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Fracture mechanics approach for failure of adhesive joints in wind turbine blades

Y.M. Ji*, K.S. Han

Graduate School of Wind Energy, Pohang University of Science and Technology, Pohang 790-784, Republic of Korea

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ABSTRACT

Composite components of wind turbine blade are assembled with adhesive. In order to assess structural integrity of blades it is needed to investigate fracture of joints. In this study, finite element analysis based on fracture mechanics was conducted to characterize failure of adhesive joint for wind turbine blade. The cohesive zone model as proposed fracture mechanics approach was verified through the comparison of numerical results with experimental data. Finite element models of wind turbine were developed to predict damage initiation and propagation. Numerical results based on fracture mechanics showed that failure was initiated in the edge of the adhesive bond line due to high level of shear stress prior to reaching the extreme design loading and propagated progressively.

1. Introduction

Energy crisis and global warming have led to a higher demand for renewable energy. Wind energy is expected to one of the important energy among renewable energy in the future. An efficient way to further improve the performance of wind turbine is to reduce the weight of the blades. Large scale wind turbine blades are mainly based on fiber reinforced polymer (FRP) composite for light weight.

The wind turbine blade is aerodynamic structure which consists of skin and webs. Adhesive joining method is used to assembly the parts of the blade, as shown Fig. 1. Adhesive joints have fewer sources of stress concentrations, higher toughness and more uniform stresses distribution through the joined area compared with mechanically fastened joints, such as rivet and screw. Adhesive bond lines in large scale turbine blades are thick and much longer than in other applications. Web to skin bond line continues along the entire length of the blade.

According to the studies concerning failure of wind turbine blade, debonding is one of the main causes of blade failure. In Ref. [1] a post mortem investigation was carried out on the failed sections of blade. Adhesive joint failure observed between skin and spar. In Ref. [2] an actual collapse testing was conducted under the flap-wise loading for a large full-scale wind turbine blade. The results showed that the aerodynamic skins debonding of the adhesive joints is the initial failure mechanism causing a progressive collapse of the blades.

Thus engineering approaches for adhesive joint have been of great interest. In Ref. [3] a three point bending test for asymmetric beam was conducted in order to study the adhesive performance between shear web and spar cap of the wind turbine rotor blade, investigating thick bond-lines. In Ref. [4] composite I-beams were numerically and experimentally investigated to examine the mechanical behavior of adhesive bond lines. A finite element model was developed to predict and simulate the damage initiation and evolution. In Ref. [5] cohesive laws were used for prediction the load carrying capacity of medium size adhesive joint specimens subjected to four point flexure. The scaling from small specimens to medium-size specimens was successfully achieved. Although these studies have made effort to investigate behavior of adhesive joint, there are differences between subcomponents and actual blades. Adhesive joints of blade do not have regular thickness and undergo complex load case. Consideration of the actual geometry and load condition of blades is required to predict accurate strength of adhesive joints.

The present study aims to verify the numerical results for adhesive joint damage compared with the experiments and to propose the fracture mechanics approach to describe the fracture behavior of adhesive joints for wind turbine blades. Adhesive joint failure of wind turbine blade was investigated by means of Cohesive Zone Model approach.

* Corresponding author. Tel.: +82 54 279 8216; fax: +82 54 279 2845.
E-mail address: cosmo@postech.ac.kr (Y.M. Ji).

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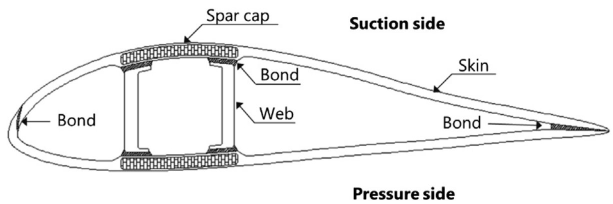

Fig. 1. Structural detail of wind turbine blade.

2. Theoretical background

In this work, fracture mechanics approach was used to characterize the initiation and propagation of damage at adhesive joint. The Cohesive Zone Model (CZM) was employed to describe material separation under a static loading. The CZM combines a strength-based failure criterion to predict the damage initiation and a fracture mechanics-based criterion to determine the damage propagation [6]. The stress transferred across the crack faces of the fracture process zone can be described in terms of cohesive laws.

Fig. 2 shows that schematic of a CZM for failure prediction of adhesively bonded joints. It is assumed that the damage initiation criterion will depend on traction stress by current state of stress [7].

The damage initiation is defined by

$$\left(\frac{\sigma^{n}}{\sigma^{n}_{max}}\right)^{2}+\left(\frac{\sigma^{t}}{\sigma^{t}_{max}}\right)^{2}+\left(\frac{\sigma^{s}}{\sigma^{s}_{max}}\right)^{2}=1 \quad (1)$$

where σ^n is the normal stress to surface of adhesive layer, and σ^t and σ^s are the shear stress components along adhesive layer.

The failure criterion is expressed as a power law:

$$\left(\frac{G_{I}}{G_{IC}}\right)^{n}+\left(\frac{G_{II}}{G_{IIC}}\right)^{n}+\left(\frac{G_{III}}{G_{IIIC}}\right)^{n}=1 \quad (2)$$

where G_{IC}, G_{IIC} and G_{IIIC} are the critical values of fracture energy in the three modes; normal and two tangential, respectively.

3. Experimental and numerical failure analysis of adhesive joints

3.1. Specimen preparation

In this study, failure behavior of adhesive joint was investigated by end notched adhesive joint specimen. The adherend was made of glass fiber reinforced epoxy composite laminates by vacuum infusion and post-cured. The lay-up of the laminates was $[0_3]$. The structural epoxy paste adhesive which is applied in the wind turbine blade was used to bond together two adherends. It was hardened at room temperature (~25 °C) for 24 h. The specimen has length of 150 mm, width of 13 mm and thickness of adhesive is 1 mm. Non-bonded region is placed at the one end of the specimen. The dimensions are schematically depicted in Fig. 3.

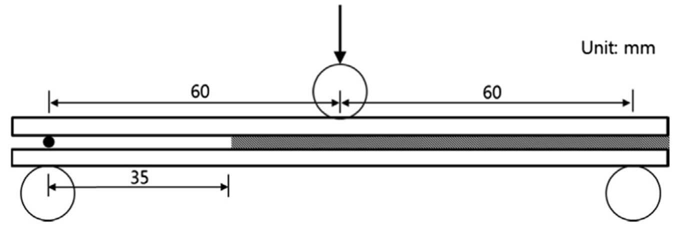

Fig. 3. Geometrical configuration of specimen.

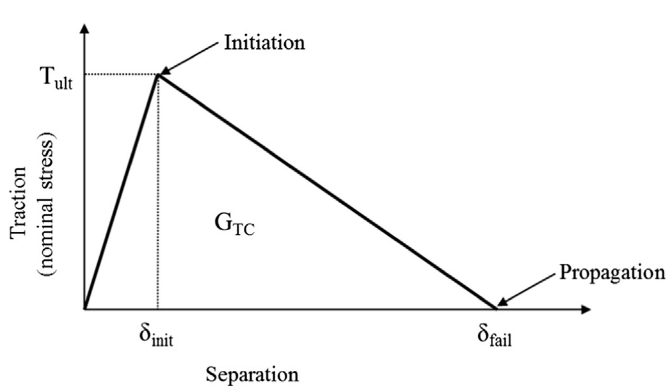

Fig. 2. Schematic of a CZM for failure prediction of adhesively bonded joints.

3.2. Experimental test procedure

The test set-up is shown in Fig. 4. The bending moment was applied by loading on top of the specimen. Constant cross head speed was 0.5 mm per minute. The applied load and displacement in the mid-span of specimens were recorded up to failure.

3.3. Experimental results

The crack initiated and propagated along the interface between the adhesive layer and the compressive adherend as shown in Fig. 5. The crack propagated to the mid-span of the specimen at 263 kN with a drop in the load. In subsequent specimen inspection, it was observed that adherends remained elastic during the entire test without any plastic deformation. This indicates that all the energy dissipation during the crack initiation and propagation process was contributed by fracture of adhesive.

Typical load–displacement curves obtained from the experimental test are shown in Fig. 6. In the current fracture test, a critical strain energy release rate is defined the G_{II} value when the maximum load is reached. The experimental value of critical strain energy release rate G_{IIC} can be calculated according to Eq. (3) [8]. It was obtained 0.8 kJ/m^2 of G_{IIC} from test results.

$$G_{IIC}=\frac{9P^{2}Ca^{2}}{2b(2L^{3}+3a^{3})} \quad (3)$$

where P is critical load at crack propagation, a is non-bounded length measured from support point, b is specimen width, C is specimen compliance and L is one-half support spacing.

3.4. Numerical method

A numerical model of specimen was developed using two-dimensional finite element (FE) method. The material properties

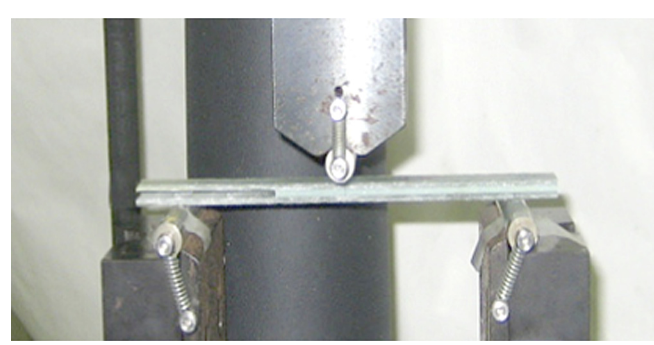

Fig. 4. Set-up of three point bending experiment.