

Chapter 13

Fatigue Life Prediction for Adhesively Bonded Root Joint of Composite Wind Turbine Blade Using Cohesive Zone Approach

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I. INTRODUCTION

In order to estimate the cost effectiveness of a wind turbine system, the fatigue life of wind turbine blades is an essential step in the design process. The blades of a wind turbine are considered to be the most basic and the most critical component of the wind turbine system. In general the major cause of wind turbine blade failure is fatigue phenomenon, where wind turbine blades are subjected during working conditions to different loads such as aerodynamics, gyroscopic and gravitational forces. These loading conditions will cause fatigue failure of the blade mainly at root joint, where the most critical zone of the blade is located.

Fatigue in the particular application of wind turbine rotor blades is discussed by Kensche [1]. Joosse and van Delft [2] expressed their concern on excluding fatigue as a research subject and reviewed research performed in the Netherlands between 1984 and 1996. Further to that, Sutherland [3] and Mandell [4] have a long record of rotor blade material fatigue research. Veers et al [5] used a computer code called FAROW to probabilistic analysis of the Fatigue and Reliability of Wind turbine component. Kong et al [6] investigated the fatigue life of a medium scale horizontal axis wind turbine system by using the S-N damage equation, the load spectrum and Spera's empirical formulae.

In aeronautical composite fatigue research, strength degradation models have been extensively formulated. These models take into account the order of load cycles, by quantifying the strength degradation in a cycle-by-cycle analysis. Comparing the instantaneous strength to the instantaneous load, these models are used as life prediction methods. Incorporating the static and fatigue scatter in the analysis creates a probabilistic life prediction estimate. Wahl [7] proposed to use residual strength analysis for composite wind turbine, and a validated non-linear model using repeated block tests and single R-value modifications of Wisper spectrum. Shokrieh and Rafiee [8] used a progressive damage model for lifetime prediction of a horizontal axis wind turbine composite blade; they employed accumulated fatigue damage modelling as a damage estimation rule and investigated fatigue of composite wind turbine blade by using developed stiffness degradation method. Jin et al [9] studied the life prediction of a composite wind turbine blade subjected to creep and fatigue loading using Micromechanics of failure (MMF) and accelerated test methods (ATM); they predicted the life of a wind blade using the master curves and load distribution that are calculated from finite element analysis of wind turbine blades. Jang et al [10] presented a methodology to predict the fatigue life of a small wind turbine composite blade using a wind speed history and the interaction between flapwise and edgewise bending moments.

Movaghghar [11] proposed an energy based model for predicting fatigue life and evaluation of progressive damage in a full composite wind turbine blade. His assumption was based on that the damage growth rate in composite material depends on the maximum value of elastic strain energy per cycle; he obtained critical stresses from ANSYS analysis and estimated fatigue life of the blade. Veers [12] described the method to produce an estimate of blade life based upon descriptions of the cyclic stresses and wind speeds in terms of probability density functions by using Miner's cumulative damage rule.

Blades of horizontal axis wind turbines (HAWT) are now completely made of composite materials due to lower weight and proper stiffness, while providing good resistance to the static and fatigue loading. Wind turbine blade root consists of several parts of composite and metal elements, these parts joint together by adhesive bonding. The most likely places for fatigue weakness are at joints and the main failure mechanism at the root joint may be debonding at the layers of composite to composite or composite to metal bonded area. The goal of this fatigue analysis is to investigate the initiation and growth of debonding in root joint and predict the fatigue life of root joint.

II. STATE OF THE ART

As a case study, a 23 m blade of a V47-660 wind turbine, manufactured by Vestas Company, was selected. Electric power that can be obtained from the wind by this model of wind turbine is 660 kW. The V47-660 blades use basic NACA-63-xxx airfoil series [13]. In the first step, wind turbine blade was modelled in full scale using Ansys 14.5 commercial finite element software [14], then forces that causing cyclic loading at the blade are calculated and in the next step fatigue analysis is performed using cohesive zone model. The main advantage of this method is that there is no need to determine initial crack before analysis. By using developed model and performing its material constants, initiation and growth of debonding is investigated and the life of the root joint is obtained.

III. MODELLING

A wind turbine blade is typically made up of an outer shell, a main spar and root joint. The outer shell gives the blade its aerodynamic profile and carries the edgewise loads; near the root the blade cross section changes from a wing profile to a circular profile. The main spar carries the flapwise loads; the current blade uses a box spar internal to the blade which can accept loads in all directions (Fig. 1).

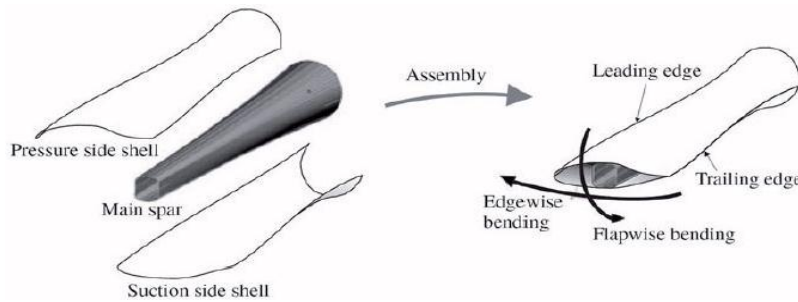


Fig. 1 Components of a wind turbine blade and their load carrying functions [15]

Cross section of the current blade is substantially rectangular, in other words first side of spar is in contact with a first inner surface of the skin and a second side is in contact with a second inner surface of the skin; Noted that the spar and shell are bonded together by adhesive. Fig. 2 shows the cross section of spar. As it can be seen from this figure the blade uses a box spar internal to the blade. In a main spar a rectangular beam containing the flanges and shear webs that are made as one piece (Fig. 3).



Fig. 2 Cross section view of blade spar

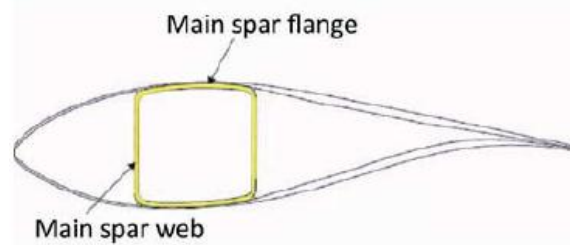


Fig. 3 Section of wind turbine blade with internal main spar

The root joint consists of several parts of composite and metal elements. These parts are joined together by adhesive bonding. The root joint is the only metallic part in the current blade that connects the whole blade structure to the hub by screws. The cross section view of the root joint is shown in Fig. 4 and the whole root joint is shown in Fig. 5.



Fig. 4 Cross section view of root joint



Fig. 5 Root joint of current blade

Profiles that provided shell shape changes from a circular tube to an airfoil section extending longitudinally from the root to tip of the blade. The trailing edge and the leading edge of the blade are both linear. Some physical characteristics data of the investigated blade are shown in Table 1 [8].

TABLE 1 PHYSICAL CHARACTERISTICS DATA OF THE BLADE [8]

Length	22900 mm
Twist	15.17°
Maximum chord	2087 mm
Station of maximum chord	R4500
Minimum chord	282.5 mm
Weight of blade	1250 kg
Station of CG	R8100
Tip to tower distance	4.5 m
Surface area	28 m ²
Airfoil cross-section types	FFA-W3,NACA-63-xxx,MIX

The finite element program used for the structural analysis is well-known commercial software Ansys 14.5 [14]. To provide data for the finite element model, in the first step the root joint components must be fully model and then the spar and outer shell must be model. To model the root joint, cross section of whole root joint consists of metal and composite parts was created and by using extrude option in Ansys finite element Software, created area was extruded around center line and the root joint was modelled. Second order cubic solid Elements SOLID185 with 8 node was used for meshing the root joint of the blade. Solid185 Structural Solid is suitable for modeling general 3-D solid structures particularly for composite structures. Fig. 6 shows the meshed model of the root joint consisting of metal part and composite parts.

To modelling spar and outer shell, a geometrical wire frame model was created based on cross section profiles of shell and spar which is the fundamental of geometrical model, geometrical modelling was completed by skinning surfaces among the cross section lines.

The 23 m blade spar and shell were meshed using shell elements. Ansys provides a wide range of different shell elements to choose from. For this reason the 4-node shell element SHELL181 was chosen for meshing the spar and shell. Using a shell element will reduce the amount of CPU (central processing unit) time necessary for analysis of the model.

Mesh density was increased near the root and a refinement study was conducted to show that the model mesh size was sufficient for convergence. Fig. 7 shows the finite element model of the turbine blade near the root.

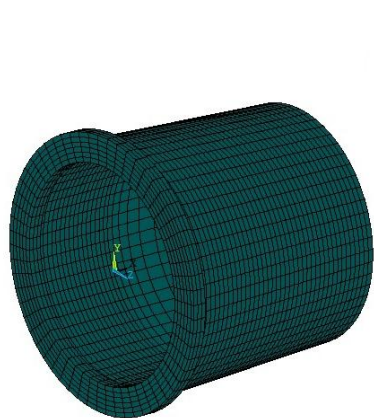


Fig. 6 Finite element model of root joint consist of metal and composite parts

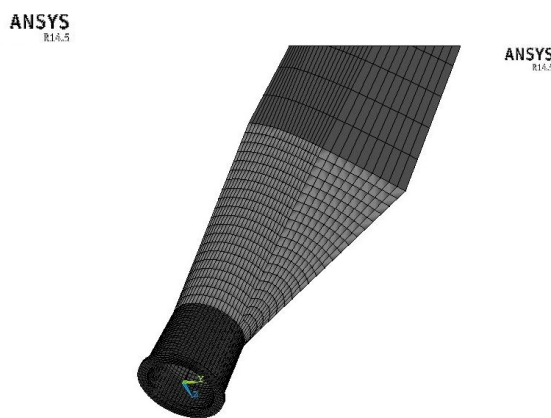


Fig. 7 Finite element model of turbine blade near the root

IV. LOADING

In general, fatigue loads are very important for the design and analysis of wind turbines. A wind turbine is subjected during its service life to a series of different loads both from the wind, gravity and during operation. In general, the loads that have significant effect on the fatigue of wind turbine are as follows:

- Flapwise and edgewise bending due to pressure load on the blade;
- Gravitational loads which change direction during the rotation and which mainly generate edgewise bending load;
- Inertia forces due to the rotation of the blade.

During operation, the blades on a wind turbine experience cyclic loading due to the Earth’s gravitational field. During one rotation, the root of a blade, specifically the leading and trailing edges, will experience a tension-compression cycle due to the weight of the blade; this cyclic loading is significant and can influence the fatigue life of the blades. Because of the relatively low rotational speed, centrifugal forces are not very significant in wind turbines, and therefore these forces are neglected. The most obvious source of loading on the blades of a wind turbine is the wind itself. These loads are directly related to the power production of the wind turbine, when an airfoil is subjected to a relative wind velocity, a component of lift and drag are induced due to the aerodynamic properties of the profile. During the entire simulation and to simplify the analysis, the mean wind speed at hub is taken equal to 10 m/s.

The total lift and drag force can be expressed respectively as follows [16]:

$$F_{drag} = \frac{1}{2} \rho V_w^2 A C_D = 32KN \tag{1}$$

$$F_{Lift} = \frac{1}{2} \rho V_w^2 A C_L = 21KN \tag{2}$$

where A is the swept area of the blade, ρ is the density of surrounded air, $C_D = 8/9$ and $C_L = 0.624$ are the drag and lift coefficients, respectively (according to Betz theory) and V_w is wind mean speed [16].

Gravity force (F_g) and centrifugal force (F_r) are equal to:

$$F_g = m \times g = 1150 \times 9.8 = 11.27kN \tag{3}$$

$$F_r = m \cdot r \cdot \omega^2 = 1250 \times 7.5 \times (28.5 \times 2\pi / 60)^2 = 83.5kN \tag{4}$$

V. MATERIAL PROPERTIES

Currently, the rotor blades are constructed from fibre reinforced polymers, where the E-glass is the most commonly used reinforcement material. The shell consists mainly of $\pm 45^\circ$ plies, with unidirectional laminate at the trailing and leading edges to carry the edgewise forces and bending moments. The aerodynamic shells are made by prepreg technology. In the investigated blade tri-axial and bi-axial fabrics are used in the shell structure. The configuration of the bi-axial laminate is $[0/90]_T$ and the configuration of the tri-axial laminate is $[0/+45/-45]_T$. The shell of the blade is a sandwich structure with a PVC foam which is provided to separate the composite skins; this will indeed increase the panel’s second moment of area and thus the resistance to buckling.

Flanges and webs of the blade are also made of glass fiber composites, where unidirectional and bi-axial fabrics are used in the spar structure. Unidirectional plies are used to provide stiffness for bending and some $\pm 45^\circ$ plies are included to provide resistance for buckling. The flanges must take high tensile stresses on the pressure side and compressive stresses on the suction side, so they are predominantly composed of unidirectional fibres in order to withstand these forces.

The shear webs are typically made up of fibres orientated at ± 45 to transfer the shear loads and keep the spar caps from moving relative to each other.

It should be noted that the composite parts of the root joint are mainly made up of bi-axial and unidirectional fabrics and the metal used at the root joint is aluminium alloy 5083. The mechanical properties of the material considered in the analysis are shown in Table 2 [9] and the mechanical properties of aluminium that require to analysis are listed in Table 3.

TABLE 2 MECHANICAL PROPERTIES OF FABRICS [8]

Composites	Configuration	E ₁ (MPa)	E ₂ (MPa)	ν_{12}	E ₆ (MPa)
Unidirectional	-	43	9.77	0.32	3.31
Bi-axial	$[\pm 45]_T$	6.8	6.8	0.06	-
Bi-axial	$[0/90]_T$	16.7	16.7	0.06	2.01
Tri-axial	$[0/\pm 45]_T$	17.6	7.01	0.52	5.07

TABLE 3 MECHANICAL PROPERTIES OF ROOT JOINT METAL (ALUMINIUM ALLOY 5083)

Property	Value
Density	2650 Kg/m ³
Modulus of Elasticity	72 GPa

VI. FATIGUE DAMAGE MODELING

In this study, the adhesive debonding on the root joint of the wind turbine blade was investigated using a cohesive zone model. The use of cohesive zone models (CZM’s) coupled to conventional FE analyses is the most widespread method of predicting static or fatigue damage uptake in structures [17]. The advantage of this method is the possibility of modeling the

debonding initiation and propagation without requirement to the presence of initial crack. Although in this method damage and delamination is modeled as the stiffness loss of the interface element, this approach does not require any remeshing for the analysis of debonding. The CZM's are based on the assumption that one or multiple fracture interfaces/regions can be artificially introduced in structures, in which damage growth is allowed by the introduction of a possible discontinuity in the displacement field. In other words, this model is based on a softening constitutive relation in the damaged area around the crack tip. The mechanism of this method for the bi-linear model is shown in Fig. 8.

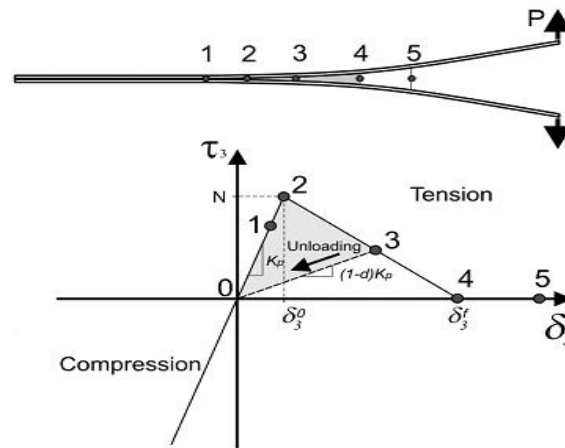


Fig. 8 The damaged area around the crack tip and the constitutive relation of cohesive zone model [18]

According to Fig. 8, the relationship between stress and strain (or displacement) in the interface element is initially linear elastic but when the stress reaches a maximum amount (that is the interlaminar strength), the stiffness degradation of the interface element starts to finally reach zero. In this state, the interface element is fully damaged. The ratio of lost stiffness to the initial stiffness in each state is called the damage variable. The technique consists of the establishment of traction-separation laws (addressed as CZM laws) to model interfaces or the finite regions. The CZM laws are established between paired nodes of cohesive elements, and they can be used to connect superimposed nodes of elements representing different materials or different plies in composites, to simulate a zero thickness interface or they can be applied directly between two non-contacting materials to simulate a thin strip of finite thickness between them, e.g. to simulate an adhesive bond.

It should be noted that in the modeling of debonding when using the cohesive zone concept, the area under the curve of constitutive equation in the stress-displacement space, is equal to the fracture toughness of corresponding loading mode. Balzani and Wagner [18] presented a robust solid like interface element based on the cohesive zone model for modeling delamination in laminated composites under mixed mode conditions. The cohesive interface element used in this study that has been implemented in the Ansys software, is based on the constitutive equations developed by the above mentioned researchers.

A. Constitutive Equations for Quasi-static Loading

The concept of cohesive zone was proposed to describe damage under static loads at the cohesive process zone ahead of the apparent crack tip, which can be understood as a phenomenon of micro voids formation that grows with the increase of the load, forming thin fibrils until the crack appears. The interface element used in this study is an 8-node solid continuum element with finite thickness called “the solid-like interface element”. The formulation of this element is based on the isoparametric hexahedral solid element formulation but it is only comprised of three components of the stress instead of the six components. Since the task of interface element is to predict the initiation and propagation of delamination, therefore the stress tensor of this element only includes the normal stress in the thickness direction and the out of plane shear stresses. Fig. 9 illustrates the schematic of this interface element [18].

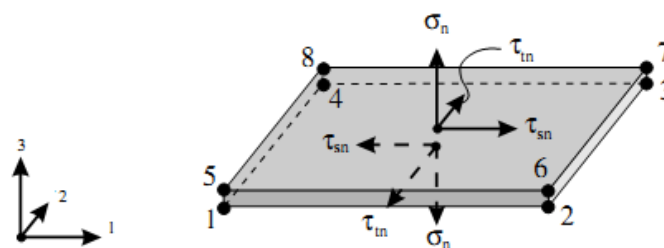


Fig. 9 A solid-like interface element [18]

In order to predict the delamination initiation considering the mixed mode condition, the summation of quadrature of stresses used in this research is as follows [19]:

$$\left(\frac{\langle \sigma_n \rangle}{\sigma_n^0}\right)^2 + \left(\frac{\tau_{sn}}{\tau_{sn}^0}\right)^2 + \left(\frac{\tau_{tn}}{\tau_{tn}^0}\right)^2 = 1 \tag{5}$$

where $\langle \rangle$ are the Macaulay brackets and given by:

$$\langle x \rangle = \begin{cases} 0 & x \leq 0 \\ x & x > 0 \end{cases} \tag{6}$$

Since normal compressive stress does not have any effect on the delamination, so operator $\langle \rangle$ has been used in which if the applied normal stress is compressive, zero value is substituted instead of it.

In this study, the damage propagation is evaluated using B-K criterion which originally proposed by Kenane and Benzeggagh [20]. This criterion is based on the fracture toughness of modes I and II likewise, parameter η which is obtained from MMB test and is expressed as follows:

$$G_{IC} + (G_{IIC} - G_{IC}) \left(\frac{G_{Shear}}{G_T}\right)^\eta = G_C, \quad G_T = G_I + G_{Shear} \tag{7}$$

The constitutive relation of cohesive zone model is expressed as follows:

$$\sigma = c\varepsilon, \quad \sigma = \{\tau_{sn}, \tau_{tn}, \sigma_n\}^T, \quad \varepsilon = \{\gamma_{sn}, \gamma_{tn}, \varepsilon_n\}^T \tag{8}$$

$$c = \begin{cases} KI & \varepsilon_m^* \leq \varepsilon_m^0 \\ (1-d)KI + dKI_c & \varepsilon_m^0 < \varepsilon_m^* < \varepsilon_m^f \\ KI_c & \varepsilon_m^* \geq \varepsilon_m^f \end{cases} \tag{9}$$

$$I_c = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{\langle -\delta_n \rangle}{-\delta_n} \end{bmatrix} \tag{10}$$

In Eq. (7), ε_m^* is the maximum value of effective strain in every load step which has been used for considering the irreversibility condition of damage process. Also, indexes 0 and f corresponds to initiating the damage process and complete failure, respectively. Parameters d, k and c are damage variable, initial elastic rigidity as well as reduced stiffness matrix of the interface element, respectively. In addition, matrix I is the identity matrix ordered 3. Using the operator $\langle \rangle$ at the Eq. (6), absence of orthogonal rigidity reduction during the presence of compressive stress due to prevent from entering the cracked layers to each other for strains more than ε_m^f has been considered.

So, the explicit equation of the damage parameter for the bilinear constitutive relation is obtained in the most general form of mixed mode as follows:

$$d = \frac{\varepsilon_m^f (\varepsilon_m^* - \varepsilon_m^0)}{\varepsilon_m^* (\varepsilon_m^f - \varepsilon_m^0)} \tag{11}$$

B. Constitutive Equations for Fatigue Loading

Turon et al [21] proposed a damage model for simulating the interlaminar failure of stacked composites under high cycle fatigue loads. Their model was based on providing a cohesive law that link fracture mechanics to damage mechanics in order to estimate the evolution of the damage variable during fatigue cycles. The model that was used in this study to predict debonding in adhesive joints of wind turbine blade root joint under fatigue loading is based on the research work presented in [21]; where the principle of this method will be described in the following section.

In order to evaluate the fatigue damage variable growth rate, researchers [21] stated that if the A_d is damaged area of

cohesive element, the rate of fatigue damage variable growth can be expressed as:

$$\frac{\partial d}{\partial N} = \frac{\partial d}{\partial A_d} \frac{\partial A_d}{\partial N} \tag{12}$$

Turon et al [21] used the concept of dissipating energy (irreversible) to define damaged area and according to Fig. 10 set the ratio of the damaged area, A_d , with respect to the area A_e associated with the area of the element equal to the ratio of dissipated energy to the critical energy release rate during the damage process in each state of damage variable [22], So:

$$\frac{A_d}{A_e} = \frac{E}{G_c} \tag{13}$$

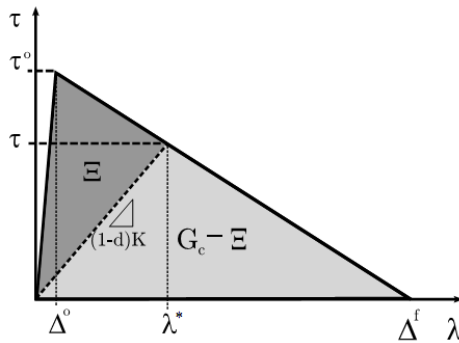


Fig. 10 The concept of dissipated energy in softening law [22]

Using Eq. (13) and Fig. 10, it can easily be shown that in the bilinear model the final equation for damaged area can be written as follows:

$$A_d = A_e \left[\frac{d\varepsilon_m^0}{(1-d)\varepsilon_m^f + d\varepsilon_m^0} \right] \tag{14}$$

Turon et al [21] defined the growth rate of the damaged area for cohesive element under fatigue loading similar to Paris law as follows:

$$\frac{\partial A_d}{\partial N} = A_e \left[\frac{C}{L_{cz}} \left(\frac{\Delta G}{G_c} \right)^m \right] \tag{15}$$

where A_e is the area of a cohesive element in the plane that delamination accrued and L_{cz} is the cohesive zone length perpendicular to the crack front. Also m and c are material constants in Paris law for crack growth rate and ΔG is equal to strain energy release rate at current fatigue cycle. It should be noted that ΔG is also defined as the area under the curve of constitute equation in the stress-displacement space.

By using Eqs. (12)-(15), the evolution of the damage variable as a function of the number of cycles can be written as:

$$\frac{\partial d}{\partial N} = \begin{cases} \frac{\left[(1-d)\varepsilon_m^f + d\varepsilon_m^0 \right]^2}{\varepsilon_m^f \varepsilon_m^0} \left[\frac{C}{L_{cz}} \left(\frac{\Delta G}{G_c} \right)^m \right] & G_{max} \geq G_{th} \\ 0 & \text{otherwise} \end{cases} \tag{16}$$

where G_{max} is the maximum energy release rate and G_{th} is the energy release rate threshold.

VII. DETERMINATION OF COHESIVE PARAMETERS

Finite element analysis that include CZM techniques offer a powerful means to account for the largely nonlinear fracture behaviour of modern adhesively bonded joints, but the CZM parameters require careful calibrations by experimental data and respective validation in order to accurately simulate the failure process. In recent years, many works were published regarding the definition of the CZM parameters (G_c and σ_c in Mode I, II and mix mode) and a few data reduction techniques are currently available that enclose varying degrees of complexity and expected accuracy of the results. The most commonly used

experimental set-ups in order to measure Mode I, Mode II and Mix mode of cohesive laws is the Double Cantilever Beam (DCB) test, the End Notch Flexure (ENF) test and Mix Mode Bending (MMB) test, respectively which are standardized in standard associations (e.g. ASTM) for unidirectional polymeric composites. Fig. 11 shows the undeformed DCB specimen, where a_0 is the original crack length, b is the specimen width, h is the thickness of the specimen, L is total length and P is the applied load [23].

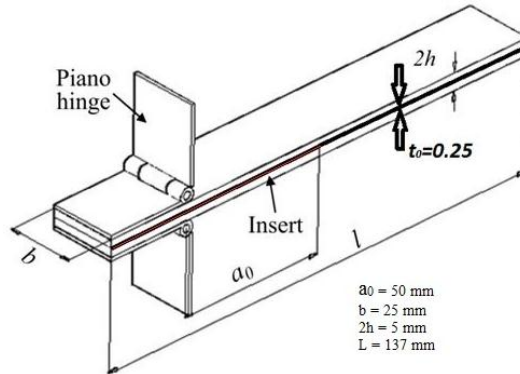


Fig. 11 Undeformed DCB specimen [23]

In order to obtain Mode I adhesive fracture toughness, tests were performed under static and fatigue loading in accordance with ASTM D5528 and D6115 [23], [24]. The adherent material selected for mechanical testing was the unidirectional fiberglass laminate and a thin film of Teflon was used as the insert. In all cases, HUNTSMAN Epoxy XB5047 / XB5067 was utilized as the adhesive material system. Before fatigue testing, static tests were conducted on the specimens to study their static failure behaviour and define the cohesive zone model. The static tests were executed in displacement control at a rate of 1 mm/min and the corresponding load level and back-face strain data were recorded. Fatigue testing was carried out at 5 Hz with a load ratio of 0.5.

In order to obtain required cohesive parameters associated with Mode II adhesive fracture toughness, ENF tests were performed under static and fatigue loading. Four series of static ENF tests were conducted on a type DP-5/3 machine with displacement control at a rate of 2mm/min and four series of fatigue tests were conducted under load control at 5 Hz with a load ratio of 0.5.

For the measurement of mixed mode cohesive parameters, different experimental set ups have been used. Efforts have been made to find a test set up that will allow testing under the full range of mode mixities. One of the most used experiment set ups is the Mixed Mode Bending (MMB) [25]. This method was standardized by ASTM standard [26]. Fig. 12 gives the MMB test base geometries.

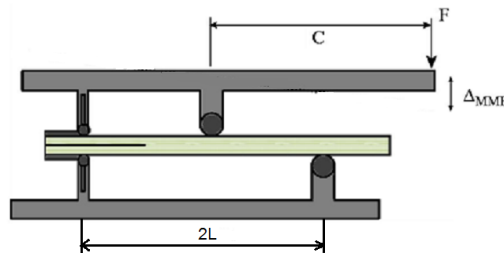


Fig. 12 Base geometry of MMB test [27]

The MMB test provides an easy variation of the mode ratio by just altering the lever length of the loading lever. Four series of static MMB tests were conducted with displacement control at a rate of 2mm/min and four series of fatigue tests were conducted under load control at 5 Hz with a load ratio of 0.5 with mode ratio of 0.5. Also, three series of SLJ tests were conducted to obtain the shear strength of the adhesive according to ASTM D5868 [28].

Two types of adhesive bonding are available at the root joint, one is composite to composite bonding and the other is composite to metal (aluminum) bonding; due to this reason all tests were repeated for composite to metal bonding. The results of performed tests are summarized in Tables 4-7.

TABLE 4 RESULTS OF STATIC TESTS FOR COMPOSITE-COMPOSITE BONDING

K(MPa)	τ_n^0 (MPa)	τ_s^0 (MPa)	G_{Ic} (N/mm)	G_{IIc} (N/mm)	η
5400	15.4	15.4	0.208	0.706	2.07

TABLE 5 RESULTS OF STATIC TESTS FOR COMPOSITE-ALUMINUM BONDING

K(MPa)	τ_n^0 (MPa)	τ_s^0 (MPa)	G_{Ic} (N/mm)	G_{IIc} (N/mm)	η
4600	13.1	13.1	0.203	0.57	2.04

TABLE 6 RESULTS OF FATIGUE TESTS FOR COMPOSITE-COMPOSITE BONDING

G_{Ith} (N/mm)	G_{IIth} (N/mm)	η_{th}	C_I (mm/Cycle)	C_{II} (mm/Cycle)	C_m (mm/Cycle)	m_I	m_{II}	m_m
0.025	0.135	5.77	0.00009	0.0054	3.41E14	3.21	6.72	7.48

TABLE 7 RESULTS OF FATIGUE TESTS FOR COMPOSITE-ALUMINUM BONDING

G_{Ith} (N/mm)	G_{IIth} (N/mm)	η_{th}	C_I (mm/Cycle)	C_{II} (mm/Cycle)	C_m (mm/Cycle)	m_I	m_{II}	m_m
0.018	0.126	5.79	0.00013	0.0061	3.49E14	3.15	6.67	7.52

It should be noted that to approximate Paris law constants in the mixed mode delamination, the method proposed by Blanco et al [29] was used.

VIII. FATIGUE INVESTIGATION OF THE BLADE

In order to evaluate the fatigue life of wind turbine blade, in the first step critical position of blade was determined. Probable critical position of the blade is horizontal position in which gravity force and lift force are codirectional and the other critical position is vertical in which gravity force and centrifugal force are codirectional. The gravity force and the centrifugal force were applied at the center of mass and the aerodynamic force was applied in the form of triangular distribution to the top surfaces of the blade. Boundary conditions corresponding to the root consisted of fixing all the six degrees of freedom of nodes.

By using cohesive zone model concept and parameters that was obtained from test results, a material called “usermat” was defined in Ansys material library. After performing static analysis on the two probable positions, results show that horizontal position is the most critical. Figs. 13 and 14 show the damage contour result for the horizontal position and vertical position respectively at the adhesive part of root joint. Fig. 15 shows x component of blade displacement under static load. As shown in Figs. 13-15, damaged area for horizontal position is more important than vertical position; which determines that horizontal position is critical.

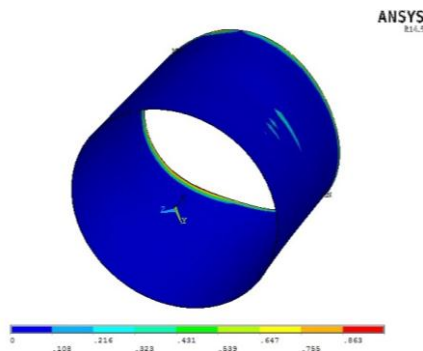


Fig. 13 Damage contour for horizontal position at the root joint adhesive

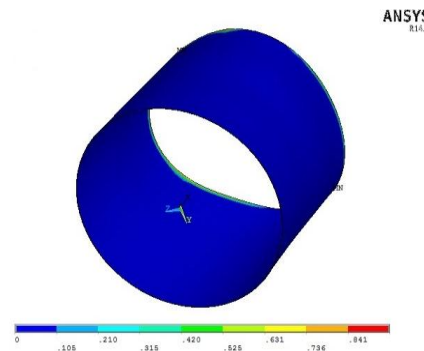


Fig. 14 Damage contour for vertical position at the root joint adhesive

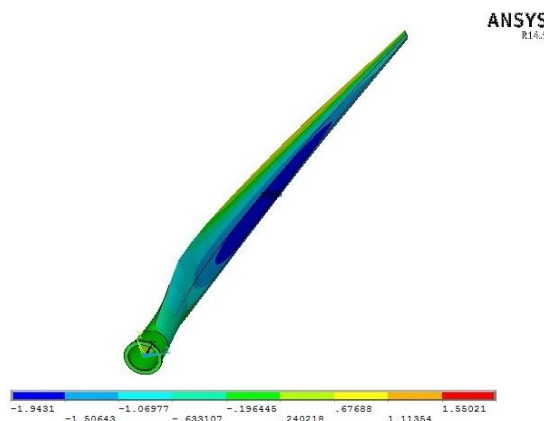


Fig. 15 X component of blade displacement under static load

By using cycle jumping strategy and executing code, debonding of adhesive joints at the root joint of the composite wind turbine blade was examined. At the end of the analysis the number of cycles to failure was obtained to be equal to 7.4×10^8 cycles. This value indicates that the blade satisfies the design requirements. Figs. 16-20 show damage variable contour at different cycles from first cycle to last cycle that failure occurs at the blade root joint. As shown in these figures, damaged area increase by increasing the number of cycles (N indicates cycle number).

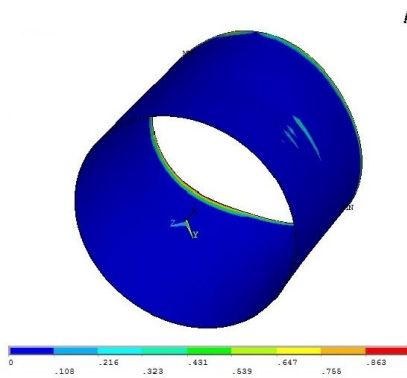


Fig. 16 Damage contour at the root joint adhesive when $N=10^2$

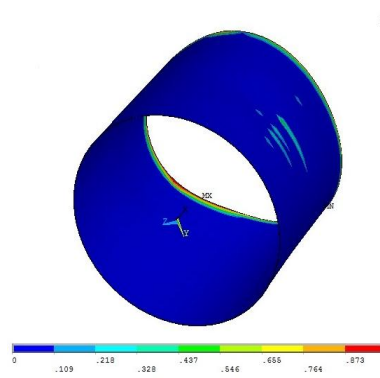


Fig. 17 Damage contour at the root joint adhesive when $N=10^5$

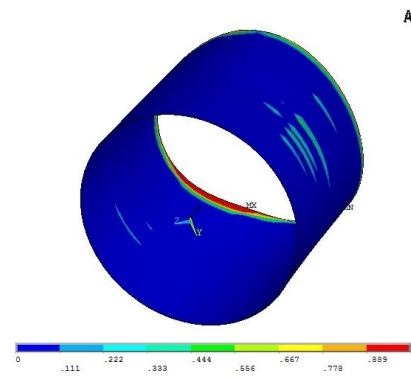


Fig. 18 Damage contour at the root joint adhesive when $N=10^6$

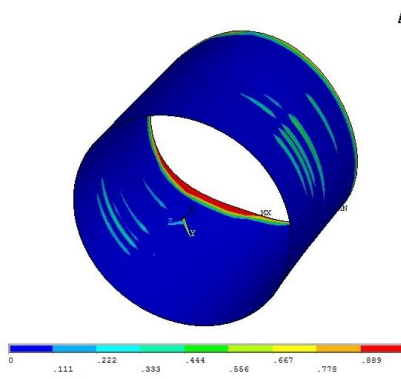


Fig. 19 Damage contour at the root joint adhesive when $N=10^8$

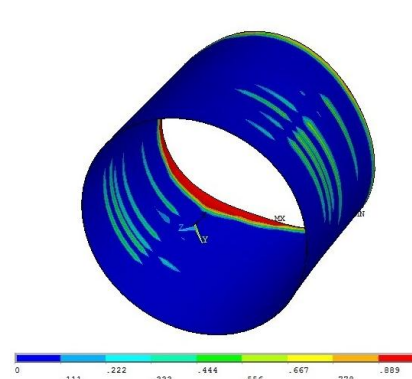


Fig. 20 Damage contour at the root joint adhesive when $N=7.4 \times 10^8$ (last cycle)

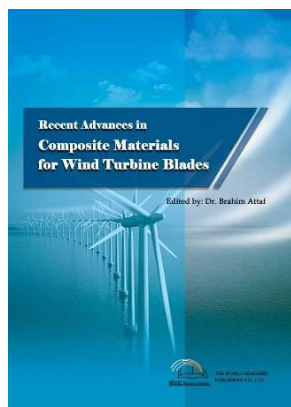
IX. CONCLUSIONS

In this study, initiation and growth of debonding at the root joint of composite wind turbine blade due to fatigue loading was investigated by using the cohesive zone model. It was estimated that 10^8 load cycles will happen in the prospected lifetime of 20 years of a wind turbine. During this lifetime, the rotor blades are exposed to various hostile conditions and loads, where structural components joined together by adhesive bonding must withstand such loading conditions. In order to predict damage due to fatigue loading in the horizontal axis of a wind turbine with 46 meter rotor diameter, a cohesive zone constitutive law based on dissipated energy was implemented and after performing a series of DCB, ENF, MMB and SLJ tests, using cohesive zone model concept and parameters that were obtained from test results, a material was defined in ANSYS material library. The static analysis was performed to determine the critical position of the wind turbine blade. Numerical results show that the horizontal position is the critical position for wind turbine blade under fatigue loading. After carrying out static analysis, the horizontal position was used to perform fatigue analysis. So, by using developed models and performing material constants, after model analysis, debonding of adhesive joints at the wind turbine blade was investigated and the fatigue life of the root joint was obtained. The estimated fatigue life obtained satisfies the design requirements.

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This book of science and technology provides an overview of recent research activities on the application of fibre-reinforced composite materials used in wind turbine blades. Great emphasis was given to the work of scientists, researchers and industrialists who are active in the field and to the latest developments achieved in new materials, manufacturing processes, architectures, aerodynamics, optimum design, testing techniques, etc.. These innovative topics will open up great perspectives for the development of large scale blades for on- and off-shore applications. In addition, the variety of the presented chapters will offer readers access to global studies of research & innovation, technology transfer and dissemination of results and will respond effectively to issues related to improving the energy efficiency strategy for 2020 and the longer term.

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