blades [4].

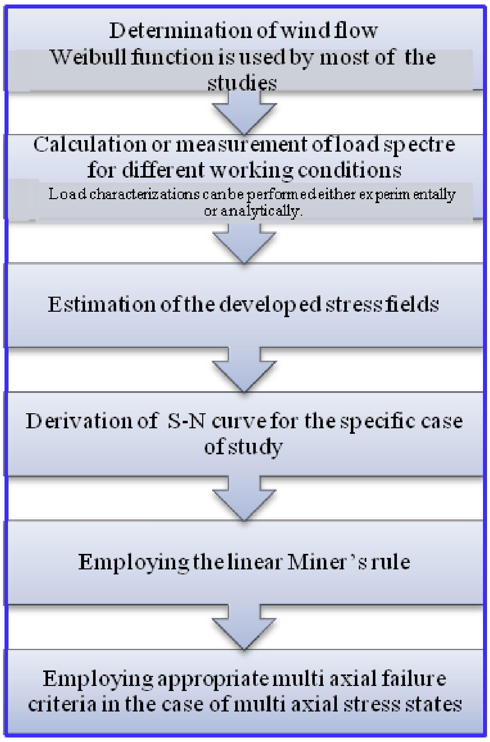


Figure 2: Different stages of fatigue investigations on wind turbine blades [4]

The presented paper is focused on discussing the different methods of load spectra characterizations, defects of wind turbine blades and prediction of fatigue life of wind turbine blades based on FME analysis data.

3. Limitations of current studies

One of the most important drawbacks of the current fatigue life investigations phenomena is that, it is based on the estimations and does not cover whole possible outcomes (deterministic approach).The real governing situation is a stochastic behaviour as a result of random variation of wind pattern. The wind turbine blade will experience each load case randomly [4]. While deterministic analysis of fatigue damage progress is limited to investigating the failure associated with the most critical load pattern, stochastic implementation captures the whole events that a wind turbine will encounter.

Deterministic approaches capture just one load pattern as a compromise, which is not necessarily representative of the real conditions imposed on a wind turbine. In stochastic simulation of fatigue phenomena, both the frequency of load occurrence and their sequence play a significant role. Moreover, the probability of a particular event is carefully addressed in stochastic analyses. Therefore, the contribution of a specific load is not taken into account identically over the whole span of working years but will be treated randomly as in a real working condition [4].

The current fatigue life estimation methods have not thoroughly considered the effect of manufacturing defects and in-service damages for fatigue life of wind turbine

blades. This is another drawback of existing wind turbine blade fatigue life estimation methods.

4. Defects of Wind Turbine Blades

4.1 Manufacturing defects of wind turbine blades

The manufacturing defects of wind turbine blades influence the fatigue properties of the blade because defects can lead to high stress concentrations in the material. This can create more crack initiations or growth of the individual defects during service life. The load carrying capacity for manufacturing defects is mainly influenced by the type, size and position of the defect [5] (Figure 1).

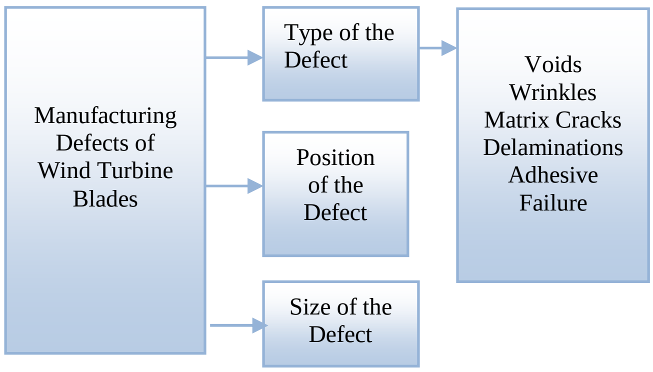


Figure 2: Manufacturing Defects of Wind Turbine Blades

4.2 In-service Damages

Wind turbines have to operate on different environmental conditions such as lightning, bird strike, ice, sand, rain, UV rays and extreme wind. This can create unintended overloaded situations that may generate in-service damages. Adhesive layer failure and delamination are the most critical in-service damages of wind turbine blades.

4.3 Position of the Defects

Identification of the locations of the defects is also vital to investigate fatigue phenomena of wind turbine blades. According to the statistics most of the defects are placed in four key areas [6, 7, 8].

[a] 30–35% and 70% in chord length from the blade root.
[b] The root of the blade.
[c] Maximum chord
[d] Upper spar cap/flange of the spar

Therefore at the FEM analysis was carried out to by varying the position of the defects as illustrated in Figure 3.

5. Framework of the developed modelling technique

Load analysis and identification of different load cases based on the real working conditions of a wind turbine have been carefully studied. The different loading conditions for wind turbine blade are discussed. A finite element analysis (FEM) methodology is illustrated to simulate the response of the structure under various load cases. FEM analysis was performed with and without pre-defined defects by using ANSYS and SolidWorks softwares. Analysis was primarily targeted to evaluate the effect of defects for fatigue life of wind turbine blades. The stress and strain result were used identify the effect of these defect for fatigue life of wind turbine blades and predict fatigue life of wind turbine blades.

5.1 The effect of loading condition

The wind turbine blades are subjected to diverse load cases arising from a wide variety of sources Germanischer Lloyd (GL) rule have presented classification of different loading conditions coupled with experiencing natural and operational events [9].

- Stand-by: Aerodynamic loads, weight, annual gust and changes in wind direction.
- Start-up: Aerodynamic loads, weight, annual gust and angular acceleration effect
- Power production :Aerodynamic loads, weight, centrifugal forces arising from angular velocity of a blade, gyroscopic effects arising from taw movements of the wind turbine, annual gust and changes in wind direction
- Normal shut-down: Aerodynamic loads, weight, activation of mechanical brake, effect of angular acceleration of a blade, annual gust.

5.2 Stress Analysis

The geometrical model was created by using SolidWorks software and it is 9 m long. The finite element model was built using second order shell elements to increase the accuracy of modelling ANSYS software. At the initial stage, material properties, maximum and minimum fatigue load, maximum number of cycles and incremental number of cycles was defined.

The analysis was performed by varying the size, type and position of the defects. Further load configurations were changed to identify how different loading conditions affect for the fatigue life of wind turbine blades.

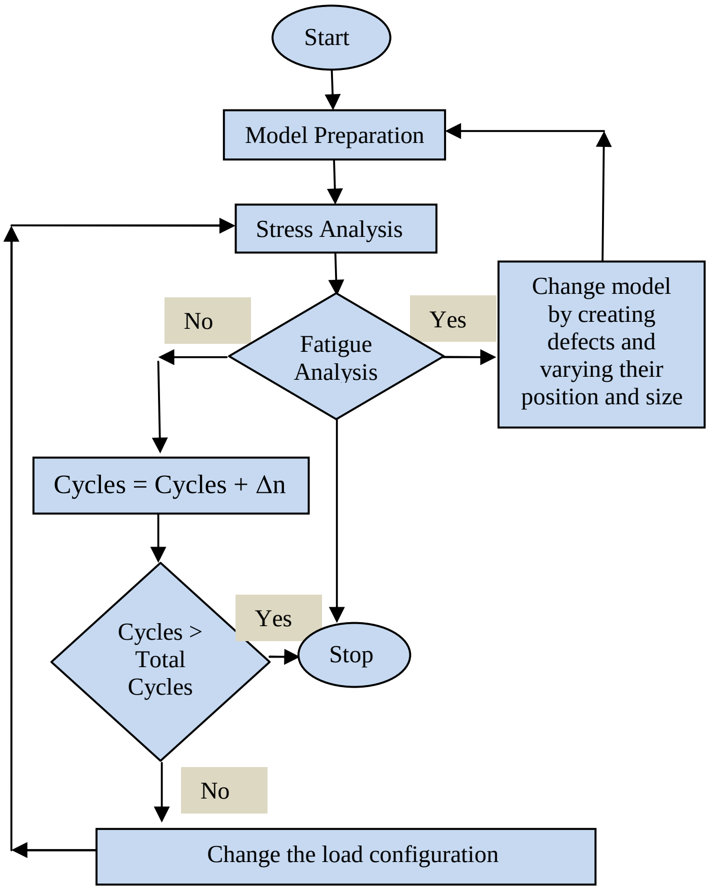
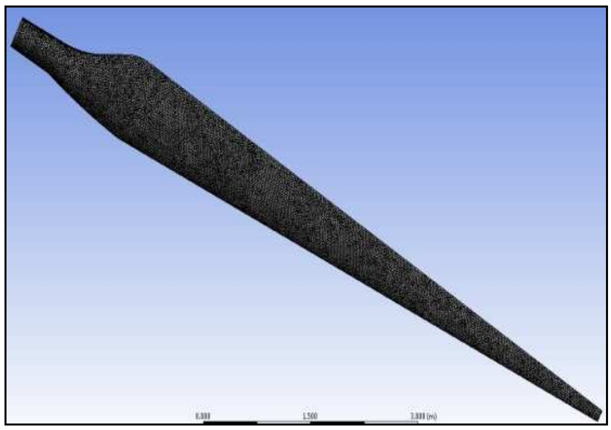


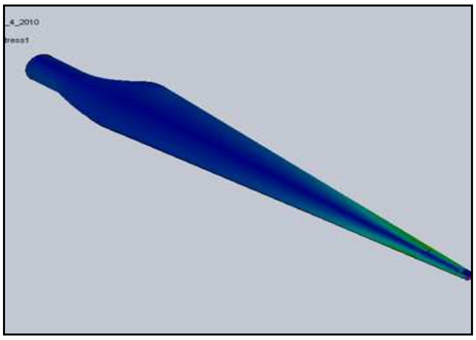
Figure 3: Finite element Stress Analysis Methodology

6. Results and Discussion

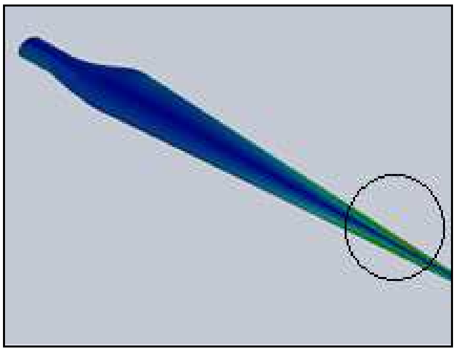
The first phase of study was targeted to study the effect of small crack at the tip of the wind turbine blades for stiffness reduction under flap wise and edgewise loading conditions. The defects of wind turbine blades increase the stress concentration near to the crack. Figure 4 shows the effect of delaminated defect for the stress distribution in wind turbine blade and Figure 5 illustrate the effect of 4mm delamination for the fatigue life.



(a) Fine meshed turbine blade



(b) Stress distribution without defects



(c) Stress increase near to the defects

Figure 4: The effect of delamination for the stress distribution in wind turbine blade

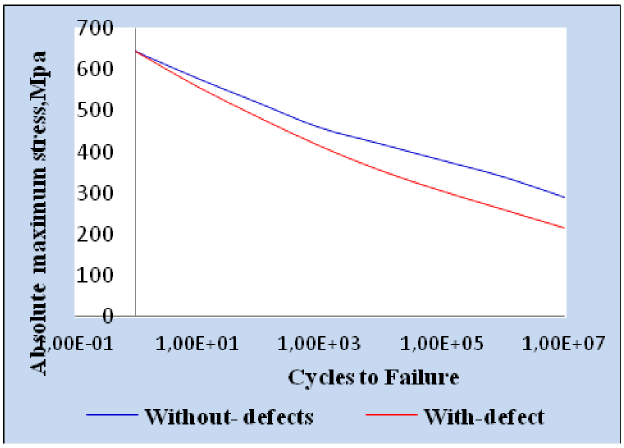


Figure 5: The influence of delaminated crack for fatigue life of wind turbine blade

The analysis was carried out by creating delaminated crack near to tip of the blade. The FEM analysis results showed 20% of life time reduction as a result of 4mm length of delamination near to tip of the turbine blade. The size of the delamination interface is increased with the number of cycles.

The study was further carried out by changing the position of the crack and observed the failure rate is even higher (30%) near to the root of the wind turbine blade. Further 12 mm length delamination near to the tip of wind turbine blade showed 32% reduction of fatigue life. However the statistics showed most of the turbines blades were failed near to the mid section of wind turbine blades (40%-65% of turbine rotor diameter length). Another parameter which affect for fatigue life of wind turbine blade is the cyclic loading pattern. Consequently it is important to carry out further analysis by changing the loading pattern as states in Figure 3.

7. Conclusion

Fatigue failure is one of a critical issue of wind turbine blades. Calculation of the load carrying capacity for wind turbine blades has been widely studied during the last decades and most of the studies were intended to investigate the structural behavior of the composite materials under unique combination of loadings. Most of the current fatigue life investigations phenomena are based on the estimations and do not cover whole possible outcomes (deterministic approach). They have not systematically considered the effect of manufacturing defects and in-service damages for fatigue life of wind turbine blades. But it is vital to consider the influence of these defects for fatigue life of wind turbine blades in future blade design applications.

The FEM analysis results of this study shows 20% reduction of fatigue life of wind turbine blade as a result of 4mm length delamination near the trailing edge of the wind turbine blade. The failure rate is even higher (30%) near to the root of the wind turbine blade for 4mm length of delamination. The size of the delamination interface is increased with the number of cycles. This evidently indicates the effect of the position of the defects for fatigue life of wind turbine blades. The results further indicate dramatic reduction of fatigue life of wind turbine blades with the length of the delamination. However the current study results are not sufficient for developing relationship to understand the influence of type, size, and position of defects for fatigue life o wind turbine blades. Therefore the FEM analysis should carried out by changing defects parameters and loading conditions. The Figure 3 presents the suitable logic sequence for FEM analysis. Then the result should be accumulated to a database. This database can be used to identify the affect of (defect and load) parameter relationships for the fatigue life of wind turbine blades. Identification of these parameter relationships is very critical to decrease large safety factors used for wind turbine blade design and useful for reducing material usage. Furthermore the FEM analyse data can be used to categorize critical regions for condition monitoring and inspection process.

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