Effect of in-plane fiber waviness on the failure of fiber reinforced polymer composites

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SINGAPORE

**EFFECT OF IN-PLANE FIBER WAVINESS ON THE
FAILURE OF FIBER REINFORCED POLYMER
COMPOSITES**

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2018

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COMPOSITES**

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A thesis submitted to the Nanyang Technological University in
partial fulfilment of the requirement for the degree of
Doctor of Philosophy

2018

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

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Abstract

As the demand for energy increases day by day, the future relies more on clean renewable energy resources. Wind turbines have a promising active contribution to meet this future demand. Wind industries are more interested to have bigger turbines to produce more power economically from a single turbine unit. Glass and carbon fiber composite materials are largely used in the light weight turbine blade manufacturing due to their high strength to weight ratio.

The spar-cap is considered as the back bone of a wind turbine blade and it consists of significant amount of unidirectional laminates. Manufacturing defects are unavoidable due to their nature and involvement in the structure. Some of these defects may affect the life expectancy of the blade as well as the whole turbine unit. Focus of the present study is related to a common manufacturing defect found in spar cap regions, ‘fiber waviness’, and its influence towards the failure initiation and propagation under compression and bending loads.

Despite its wide spread occurrence, in-plane fiber waviness defect found throughout the thickness of composite laminates is not well studied. Therefore, a coupon level in-plane fiber waviness defect was induced in unidirectional composite samples and tested under numerous loading conditions. Variations in both mechanical strength and failure modes of waviness induced samples were characterized. In addition, double cantilever beam experiments were conducted to study the effect of fiber waviness on the fracture energy and crack propagation.

Further, an analytical model has been prepared by adding sinusoidal waviness into the laminate to estimate the reduction in modulus based on the constitutive relations. Also, finite element analysis was used to predict the compressive strength and failure modes under the static compression loads based on a physical based failure theory (LaRC02) using ABAQUS 6.13TM software.

Finally, a 6-m wind turbine blade shell model was designed using NuMAD software. Fiber waviness was introduced at various locations of the spar-cap region and a static flap-wise bending analysis was performed at designed

maximum bending moment of the blade. The longitudinal strain deformation during flap-wise bending analysis at the fiber waviness region of those blade models was validated with the help of four-point bending test of a composite I - beam consisting of waviness defect.

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Abbreviations

FRP	Fiber Reinforced Polymer
GFRP	Glass Fiber Reinforced Polymer
U	Unidirectional
FE	Finite element
FEM	Finite element method
P	Power
ρ	Air density
A	Swept area
V	Wind velocity
α	Aerodynamic efficiency coefficient
E	Young's Modulus
ν_{12}	Poisson's ratio
HAWT	Horizontal Axis Wind Turbine
VARIM	Vacuum Assisted Resin Infusion Molding
ASTM	American Standard for Testing of Materials
HCCF	Hydraulic Composite Compression Fixture
DCB	Double Cantilever Beam
MBT	Modified Beam Theory
CC	Compliance Calibration
MCC	Modified Compliance Calibration
SEM	Scanning Electron Microscope
CT	Computed Tomography
NREL	National Renewable Energy Laboratory
NuMAD	Numerical Manufacturing and Design

Publications

- 1) Swaroop Narayanan Nair, Aravind Dasari, Chee Yoon Yue, and Srikanth Narasimalu. "Failure Behavior of Unidirectional Composites under Compression Loading: Effect of Fiber Waviness." *Materials* 10, no. 8 (2017): 909.
- 2) Swaroop Narayanan Nair, Aravind Dasari, Chee Yoon Yue, and Srikanth Narasimalu. "Effect of fiber waviness on the delamination onset and Mode - I fracture energy of polymer composites" (Drafted).

Chapter 1

Introduction

In this chapter, the background of the research work presented in this thesis along with the scope and objectives are discussed. Finally, a detailed layout of the dissertation is presented.

1.1 Background and motivation

The contribution of renewable energy is highly remarkable to mitigate the future global energy crisis. It also helps to reduce the dependency on fossil fuel. Wind energy is one of the cleanest and environmental friendly renewable forms of energy. It is expected that up to 20% of global renewable energy will be derived from wind energy by 2020 [1]. In a survey conducted by the global wind energy council, the total installed wind energy production reached 282.4GW by the end of 2012 [2]. Among the wind energy producing countries, China is leading with a cumulative capacity of 75,564MW and a production percentage share of 26.8%.

As the future is dependent on environmental friendly renewable energy, improving the reliability of wind turbine blades is critical. Adoption of polymer matrix composites technology in wind turbine industry enabled the manufacturers to produce bigger rotor blades with higher strength to weight ratio. When the size of the turbine increases, it is equally important to have an extended life span of the blades to balance the cost of manufacturing.

The turbine rotor blade is one of the key components in a wind turbine, which converts the wind energy into kinetic energy to produce power. Blades are critical components in the design and manufacturing of wind turbine system as they are designed to withstand environmental conditions. Composite materials are commonly used for manufacturing wind turbine blades due to their high strength

to weight ratio and stiffness. Figure 1.1 shows the internal structure of basic wind turbine blade made up of composite materials. The amount of energy produced per turbine is directly proportional to the swept area covered by the turbine blades, so the solution for greater power is bigger turbines with bigger blades. As the size of the blade increases, their design and manufacturing become very critical [3].

Figure 1.1: A wind blade internal structure schematic [4].

There are two common design approaches on the basic structure of a turbine blades as shown in Figure 1.2, one with 'I' section and the other with box girder section. The top and bottom of both sections consists of spar-caps, which can be an integral part of the structural sandwich shell or a part of the shear web [5].

Figure 1.2: Cross section of a blade [6].

Blades are generally made up of large tow fiber fabrics to build up the thickness rapidly. Several layers of fiber impregnated with adhesive resins are present in the structure. These composite layers are generally very stiff and strong along the fiber direction, but weak across the plane perpendicular to the fiber axis. The in-plane properties are mainly determined by the fibers, and out of plane properties are by the matrix. Composite properties have dependents on the lay-up sequence, fiber volume and the technique used for manufacturing. Blade stresses are predominant in the longitudinal direction due to flap-wise and edge-wise bending loads. Spar-caps are designed to act as reinforcement and they generally consist of thick unidirectional laminate whereas internal shear web is designed to carry shear loads, so they are usually sandwich structures with $\pm 45^\circ$ biaxial laminates. Balsa wood or polymer foams are generally used as sandwich cores and they are the body skin of blades [5].

According to historical wind farm data [7], 10% of the wind turbine down time has been due to blades and rotor failure. Additionally, with the current trend in wind turbine design (~ 7 -8 MW capacity and ~ 70 -80 m blade length made of polymer composites), better characterization and understanding of the design and manufacturing flaws in blades is essential. Postmortem analysis of failed blades has indicated manufacturing flaws like porosity, improper wetting of fibers with matrix, fiber waviness etc.[8]. Many mechanical (particularly compressive strength, a major design driver in this application) and physical properties of the blades are affected by these defects, which have had a deep economic impact [7].

Figure 1.3: Fiber waviness found in the composite structures [9], (a) In-plane waviness over the surface, (b) Out of plane waviness throughout the thickness.

Fiber waviness is a type of fiber misalignment that is defined as the sinusoidal fiber deflection/bending during processing of the laminate structure. Both in-plane and out-of-plane fiber waviness can occur over a lamina, multiple laminates or throughout the thickness of the structure, in a uniform or non-uniform format. This may arise in any part of the structure due to excessive reinforcement during ply stacking or even due to ply drop situation [10][14]. In the thesis, the after effects of fiber waviness in the unidirectional laminates of the spar-cap region were considered. Though some studies have been conducted on evaluating the effect of out of plane waviness defect and stiffness / strength reduction due to waviness defects [9] there is limited work on the experimental investigation on the effect of through thickness in-plane fiber waviness aspect and associated failure mechanisms.

The above background is the motivation for the present study to develop an understanding of the influence of the in-plane fiber waviness defect on the mechanical properties and the failure behavior. Similar kind of defects with known features are intentionally induced on to the laminates to study their influence in mechanical properties. Among different kinds of in-plane waviness, a single waviness throughout the thickness of the laminate is considered for the entire thesis. A finite element model is also developed to predict the influence of waviness on strength and failure behavior under static analysis.

1.2 Objectives

- 1) To understand the failure behavior of unidirectional GFRP laminates under static compression loading, static and fatigue flexural loading in the presence of through thickness in-plane waviness defects.
- 2) To establish an FE model for predicting the compressive failure strength and failure behavior due to the influence of in-plane waviness.
- 3) To develop a blade model to understand the influence of in-plane waviness at different spar cap locations under extreme bending loads.

- 4) To validate the waviness effect on the strain deformation at the suction side and pressure side of a turbine blade (that is supported with the help of composite I-beam) under bending loads.

1.3 Scope of the thesis

The literature is reviewed to understand the basic design of composite wind turbine blades and the effects of several common manufacturing defects on mechanical properties. Various types of failures found in the composite laminates under static and fatigue bending and compression loading are studied.

An in-plane waviness defect with different severity levels are intentionally induced in the unidirectional laminate while manufacturing to study the effect of waviness defect. Static bending and compression tests are conducted on the waviness induced specimens and the results are compared with those from defect-free samples. The failures are thoroughly examined and various failure modes are identified.

Both analytical and numerical models have been developed to study the through thickness in-plane fiber waviness under compression conditions at various fiber severity level. The numerical model (commercial FE package AbaqusTM) is developed based on the constituent based failure theory under the influence of in-plane waviness defect. The results obtained from the FE model and the analytical model are compared and validated with the experimental findings.

To study the influence of flap-wise wind loads acting on the blades with waviness, all the specimens with in-plane fiber waviness are tested under fatigue flexural loads. As most of the wind load acts in the unidirectional flap-wise way, the specimens are tested in bending with stress ratios (R) 0.1 and 0.5. After the test, the effects of in-plane fiber waviness defect on specimen cycle lives are analyzed and failure modes are thoroughly examined.

A 6 m blade shell model to study the influence of fiber waviness on blade tip deflection and longitudinal strain at different spar-cap locations under extreme bending loads. Experimental validation on the influence of waviness defect on

suction side and pressure side is achieved through a four-point bending analysis on a composite I – beam with waviness on the top flange and the bottom flange separately.

1.4 Dissertation outline

The outline of the remainder of the thesis is:

A literature review on the manufacturing defects in turbine blades and the different types of failures that exist in composite laminates is outlined in Chapter 2. In Chapter 3, a method to intentionally induce in-plane waviness into a composite laminate is discussed. The influence of waviness on the mechanical properties based on experimental studies on specimens with and without waviness defects is explained in detail. In Chapter 4, static compression analysis of defect-prone unidirectional specimens is outlined and discussed. The failure modes in the specimens are also studied along with the influence of waviness on the fracture energy of delamination. Next, in Chapter 5, an analytical model that has been developed to explain the experimental results is outlined. An FE model to predict failure in waviness-induced specimens under compression loading has also been built. Flexural static and fatigue analysis on the waviness induced specimen is considered and discussed in Chapter 6. Chapter 7 details a 6 m turbine blade model that was developed to investigate the effect of waviness at different spar-cap locations and its influence under extreme flap-wise bending loads. Finally, the conclusions and scope for future research are outlined in Chapter 8.

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Chapter 2

Literature review

In this chapter, basics of wind turbine blades, typical blade design, types of loads acting on the blade and different manufacturing defects and their effects on various mechanical properties along with failure modes of wind turbine blades are discussed. Special focus is on the fiber waviness defect and the previous research on the effect of waviness on the mechanical properties and failure modes under extreme compression and bending load conditions. Also, various research studies on coupon level fatigue flexural failure of unidirectional composite laminates are discussed to understand the different failure modes presented.

2.1 Wind turbine

The primary component of the wind turbine is the energy converter which converts the kinetic energy of the wind to mechanical energy, and subsequently to electrical energy. The amount of power produced depends on various factors like the density of air (ρ), swept area of rotor blade (A), the wind velocity (v) and is given by,

$$P = \alpha \rho A v^3 \quad (2.1)$$

α is the aerodynamic efficiency coefficient.

In general, rotor is mounted over a tower and a blade with aerodynamic in shape to capture the wind and to rotate the rotor by facing in the wind direction. Nearly all wind turbines have a rotor mounted in a vertical plane with three blades rotating in a horizontal axis (called Horizontal axis wind turbine, HAWT).

2.2 Material requirements for wind turbine blades

The general property requirements for a wind blade material include high stiffness, light-weight and long-fatigue life. Undoubtedly the advantages of the fibrous composite materials are their high specific stiffness and high specific strength as compared to the traditional engineering materials. Figure 2.1 shows the Young's modulus and density of various engineering materials.

Figure 2.1: Relation between Young's modulus (E) and density (ρ) [1].

The basic design aspects of the blade are material selection and aerodynamic shape. Figure 2.2 shows the basic aerodynamic shape of the cross section of a rotor blade. The aerodynamic outer contour shape is called shell made up of thin layer of composites. The contour is supported by a longitudinal beam, with a cross section of box or I-section. The longitudinal beam consists of a thick composite layer of spar-caps (on top and bottom) and a sandwiched vertical structure of shear web. The weight and thickness of the rotor blade gradually decreases from root to tip to optimize the load distribution along the cantilever structure.

Figure 2.2: Basic blade cross section [2]

Based on the turbine working environment conditions and operational parameters the lead requirements for a blade material is their density, stiffness and fatigue life. High stiffness is needed for an optimal aerodynamic performance, low density materials are preferred for a reduced gravitational force and a material with minimum property degradation for a better fatigue life. From the listed requirements, fiber reinforced composite material is a leading choice [3]. Material performance is measured by conducting coupon level static and fatigue tests to ascertain the material qualification and the design demand calculated from the aero-elastic model based on wind loads.

2.3 Fiber Reinforced Polymer (FRP) Composites

Blades are generally made up of large tow fiber fabrics to build up the thickness rapidly. Several layers of fiber impregnated with adhesive resins are present in the structure. These composite layers are generally very stiff and strong along the fiber direction, but weak across the plane perpendicular to the fiber axis. The in-plane properties are mainly determined by the fibers, and out of plane properties are by the matrix. Composite properties have dependents on the lay-up sequence, fiber volume and the technique used for manufacturing. Blade stresses are predominant in the longitudinal direction due to flap-wise and edge-wise bending loads. Spar-caps are designed to act as reinforcement and they generally consist of thick unidirectional laminate whereas internal webs are designed to carry shear loads, so they are usually sandwich structures with +/-

45° biaxial laminates. Balsa wood or polymer foams are generally used as sandwich cores and they are the body skin of blades [4].

FRP Composites are layered structures made up of several layers of fiber fabric called lamina. A lamina may consist of long fibers, short fibers, braided or woven fibers stacked together and bonded with the help of a polymer matrix material to form a laminate. The bonding between the fiber and matrix helps to form a load bearing structural element. The fiber consists of many filaments in the diameter range 5 to 20 μm . Generally used fiber materials are glass, carbon, Kevlar®, aramid and so on. Polymer matrices are divided into thermoset and thermoplastic, e.g. polyesters, epoxies, polyamides and bismaleimides. While curing, the thermoset polymers were crosslinked to create a three-dimensional network which is irreversible. Due to their three-dimensional crosslinking ability, thermosets have high temperature resistance and dimensional stability. On the other hand, thermoplastics are reversible so that they will return to the viscous liquid form once they are heated to their melting temperature. Currently, thermoplastics are employed for the low temperature and impact resistance applications. However, nowadays high-performance thermoplastic/fibrous composites are getting more attention from industries. Glass and carbon fibers were widely used for the fabrication of blades.

Glass fibers have high strength, moderate density and moderate stiffness properties (69 to 80 GPa) [5, 6]. They are composed of SiO_2 , Al_2O_3 with smaller amount of other oxides such as CaO , MgO , ZnO , TiO_2 etc. Glass fibers have amorphous (non-crystalline) structure and considered as isotropic in nature. They are generally in between 10 to 20 μm in diameter. The fiber surfaces were normally coated (sizing) with silane compounds to protect from cracking while drawing. Also, fiber sizing improves the bonding properties of glass fibers with matrix material.

Carbon fibers are composed of pure carbon in a crystallographic lattice form with a hexagonal shape (Graphite). Within the hexagonal plane, atoms are bonded together with strong covalent bond and in between the hexagonal plane, they are

bonded weakly. Hence, carbon fibers show greater degree of anisotropy in their mechanical and thermal properties. Carbon fibers have excellent stiffness (200 to 250 GPa) and strength properties as compared to glass. However, they are very expensive as compared to glass fibers. Nowadays, both fibers are commonly used for the fabrication of moderate size blades (5 to 20 m length).

Wind industries commonly uses thermoset polymers as matrix material due to their matching densities with fiber material ($1.1 - 1.3 \text{ g/cm}^3$) and higher strength, thermal resistance properties as compared to thermoplastics. The properties of the composite depend on the combined properties of fibers and matrix. Most importantly, the mixing ratio and the established interface between the fiber and matrix materials. On a general note the effective stiffness (E_c) of a composite with no porosity ($V_f + V_m = 1$) can be calculated as,

$$E_c = V_f E_f + V_m E_m \quad (2.2)$$

V_f , E_f and, V_m , E_m represents the volume fraction and effective stiffness's of fiber and matrix respectively.

The common techniques followed by blade industries are resin infusion technology and prepreg technology. In resin infusion technique, dry fibers were placed in the blade mold and sealed tightly. The liquid resin was injected into the package and allowed to flow through the whole fiber package. However, it is important to make sure that the resin wets all the fibers completely. In prepreg technology, a semi raw product of fiber fabrics was pre-impregnated with resin. At room temperature, the prepreg material would be in a tacky solid and this tacky prepreps were stacked together to form the required structure. For curing, these stacked layers were consolidated under the vacuum bag and a curing step cycle was followed at required pressure and temperature range as per the manufacturers requirement.

Most of the turbine blades are prepared as two segments in separate molds and bonded together with the help of adhesives like epoxy and polyurethane. The adhesive must have the capability to hold a large area of airfoil shell and longitudinal supporting beam under extreme cyclic loads. The shell and the shear

webs are made up of sandwich structures using low density core materials such as balsa wood and polymer foams.

2.4 Forces acting on wind turbine blades

The total force produced on an airfoil is the summation of air pressure distributed on the outer surface. The produced aerodynamic force can be divided into two components with one normal to the wind direction called ‘lift force’, and the other, parallel to the wind direction called ‘drag force’.

Figure 2.3: Lift and drag in an airfoil.

Wind turbine blade works on this lift and drag principle. The convex side of airfoil generates a low air pressure while the high air pressure on the concave side pushes and create the lift force perpendicular to the direction of wind flow (see Figure 2.3). The lift force increases with greater angle of attack of the wind. But for a very large angle of attack, the blade stalls and leads to decrease in lift force and a dramatic increase in drag force. Hence the blade always placed at an optimum angle of attack to produce maximum lift force. The operating angle of attacks always comes slightly less than the maximum lift angle where the blade reaches the maximum lift/drag ratio.

Figure 2.4 shows the typical power curve of a small wind turbine. As the wind speed crosses cut-in speed (around 3 to 4 m/s), the turbine starts generating power. Along with the increasing wind speed the power output also increases and reaches the limiting power capacity called rated power output. The corresponding wind speed is called rated output wind speed (around 12 to 17 m/s). As the speed increases above rated output wind speed, there is a risk of damaging the rotor. At this stage, normally, a braking system will bring the rotor to a standstill. This is

called cut-out speed (around 25 m/s). The power coefficient (C_p) of a wind turbine is the ratio of actual power divided by the available power.

Figure 2.4: Plot of power output and power coefficient versus wind speed (m/s). [Credit: Enercon E141 – Datasheet].

Figure 2.5: A full scale testing of a blade subjected to static load in the flap-wise direction. [Credit: LM Glassfiber A/S]

The rotor blades are exposed to wind loads and gravity loads. The wind load acts in the flap-wise direction and the gravity load acts in the edgewise direction of the blade. A flap-wise bending load acts due to the wind and a varying edgewise bending acts in tension/compression at both leading and trailing edge. During operation, centrifugal force acts on the blade due to the rotation. However, centrifugal force is relatively low as compared to the flap-wise loads and neglected during the blade design calculation. The blades are designed as per IEC 61400-1 [7] by considering both static and cyclic loads subjected to a wide range of environmental conditions such as temperature, humidity, wind gust.

Full-scale testing of blades is mandatory to check whether the blade is satisfying certain categories of limit states as per Det Norske Veritas (DNV) [8]. They are ultimate limit state (ULS), fatigue limit state (FLS) and serviceability limit state (SLS). A limit state is defined as the state beyond which the structure no longer satisfies the design requirement. Also, full scale blade helps to validate certain design assumptions used in the load calculations. Figure 2.5 shows the full-scale blade testing in a flap-wise direction for the ultimate limit state (ULS).

2.5 Manufacturing defects

Though the composites have good engineering qualities, they still lack in giving an improved life expectancy for the blades. The main problem faced by the blade industry is due to the defects induced in the blade during the manufacturing process. Postmortem reports on failed blades indicate that 64% of blade failures are due to manufacturing defects (wrinkles, voids and porosity)(see Figure 2.6) [9]. Common manufacturing defects that are found in the blades are waviness and porosity/voids [10]. Waviness can occur due to misalignment of the fiber (makes waviness in the plane of laminate) and misalignment of the lamina (makes waviness out of plane of the laminate). Porosity/voids are generally a result of the presence of air bubbles and/or foreign impurities during the time of curing of the blades.

Research on waviness in laminates revealed that it causes significant reduction in mechanical properties [11] and the impact is large in unidirectional

laminates, [10, 12-15]. It was also found that the blade reinforcing components reduces its strength (such as spar-caps). From the design perspective, the compressive strength of a composite is the key property for structural components [16]. Though unidirectional laminates have good tensile strength and stiffness along the fiber direction, they are weak in compression. Waviness or wrinkles may arise in any part of the structure due to excessive reinforcement during layup on curved section of the mold structure or due to the ply drop situation. The current focus of research is on waviness induced unidirectional ply present in the spar-cap area. During turbine operation, defects can deteriorate the material properties dramatically and initiate damage in the spar-cap. Once the reinforcement fails, the whole blade structure will be in a critical condition and it may lead to catastrophic failure of the whole turbine unit due to dynamic mass imbalance.

Figure 2.6: In-plane waviness on the surface, out of plane waviness and porosity/voids [17].

Unidirectional fibers over spar-caps should withstand the predominant flap-wise bending due to wind load. Full scale failure analysis of blades is expensive, but at the coupon level many studies have shown that waviness deteriorates the compressive strength of unidirectional composite laminate [13, 15, 17-19]. The

compression strength decreases steadily with increase in both wave severity and the number of 0° ply's containing waviness [10]. Adams et al [11] found that the percentage reduction in strength is approximately equal to the percentage of 0° ply containing waviness and a reduction of 35% in strength was observed with 0° plies containing 33% waviness.

2.5.1 Fiber waviness

To define the extent of fiber waviness, Adams [12] characterized the wave geometry (see Figure 2.7) with a set of parameters such as wave amplitude (A) and wavelength (L). He defined wave severity (W_s) as the ratio of wave amplitude to the wave length.

Figure 2.7: Shape of an in-plane waviness with wave length ' L ' and amplitude ' A '.

2.6 Failure modes in wind turbine blades

Failure modes of a blade is defined as the stages of its operation where the blade loses its load bearing capabilities. This could be a damage mode that further lead to the failure or repair. Failure of a blade involves crack initiation, progression of crack and final failure. Table 2.1 and Figure 2.8 shows the various failure modes that are common in a turbine blade tested to failure [20]. In the following section and sub-sections, a general overview of these failure modes on the composite laminates are discussed.

Figure 2.8: Sketches of different failure modes in a wind turbine blade [20].

Table 2.1: Various failure modes

Basic damage mode	Types of damage
Adhesive joint failure	Cracks in adhesive layer, laminate/adhesive interface cracking.
Sandwich failure	Interface cracking
Laminate failure	Tensile failure (fiber or matrix failure), Compressive failure (fiber failure), shear failure, fiber/matrix debonding, fiber splitting, delamination failure.
Gelcoat delamination and crack	Interface cracking, thin film cracking.

2.7 Failure mechanisms in laminated composites

In the wind turbine blades, the major forces acting over the laminates under extreme loading conditions are bending, tension, compression and shear forces. In this section, failure mechanisms found in composite laminates under these test conditions were discussed. The prime idea of this research is to understand the effect of manufacturing defect on the failure modes in the wind turbine blade.

2.7.1 Fiber failure

As mentioned in Table 2.1, fiber failure mechanism occurs under tensile and compressive loading conditions. Figure 2.9 shows the fiber breakage in unidirectional glass fiber reinforced composites subjected to tensile load [21].

Figure 2.9: Broken specimen and fibers from a tensile experiment [21].

On the other hand, when unidirectional FRP composites subjected to compressive load, a sequence of failure mode in an order of fiber micro-buckling followed by kink band and crushing of the whole specimen.

Figure 2.10: Fiber breakage after kink band and crushing.

Figure 2.10 shows that the fiber breakage occurs after the kink band and crushing of the specimen in a compression experiment of unidirectional FRP composite. When a fiber breaks, the net load distribution over the remaining unbroken fibers increases, thus the average stress over the cross section. There by increases the probability of breakage of more fibers and resulted into crushing failure mode.

2.7.2 Matrix failure

The matrix material binds the fibers each other and helps to distribute the loads among the fibers. Matrix has lower compressive and tensile strength as compared to fiber material, hence chances of matrix failure is higher than the fiber failure. Matrix failure generally occurs during transverse tension and shear loads. The Figure 2.11 shows the crack propagation in a matrix material during transverse tension failure [22]. Here, the fiber acts as a point of local stress concentration. On a macroscopic approach, under transverse tension failure the failure mode transforms from transverse tension to a combination of transverse tension and shear (also called peel).

Figure 2.11: Crack propagation in the matrix [22]

Figure 2.12: a) Cusps formation during shear failure, b) Cusps in peel fracture, c) Peel fractured surface[22].

One important phenomenon which forms during shear failure apart from the transverse tension failure is cusps (Figure 2.12(a)). Shear failure usually occurs in lamina interfaces with different fiber orientation. Shear failure follows the path of the fiber, which is close to the shear stress direction [23]. Irrespective of the fiber direction, the cusps always tend to align perpendicular to the shear stress direction. The peel fracture always occurs normal to the fiber direction as shown in Figure 2.12(c).

2.7.3 Fiber/matrix debonding

This failure mode usually occurs when the interfacial strength is weak and end up with a fiber failure. Every failure mode initiates with a micro-crack and during transverse tensile failure the interfacial shear stress causes the crack to propagate and end up with fiber/matrix debonding [24]. Figure 2.13 displays the SEM micrographs of fiber/matrix debonding in a glass fiber/vinyl ester composite subjected to shear test. The factors that affects fiber/matrix debonding are moisture, temperature, fiber surface and matrix wettability.

Figure 2.13: Fractured surface of glass fiber/vinyl ester composites due to extensive interfacial debonding[24].

2.7.4 Delamination failure

Delamination is one of the root causes in many major failures observed in wind turbine blades. It is the process of separating the adjacent plies due to significant loss in mechanical toughness. The lateral strength of the fibers is relatively low compared to longitudinal strength and the interface ply bonding strength more relies on relatively weak matrix properties. Delamination failure initiates at the point at which the interlaminar stress exceeds the through-thickness strength.

Laminate layup configuration and type of curing service may cause delamination. The moisture absorption and coefficient of thermal expansion of fibers layers and matrix are different, hence the shrinkage rate and moisture content in each ply varies during curing procedure. This may lead to the residual stresses and favors delamination in the laminate [25]. The presence of resin rich

region affects the curing time in adjacent plies and decrease the interface properties, which may cause delamination [26].

Delamination can be divided into surface delamination and internal delamination. Internal delamination occurs at the ply interface due to micro cracks. Generally, occurs in compressive loading conditions and further reduces the load carrying capacity of the laminate. Figure 2.14 shows different surface delamination possibilities in composite components. Under static or cyclic loading, the surface delamination reduces the strength and end up with a catastrophic failure of the components.

Figure 2.14: Different types of surface delamination[26]

There are totally three modes of delamination based on fracture toughness of the resin state, they are opening mode (mode I), shear mode (mode II) and tearing mode (mode III) as shown in Figure 2.15. Fracture toughness is the amount of energy required to create a fracture surface. The crack propagates and interface debonding will occur when strain energy reaches any of the maximum mode energy value [27].

Figure 2.15: Opening mode, shear mode and tear mode

2.8 Failure theories

The ultimate goal of failure criterion based prediction is to forecast the results of simple and complex real world structural problems. Based on the lamina failure, the proposed failure criteria could be divided into two groups. One group with failure criteria which is not associated with failure modes (Generalized failure criterion) and other group associated with failure modes (physically-based failure criterion).

2.8.1 Generalized failure criterion

In generalized failure criteria, the failure is predicted based on the ply stress and strength parameters [28].

$$f(\sigma_1, \sigma_2, \sigma_3, \tau_{23}, \tau_{13}, \tau_{12}, F_1, F_2, \dots) \begin{cases} < 1 \text{ no failure} \\ = 1 \text{ failure limit} \\ > 1 \text{ failure} \end{cases}$$

where as $\sigma_1, \dots, \tau_{12}$ are the ply stresses and $F_1, F_2, \dots$ are the strength parameters related to principal directions. This includes all the polynomial and tensorial criteria such as Tsai-Wu criteria [29], Tsai-Hill criteria [30], Hoffman criteria [31], etc. Each failure criterion provides the load at which the first ply-failure occurs during a simple tensile or compression experiment. Also, it is the point at which the load - displacement curve changes its path from linear direction. After the first ply failure, the remaining ply will carry the applied load, hence as the applied load increases, there will be a sequence of ply failure until the complete laminate failure. The ultimate failure load might be higher than the first ply failure load. The generalized failure criteria will not give any details regarding the failure mechanism and mode of failure. The below inequality represents the general form of the quadratic failure criterion up to second order.

$$\begin{aligned}
& F_1\sigma_1 + F_2\sigma_2 + F_3\sigma_3 + F_4\sigma_{23} + F_5\tau_{13} + F_5\tau_{13} + F_6\tau_{12} \\
& + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{33}\sigma_3^2 + F_{44}\tau_{23}^2 + F_{55}\tau_{13}^2 \\
& + F_{66}\tau_{12}^2 \\
& + 2(F_{12}\sigma_1\sigma_2 + F_{13}\sigma_1\sigma_3 + F_{14}\sigma_1\tau_{23} \\
& + F_{15}\sigma_1\tau_{13} + F_{16}\sigma_1\tau_{12} + F_{23}\sigma_2\sigma_3 \\
& + F_{24}\sigma_2\tau_{23} + F_{25}\sigma_2\tau_{13} + F_{26}\sigma_2\tau_{12} \\
& + F_{34}\sigma_3\tau_{23} + F_{35}\sigma_3\tau_{13} + F_{36}\sigma_3\tau_{12} \\
& + F_{45}\tau_{23}\tau_{13} + F_{46}\tau_{23}\tau_{12} + F_{56}\tau_{13}\tau_{12}) < 1
\end{aligned} \tag{2.3}$$

σ_{ij} and τ_{ij} are the derived coordinate stress values from the applied load and F_{ij} 's are the material dependent strength parameters. No failure will occur when the inequality is less than unity. In Figure 2.16, the middle graph shows the failure surface, and at this region the resultant stresses will be equal to the failure stresses ($\sigma_{ij} = \sigma_{ij}^f$).

Figure 2.16: Condition for failure for the applied stresses σ_1 and σ_2 [32].

Orthotropic material has three mutually perpendicular planes of symmetry. The final inequality relation for failure can be re-written as,

$$\begin{aligned}
& F_1\sigma_1 + F_2\sigma_2 + F_3\sigma_3 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{33}\sigma_3^2 + F_{44}\tau_{23}^2 \\
& + F_{55}\tau_{13}^2 + F_{66}\tau_{12}^2 \\
& + 2(F_{12}\sigma_1\sigma_2 + F_{13}\sigma_1\sigma_3 + F_{23}\sigma_2\sigma_3) < 1
\end{aligned} \tag{2.4}$$

Among the strength parameters, $F_1, F_2, F_3, F_{11}, F_{22}, F_{33}, F_{44}, F_{55}, F_{66}$ are called non-interaction strength parameters and the values are obtained from

uniaxial tensile, compressive and shear experiments. Similarly, F_{12} , F_{13} and F_{23} are called interaction strength parameters and their values are determined from off-axis uniaxial and biaxial experiments.

For transversely isotropic material, because of the transverse symmetry about one unique axis some of the stress parameters becomes identical. Final inequality can be written as,

$$\begin{aligned} F_1\sigma_1 + F_2(\sigma_2 + \sigma_3) + F_{11}\sigma_1^2 + F_{22}(\sigma_2^2 + \sigma_3^2) + 2(F_{22} \\ - F_{23})\tau_{23}^2 + F_{66}(\tau_{12}^2 + \tau_{13}^2) \\ + 2F_{12}(\sigma_1\sigma_2 + \sigma_1\sigma_3) + 2F_{23}\sigma_2\sigma_3 < 1 \end{aligned} \quad (2.5)$$

Similarly, for isotropic the failure criterion becomes,

$$\begin{aligned} F_1(\sigma_1 + \sigma_2 + \sigma_3) + F_{11}(\sigma_1^2 + \sigma_2^2 + \sigma_3^2) \\ + 2(F_{11} - F_{12})(\tau_{23}^2 + \tau_{12}^2 + \tau_{13}^2) \\ + 2F_{12}(\sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3) < 1 \end{aligned} \quad (2.6)$$

2.8.2 Physically-based failure criterion

According to physically-based failure criterion, based on the constituent material properties various failure modes will be present during failure progression such as fiber failure, transverse matrix cracking, shear matrix cracking etc. Based on the failure criteria associated with, the physically-based failure criterion can be sub-divided into non-interactive and interactive type criterion.

In a non-interactive criterion, the stress - strain interaction in the lamina not taken into consideration. E.g.: Maximum stress criterion and Maximum strain criterion. Here the failure modes are predicted based on comparing the stresses and strain values with ultimate limits. As per maximum stress criterion, the composite is failed when the stress components in the longitudinal and transverse direction reaches the allowable stress limit. The failure inequality conditions are,

$$\sigma_1 \geq \sigma_1^f, \quad \sigma_2 \geq \sigma_2^f, \tau_{12} \geq \tau_{12}^f \quad (2.7)$$

Similarly, for maximum strain criterion the failure will occur when the strain exceeds the ultimate strain value.

$$\varepsilon_1 \geq \varepsilon_1^f, \varepsilon_2 \geq \varepsilon_2^f, \gamma_{12} \geq \gamma_{12}^f \quad (2.8)$$

The above maximum stress and maximum strain conditions are meant for two-dimensional state condition. Though these non-interactive theories are poor in predicting the failure, their easiness in implementation and understanding makes them popular.

In interactive mode of failure, the stress/strain interaction will be present and failure is predicted based on a mechanism (physically based) such as fiber-dominated failures and matrix-dominated failures. E.g.: Hashin's [33], Christensen [34], Puck's [35] and LaRC02 [36].

2.8.2.1 Hashin's failure criterion

In 1973, for the first time Hashin [33, 37] established two separate failure criteria for matrix and fiber based on tensile experiment. The criteria assume a quadratic interaction between the tractions related with failure plane. In 1980, a distinction has been made by him on the matrix and fiber failure criteria in tension and compression related failure. The recent 3D version [33] of the criteria derived using the quadratic interaction between stress invariant was purely based on the logical reasoning. Though the criteria was developed for unidirectional laminates, it also been applied for the progressive failure analysis of laminates by constraining the inter lamina interaction in situ with the unidirectional strength [38]. The following equation represents the fiber-matrix failure criteria under tension and compression.

Matrix failure criteria,

In tension $\sigma_{22} \geq 0$

$$FI_M = \left(\frac{\sigma_{22}}{Y^T} \right)^2 + \left(\frac{\tau_{12}}{S^L} \right)^2 \quad (2.9)$$

In compression, $\sigma_{22} < 0$

$$1973: FI_M = \left(\frac{\sigma_{22}}{Y^C}\right)^2 + \left(\frac{\tau_{12}}{S^L}\right)^2 \quad (2.10)$$

$$1980: FI_M = \left(\frac{\sigma_{22}}{2S^T}\right)^2 + \left[\left(\frac{Y^C}{2S^T}\right)^2 - 1\right] \frac{\sigma_{22}}{Y^C} + \left(\frac{\tau_{12}}{S^L}\right)^2 \quad (2.11)$$

Fiber failure criteria,

In tension, $\sigma_{11} \geq 0$

$$FI_F = \left(\frac{\sigma_{11}}{X^T}\right)^2 + \left(\frac{\tau_{12}}{S^L}\right)^2 \quad (2.12)$$

In compression, $\sigma_{11} < 0$

$$FI_F = \frac{\sigma_{11}}{X^C} \quad (2.13)$$

Apparently, Hashin's criteria failed to predict the increase in shear strength during transverse compression failure. Also, Hashin's criteria does not consider the effect of in-plane shear during fiber compression, which has significant effect on the effective compressive strength of the lamina. Several researchers further modified the Hashin's criteria for an improved failure prediction.

2.8.2.2 Puck's failure criterion

In 1995, Puck [39] introduced a failure criteria by incorporating Mohr-Coulomb criterion [40] into Hashin's criterion and to be known as the first mechanism-based failure theory. The failure was proposed based on the matrix compression failure. For unidirectional composites, Puck's failure criterion identifies the fiber failure and matrix cracking failure. In tension, the major failure mode is fiber failure and in compression the failure mode is fiber kinking.

Fiber failure criteria,

In tension, $\sigma_{11} \geq 0$

$$\frac{1}{\varepsilon_{1T}} \left(\varepsilon_1 + \frac{\nu_{f12}}{E_{f1}} m_{\sigma f} \sigma_2 \right) = 1 \quad (2.14)$$

In compression, $\sigma_{11} < 0$

$$\frac{1}{\varepsilon_{1c}} \left| \left(\varepsilon_1 + \frac{\nu_{f12}}{E_{f1}} m_{\sigma f} \sigma_2 \right) \right| = 1 - (10\gamma_{21})^2 \quad (2.15)$$

The Puck's criterion on the fiber material, for glass fiber the value of $m_{\sigma f} \approx 1.3$ and for carbon fiber $m_{\sigma f} \approx 1.1$.

The matrix cracking or fiber/matrix debonding are distinguished based on the fracture plane angle. The first mode of matrix cracking is with 0° fracture angle, this criterion invokes with a transverse stress greater than zero ($\sigma_{22} > 0$) and the crack propagate perpendicular to the transverse load. The second mode corresponds to transverse compressive stress ($\sigma_{22} < 0$) coupled with a longitudinal shear stress. Third mode of matrix cracking resulted with an inclined fracture plane relative to the reinforcing fiber. This mode usually happens for a significantly large longitudinal shear stress.

2.8.2.3 LaRC02 failure criterion

LaRC02 failure criterion [41] is an improvement to Hashin's model combined with the fracture plane concept of Puck [35] failure criterion. This criterion identifies the fiber failure and matrix cracking in unidirectional composites (initiation and instantaneous damage progression) [35, 42] based on the below mentioned constitutive relations. The matrix cracking failure under transverse compression, is calculated based on the same Mohr-Coulomb effective stresses. Under longitudinal compression, the fiber kinking failure is predicted by measuring the fiber misalignment angle based on the load applied and applying the matrix failure criterion at the coordinate plane of fiber misalignment.

Based on LaRC02 failure criterion, under uniaxial compression loading, (1) fiber failure is further divided into (1.a) fiber compressive failure with matrix compression, and (1.b) fiber compressive failure with matrix tension. (2) Matrix cracking is again divided into (2.a) matrix cracking in tension, and (2.b) matrix cracking in compression. The fiber compression failure scenario was explained due to the collapse of fibers subjected to initial misalignment, leading to shear kinking and further extending to the supporting matrix [43, 44].

- (1) As mentioned earlier, under fiber compression $\sigma_{11} < 0$, two stress states (matrix under compression and matrix under tension) were considered to evaluate the fiber failure [1].

- (1.a) For matrix compression ($\sigma_{22}^m < 0$)

$$\text{Failure index } FI_F = \left\langle \frac{|\tau_{12}^m| + \eta^L \sigma_{22}^m}{S^L} \right\rangle \quad (2.16)$$

- (1.b) For matrix tension ($\sigma_{22}^m \geq 0$)

$$\text{Failure index } FI_F = \left(\frac{\sigma_{22}^m}{Y^T} \right)^2 + \left(\frac{\tau_{12}^m}{S^L} \right)^2 \quad (2.17)$$

- (2) For the matrix compression failure criterion,

- (2.a) $\sigma_{11} \geq Y^C$

$$\text{Failure index } FI_M = \left(\frac{\tau_{eff}^T}{S^T} \right)^2 + \left(\frac{\tau_{eff}^L}{S^L} \right)^2 \quad (2.18)$$

- (2.b) $\sigma_{11} \leq Y^C$ at this stage the material is in a moderate biaxial compressive state and the condition is,

$$\text{Failure index } FI_M = \left(\frac{\tau_{eff}^{mT}}{S^T} \right)^2 + \left(\frac{\tau_{eff}^{mL}}{S^L} \right)^2 \quad (2.19)$$

2.9 Compressive failure analysis of FRP composites

Compressive strength of composite laminates is one of the major design drivers in wind turbine industry. Compressive failure in these materials is complex, as it involves multiple modes of failure like fiber kinking, splitting, buckling and delamination [45-48]. Also, the failure event could be sudden and catastrophic. In 1965, Rosen [45] attributed the compressive failure to elastic instabilities resulting in a fiber-buckling mechanism. When the fiber buckles in the out of phase it is called extension mode and if it buckles in-phase, it is called shear mode. According to Rosen model, the compressive strength of composite in the longitudinal direction is

$$X_c = \frac{G_m}{1 - V_f} \quad (2.20)$$

G_m is the matrix shear modulus and V_f is the fiber volume fraction. Compared to experiment results both the shear mode (Eq: 2.20) and extension mode overestimate the actual compressive strength by a factor of four or five.

Greszczuk [49] introduced a 3D model corresponding to Rosen model and was in good agreement with metal/matrix composites and failed to perform among graphite and boron/matrix composites. Later a lot of researchers modified the Rosen model by introducing certain factors into account such as Steif model [50], Xu and Reifsnider model [51] but all these models did not gave much refinement to the final result. A model with a single fiber layer with infinite matrix, by Waas [52] concluded that, if the interface is greater than 1/10th of the fiber diameter, it causes reduction in compressive strength of the unidirectional composites. Through elasticity approach Zhang et al [53] concluded that shear mode failure is dominant in all range of volume fraction except 0.05 and this contradicts Rosen's model. The main disadvantage of micro-buckling model is that it does not consider the effect of fiber misalignment and over prediction of the result.

Fiber kinking is a highly-localized buckling caused due to inelastic deformation of matrix, which happened because of fiber misalignment from their reinforced direction. In this area the pioneer model is considered as Argon model [54]. He considered both shear stress and fiber misalignment angle to calculate the kinking stress of the composite laminate. The critical compressive stress decreases with increasing fiber misalignment (rotation) angle, and the stress is

$$X_c = \frac{\tau_y}{\bar{\phi}} \quad (2.21)$$

where τ_y is the yield stress in longitudinal shear and $\bar{\phi}$ is the initial fiber misalignment. Later on, Argon model is improved by Budiansky [55], Fleck and Budiansky [46, 56], Hahn and Williams [57] with the addition of fiber

misalignment. Budiansky Model [55] is especially for elastic-ideally plastic composites.

$$X_c = \frac{\tau_y}{\gamma_y + \bar{\phi}} = \frac{G}{1 + \bar{\phi}/\gamma_y} \quad (2.22)$$

G is the shear modulus of the composite and $\bar{\phi}$ is the initial angular misalignment of the fiber. At $\bar{\phi} = 0$, it gives Rosen's bifurcation stress and at larger values of $\bar{\phi}$ the results are asymptotes to the Argon Model results Eqn: 2.21. Still this model predicts a better result for the compressive strength and considered as the basic model for the compression failure of unidirectional composites.

However, subsequent studies accepted that compressive failure of unidirectional composite systems are due to plastic micro-buckling. These investigations concluded that compressive failure of fiber reinforced composites is predominantly a result of plastic micro-buckling of the fibers in an idealized inelastic matrix medium [46]. Along the same lines, Kyriakides et al. [58] observed regularly spaced in-plane kink bands with a width of ~1-1.5 mm during compression testing of the composites. In addition, Vogler and Kyriakides [59, 60] showed that kink bands formation is a post-buckling event and initiate from a local imperfection in the sample. In a micromechanical study, Prabhakar et al. [61] observed an interaction between the kink band and splitting failure modes and concluded that mode II cohesive shear strength has a greater influence in failure mode interaction.

The point of failure initiation depends upon the type of specimens used for the experiment. However, the failure initiation and progressions in the unnotched specimens are highly unstable and spontaneous. The primary interest of all the scientists was to determine failure mechanisms at the peak load and it was globally acclaimed that kink band formation is the limiting mechanism which leads to the failure of unidirectional composite at the peak load. Since the kink band formation is a micro-level mechanism, it is very difficult to detect this

failure during the time of testing, however, some of the researchers succeeded in locating the failure mechanism in notched specimens using advanced technologies.

Hapke et.al [62] did an in-situ SEM analysis on UD carbon/epoxy material with a notched specimen to localize the initiation. In the sequence of event they observed a plastic shearing in the matrix. Later, the straight fibers are locally deflected and form a kink shape followed by a sudden and catastrophic failure. In some models, fracture of fiber is not necessary for the initiation and development of kink bands. There is no longitudinal splitting observed in the sequence of events. In the later discussion, it was pointed out that the splitting mechanism has greater importance in fiber diameter and fiber volume fraction.

2.9.1 Effect of matrix properties in the compressive failure mechanism

From the kinking mechanism, it was clear that matrix undergoes shear deformation. The failure is effective only when the matrix shows an elastic - plastic behavior during deformation. If the matrix is brittle and the reinforcing fiber has larger diameter, the chances of fiber-matrix interface failures are high and this leads to splitting mechanism. This splitting mechanism is found common in glass fiber composites due to their larger diameter compared to carbon fiber and it was experimentally proved by Lee and Waas [47], Oguni and Ravichandran [63].

Pimenta et.al [64] did experiment and a micro-mechanical model analysis to study the propagation of kinking failure in the composite. The material used for the study was carbon/epoxy prepreg. An in-situ microscopy method is used in experimental study and in the model the matrix is considered as elastic-plastic in nature. In the sequence of kinking failure mechanism, composite undergoes a global elastic deformation followed by an initiation of matrix yielding until the peak load is reached. Finally, during the softening time the matrix yield and composite deformation localized in to a narrow band and the fiber starts failing in that narrow band. Figure 2.17 shows the micro graphs of kink bands of the specimen from an unloaded condition using optical microscope.

Figure 2.17: Kink–band with matrix yielding and no fiber failure (unloaded) [64]

2.9.2 Effect of fiber diameter on compressive failure mechanism

The earlier model proposed by Argon, Budiansky and Fleck does not mention any importance of fiber properties in the compressive strength prediction. But Lee and Waas [48], Yerramalli and Waas [65] considered fiber properties to determine the compressive strength. When the mechanism become splitting, especially in the case of glass fiber polymer matrix composite the expression for splitting compressive stress σ_c^{sp} is

$$\sigma_c^{sp} = \sqrt{\frac{8V_f^2\gamma_f}{r_o(1/\delta - \beta)}} \quad (2.23)$$

V_f - fiber volume fraction, γ_f – Interfacial fracture energy, r_o - Fiber radius, δ and β are constants which depends on the elastic properties of the fiber and matrix.

$$\begin{aligned} \delta &= E_f + E_m \left(\frac{1}{V_f} - 1 \right) \\ \beta &= \left[E_f + (V_f^{-1} - 1) \left\{ E_m + 4\alpha(v_f - v_m)^2 \right\} \right]^{-1} \\ \alpha &= \left[\frac{2(1 + v_f)(1 - 2v_f)}{E_f} (V_f^{-1} - 1) \right. \\ &\quad \left. + \frac{2(1 + v_m)(1 - 2v_m + V_f^{-1})}{E_m} \right]^{-1} \end{aligned} \quad (2.24)$$

An experimental study was performed by Yerramalli [66] for two different diameter (13.5 μm and 24 μm) of glass fiber polymer composite for a given fiber volume fraction. Instead of getting an increase in compressive strength with

decrease in fiber diameter, the values were comparable. The failure mechanism shifted from splitting to kinking with increase in fiber volume fraction. It was observed that small diameter fiber reinforced polymer composites failed due to fiber kinking in all fiber volume fractions and splitting failure was observed more in larger diameter fiber composites.

2.10 Effect of fiber waviness on compressive strength

Several researchers have studied various kinds of waviness which developed during the manufacturing of composites and their effect on compressive strength. Adams et. al [12] did an out of plane waviness study on several cross-ply laminates and found that reduction in compressive strength is more significant in laminate with unidirectional ply having waviness as compared to other cross-ply laminates. A reduction in strength of 36% was observed with 20% of 0° laminates carrying out of plane waviness.

Figure 2.18: Post failure analysis of laminate with moderate waviness and severe waviness [12].

Figure 2.18 shows that with increase in wave severity broom type failure (on the right) was observed at the gage section. Avery et. al [15] studied the effect of fiber misorientation due to ply drop, ply joints and mold geometry by using various fiber fabric and matrix material. He has selected straight fabric, prepreg fabric, stitched with large tows and woven fabrics for the study. An average of 0.6 to 0.8% reduction in failure strain was observed with inclusion of fiber waviness on the large tow carbon fiber laminate. A failure strain of 0.3 to 0.5% was reduced due to ply drop situation in a prepreg material.

2.11 Flexural failure of unidirectional composite laminate

Wind turbine blades were subjected to various amplitude of wind loads in both flap-wise and edge-wise direction during its operational life. In this section,

various research conducted on the flexural failure of composites were discussed. Generally observed failure modes are fiber failure at both sides of the specimen, interlaminar shear failure followed by delamination and extensive splitting of fibers along the fiber direction. The outermost layer of the specimen was failed due to tension and the innermost was due to compression. The failure modes are generally the same kinds that discussed earlier in this section.

2.12 Fatigue failure behavior of unidirectional composite laminate

Wind turbine blade subjected to various kinds cyclic loads during its service life such as aerodynamic load, gravitational load and the centrifugal forces. As the wind is a chaotic form of energy, most of the turbine failures were reported with fatigue failure of blades [67]. Therefore, it is important to understand the fatigue behavior of the composites used in the blade fabrication for the better understanding of the service life of a blade.

In general fatigue strength of a material is always below the ultimate strength value and for composites subjected fatigue loads associated with a degradation in both stiffness and strength. Stiffness can be related with fatigue strength of the material and the degradation in the stiffness is depends on the load ratio, layup sequence and the type of cyclic load acting [68]. In a static and fatigue experiment conducted by Philippidis et.al [69] on a multidirectional GFRP specimen found that for a 95% reliability level the stiffness degradation was found close to 5 to 20%. When a composite specimen fails under an applied stress ratio in a force controlled fatigue test, the point of failure is considered as the load bearing capacity of that material for the applied stress ratio [70]. For a unidirectional composite laminate under displacement – controlled fatigue test by Shih [71], a 10% load drop was considered as the failure criteria. Similarly, for a force – controlled tensile fatigue test of $[0/90^\circ]_s$ epoxy based laminate by Jones, a 15% degradation of stiffness was considered as the failure criteria [72]. For the past 25 years, several researchers had delivered different failure criterion based on the stiffness degradation. While looking on to the damage mechanism and failure modes presented in a fatigue failure Talreja [73], concluded that fiber failure,

matrix cracking, delamination and the fiber/matrix debonding are the major failures presented.

The failure modes and damage mechanisms varied based on the stress level. At lower stress level matrix cracking is the major failure mode and in medium loads delamination were observed. At higher load ratios fiber failure was the dominant failure mode. Wind turbines generally operates at lower load, hence matrix cracking was the common failure observed in many of the blades under repair [74, 75]. Ogin [76] found a relationship between the transverse matrix crack and the stiffness degradation for a cross-ply made up of GFRP. According to Kashtalyan [77], matrix cracking is not the only reason for the final failure of a laminate. But matrix cracking presented at the ply interface may lead to delamination onset due to local stress concentration.

Daniel [78] performed a compression fatigue analysis on thermoplastic cross-ply laminates with fiber waviness and established an S – N curve. Brooming failure and delamination were the major failure modes. As compared with a defect free sample (with a one million run out cycle), a moderate wave induced sample showed 45% reduction in static compressive strength and a 75% reduction in fatigue strength. Horrmann [79] has prepared an out of plane waviness induced sample by inserting polymer rods in between the layer and conducted both static and fatigue analysis. The study found that under C-C and T-C loading conditions, 50% reduction in fatigue life was observed as compared to no-defect sample under the same load conditions.

The fatigue failure mechanism of FRP composites are found to be complex and the failure mechanisms have greater dependence on the load ratio and the layup sequence (in a way fiber orientation). Many researchers found that matrix cracking as the major failure mode and some others found fiber failure as the major failure mode. So, for the current research it is vital to observe the fiber waviness effect on the crack propagation and damage accumulation.

2.13 Summary

In this chapter, basics of wind turbine blades, typical blade design, types of load acting on the blades and different manufacturing defects in the wind turbine blades were explained. Special attention was given to the fiber waviness defect and the previous research on it. The failure mechanisms and different failure modes of composite materials under extreme compression and bending load conditions were explained. Previous research on failure analysis of composites based on different failure theories was explained. Various research aspects on coupon level bending and compression fatigue failure analysis of unidirectional composite laminates were discussed to understand the different failure modes presented.

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Chapter 3

Experimental methodology

In this chapter, the details of the materials used, laboratory preparation of in-plane fiber waviness induced specimens and various experimental procedures followed for the entire thesis study were detailed. Along with this, procedures and principles behind the characterization techniques employed for the fabrication of GFRP composites, mechanical testing and damage characterization were presented.

3.1 Materials

All the materials used for this study are of industrial grade specifically used for the fabrication of wind turbine blade. This is to ensure the applicability of the results obtained in various mechanical testing and for a fair comparison with existing data. Since the study focuses on the manufacturing defect in unidirectional (UD) laminate, the fabric used for the entire study is of the same kind. UT-800 glass fiber fabric from Wee Tee Tong and epoxy resin from Hexion are the constituent fiber and matrix, respectively. The physical properties of the fiber fabric are listed in Table 3.1.

Table 3.1: Material properties

UT - 800	
Material	E - glass
Layer weight (g/m ²)	805 ± 3 %
Fiber diameter	18 – 20 µm
Fiber strand width	≈ 4 mm
Fabric thickness	≈ 0.62 mm

The epoxy consists of two parts, namely resin and hardener. The resin used is EPIKOTE MGS RIMR-135 along with extra slow hardener EPIKURE RIMH-137 as curing agent. Based on the Hexion specified mix ratio of 100:30 by weight, were mixed together just before the resin infusion.

3.2 Vacuum assisted resin infusion molding (VARIM)

The general principle of infusion technology is to ‘suck’ resin into the stacked fiber fabrics with the help of vacuum pressure. The vacuum pump generates a pressure gradient at the outlet and forces the resin from inlet to outlet through the fiber stack. As shown in Figure 3.1, initially all the fiber fabrics were placed on the mold tool or mold plate followed by a peel ply. A sealant tape was used on the boundaries to fix the vacuum bag. An 8-mm tube was inserted on one end for the resin inlet and another on the opposite end for the outlet to the vacuum pump. The resin inlet to outlet flow were opted in the fiber direction for creating a path with least resistance to the resin flow. If the resin needs to cover longer path, the inlet will be considered at middle and two outlets should be provided on both ends (see Figure 3.2). The inlet and outlet line should be installed before closing the vacuum bag. After placing all the dry materials and inlet-outlet tubing, the vacuum bag gets sealed. Before infusing the resin, the resin line is clamped and the vacuum bag tested for air leak. After infusion, the whole vacuum bag setup allowed to cure at the same vacuum pressure (75mbar) and ambient condition (23°C, 60%RH) for the next 24h. For the resin used, a post curing of 8 to 15 hours was recommended at an elevated temperature of 60°C – 65°C to achieve an improvement in mechanical properties.

Figure 3.1: Schematic of resin infusion [1]

Figure 3.2: The resin inlet is given at the middle and two outlets to the vacuum pump are provided at both right and left ends.

Following parameters has dependents on the speed and infusion distance along the fabric stack.

Resin viscosity	η
Fabric stack permeability	D
Gradient of pressure acing	ΔP

The speed of infusion process (v) has the following relationship with the above parameters

$$v \propto \frac{D * \Delta P}{\eta} \quad (3.1)$$

Wind turbine industries generally use low viscosity resin or the resin temperature get increased by 10 - 15°C while using to reduce the viscosity by roughly half [1]. However, elevated temperature infusion is not recommended due to the accelerated reactivity in the curing process. As the curing progresses the viscosity increases exponentially and forms a soft gel followed by glassy solid.

3.3 Fiber waviness

Waviness is a manufacturing defect that is generally found in composite structures due to the imbalance in ply stacking, complicated mold structure or due to ply drop situation [2]. Waviness can be of in-plane and out-of-plane and can occur over a lamina, multiple laminates or throughout the thickness of the structure, in uniform or in non-uniform format. In-plane waviness was generally found along the stacked plane in a single lamina or in multiple laminate. Out-of-plane waviness was found perpendicular to the fiber direction (or ply) in multiple laminates. For the current study, a single sinusoidal wave of known severity (similar to that found in full scale blade) was replicated on each ply to produce an in-plane fiber wave throughout the thickness. The wave severity is defined below. The parameters considered are wave geometry, wave position and percentage of wavy layer present in the laminate. Adams [3] characterized the wave geometry (Figure 3.3) with a set of parameters wave amplitude (A) and wavelength (L) and the ratio called as wave severity.

$$\text{Wave severity} \quad W_s = \frac{A}{L} \quad (3.2)$$

As shown in Figure 3.3, the idea was to introduce a single wave of fibers intentionally on each lamina of the unidirectional fabric. A ply was laid over a cylindrical tube which is held perpendicular to the fiber direction as shown in Figure 3.3(a). The diameter of the tube (5 mm and 8 mm internal diameter) was approximately equal to the height of waviness to be generated. The required wave span was held on both sides of the cylindrical tube to create an out of plane fiber waviness. From that holding position, the tube was removed and a uniform shear load was applied normal to fiber direction to make the out of plane waviness into in-plane waviness. After that operation, the wavy in-plane fibers were pressed towards the table for 10 to 15 min. Same procedure was repeated for each ply to be stacked. Thereafter, plies were stacked under vacuum bag for the curing procedure. To get a different wave height using the same tube, the laminas allowed to relax for one or two days. The final wave severity was measured after the curing. To accommodate the waviness peak region at the gage portion of

various standard testing coupons, different wave severities were achieved by changing the wave amplitude rather than changing the wavelength of the waviness defect.

Figure 3.3: Fabrication of an in-plane fiber waviness

Figure 3.4 shows the fiber waviness on a lamina and laminate before and after the curing. After curing, panels were visualized under optical microscopes and wavelength and amplitude were measured at different locations over the laminates and average fiber waviness was calculated based on the measurement. The wavelength was always fixed in the range of 35 to 40 mm for a laminate to be cured and based on the wave severity requirement, the amplitude varies from 0.35 to 2.6 mm. The range of average fiber wave severity achieved was 0.01, 0.025, 0.035 and 0.075. As per the experiment standard requirement, specimens were cut using the diamond cutter and the sharp edges were grinded with grit paper starting from 180 to 400. The specimens were cut in a way that the fiber waviness portions are exactly in the middle of the gauge portion of the specimen.

Figure 3.4: a) Fiber waviness over a lamina before curing b) fiber waviness a laminate after curing

3.4 Fiber volume fraction

It is the ratio of total fiber volume presented per unit volume of composite. This fraction should always be in the optimum range of 0.45 to 0.55 for better mechanical properties. Burning off the cured resin based on ASTM D2584 [4] standard was followed. Minimum of 5 samples were cut with approximate weight of 5 g and 2.5 by 2.5 cm dimension. Each sample was placed in a crucible and weighed to the nearest 1 mg. The crucible was then heated in the muffle furnace at 600°C until all the resin material had disappeared (see Figure 3.5). After, the crucible was cooled back to room temperature, the final weight was measured. From the samples taken from each panel, cured based on resin infusion technique, an average fiber volume fraction in the range of 0.52 to 0.57 was obtained. It was always made sure that for one set of experiments, the samples were cut from the same panel to achieve the uniform fiber volume fraction.

Figure 3.5: Bare fiber after the resin burn out

3.5 Mechanical testing

Initially, a set of mechanical testing was performed on defect free unidirectional samples to determine the tensile strength, compressive strength and in-plane shear strength. These properties were used as the layup properties for the FE model developed using Abaqus. In separate, all these tests were conducted on the waviness induced specimens for determining the reduction in mechanical properties. Additionally, a static flexural experiment, double cantilever beam testing (DCB) and fatigue flexural testing were conducted on both waviness induced specimen and defect free specimen. This was to compare the variation in flexural, fracture and fatigue properties and failure behavior under the influence of fiber waviness defect at different fiber wave severity level.

3.5.1 Tensile testing

Tensile tests were conducted to determine the in-plane tensile properties and the Poisson's ratio of the studied materials. The test follows ASTM standard D3039 [5], which includes the method of material preparation, lay-up, the specimen gripping, testing environment condition and speed of test. Ultimate tensile stress (S_{11}), modulus of elasticity in the test direction (E) and Poisson's ratio (ν_{12}) were determined from the test data.

Figure 3.6: Tensile testing, (a) With clip-on extensometer, (b) Strain gage with two element rosettes.

Specimens were cut along the fiber direction and tested on Instron 5500 with a 50 kN load cell. Another set was tested with clip on extensometer to measure the strain. In yet another set, two element rosette strain gages (GFCA-3-350-70 from Tokyo Sokki Kenkyujo Co. Ltd) were bonded (see Figure 3.6 (b)) to measure both linear and lateral strain simultaneously.

Ultimate tensile stress (MPa)	$F^{tu} = P^{max}/A$
Tensile stress (MPa)	$\sigma_i = P_i/A$
Tensile strain	$\varepsilon_i = \delta_i/L_g$
Tensile Modulus of elasticity (GPa)	$E = \Delta\sigma/\Delta\varepsilon$
Poisson's ratio	$\nu = -\Delta\varepsilon_t/\Delta\varepsilon_l$

3.5.2 Compression testing

Compression experiments were conducted to determine both compressive strength and the reduction in compressive properties due to the involvement of waviness defect. The tests were performed as per ASTM D6641 [6] on a 100 kN servo-hydraulic Instron 8801 machine with Zwick Hydraulic Composite Compression Fixture (HCCF). A typical compression experiment specimen is 140 to 150 mm in length and 13 mm wide with an unsupported gage length of 13 to 20 mm. Wrinkle free specimens were prepared based on the same standard dimensions. A width of 25 mm was considered for defect induced specimens (see Figure 3.7 (a)) to minimize the percentage amount of discontinuous fibers due to waviness inclusion in the coupon. Compression test fixtures were selected based on combined shear and end loading [7, 8]. However, tab bonding should be strong enough to avoid debonding failure due to shear loading. The combined end and shear loads were applied hydraulically on the coupon at a constant crosshead speed of 1 mm/min. The bonded strain gages (see Figure 3.6 (b)) on both sides of the gage part were connected to the data logger for the compressive strain measurement. During the test, failure progressions were captured using a high-resolution video camera at the rate of 50 frames/sec. Tests on each types specimen were repeated 5 times for getting statistically significant data.

$$\text{Laminate compressive strength (MPa)} \quad F^{cu} = P^{max}/wh$$

where, p^{max} = Maximum load (N)
 w = Specimen width (mm)
 h = Specimen thickness (mm)

Figure 3.7: a) Schematic of a typical compression test specimen, and b) the actual HCCF set up with sample.

3.5.3 Shear testing

V-Notched rail shear test method was used to determine the shear properties of the current material. As per the ASTM standard D7078 [9], the notched specimens were prepared as shown in Figure 3.8. A bonded strain gage with two 90° element rosette was used to measure the strain at +45 and -45 directions (see Figure 3.8(c)). The strain gages were connected to the data logger to measure the strain at one second interval. When the fixture loaded in tension, the clamped rails on both sides of the specimen surface introduces a shear force. Usually the experiment conducted on unidirectional laminates with fiber orientation either parallel or perpendicular to the rail grip to ensure the balance and symmetry. Since the waviness defect is symmetric about the neutral plane, it ensures the geometric symmetry.

Figure 3.8: a) Shear test fixture b) V-notched specimen with waviness, c) Fixture with specimen during loading.

$$\text{Shear Stress} \quad \tau_i = P_i / A$$

$$\text{Shear Strain} \quad \gamma_i = |\varepsilon_{+45}| + |\varepsilon_{-45}|$$

$$\text{where } P_i = \text{Applied load (N)}$$

$$A = \text{Cross-section area at the middle of the specimen (mm}^2\text{)}.$$

$$\varepsilon_{+45}, \varepsilon_{-45} = \text{Measured strain corresponding to applied load.}$$

3.5.4 Flexural testing

Flexural properties of both unidirectional and waviness induced samples were determined by three-point bending method. Specimens were cut from laminates with 6 layers of unidirectional fabrics. At least 5 sets of samples were tested in the flatwise configuration. Each specimen with average thickness 3.72 mm, width 20 mm and span length of 120 mm. A standard span to thickness ratio of 32:1 was chosen at the surface of the specimen due to bending moment. The Figure 3.9 shows the three-point bending fixture with specimen.

Figure 3.9: Three-point bending fixture with specimen

Maximum flexural stress (MPa) $\sigma_b = \frac{3PL}{2bh^2}$

whereas P = Maximum load (N)

L = Span length (mm)

b = Specimen width (mm)

h = Thickness (mm)

3.5.5 Double cantilever beam (DCB) experiment

Double cantilever beam is the most common configuration to determine mode-I and the critical strain energy release rate. Davidson [10] analyzed that the growth of crack front in a DCB specimen was curved and in the form of a thumb nail shape. The mode separation energy release rate required for the delamination growth is equal to the resistance offered by the material for the crack to grow. Double cantilever beam specimens were prepared with and without fiber waviness defect. ASTM standard D5528 [11] was recommended to characterize the fracture properties of double cantilever beam specimens. Before resin infusion, a Teflon film of thickness 20 μm was inserted exactly at the middle of the layup for the initial crack.

Figure 3.10: Specimen geometry, the bottom pictures show the inside waviness portion after the crack initiation front (Shown with red line).

For the current investigation, a set of four unidirectional samples with waviness defect (W6, W8) through the thickness and without waviness defect (U6, U8) were tested. The defect free set of samples were fabricated and tested for the comparison purpose. The geometry and the fiber wave severity (W_s) details were mentioned in Table 3.2. As shown in Figure 3.10, the W6 and W8 samples differ in their crack initiation point. In W6, the crack initiation point or the end of Teflon slit was situated on the fiber waviness area, whereas in W8 samples the crack initiation point was ahead of fiber waviness area. As per ASTM D5528, the initial crack length to the thickness ratio (a_0/h) was selected to be between 8 and 20 to reduce the transverse shear deformation effect for the fracture toughness calculation. Currently, for W6 and W8 specimens it was 8.5 and 10.6 respectively.

Table 3.2: Glass/epoxy DCB specimen

Specimen	Lay up	Wave severity (W_s)	Initial crack length a_0 (mm)	Thickness (mm)	Width (mm)
U6	$[0]_6$	Nil	30 (± 0.43)	3.55 (± 0.01)	24.50 (± 0.11)
W6	$[0]_{6w}$	0.03	30 (± 0.71)	3.55 (± 0.01)	24.50 (± 0.12)
U8	$[0]_8$	Nil	50 (± 0.37)	4.70 (± 0.01)	24.50 (± 0.07)
W8	$[0]_{8w}$	0.04	50 (± 0.15)	4.70 (± 0.02)	24.50 (± 0.04)

An Instron 5500 was used to conduct the DCB experiment with a load cell of 5 kN. The other ends of adhesively bonded piano hinges were firmly gripped on the top and bottom of the machines loading grip. A quasi-static test was performed under displacement control with the cross-head set speed of 1 mm/min. The normal load and the crack opening vertical displacement were recorded by the machine (As shown Figure 3.11). The entire experiment was video recorded in real time using a high-resolution camera and the recorded video converted into an image file with a frame rate of 50 frames per second using MATLAB tools. A 2X enlarging lens placed in between the camera and the sample for an additional zoomed view. The crack initiation point was precisely captured by visualizing the image sequences of the experiment. Corresponding to load - displacement, the prevailing crack length was measured using the image sequence. A measurement scale with a millimeter accuracy was attached above the crack opening area for the instantaneous measurement of crack opening length from the captured frames.

Figure 3.11: Double Cantilever Beam experiment setup and crack propagation

As per the ASTM standard, the mode-I critical energy release rate can be experimentally determined by, the modified beam theory (MBT) method, compliance calibration (CC) method and modified compliance calibration (MCC) method.

Figure 3.12: Double cantilever beam specimen.

According to Modified Beam Theory (MBT) method,

$$G_{IC} = \frac{3P\delta_0}{2W|a_0 + \Delta|} \quad (3.3)$$

where Δ may be determined experimentally by generating a least squares plot of the cube root of compliance ($C^{1/3}$), as a function of delamination length. The

compliance (C), is the ratio of the load point displacement to the applied load (δ/P).

as per Compliance Calibration (CC) method,

$$G_{IC} = \frac{nP\delta_o}{2Wa_o} \quad (3.4)$$

where ‘ n ’ is the slope of the plot drawn $\log\left(\frac{\delta_i}{P_i}\right)$ versus $\log(a_i)$, quantities with subscript ‘ i ’ denotes the incremental values of load (P), load point displacement (δ) during regular intervals.

In Modified Compliance Calibration (MCC) method

$$G_{IC} = \frac{3P^2C^{2/3}}{4A_1Wh} \quad (3.5)$$

where A_1 is the slope of least square plot, normalized delamination growth $\left(\frac{a_o}{2h}\right)$ versus cube root of the compliance ($C^{1/3}$) available from earlier method.

3.5.6 Fatigue flexural analysis

The wind turbine blades are subjected to long term fluctuating load and a fatigue in the structure occurs when it is subjected to cyclic stresses. Hence it is mandatory to study the resistance of defect containing specimens subjected to fatigue loading. A dynamic reversible flexural load was applied on both defect-free and wave defect containing unidirectional specimens to determine the fatigue properties. A fluctuating three-point bending analysis was carried out with stress ratios $R = 0.1$ and 0.5 at frequency 3 Hz, where $R = \text{Min. load}/\text{Max. load}$. The tests were carried out in MTS810 with a load cell 10 kN under load control and constant amplitude in the sinusoidal waveform (the Figure 3.13). Rather than the expected fatigue strength reduction due to the waviness defect, the focus was on the different failure modes occurring on the tension and compression side. Three sets of specimens were tested at each stress level.

Figure 3.13: The sinusoidal load wave form representation for a unit maximum load with respect to time

3.6 Damage characterization

The following subsection details the different characterization techniques used for the damage analysis composite laminate.

3.6.1 Digital microscope

Optical microscope is a standard tool used in the laboratory to produce a magnified image of an object either through reflected or transmitted light. Similarly, digital microscopes have a single or compound lenses to magnify the sample, but instead of eyepiece uses a computer to visualize the image.

3.6.2 Scanning Electron Microscope (SEM)

SEM is used to generate high resolution images of an area in the range of 1 cm to 5 μm with a magnification range of 20X to ~30,000X. SEM generates a high-energy electron beam from a tungsten filament or a field emission gun under vacuum environment and impinges the specimen of interest to create an image. The electron beam is accelerated with the help of high voltage, and with the help of electromagnetic lenses it is narrowed into a thin beam of electrons. The interaction of electron beam with the sample surface ultimately produces a variety of information about the composition and surface topology [12]. The specimen of interest should be conductive and to make the glass fiber composite

conductive, a thin layer of carbon is sputter coated on the specimen. For the present study, JEOL JSM-5600LV SEM was used for the fractography analysis.

3.6.3 Laser Shearography

This is a non-destructive test method used to obtain the subsurface features like voids, crack and delamination. The specimens which were undamaged after completing a million cycles of stress reversals were observed under the laser shearography for the subsurface damage.

A laser light is illuminated over the surface under investigation. A speckle pattern will be generated by the component surface and this pattern will be recorded using a digital camera. Then after, a mechanical or thermal excitation was given to the component surface that will lead to the change in speckle pattern due to stress deformation. The new speckle pattern will get subtracted from the old pattern and a shearographic fringe pattern will be displayed. This final black and white fringe displays all the information about the relative deformation before and after the excitation.

3.6.4 Computed Tomography (CT)

Among the different non-destructive techniques, CT technology is proven to be the best technique to characterize the damage of the materials. The set up consists of an X-ray source, detector, a multi axial sample holder, a computer system to store and reconstruct the captured image and to display the results.

The object to be scanned is fixed in between the detector and the gun. The X-rays emitted by the gun passes through the object before received by the detector panel. The scanning is repeated for each increment of rotation about the third axis until the rotation angle reaches 360°. To get higher spatial resolution, the object should be positioned as closer to the target with a smaller increment of rotation. Yxlon X-ray CT system was used for the scan operated at 55 kV and 46 μ A. The increment of rotation was 0.5°, therefore a total projection of 720 were made over a 360° scan.

3.7 Summary

In this chapter, the particulars of materials used for the specimen preparation and the detailed procedure of composite laminate fabrication with fiber waviness inclusions were discussed. Various mechanical testing procedures followed for the evaluation of wavy fiber specimens were explained. The techniques used for the damage characterizations were discussed.

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Chapter 4

Compression and double cantilever beam experiment

In this chapter, coupon level unidirectional GFRP composites with waviness defect were tested under compression. The results were compared with defect free samples. Further, the effect of waviness defect on mode – I fracture energy and delamination onset were also studied using a double cantilever beam (DCB) setup.

4.1 Introduction

The backbone of any structure is their reinforcement part, similarly for wind turbine blade it is the spar-cap. Hence, the defect that affects the spar-cap will deteriorate the life span of whole blade structure. The spar-cap is made up of unidirectional fibers for getting high strength and stiffness. The blades were designed to undergo extreme wind load in flap-wise and edge wise direction. From the earlier research of a concave up wave in bending analysis, a 37% reduction in bending strength was noted [1]. Therefore, in the current work, coupon level bending tests were conducted on unidirectional specimens with in-plane fiber waviness defect. The different failure modes were also analyzed.

From the design perspective, compressive strength is one among the key property for structural components made up of composite materials [2]. Though unidirectional laminates have good tensile strength and stiffness along the fiber direction, they are weak in compression. Under the compression loading condition, the fiber waviness defect shows a significant reduction in compressive strength and stiffness of the composite laminates. Further, double cantilever beam tests were performed on the wave induced specimen to investigate the effect.

4.2 Compression experiment

Various studies on multiple layer waviness revealed that it caused significant reduction in mechanical properties [3] and the impact was severe in unidirectional laminates [4-8], in which a huge deterioration in the compressive strength of composite laminates was observed [5, 8-11]. The compressive strength decreased steadily with increase in both wave severity (W_s) and number of waviness containing 0° plies [7]. Adams et al. [3] found a reduction of 35% in strength when 0° plies contained 33% fiber waviness defect. Waviness or wrinkles can arise in any part of the structure due to excessive reinforcement during ply stacking on mold structure or due to ply drop situation.

A full-scale failure analysis of blades is expensive and testing of spar cap with actual thickness of around 50 to 60 mm, is extremely difficult. In usual practice, the test is performed on coupons with thicknesses between 2 to 6 mm with fiber wave severity similar to that found in blade structure. The parameters to be considered are wave geometry, wave position and percentage of wavy layer present in the laminate.

4.2.1 Experimental procedure

As discussed in chapter 3, different wave severities were achieved by changing the wave amplitude rather than changing the wavelength of the defect (due to size limitations for testing and analysis). The $[0]_6$ layer panels were prepared with different wave severity levels using unidirectional glass fabrics. Each layer has an average thickness of 0.62 mm. Compression tests were conducted as per ASTM D6641 standards on a 100 kN servo-hydraulic Instron 8801 machine with Zwick Hydraulic Composite Compression Fixture (HCCF).

4.2.2 Results and Discussion

As listed in Table 4.1 and shown in Figure 4.1, the mean failure strength of the composites significantly decreases with increase in fiber wave severity. For instance, with a severity of 0.075, a 75% drop in strength is noted. Joyce and Moon [12] have reported a similar but linear trend of decreasing compressive strength with increasing (in-plane) fiber waviness severity. This has been

attributed to the formation of kink bands at the fiber misorientation sites in the wavy regions leading to catastrophic failure. In the current work, though a catastrophic failure is observed with defect-free samples, with waviness defect, the failure is not catastrophic. The Figure 4.2 represents the stress strain behavior in the compression experiment.

Figure 4.1: Drop in compressive strength with wave severity

Figure 4.2: Stress-Strain curve of sample A0 and A3.

Table 4.1: Compression test results of composites with and without waviness defect.

Sample	Wave severity (W_s)	Mean failure strength (MPa)	Standard Deviation (MPa)
A0 (unidirectional)	0	614	19.61
A1	0.01	479	34.5
A2	0.025	303	12.25
A3	0.035	222	13.16
A4	0.075	158	14.40

4.2.3 Mechanisms of failure

- *Unidirectional laminates without waviness defect:* - Optical and SEM observations of the failed samples reveal the presence of angled fracture plane due to shear failure (Figure 4.3). Fiber strand debonding, micro-buckling and matrix cracking were also clearly visible in the gage area. These observations follow the traditional and expected mode of failure [13]. Fiber micro-buckling is a resultant of shear instability process that occurs at higher strains for the matrix to plastically yield. This results in the formation of kinks in a localized region and ultimately leads to the formation of fiber kink-bands. However, it is important to note that kinking stresses are very sensitive to fiber misalignment. Even a misalignment angle in the range of 0.8 - 2.3° is enough to cause kinking [14]. Moreover, with misaligned fibers, kinking stresses are reportedly 25% of the elastic micro-buckling stresses of composites.

Figure 4.3: Catastrophic failure of waviness-free specimen under compressive loading conditions.

- *Unidirectional laminates with waviness defect:* - As compared to defect free specimens, the failure progression of the wavy specimens was slow and gradual (particularly, A4 with a wave severity of 0.075). Figure 4.4 shows a few selected snapshots of crack initiation and progression from the video of the test captured with a high-speed camera operated at a frame rate of 50 frames/s. As discussed earlier, axial compression failure of unidirectional composites occurs by plastic kinking in the presence of fiber misalignment sites along with plastic shear deformation in the matrix. As shown in Figure 4.5, failure initiated with a visible fiber kinking followed by an inclined shear crack across the fiber direction on the wavy area, ultimately resulting in fiber strand splitting. Previously, it has been noted that glass fibers fail in compression by longitudinal splitting, when the uniaxial strain in the composite equals the intrinsic crushing strain of the fibers [15]. Nevertheless, the gradual kink-band formation, and the resultant fiber kinking failure mode are more evident at higher fiber wave severities (A3 and A4 samples). For example, Figure 4.5 shows the failure progression in A3 with wave severity 0.035.

Figure 4.4: Sequence of crack propagation before complete failure in sample A1.

Figure 4.5: (a) Fiber kinking and fiber splitting along the wavy fiber direction in sample A3, b) Magnified fiber kinking view, (c) Kink band view at the free edge of the width, d) Fiber breakage.

A clear transition in the failure mode is seen in composites with and without waviness defect. Also, the crushing phenomenon during the failure is absent with higher fiber wave severity. However, audible crushing and/or knocking sounds are heard in composites with a wave severity 0.025 (Sample A2, misalignment angle $\sim 5.7^\circ$) and below. Thus, a wave severity of 0.025 seems to be the transition point in failure mode. The width of the kink band increases with increase in wave severity. The kink band width changed from ~ 0.1 - 0.12 mm in A0 sample to ~ 1.5 - 2 mm in A4 sample.

4.2 Double Cantilever Beam (DCB) experiment

DCB is the most popular specimen configuration to determine mode-I and critical strain energy release rates. Davidson [16] analyzed that the growth of crack front in a DCB specimen was curved and in the form of a thumb nail shape. It is believed that the mode separation energy release rate required for the delamination growth is equal to the resistance offered by the material to delamination to growth. It was found from various studies that a waviness defect can easily be induced in unidirectional laminates during manufacturing, and it

causes a reduction in strength and stiffness of the laminates [1, 12, 17]. Hence, the effect of this defect on the delamination resistance and the fracture toughness when compared with the unidirectional laminates should be considered and answered.

The specimen preparation and experiment procedures were discussed in Chapter 3. A set of four unidirectional samples with through thickness waviness defect (W6 - with 6 layers, W8 – with 8 layers) and without waviness defect (U6 – with 6 layers, U8 – with 8 layers) were tested. In W6, the crack initiation point or the end of Teflon slit was situated on the fiber waviness area, whereas in W8 samples, the crack initiation point was ahead of fiber waviness area. As per ASTM D5528 [18], the initial crack length to the thickness ratio (a_0/h) was selected to be between 8 and 20 to reduce the transverse shear deformation effect for the fracture toughness calculation.

4.2.1 Factors affecting on DCB test

The waviness defect is included in each layer of the lamina. The type of defect considered was in-plane waviness and that would not affect the symmetric nature of the layup about the mid-plane. Hence, the stiffness of the two arms of defect containing specimens should be the same to ensure the perfect mode - I design condition. Apparently, the fiber waviness induced samples were not orthotropic in nature as compared to the unidirectional specimens. In the laminate constituent relations, the extension – bending coupling stiffness ($[B]$) would be absent due to the symmetry about the mid-plane, thereby eliminating the effect of residual thermal stresses while curing. But there were a few non-zero terms present at the extensional and bending stiffness ($[A]$ and $[D]$) matrices.

The delamination curvature due to the longitudinal - transverse bending coupling was influenced by the term D_c , introduced by Davidson [19], where $D_c = D_{12}^2/D_{11}D_{22}$ and D_{ij} 's were the components of bending stiffness matrix $[D]$. Davidson found that, with an increase in D_c ratio, the curvature of the delamination front increases. It was suggested that the stacking sequence of the laminate should have been designed with $D_c = 0.25$ as upper limit [19] for a

uniform fracture toughness distribution. A coupling between in-plane shear and extension would be present if $A_{16} = A_{26} \neq 0$, similarly a coupling between out-of-plane bending and twisting would be present if $D_{16} = D_{26} \neq 0$. From Table 4.2, these terms are non-zero for both W6 and W8. Since the specimen arms undergo light bending during the DCB test, the effect of bend-twist coupling can be quantified with a term B_t , which is $|D_{16}|/D_{11}$ [19].

Table 4.2: Initial specimen arm properties of the DCB specimen

Specimen	U6	W6	U8	W8
A_{11} (MN/m)	74.4	72.5	98.8	94.3
A_{12} (MN/m)	5.2	6.2	7.0	9.2
A_{22} (MN/m)	18.8	18.7	25.0	24.9
A_{66} (MN/m)	5.8	6.8	7.7	10.0
A_{16} (MN/m)	0	5.1	0	5.0
A_{26} (MN/m)	0	-1.9e9	0	-1.9e9
D_{11} (Nm)	19.4	18.9	45.5	43.4
D_{12} (Nm)	1.3	1.6	3.2	4.2
D_{22} (Nm)	4.9	4.9	11.5	11.4
D_{66} (Nm)	1.5	1.7	3.5	4.6
D_{16} (Nm)	0	1.3	0	2.3
D_{26} (Nm)	0	-5.1e8	0	-9.0e8
D_c	0.017	0.028	0.019	0.036
B_t	0	0.07	0	0.05
$E_{f\text{-ini}}$	41.4	39.8	41.4	41.4

Load versus vertical opening displacement was recorded during the test by the machine. The video recording was also synchronized with the load displacement data for the crack length measurement from the frames. The test was continued until a crack extension length of approximately 20 to 30 mm. DCB tests were performed on all the samples with fiber waviness defects and without waviness defects having two different thicknesses and crack opening positions.

4.2.2 Results and Discussion

- *Load vs Displacement behavior*

The typical load displacement curves of all the four different specimens were shown in Figure 4.6 and Figure 4.7. In all the test samples, the response was linear up to the crack initiation point or so-called point of non-linearity (NL). As per the test standards, the point of NL is not visually observable. Hence, the fracture energy measured for a visually observable crack is higher. It was assumed that the crack initiated at the middle of the insert and after the initiation, slope of the $P - \delta$ curve decreases. Along with crack propagation, the presence of fiber bridge dominates in the delamination area. Initially the fiber bridge has strong hold compared to crack propagation, hence the crack grows very slowly and the crack opening load also increases. In the second stage, the fiber bridging and crack opening have equal hold in the delamination area, and the load come into a saturation stage. In the final stage, the crack starts growing very fast and the load drops simultaneously. A sudden drop in the load-displacement curve can be observed due to unstable growth of the delamination crack front. The slope of the NL part depends on the fiber bridging strength and the stiffness of the specimen arm. Among them, the stiffness of the specimen arm depends on the fiber orientation. An entangled fiber network was present along the crack growth and this bridging offers resistance to the delamination growth.

Figure 4.6: Load vs displacement plots for U6 and W6

- **6-layer DCB specimen**

It was clear from the load – displacement curves of U6 and W6 specimen, that the slope of the linear curve depends on the effective longitudinal flexural stiffness of loading arm. As compared to U6 specimen, the inclusion of fiber waviness in W6 specimen causes increase in compliance and thus the drop-in slope. From Table 4.2, the initial flexural stiffness (E_{f-in}) of loading arms was calculated based on the classic laminate theory (CLT) [20]. It was observed that there was a 3.6% reduction in flexural stiffness due to involvement of fiber waviness. But the presence of discontinuous fibers (due to fiber waviness), while cutting the specimen along the fiber direction were not taken into consideration for the stiffness calculation. Additional reduction in the stiffness was expected because of this reason. From Table 4.3, the average critical load required for the crack initiation seems to be in the similar range for both the U6 and W6 samples at different crack opening displacement.

Figure 4.7: Load vs displacement plots for U8 and W8

- **8-layer DCB specimen**

For the W8 specimen, the waviness defect was not present in the initial loading arm, hence there was no stiffness drop in the linear portion of the curve. The average critical load required for the crack initiation was almost similar. After the crack initiation, as compared to U8, a slight drop in the load rate was observed for W8 specimen.

Table 4.3: Average values of load, displacement and the delamination initiation toughness.

Specimen	Initial crack length (a_0) (mm)	Point of Non-linearity (NL)		Maximum load (N)	Fracture toughness based on CC method G_{Ic} (kJ/m ²)
		Load (N)	Displacement (mm)		
U6	30	53.1	3.67	77.1	1.10
W6		49.7	10.1	65.1	0.84
U8	50	56.8	18.3	90.8	1.21
W8		58.0	21.1	92.2	0.84

- **Mode-I fracture toughness and R-curve (Resistance curve)**

The delamination resistance measured as fracture toughness G_{Ic} (kJ/m²). As mentioned in Chapter 3, the fracture toughness values were calculated based on

modified beam theory (MBT), compliance calibration (CC) and modified compliance calibration (MCC) method. Among them the lowest value of fracture toughness (here CC method) was selected for the further comparison of results. From the R – curve plotted (see Figure 4.8 and Figure 4.9) based on data reduction scheme suggested by ASTM D5528, it can be said that the initial fracture toughness was the minimum value (0.8 to 1.0 kJ/m²) and increases to a maximum range (1.5 to 2.5 kJ/m²) after 20 to 25 mm of crack propagation. Among the 3 methods, MBT gave the highest value of fracture toughness. It was found that the crack initiation took place under risings loads, hence there observed a steep initial slope in R – curves.

Figure 4.8: Fracture toughness calculated (R – curve) based on MBT, CC and MCC for U6 and W6 specimens.

Figure 4.9: Fracture toughness calculated (R – curve) based on MBT, CC and MCC for U8 and W8 specimens.

The results confirm that inclusion of waviness in the unidirectional laminate would increase the compliance of the specimens. The average fracture initiation energy (G_{IC}) of U6 and U8 specimens were slightly higher than that of W6 and

W8 specimens. The resistance to delamination offered by the W6 specimens was higher due to the increased compliance and the orientation of fibers (see Figure 4.10). At the waviness region, fiber orientation involved in the crack opening plane was greater than zero. Also, the crack growth along the waviness region was slow compared to the UD specimens.

For the W8 specimen, the wave region starts just after the crack initiation, thus a sudden increase of resistance to delamination was observed (see Figure 4.11 for W8 specimen), once the crack reaches the fiber waviness peak.

Figure 4.10: R – curves of U6 and W6 DCB specimens

Figure 4.11: R – curves of U8 and W8 DCB specimens

The W6 samples were tested to understand the influence of fiber waviness on crack initiation, initial and final fracture toughness (mode-I), whereas W8 samples were tested to understand the influence of waviness during crack propagation. Laminates with 0° orientation has the least G_{IC} propagation value and highest for 90° orientation [21]. From the Figure 4.10 and Figure 4.11 it can be seen that G_{IC} propagation value for wavy specimen increases due to fiber orientation.

- ***Delamination shape and crack propagation rate***

Unidirectional samples generally follow a curved delamination front throughout the delaminating interfaces. The shape of the delamination front has greater dependence on the non-dimensional term D_c and is the reason behind the anticlastic curvature shape across the specimen width. The DCB specimen has the highest energy release rate (ERR) in the middle and was lowest at the edges [16]. The difference in the fracture toughness values at the middle and edges can be correlated with the D_c number. When compared to the unidirectional specimens, the current fiber waviness induced specimens have 60% to 90% higher D_c value at the defect containing region. Hence, the maximum to minimum fracture energy distribution along crack front for wave induced specimen will vary accordingly.

The skewness of the ERR distribution across the width was dependent on the non-dimensional ratio: B_t [19]. This value shows the involvement of bend-twist coupling on the specimen. The B_t value was non-zero for both waviness induced specimens. Over the first half of the fiber wave, the crack front dominates at the top edge but over the second half of the wave, the bottom edge of the crack front was dominant. This was due to the involvement of an equal amount of twist on both the loading arms at the wave induced region. This is responsible for the non-uniform crack front path along the delamination path (see Figure 4.12). In Figure 4.13(b & c), the obtained crack front was clearly visible. Due to the variation observed in the crack opening in the experiment, all the crack lengths were measured from the top edge of the specimen (W6, W8). That means the measured

rate of crack front till the peak of the waviness would be fast as compared to the rest of the opening speed, and this statement was confirmed from the graph shown in the Figure 4.14 and Figure 4.15. When the crack passes through the waviness peak, compared to the top edge, an abnormal crack growth was observed for the bottom edge in the wavy region.

Figure 4.12: Shape of delamination front at different stages of W8 specimen. a) Crack initiation point, b) Initial shape, c) Shape before reaching the peak of fiber waviness, d) Shape after the wave crest, e) Regaining the initial shape

Figure 4.13: a) Fiber bridging (W8 specimen). Shape of crack front: - b) before the waviness peak region, c) After the waviness peak area.

Figure 4.14: Crack opening rate along the delamination path of U6 and W6 DCB specimens

Figure 4.15: Crack opening rate along the delamination path of U8 and W8 DCB specimens

4.3 Summary

A coupon level unidirectional GFRP with waviness defect were tested under static compression loads. Specimens were tested with various fiber wave severity and the results were compared with defect free samples. The reduction in compressive strength and variation in failure modes on each wave severities were analyzed. Effect of fiber waviness on mode – I fracture energy and delamination onset were studied using DCB experiment. Two sets of wavy DCB specimens with different waviness positions and geometrical parameters were tested and compared with standard DCB specimens. The variation in the crack propagation and the shape at the waviness effected areas were studied.

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Chapter 5

An analytical model and a numerical model: Effect of fiber waviness

In this chapter, the reduction in the stiffness of unidirectional composites due to the presence of a through thickness in-plane waviness is predicted based on an analytical model. Also, finite element analysis is carried out based on a physical based failure theory to identify the failure modes.

5.1 Introduction

In this chapter an analytical model is discussed to estimate the moduli of unidirectional laminate with increase in wave severity. In the literature various failure theories were discussed. Among various failure theories LaRC02 criterion is found to be successfully predicting the compressive strength and failure modes of the unidirectional laminate with waviness defect.

5.2 An Analytical model with in-plane waviness

In Chapter 4, a reduction in both stiffness and strength values due to the fiber waviness effect were found. The analytical model results are compared with the experimental findings from the last chapter 4. The model specifically focuses on to address the reduction in Young's modulus due to the through thickness in-plane fiber waviness. In the current analytical model, the effect of in-plane waviness throughout the thickness of a unidirectional composite laminate under compressive loading was considered.

5.2.1 Geometry of an In-plane waviness

A typical geometry of a unidirectional composite laminate is considered with fibers aligned along the length directions. In the case of the laminate with fiber

waviness, a uniform planar sinusoidal wave is considered. The same waviness trend is followed in each lamina throughout the thickness. The waviness is mathematically described as,

$$y = A \sin\left(\frac{2\pi x}{L}\right) \quad (5.1)$$

where A and L are the amplitude and wavelength of the wavy in-plane fiber, respectively (see Figure 5.1).

Figure 5.1: A representative volume of an in-plane waviness in an x-y plane

To calculate the effective elastic properties, the representative volume element (shown in Figure 5.1) was divided into a small slice of thickness dx each along the longitudinal fiber axis. Each slice was an off-axis lamina in the loading direction. The compliance of each slice was calculated from the compliance transformation matrix relationship. Using the equation (5.2), the strains were integrated over the wavelength along the x-direction to obtain the average strain.

$$\bar{\epsilon}_x = \left\{ \frac{1}{L} \int_0^L S_{xx} dx \right\} \bar{\sigma}_x \quad (5.2)$$

where S_{xx} is the compliance of the slice of length x .

The detailed derivation of the average strain is given in Appendix A.

After the integration, the resulting equation will be,

$$\bar{\epsilon}_x = [S_{11}I_1 + (2S_{12} + S_{66})I_3 + S_{22}I_5]\bar{\sigma}_x \quad (5.3)$$

I_1, I_3 and I_5 are the integration components.

$$I_1 = \frac{1 + \alpha^2/2}{(1 + \alpha^2)^{3/2}}$$

$$I_3 = \frac{\alpha^2/2}{(1 + \alpha^2)^{3/2}}$$

$$I_5 = 1 - \frac{1 + 3\alpha^2/2}{(1 + \alpha^2)^{3/2}}$$

and

$$\alpha = 2\pi \frac{A}{L} = \tan \theta_{max}$$

From the equation (5.3), the Young's Modulus is given as,

$$E_x = \frac{1}{[S_{11}I_1 + (2S_{12} + S_{66})I_3 + S_{22}I_5]} \quad (5.4)$$

In general, individual stresses and strains can be analyzed based on the classical laminate theory.

$$\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{bmatrix} \epsilon^0 \\ \kappa \end{bmatrix} \quad (5.5)$$

where A is the extensional stiffness matrix, B is the coupling stiffness and D is the bending stiffness matrix. The current analysis was done for unidirectional laminate and considering that the defect on each lamina consist of same severity and size; hence the individual lamina stresses and total laminate stresses will be the same. The analytical model was used to understand the stress-strain behavior of the laminate at various severity levels. In this model, the severity of the waviness is characterized based on the amplitude to the wavelength ratio (A/L) called as wave severity. The severity ratio was varied from zero to a maximum of 0.075 to correlate the experimental waviness geometry of severity 0.01, 0.025, 0.035 and 0.075. The geometry details of the current waviness are as follows,

Amplitude $A = 0 - 2.6 \text{ mm}$

Wave length $L = 35 \text{ mm}$

Wave severity $W_s = 0 - 0.075$

The experimentally determined lamina material properties used as follows

Young's modulus $E_1 = 41.4 \text{ GPa}$, $E_2 = 10.4 \text{ GPa}$, $E_3 = E_2$

Poisson's ratio $\nu_{12} = 0.28$, $\nu_{13} = 0.27$

5.2.2 Analytical model results

Figure 5.2 shows the reduction in Young's modulus on x, y and z coordinate axis. In the longitudinal axis with a wave severity of 0.07, the Young's modulus is reduced by 45%. Compared to the elastic modulus in the lateral direction, waviness defect had more influence in the longitudinal direction. There was no change observed in the modulus value along the z axis. The waviness was literally laid in the x-y plane (see Figure 5.1) and the symmetry of the laminate about the x – y plane still intact as similar to the unidirectional laminate. Figure 5.3 illustrates the variation in shear strength, which shows a slight increase in the in-plane shear strength with increase in wave severity. All the comparison with experimental results will be explained in the section 5.3.

Figure 5.2: Normalized Young's modulus with respect to wave severity

Figure 5.3: Normalized shear modulus with respect to wave severity.

5.3 Abaqus Model

ABAQUS is a finite element modelling and simulation software used to analyze complex problems in the engineering with the help of a numerical solvers. The different modules in the software helps to model the components and analyze the problem by employing different integration scheme, such as Abaqus/Standard, Abaqus/Explicit etc. Abaqus/Standard is a general-purpose solver and uses implicit integration scheme to solve the problem. On the other hand, Abaqus/Explicit is used to solve nonlinear dynamic, transient loads and quasi-static problems with the help of explicit integration scheme.

In the explicit method, Abaqus does not use iterative solver to reach the equilibrium stage. Instead, a central difference method is used to solve the equation with the help of inertia force and viscous damping coefficient. When explicit method applied to quasi-static problem, the loading rate is considered to be as small as possible for a negligible kinetic energy. The analysis efficiency can be improved by taking the analysis time as minimum as possible and the mass scaling factor as maximum as possible.

In the analysis of laminated composite materials using ABAQUS, the general failure criteria included are Max Stress, Max Strain, Tsai-Wu [1], Tsai-Hill [2] and Hashin's [3]. Except Hashin's failure, all these failure initiation criteria are

not based on individual constituent materials and resulted in poor failure prediction. These failure criteria are used to predict the failure initiation over the integration points defined in the model. Once the model satisfies the initiation condition at any of its integration points, it will follow the default stiffness degradation method unless otherwise any degradation is mentioned.

In ABAQUS, the progressive damage initiation and damage evolution of both matrix and fiber material constituents are predicted based on the composite average state of stresses and strain. The damage progression is purely based on in-plane stresses and strain components and completely ignoring the effect of transverse stresses and strains. In the damage evolution part, Abaqus damage model considers the stiffness reductions of in-plane constituents such as E_{11} , E_{22} , G_{12} and leaving behind the transverse stiffness such as E_{33} , G_{13} , G_{23} unchanged. In order to avoid these limitations, an Autodesk plugin called Helius PFA [4] for the simulation of composite analysis is included to incorporate the constituent (matrix and fiber) level failure initiation criterion like MCT based failure [5], Christensen [6], Puck [7] and LaRC02 [8] into the model.

Helius PFA [4] uses separate material manager to include the composite lamina properties. Based on the input provided to the material manager, Helius PFA provides the constitutive relations for composite materials as per the required failure theory to the ABAQUS input. As seen in Table 5.1, the lamina material properties were derived from the individual material properties input (fiber and resin properties) given to the material manager of Helius PFA.

In the current work, LaRC02 failure criterion (based on an improvement to Hashin's model) was preferred as it combines the fracture plane concept of Puck [7] as well. This criterion identifies the fiber failure and matrix cracking in unidirectional composites (initiation and instantaneous damage progression) [7, 9] based on the below mentioned constitutive relations. The uniaxial tensile strength (S_{11}), compressive strength ($-S_{11}$), and in-plane shear strength (S_{12}) were obtained from the experiments conducted. The out-of-plane shear strength values

S_{23} and S_{13} were considered equal to in-plane shear value. The transverse parameters S_{22} and S_{33} were taken as $\sqrt{3}$ times S_{23} .

Individual plies were defined under composite layup sequence with orthotropic non-linear elastic material properties based on experimental measurements. Experiments were conducted on the same material to determine the maximum tensile, compressive and shear strength properties. The detailed material properties used for the model were listed in Table 5.1 to Table 5.3. Based on LaRC02 failure criterion, under uniaxial compression loading, (1) fiber failure is further divided into (1.a) fiber compressive failure with matrix compression, and (1.b) fiber compressive failure with matrix tension. (2) Matrix cracking is again divided into (2.a) matrix cracking in tension, and (2.b) matrix cracking in compression. For the current model, due to the presence of fiber waviness imperfection in the cured laminate, it was assumed that majority of failure progression occurred due to fiber kinking. The fiber compression failure scenario was explained due to the collapse of fibers subjected to initial misalignment, leading to shear kinking and further extending to the supporting matrix [10, 11]. The detailed matrix and fiber failure criteria were explained in the literature chapter.

Table 5.1: Constituent elastic properties used in the Abaqus model (based on material data sheet).

Fiber		Matrix	
Young's modulus	Poisson's ratio	Shear modulus	Poisson's ratio
E_f [GPa]		G_{12} [GPa]	
73	0.24	1.2	0.35

Table 5.2: Lamina strength properties used in the Abaqus model (Experimentally determined).

Ultimate tensile strength	Ultimate compressive strength	Ultimate shear strength
X_T [MPa]	X_C [MPa]	G_{12} [MPa]
728	630	50

Table 5.3: Comparison of lamina material properties from experiment and model

	E_{11} [GPa]	E_{22} [GPa]	G_{12} [GPa]	ν_{12}
Based on Autodesk Helius PFA	41.4	9.99	3.58	0.27
From experiment	41.4	10.29	2.78	0.28

5.3.1 Mesh Modelling

Initially, an Abaqus model for the unidirectional specimen was prepared. The kind of failure modes presented in unidirectional model is unimportant, rather the model was used to compare the stress-strain behavior with the fiber waviness induced model. A specimen model has been prepared in the same dimension of the experimental specimen. A solid continuum element (C3D8R) with reduced integration and enhanced hourglass control were used. Hourglassing is the process of mesh instability caused due to the use of reduced integration. With the help of fine mesh and enhanced hourglass control, the mesh instability is controlled and confirmed that the artificial energy is less than 1% of internal energy. A sweep mesh with mesh stack orientation perpendicular to the laminate plane was preferred for getting a uniform mesh throughout the section. At the gage portion, the waviness was obtained by aligning the elements in a predetermined wave path. Based on the wave severity geometry, different wave paths were created on each model. As shown in Figure 5.4, the mesh was followed a path specially created for the wave severity 0.075 and the orientation of each element in that wavy area follows the same path.

Figure 5.4: (a) Abaqus specimen model, (b) Zoomed vies at gage portion, (c) Mesh flow in the gauge area along the waviness path, (d) Element orientation at the waviness region.

The gage portion has a thickness of 3.72 mm and gage length of 20 mm. A mesh refinement study has been performed on the wavy specimen to ensure the simulation results obtained are adequate (see Figure 5.5). Neither the tabs nor the adhesive joint of the tabs were failed during the experiment. Hence least importance was given to the failure mechanisms of tab materials and adhesive bonds.

Figure 5.5: Mesh refinement for both unidirectional and wave induced model (Wave severity = 0.075).

5.3.2 Boundary conditions

In the model, one end of the specimen was fixed and a quasi-static displacement load was applied on the other end. Fully constrained boundary conditions were applied on the left (fixed) end and displacement boundary conditions were applied to the load direction by constraining the other directions to a reference point on the right end. The reference point and the right end of the model were bonded with an equation based directional constraint. So, the displacement given to the reference point would reflect to the right end face of the model. Figure 5.6 shows the 2D view of the trimmed model having 6 layers of ply material, tab bonding with boundary conditions at both the ends and tab sides.

Figure 5.6: Boundary conditions at both ends of the model.

5.3.3 Damage initiation and progression

An explicit analysis technique was followed by applying a small displacement at one end for a short period of 0.04 second. The damage will be initiated when either of the failure index (FI) of matrix or fiber satisfies initiation condition. The damage evaluation process starts immediately after the damage initiated at any of the individual integration points. An instantaneous degradation method is followed for the stiffness degradation. The degradation ratio for both the matrix and fiber were predefined as user material constants (UMC) before the analysis. In here, the degradation ratio for matrix was set as 0.1 and for fiber, it was $1\text{E}-06$. The stiffness of the composite remains to be constant until the matrix

failure occurs. Once the matrix fails, the matrix stiffness drops correspond to matrix degradation ratio and thus the composite stiffness. When fiber failure occurs, the fiber stiffness reduced as per user material constant assigned and which in turns a further drop in composite stiffness.

Based on these constitutive equations of LaRC02 failure criteria, Abaqus identifies the failure initiation at individual integration points in the model. The results were interpreted based on the State Dependent Variables (SDV). SDV = 1.0, signifies no damage in both fiber and matrix and SDV = 2.0 signifies failed matrix. When SDV reaches 3.0 on a specified location, it was confirmed that both matrix and fiber failed in that area.

5.3.4 Simulation results

Initially, a qualitative visual comparison study of both unidirectional and waviness model simulation was performed. Similar to the experiment, a sudden catastrophic failure was observed in unidirectional specimen.

Figure 5.7: Damage over the gage area in unidirectional laminate with respect to SDV.

Figure 5.8: Damage over the gage area in wavy laminate with respect to SDV.

The Figure 5.7 and Figure 5.8 shows the damage over the gage portion of the specimen with respect to the solution dependent variable. It was seen that the total gage portion of the unidirectional specimen was damaged similar to the experiment. Similarly, for the wavy model, the damage was observed in an angled plane along the width. This phenomenon is very similar to the kink band formation found in the experimental specimen. A detailed comparison of the compressive strength reduction, Young's Modulus and failure mechanisms is explained in the next session.

5.4 Comparison of analytical and simulation results with experiment

Figure 5.9 shows the stress vs strain behavior calculated for the unidirectional samples. Both analytical and Abaqus simulation followed a linear path and experiment shows a slighter deviation after a strain of 0.5%. This pre-failure nonlinearity observed in the experiment can be explained with the help of shear properties.

Figure 5.9: Stress vs Strain behavior of models and experiment

Under compression, unidirectional laminates typically exhibit a non-linear shear response in the longitudinal direction prior to the failure [12]. It is due to the presence of micro-cracks in the matrix material. Under compression loading, the matrix material deforms due to shear in the longitudinal plane. During shear deformation, the micro-cracks accumulate and lead to the degradation of matrix in shear and a progressive degradation in the shear behavior of composite [13]. To understand the longitudinal shear behavior, a V-notch rail shear test was conducted on the same material as per ASTM D7078 [14]. It was clear from the shear experiment that the unidirectional composite exhibit non-linear shear response prior to failure (see Figure 5.10). A same shear experiment was performed on the wavy laminate and found a similar response as compared to unidirectional laminate. A wave severity of 0.035 was measured on the shear testing sample with fiber waviness.

Figure 5.10: Shear response of both unidirectional and wavy laminate.

It was observed that waviness has not much impact on the shear strength of the laminate since the fiber waviness is affected only in-plane of the laminate. For a wave severity of 0.035 the shear modulus is increased by 10% and the shear strength is decreased by 8%. From the analytical model, (see Figure 5.3) for the same wave severity the shear modulus is only increased by 7%.

The Young's modulus of the material decreases with increase in wave severity. It was obvious that laminates with straight fibers have the highest stiffness and with increase in fiber orientation angle from 0° the stiffness starts decreasing. Similarly, the fiber waviness causes fiber to misalign from the longitudinal direction. Figure 5.11 shows the reduction in Young's modulus with increase in the fiber waviness. The analytical model over predicts the reduction in Young's modulus and the prediction by Abaqus model as well slightly higher than the experimentally determined value.

Figure 5.11: Normalized Young's modulus vs wave severity.

In the analytical model of waviness induced composites under axial compression, a local in-plane bending deformations induced due to the in-plane wavy laminate. However, there is no chances of global buckling since the effective response is considered as orthotropic.

In the Abaqus model, LaRC02 failure criteria was used to predict the failure strength. This failure criteria succeeded in predicting the failure mechanism and the failure strength in comparable range. The advantage of using LaRC02 failure criterion is that under compression condition, the fiber failure is developed by shear kinking and damage of the matrix. The misalignment of the fibers due to the waviness defect advances the failure towards kink band formation, which is exactly similar to the failure mode observed in experimental testing.

A comparison of compressive strength obtained from models based on kinking is shown in Figure 5.12. Argon [15] proposed that the components of interlaminar shear stress due to the presence of misalignment produces kinking. Budiansky model [16] gives better prediction of compressive strength at higher fiber misalignment angle.

Figure 5.12: Comparison of compressive strength obtained with Argon model and Budiansky model mentioned in literature.

Figure 5.13: Comparison of failure strength with different wave severity

From the Figure 5.13, it is evident that compared to the analytical model results, the compressive strength predicted using the Abaqus model was well matched. A single through thickness fiber waviness of severity 0.025 is enough to bring about a reduction of up to 50% in the compressive strength. Figure 5.14 shows the comparison of gage area of both unidirectional and wavy laminate after the complete failure.

Figure 5.14: (a) Experimentally failed specimens and (b) Model prediction of both defect free and waviness defect containing samples.

Unlike the brooming failure observed on the unidirectional specimen gage area, the Abaqus model shows a very random failure at the gage portion. In the experiment, fiber breakage and matrix cracking was evident, but in the Abaqus model the fiber damage and matrix damage are together represented with the help of solution dependent variables (SDV). However, the LaRC02 succeeded in predicting the failure mechanism and the failure mode in the wavy laminate. A fiber and matrix failure in the form of a kink band is clearly visible in Abaqus model. It was also found that as the wave severity increases, a transition from a sudden catastrophic failure to a slow and gradual failure will occur at the gage area.

5.4 Summary

An analytical model study based on the laminate constitutive relation has been done on the wavy laminate. A single uniform waviness in the form of a sine wave was considered on each lamina and modulus properties were calculated. Similarly, an Abaqus model has been prepared with the help of Helius PFA to include the LaRC02 failure criteria. A comparison study has been performed on the experimentally determined Young's modulus and compressive strength results with the results obtained from analytical and numerical simulation. The Abaqus simulation succeeded in predicting the failure modes observed due to the waviness defect.

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Chapter 6

Static and fatigue flexural testing of laminate with waviness defect

In this chapter, the experimental analysis of unidirectional laminates having through thickness in-plane waviness under both static and flexural fatigue loading is explained. The static flexural experiments were carried out on both unidirectional and wavy specimens to compare the outcomes. The flexural fatigue experiments were conducted at stress ratios of $R = 0.1$ and $R = 0.5$. The experimental findings such as reduction in flexural strength, stiffness, fatigue life and variation in the failure modes are discussed.

6.1 Introduction

As mentioned earlier in Chapter 2, wind turbine blade carries load in both flap-wise and edgewise directions. The aerodynamic shape consists of two parts namely suction side and pressure side. Usually the upper shell of the blade portion is suction side and the lower portion is the pressure side. The spar-cap is considered as the primary load carrying member and nowadays most of the modern wind turbine spar-caps are made up of laminated polymer composites. In this chapter, these materials with fiber waviness defect were flexural tested under static and fatigue loads to understand their failure behavior in various operating loads.

6.2 Static flexural test

An analytical FEM study was conducted by Wisnom [1] on the waviness defect and compared the compressive strength under compression and bending.

He predicted that bending strength may be higher than the pure compressive strength due to stress gradient in bending. In another study, Chan and Chou [2] determine the bending strength of out of plane wavy laminate in terms of compliance properties. Similarly, Chun and Shin [3] derived the flexural modulus of wavy laminate using strain energy concept. With the help of a 2D compression model, Fleck and Liu [4] found micro buckling failure due to fiber misalignment could be used for thin laminate under bending. But the same model is not applicable for thick laminate due to the stress gradient in bending. Allison [5] had studied the effect of out of plane waviness in bending and found a 37% reduction in compressive strength due to a large concave wave. But he found that smaller waviness in the direction of bending provides greater strength.

In the present study, a three-point bending test were conducted on a through thickness in-plane waviness induced laminated specimen. The study focuses on the effect of waviness on the bending properties and the failure progression. Similar to the specimen preparation method mentioned in previous chapter, vacuum assisted resin infusion technique was followed. The specimens were prepared in such way that waviness defect is presented at the exact middle of each sample. For the comparison of results obtained, similar size unidirectional samples were prepared without any waviness defect. Both set of samples were tested for the same span to thickness ratio.

6.2.1 Specimen geometry and testing

The samples for mechanical testing were prepared according to ASTM D7264 [6] using a diamond wheel cutter with water as coolant. Each specimen consists of six layers of unidirectional fabric with an average thickness of 3.72 mm and 20 mm width. As per standard, a span to thickness ratio of 32:1 was chosen so that the failure is on the outer surface of the specimen due to the bending moment. An extra allowance of 20% was given to the specimen length from the calculated support span. A set of seven specimens without any waviness defect and another set of six specimens with waviness defect (in the middle) were prepared. A wave severity of 0.035 was measured on the waviness induced

specimen. Figure 6.1 shows the test specimen over the three-point bend fixture. All the edges and edge faces were polished to avoid stress concentration and further crack propagation during the test. Made sure the alignment of the loading nose at the top surface was perpendicular and in the middle of the support spans. A cross head speed of 1 mm/min was selected for the testing.

Figure 6.1: An illustration of the three-point bending fixture with specimen.

The force applied on the specimen with specified crosshead speed and force-deflection data points were taken during the test. All the specimens were tested under the same crosshead speed and span to thickness ratio for a better comparison of the strength and stiffness values. The results and failure characterization are discussed in the following section.

6.2.2 Results and discussion

The maximum flexural stress can be calculated based on the below equation if the specimen follows a linear stress-strain path up to the point of rupture.

$$\sigma_b = \frac{3PL}{2bh^2} \quad (6.1)$$

σ_b = Bending stress at the outer surface (MPa)

P = Applied load (N)

L = Support span (mm)

b = width of the beam (mm)

h = Thickness of the beam (mm)

The maximum strain at the outer surface can be calculated as

$$\varepsilon_b = \frac{6\delta h}{L^2} \quad (6.2)$$

ε_b = Maximum bending strain (mm/mm)

δ = Mid span deflection (mm)

As shown in Figure 6.2, all the samples followed the linear stress-strain path until failure. From the graph, it is evident that the inclusion of fiber waviness decreases the stiffness and flexural strength.

Figure 6.2: Stress – Strain behavior under bending

Figure 6.3: Comparison of unidirectional and wavy specimens, a) Flexural strength, b) Flexural modulus

It was found that even with the presence of a wave severity of 0.035, the flexural strength dropped by 35% and the flexural modulus of elasticity dropped by 16%. Figure 6.3 shows the deviation from the average flexural strength and flexural modulus calculated from experiment. From the investigation conducted on out-of-plane fiber misalignment, Potter et al. [7] found that flexural strength dropped more when the misalignment affected the tension side as compared to the compression side. As compared to the previous compression experiment, the reduction in strength in flexural testing was 30% less for the same severity level.

Figure 6.4: Failure over the tension side and compression side of the unidirectional specimen.

Failure modes found in the failed specimens were observed visually and through optical microscope. For the unidirectional specimen, the compression side was failed due to fiber micro-buckling and in the tension side, the failure was initiated with matrix crack along the fiber direction. In majority of the specimen final failure ended up with delamination of the outer layer at the middle region. Figure 6.4 (a, b), shows the visual observation of the failure on both the

surfaces. From the optical microscope observations shown in Figure 6.4 (c), a matrix crack at the tension side and micro-buckling followed by fiber breakage were clearly visible at the compression side.

Figure 6.5: Final failure over wavy specimen. a) Outer surface failed due to tensile stresses, b) Inner surface failed due to compression stresses, c) Damage at the specimen thickness region, d) Fiber kink band with corresponding orientation angle 18.5° .

Figure 6.5 shows the damage observed over the waviness induced specimen under flexural testing. On the tension side, similar to the earlier observation, matrix cracks were found along the fiber waviness path. At the bottom free edge (see Figure 6.5(a)), the extended matrix crack detached the surface lamina from the laminate due to the fiber discontinuity. This was happened due to cutting of the specimen into standard size along the fiber direction. However, the fiber discontinuity situation may not be present at the waviness region in a real structure. The loading nose passes through the black marker line shown at the mid-section (see Figure 6.5 (b)) and the left side of the marker line shows the damage over the compression side. The micro-buckling of the fibers occurs perpendicular to the fiber orientation and propagates away from the middle loading line due to the fiber waviness. The fiber breakage is also visible over the

thickness from the top side of the waviness sample. Figure 6.5(d) shows the kink band formation over the compression side after a fiber micro-buckling.

For unidirectional specimens, there exhibit surface cracks at the outer surface (under tension) and local buckling (micro-buckling or ply level buckling) at the inner surface (under compression) preceded by delamination of the outer ply. The delamination of outer ply occurs only when the shear stress of the specimen exceeds the interlaminar shear strength. Compared to unidirectional specimen, the current wavy specimen with wave severity 0.035 requires 35% less load towards the flexural strength. Moreover, from the shear test conducted (in Chapter 5), both unidirectional and wavy specimens have comparable shear strength irrespective of defect. Thus, for wavy specimen the chances of a delamination failure before maximum flexural stress at the inner surface is negligible.

On the wavy specimens, the damage initiation was not uniform along the width. The top side of the waviness defect seems to be damaged more as compared to the bottom side of the defect. This can be explained with the help of bending stiffness matrix ($[D]$). Due to the presence of through thickness in-plane waviness defect, the laminate loses its symmetry about x-z plane (x – along the fiber direction and z – perpendicular to the lamina plane) and this leads to the existence of some non-zero terms in $[D]$. This will cause the involvement of bend-twist coupling and when the specimen is under bending, the amount of twisting can be quantified with the help of a non-dimensional number $B_t = |D_{16}|/D_{11}$ [8]. Hence, while bending, the waviness defect containing specimen will undergo a localized clockwise twist (looking from the left side). This causes stress concentration and more damage on top side of the specimen.

6.3 Flexural fatigue test

The fracture mechanism of composite materials under cyclic loading is complex. According to the previous studies conducted on the fatigue life of the composite materials, there are four different basic failure modes that generally

occur during cyclic loading. This includes matrix cracking, delamination, interface debonding and fiber breakage [9].

The wind turbine blades are subjected to a pushing wind force, gravitational force due to blade weight and a centrifugal force during rotation. Because of the lower rotating speed, the effect of centrifugal force is generally ignored during the blade design. The bending stresses due to the blade weight in the edgewise direction and due to the blowing wind in the flap-wise direction are the major active cyclic stresses on the blade. Currently, the cyclic pushing load due to wind load on the blade structure was taken into consideration. During the operation, the wind load makes the blade to bend in the flap-wise direction and the fibers on the pressure side are subjected to tension and on the suction side, compression. This tensile stress or compressive stress on one side of the blade are fluctuating but not reversible during the flap-wise bending. Similarly, a fluctuating irreversible load acting on the unidirectional specimen made up of blade material was studied here. Both unidirectional specimen and fiber waviness induced specimens were prepared and tested under cyclic loads.

Sakin [10] had studied three point bending fatigue on GFRP material with fiber weight densities 800gsm, 500gsm, 300gsm and 200gsm and found that fatigue life decreases with decrease in weight per unit area of fiber and fatigue life has greater dependence on fiber anisotropy. Belingardi [11] did a bending fatigue on both cross-ply and angle ply made up of carbon-glass/epoxy hybrid laminate. He found that for the 85% of the ultimate bending strength the damage was more significant on the cross-ply laminate as compared to the angle-ply. He also found that the reduction in material strength and elastic modulus measured after one million cycle has dependence on the stress ratio and laminate geometry. Daniel [12] had performed a pure fatigue compression analysis on carbon/polysulphone composite with layer waviness. He found both reduction in fatigue life and compressive strength with a moderate level of layer waviness. Similarly Horrmann et al. [13] had studied the out of plane fiber waviness effect on CFRP material under C-C and T-C situation and found difference in failure

mode with fiber defect angle. There is no previous flexural fatigue study conducted on fiber waviness defect induced specimens. Both fatigue life and failure modes of the in-plane wavy specimens were investigated in this flexural fatigue testing.

The bending fatigue test was conducted with load control. The stress ratio can be considered as compression-compression for one side of the specimen or tension-tension on the opposite side of the specimen. From the machine point of view, the applied load is in compression, but the stress ratios were considered as in between 0 and 1. The specimens were tested at stress ratios $R = 0.1$ and $R = 0.5$. Where R is the ratio of minimum to the maximum applied stress in fatigue. The Figure 6.6 a pictorial representation of a sinusoidal load (at 3 Hz) with a unit (1.0) maximum load and 0.5 unit, 0.1 unit minimum load corresponds to $R = 0.5$ and $R = 0.1$ respectively. That means the maximum stress (σ_{max}) during each loading cycle was 2 times and 10 times higher than the minimum stress (σ_{min}).

$$\text{Stress ratio} \quad R = \frac{\sigma_{min}}{\sigma_{max}}$$

Figure 6.6: Representation of stress amplitude for a unit maximum load with respect to time.

6.3.1 Specimen geometry and testing

A three-point bend loading system was used for the testing procedure (see Figure 6.7). As per ASTM standard D7774 [14], a rectangular cross sectioned

specimen was prepared with a span to thickness ratio of 18:1. The specimen was cyclically loaded into one direction since both maximum and minimum stresses are positive. Each specimen consists of eight layers of unidirectional fabric with an average specimen thickness of 4.78 mm and 25 mm width.

Figure 6.7: Three-point bending fixture and specimen mounted on fixture (insight).

All the specimens were cut from a single cured panel using diamond cutter and sharp edges were polished. The specimens were prepared in such way that waviness defect is presented at the exact middle of each sample. For the comparison of results obtained, similar size unidirectional samples were prepared without any waviness defect. Both set of samples were tested for same span to thickness ratio. An overhanging allowance of 10% was given to both end of the span length to avoid the slippage from the support.

A sinusoidal wave form was followed (see Figure 6.6) to implement the dynamic load in the specimen at 3 Hz frequency. The effect of temperature was not taken into consideration for the current fatigue study. The machine records the deflection, time and the number cycles for each stress ratio. Three specimens were tested for each set of stress amplitude. Initially a static flexural test was performed to determine the maximum flexural strength for the current span to

thickness ratio. Cyclic loading was continued until the specimen fails or it reaches one million cycles. Under the load control tests, the testing continues until the specimen yields if the maximum deflection increases more than 10% during the test or with a specimen rupture [14].

6.3.2 Results and Discussion

The specimens were tested under constant stress cycle and cycle life were measured. The graphs in Figure 6.8 and Figure 6.9 shows the comparison of unidirectional and wavy specimen tested at two different stress ratios for one million cycle life. D'amore [15] had studied the effect of stress ratio on the flexural fatigue behavior of continuous fiber composites and found that stress ratio has strong influence on the fatigue life. He found that when the stress ratio increases from $R = 0.1$ to $R = 0.7$, there is two decades increase in the fatigue life. Similar way in the current experiment on both unidirectional and waviness induced specimens, the fatigue life at $R = 0.5$ was higher than that of specimens tested at $R = 0.1$. Figure 6.10 shows the increase in fatigue life of wavy specimen when the stress ratio from $R = 0.1$ to $R = 0.5$. At high stress ratio ($R = 0.5$), the stress amplitude is small with a high average displacement. Though the damage initiates earlier, the damage propagates slowly due to lower stress amplitude and a longer fatigue life with minor damage after one million cycles. Similarly, low stress ratio ($R = 0.1$), corresponds to larger stress amplitude with small average displacement, hence a smaller damage initiation ends up with a high growth rate in damage due to large stress amplitude and lead to shorter fatigue life. Table 6.1, represents the cycle life measured during the test and the observed reduction in cycle life due to fiber waviness. Compared to low amplitude stress ratio ($R = 0.5$), the drop-in fatigue life was drastic (10^4 to 10^5 cycles) in high amplitude stress ratio ($R = 0.1$). The trendline on each graph shows the reduction in fatigue life on a logarithmic scale.

Table 6.1: Fatigue test results of specimen

Maximum load (N)	Maximum stress (MPa)	Number of cycles			
		R = 0.1		R = 0.5	
		Wavy	UD	Wavy	UD
3250	1472/1673(Static)	1	1	1	1
3000	1359	245	4390	16562	386030
3000	1359	751	65011	26929	214207
3000	1359	820	32535	46766	197612
2500	1133	3452	485633	380465	1000000
2500	1133	6725	304970	780021	1000000
2500	1133	9125	574563	348760	1000000
2000	906	53854	1000000	1000000	1000000
2000	906	70621	884358	1000000	1000000
2000	906	33703	914965	1000000	1000000
1500	680	238744	1000000	1000000	1000000
1500	680	345955	1000000	1000000	1000000
1500	680	578206	1000000	1000000	1000000
1000	453	1000000	1000000	1000000	1000000
1000	453	1000000	1000000	1000000	1000000
1000	453	1000000	1000000	1000000	1000000

Figure 6.8: Comparison of S-N plots for unidirectional and wavy specimen at stress ratio $R = 0.5$

As expected for the same load conditions, the fatigue life of waviness induced specimens was less than that of normal unidirectional specimens (see Figure 6.8 & Figure 6.9). For the same fiber wave severity, compared to stress ratio $R = 0.5$

the drop-in fatigue life trend is higher at $R = 0.1$. At $R = 0.5$, the approximate reduction in the endurance stress for the wavy specimens compared to unidirectional is 5% (considering 10^6 as cycle life). Similarly, at $R = 0.1$, the reduction in endurance stress for the wavy specimen is 25%. Hence for the same wave severity, the fatigue life of wavy specimens (see Figure 6.11) decreases more than that of unidirectional specimens with decrease in stress ratio (from $R = 0.5$ to $R = 0.1$).

Figure 6.9: Comparison of S-N plots for unidirectional and wavy specimen at stress ratio $R = 0.1$

Figure 6.10: Comparison of S-N plots for wavy specimens at stress ratio $R = 0.1$ and 0.5 .

Figure 6.11 shows the damage observed on the tension side and compression side of the four-different waviness induced specimens at a stress ratio $R = 0.1$. On the tension side, the damage is due to fiber-matrix debonding and outer layer delamination and on compression side, the damage is due to fiber micro-buckling. At lower stresses, the damage is more on the tension side as compared to compression side. For specimen that completes one million cycles, there is little damage on the compression side but fiber strand debonding is visible over tension side. Similar type of damage is found in specimens tested at $R = 0.5$ as well. Hence for both the stress ratios at $R = 0.5$ and $R = 0.1$, the damage on the tension side was more severe as compared to compression side.

Figure 6.11: The visible damage on failed specimens over the outer (in tension) and inner (in compression) surface at various loads.

A comparison study on the failure modes was done between the unidirectional and waviness defect containing specimens that completed one million cycles. As discussed earlier, compared to compression side, more damage was seen on the tension side in both the specimens. From Figure 6.12, it is evident that unidirectional specimen was damaged due to fiber matrix debonding at the middle region of the specimen (on tension side). But for wavy specimen, fiber strand debonding was the major failure mode on the tension side and this could

be reflected over the compression side as well. A laser shearography analysis was performed on the damaged surface and found that compared to the surface damage on the unidirectional specimen, more internal damages occurred on the wavy specimen due to strand debonding (see Figure 6.13). From the earlier research, it was found that unidirectional laminates at high stress amplitude ($R = 0.1$) were failed due to damage over the tension side and the major failure mode observed was fiber matrix debonding and delamination [16]. Similar failure mode was observed for unidirectional specimen but not for wavy specimen.

Figure 6.12: Comparison between unidirectional and wavy specimen

Figure 6.13: Laser shearography over the damaged area.

X-ray tomography scanning was done on the same (damaged) area to visualize the internal damage (see Figure 6.14 and Figure 6.15). The delamination failure on the tension side of the unidirectional specimen is clear

from Figure 6.14(a, c, d). For the waviness containing sample, Figure 6.15(b) shows the damage across the thickness at the plane of loading nose and the strands are totally displaced internally as compared to unidirectional specimen. Though there was reduction in fatigue life due to waviness, chances of damage due to delamination failure mode were fewer on a wavy specimen subjected to flexural fatigue loading.

Figure 6.14: 3D tomographic scan of unidirectional specimen.

Figure 6.15: 3D tomographic scan of wavy specimen.

6.4 Summary

Static and fatigue flexural testing were performed on the in-plane wavy specimen. From the static flexural analysis, a reduction of 35% in flexural strength and 16% in flexural modulus were found due to 0.035 wave severity. A change in the failure modes were observed due to fiber waviness under static flexural loading. Flexural fatigue analysis was studied at two different stress ratios ($R = 0.1$ and $R = 0.5$). It was found that both fiber waviness and stress ratio has dependence on the cyclic life. In fatigue experiment, a delamination failure mode was found on the tension side of the unidirectional specimen. But for wavy specimen, a fiber strand debonding was the major mode of failure.

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Chapter 7

Analysis of a wind turbine blade with a fiber waviness defect on spar-cap

In this chapter, the basic blade design procedure is presented. A frame work design of a blade with 6 m blade radius based on an existing aero-elastic turbine model using NuMAD tool is explained. A flap-wise bending analysis of the blade shell form in ABAQUS software is carried out to study the effect of waviness on spar-cap region. To further understand and validate the influence of fiber waviness under bending on both pressure side and suction side of the blade, a four-point bending experiment is performed on a composite I - beam with fiber waviness on top and bottom of the flange.

7.1 Introduction

Wind turbine blade is an aerodynamic structure which carries load in both flap-wise and edgewise direction. The aerodynamic shape consists of two parts namely suction side and pressure side. The upper shell of the blade portion is suction side and the lower shell is the pressure side. The spar-cap in the aerodynamic structure is considered as the primary load caring member and most of the modern wind turbine spar-caps are made up of laminated composites.

7.2 Design procedure

In this section, the details of parameters to be considered for a basic blade design are explained. The bending moment data is taken from an existing 6 m radius blade model developed by Energy Research Institute at NTU (ERIAN). The design consists of an aero-elastic model developed using FAST software at gust wind speed for 50 years of recurrence period. From the existing design, the

bending moment data at different sections of the beam based model was derived. Subsequently, an approximate blade thickness was calculated for the maximum tip deflections. Based on the existing design and with the help of NuMAD software, a blade profile was generated. The generated profile then transferred to ABAQUS and a static flap-wise bending analysis was performed by applying a load equivalent to the derived bending moment at selected sections of the blade. An optimum spar-cap thickness was calculated based on the allowed tip deflection. For the current Abaqus shell model, fiber waviness defect was introduced at four different spar cap locations of the blade. The effect of the waviness was studied by considering the waviness on both suction side and pressure side.

For wind turbines, IEC 61400-1 [1] was followed for design evaluation and testing. The design is subdivided into another category called small wind turbines (SWT) (IEC 61400-2) [2] with rotor swept area of less than or equal to 200 m². The present wind turbine design comes under class IV with average wind speed (V_{ave}) 6 m/s. The class was selected based on the wind condition, environment condition and electrical load conditions.

7.2.1 Structural design

It includes the verification of the whole structural integrity of turbine components in the critical load path from bottom foundation to top blade tip comprising of rotor blade, hub, shaft, tower, nacelle, yaw haft and connections. The design loads can be determined by a) simplified load methodology b) simulation model or by c) full scale measurement. For the existing developed model, a simulation model methodology was followed with the help of FAST software [3]. FAST is an aerodynamic computer-aided engineering tool used to design horizontal axis wind turbines (HAWT). FAST is a cluster of different dynamic models, which are coupled through modular interfaces. The loads acting on the wind turbine consists of vibrations, gravitational load, aerodynamic loads, operational loads, etc. A partial safety factor of 1.35 was considered for the ultimate loads to account the uncertainty in load estimation process.

Table 7.1: Calculated bending moments

Station	Discrete mass (Kg)	Discrete Load (N) in y-direction	Blade length (m)	Bending Moment at the stations (Nm)	BM without Safety factor (Nm)	BM with Safety factor=1.35 in (Nm)
1		0	0.000	9499.0	7033.8	9495.59
2		0	0.130	9017.6	6670.3	9004.918
3		0	0.230	8647.3	6390.7	8627.478
4		0	0.330	8276.9	6111.1	8250.038
5		0	0.430	7906.6	5831.6	7872.599
6		0	0.530	7536.3	5552.0	7495.159
7		0	0.640	7128.9	5244.4	7079.975
8		0	0.800	6536.4	4797.1	6476.072
9		0	0.930	6055.0	4433.6	5985.4
10		0	1.180	5129.2	3734.7	5041.8
11	185	1814.85	1.440	4166.3	3007.7	4060.457
12		0	1.720	3637.5	2582.0	3485.689
13		0	2.020	3071.0	2125.8	2869.866
14	80	784.8	2.320	2504.5	1669.7	2254.044
15		0	2.630	2162.4	1441.6	1946.132
16		0	2.930	1831.3	1220.9	1648.154
17		0	3.240	1489.2	992.8	1340.242
18		0	3.540	1158.1	772.0	1042.263
19	60	588.6	3.840	827.0	551.3	744.2847
20		0	4.120	682.8	455.2	614.4984
21		0	4.380	548.9	365.9	493.9826
22		0	4.630	420.1	280.1	378.1019
23		0	4.860	301.7	201.1	271.4918
24		0	5.070	193.5	129.0	174.152
25		0	5.250	100.8	67.2	90.71798
26	45	441.45	5.400	23.5	15.7	21.1896
27		0	5.530	14.0	9.3	12.58133
28		0	5.630	6.6	4.4	5.959575
29		0	5.690	2.2	1.5	1.986525
30	7.5	73.575	5.720	0.0	0.0	0

In Table 7.1, the last columns in blue color shows the calculated bending moments based on aero-elastic model. The blade length of 5.72 m is divided into 29 sections and 30 stations. A discrete set of masses were applied on to various station points and the amount of mass needed to achieve the design bending

moments were calculated. Figure 7.1 shows the bending moment based on applied load along the span from root to tip.

Figure 7.1: Bending moment distribution along the blade span.

7.2.2 Airfoil

Airfoil is another parameter that can be changed to optimize the blade design by changing the lift coefficient and optimal angle of attack. The airfoil towards the tip of the blade generate high lift due the high relative tip speed. While the airfoil towards the root is purely a structural contribution rather than aerodynamic performance. Hence, thicker airfoils were used at the roots. For the current blade, S822 airfoil developed by National Renewable Energy Laboratory (NREL) was considered [4].

7.3 NuMAD

In the last couple of decades, dramatic changes were observed in the design of modern wind turbine blades which has resulted in refining of the structural level blade design and its analysis. Though beam models are often adequate for preliminary design, a more robust structural finite element analysis (FEA) is necessary to verify the final blade design.

A design tool called NuMAD (Numerical Manufacturing And Design tool) developed by Sandia National Laboratories (SNL) [5] was used for developing

the three-dimensional architectural design of the blade. NuMAD provides an intuitive interface for defining the outer blade geometry, shear web locations in the blade. Later, the complete 3D architecture transferred into any finite element analysis package (presently ABAQUS). Once the model is imported, a static analysis was done to understand the strength and response of the blade.

Initially, blade was divided into a set of station along the length from root to tip. The hub radius is 250 mm. The blade root starts at station point 1 with blade span coordinate 0.27 mm and ends at 5.99 mm. Based on the station, parameters such as generalized airfoil coordinates, station location from root, maximum chord length, twist angle and aero dynamic center were added into the design tool to generate the blade profile (Table 7.2). Each airfoil shape then partitioned into different zone such as root, leading edge, trailing edge, spar-cap and shear web for the easy selection of parameters during FE analysis.

Table 7.2: Blade airfoil parameters along the blade span.

Station	Blade span (m)	Twist (deg)	Chord (m)	aero center
1	0.27	20.59	0.20	0.500
2	0.40	18.35	0.20	0.500
3	0.50	16.04	0.20	0.500
4	0.60	13.50	0.24	0.267
5	0.70	12.70	0.33	0.267
6	0.80	11.50	0.39	0.267
7	0.91	10.90	0.41	0.267
8	1.07	9.02	0.43	0.267
9	1.20	8.44	0.41	0.267
10	1.45	7.02	0.39	0.267
11	1.71	5.81	0.37	0.267
12	1.99	4.75	0.34	0.267
13	2.29	3.83	0.32	0.267
14	2.59	3.04	0.29	0.267
15	2.90	2.36	0.27	0.267
16	3.20	1.77	0.25	0.267
17	3.51	1.28	0.23	0.267
18	3.81	0.86	0.21	0.267
19	4.11	0.51	0.19	0.267
20	4.39	0.23	0.18	0.267

21	4.65	0.00	0.16	0.267
22	4.90	-0.18	0.15	0.267
23	5.13	-0.32	0.14	0.267
24	5.34	-0.43	0.13	0.267
25	5.52	-0.49	0.13	0.267
26	5.67	-0.55	0.13	0.267
27	5.80	-0.57	0.12	0.267
28	5.90	-0.59	0.12	0.267
29	5.96	-0.60	0.12	0.267
30	5.99	-0.61	0.12	0.267

Figure 7.2: Generated blade skeleton in NuMAD

The Figure 7.2 shows the generated 3D model. This model later transferred into ABAQUS for the flap-wise bending analysis based on the discrete mass calculated in Table 7.1.

7.4 Static analysis

A static flap-wise analysis was done on the blade to find the maximum stresses and strains over the blade and the tip deflection based on the design load conditions. The details of material properties used for the blades design is listed in Table 7.3.

Table 7.3: Properties of material used for the blade design.

Type	Unit	Triaxial	Unidirectional		Foam core	Soric
		Orthotropic	Orthotropic glass	Orthotropic carbon	Isotropic	Isotropic
Layer Thickness	[mm]	0.689	0.62	0.343	25	2
E ₁₁	[MPa]	54200	41400	100750	2.74	1000
E ₂₂	[MPa]	14970	10430	7583		
E ₃₃	[MPa]	14970	10430	7583		

G_{12}	[MPa]	9970	3335	5446	30	26
G_{23}	[MPa]	8970	3472	2964		
G_{13}	[MPa]	9970	3472	2964		
ν_{12}	[-]	0.37	0.28	0.32	0.3	0.3
ν_{23}	[-]	0.35	0.4	0.37		
ν_{13}	[-]	0.32	0.3	0.35		
density	[kg/m ³]	1550	1550	1550	100	470

Each region of the blade was stacked with different layup sequence. The spar-cap was made up of gradually decreasing stacking sequence from the root to tip. At the maximum thickness area, 11 layers of laminates with thickness 6.12 mm were used. When it reaches to the tip area, the number of layers reduced to two with thickness 1.37 mm. Table 7.4 represents the stacking sequence and the material used at different locations of the blade.

Table 7.4: Stacking sequence at various blade region.

Location	Material	Number of layers	Rotation angle
Root	Triaxial	1	0/+45/-45
	Unidirectional glass	3	0
	Unidirectional carbon	3	0
	Unidirectional glass	3	0
	Triaxial	1	0/+45/-45
Shear web	Unidirectional carbon	1	+45
	Unidirectional carbon	1	-45
	Foam core	1	0
	Unidirectional carbon	1	-45
	Unidirectional carbon	1	+45
Shell	Triaxial	1	0/+45/-45
	Soric	1	0
	Triaxial	1	0/+45/-45
Spar cap near to root	Triaxial	1	0/+45/-45
	Unidirectional glass	3	0
	Unidirectional carbon	3	0
	Unidirectional glass	3	0
	Triaxial	1	0/+45/-45
Spar cap at tip	Triaxial	1	0/+45/-45
	Triaxial	1	0/+45/-45

The whole 5.72 m blade model was sweep meshed with a 0.5 mm shell element S4R. The root surface was constraint to one reference point at the center of the root with zero degrees of freedom. The stations 11, 14, 19, 26 and 30 were selected for applying the load in the flap-wise direction with a magnitude of

1814.85 N, 784.8 N, 588.6 N, 441.45 N and 73.575 N respectively (Table 7.1). The loads were applied from the pressure side of the blade through a reference point, which act as a locus of all the surface airfoil coordinates of the loading station (see Figure 7.3).

Figure 7.3: Boundary conditions for the blade loaded in flap-wise direction.

Abaqus/standard analysis was performed and the tip deflection, maximum Von-Mises stresses were estimated from the stress plot.

Figure 7.4: Stress plot of the blade at maximum deflection.

From the visualization module, a stress concentration was observed at the root transition region of pressure side with a maximum stress of 125 MPa (see Figure 7.4). A tip deflection of 54.4 cm was calculated for the applied load based on maximum bending moment. As per IEC 61400 – 2[2] no part of the blade shall hit the tower under the most severe bending moment distribution for the design load cases and the observed tip deflection was within the safe limit.

7.4.1 Influence of waviness at spar-cap region

In the past research, fiber waviness defects were found on failed blades [6, 7]. This manufacturing defect, as explained thoroughly in this thesis, could lead to the strength and stiffness drop and failure of the whole structure [8, 9]. By considering this fact into account, currently the effect of fiber waviness at various spar-cap region was studied with the help of ABAQUS simulation. A through thickness in-plane fiber waviness was chosen with a wave severity of 0.07 (with wavelength 65 mm and amplitude 4.55 mm) that is typically observed in the actual blade[7] was introduced on spar-cap region at center zone (approx. 3 m from root section) and transition zone (near to root section) separately. An Abaqus/standard analysis was performed with the same design load and boundary conditions. Since the blade consist of two spar-caps each at suction side and pressure side, analysis of those four sets were performed separately. Table 7.5 outlined the waviness location and Figure 7.5 shows the induced waviness at center zone and transition region of the blade model.

Table 7.5: Waviness location

Region		Waviness location	Wave severity	Tip deflection (m)
		No waviness	0	0.544
Spar-cap	Pressure side	Transition zone	0.07	0.596
		Center zone	0.07	0.601
	Suction side	Transition zone	0.07	0.548
		Middle zone	0.07	0.548

Figure 7.5: Blade spar-cap with fiber waviness a) Waviness at the middle region, b) Waviness at the transition region.

It was found that for the same load condition, the waviness defect over pressure side causes additional tip deflection of 48 mm to 53 mm as compared to the waviness at suction side (see Figure 7.6). While bending, the outer surface of a beam elongates more, hence during flap-wise bending the outer layer at the pressure side would strain more as compared to inner layer at the suction side. From the experimental study conducted in previous chapters, it was found that a through thickness in-plane waviness reduces the stiffness properties while bending. Due to higher strain deformation at pressure side and the stiffness reduction of the waviness affected area, causes an additional bending with an extra tip deflection was observed.

Figure 7.6: Effect of waviness at transition and middle region over the tip deflection.

From the deflection graph along the blade length shown in Figure 7.7, it was confirmed that the additional deflection is caused due to the reduction in material stiffness at the waviness induced region. The waviness at the transition region caused the blade an additional deflection right after the transition region. Similarly, a waviness at the mid region on the spar-cap, cause the blade to deviate from the normal deflection path and finish with an additional tip deflection. In the stress plot, a stress concentration was observed and the maximum stress over the structure shifted towards that waviness affected region.

Figure 7.7: Blade tip deflection because of waviness at the pressure side.

Figure 7.8: Location of strain measurement from element node at region 1 and 2.

Under the design load condition, the maximum stress and maximum strain was found concentrated at the waviness region of the blade. To understand the strain variation over the section along the blade thickness, surface true strains of the waviness affected regions were calculated from the nodal points in the model. At the waviness induced blade central spar-cap region, two strain values were measured from the region 1 and region 2 as shown in Figure 7.8. In addition, a third strain value was measured from the opposite face of the waviness induced region.

Figure 7.9: The strain across the cross section at the waviness effected area of the blade model, a) waviness at the spar-cap on blade top (suction side), b) Waviness at the spar-cap on blade bottom (Pressure side).

The pressure side of the blade would be under tension, and the suction side would be under compression during the flap-wise bending analysis. For a beam in bending, the outer layer strain would be more than the inner layer strain due to the difference in the radius of curvature. In addition to that, when the waviness affects the outer layer (pressure side), the increase in layer compliance causes further increase in strain at the waviness affected region of the outer layer. Figure 7.9 shows the measured strain from the model at the outer and inner layer of the spar-cap based on the waviness location. To validate the measured strain

behavior from the FE simulation, a flexural study had been conducted on a composite I-beam with waviness at outer and inner flange separately.

7.5 Composite I-beam

Spar-cap is the main load bearing component in a blade structure and an I – section was used to model the spar-cap and shear web of the blade. Irrespective of various design concept, the key responsibility of the spar-cap is to provide the required bending strength and stiffness. Considering the waviness effected middle region of the current spar-cap design, 4 mm thick laminates were presented with majority of unidirectional GFRP with a cross section of approximately 80 mm thick at the root and 3 to 5 mm thick at the tip. To validate the simulation results, an I-beam with six layers (≈ 3.72 mm) of unidirectional GFRP laminate at top and bottom flange with a polyurethane (PU) foam as web (height – 50 mm, density – 100kg/m^3) were made using the same material used for the blade model. Each I-beam measured an average height of 57.45 mm. In the blade model, the center of the spar-cap is approximately 60 mm thick and consists of 6 layers of unidirectional layers at top and bottom flange. The dimension of the I-beam is approximately equal to the model blade cross sectional dimension at the mid span. A four-point bending analysis has been performed on the I-beam with span length of 250 mm, width 50 mm and load span of one third of the span length (83.33 mm). The maximum strain over the beam will always be at the point of maximum bending moment. As shown in Figure 7.10, a through thickness in-plane waviness was introduced at the middle of the beam flange.

Figure 7.10: A composite I-beam with waviness at the top and bottom flange.

The flexural experiments were conducted by considering the waviness on both tension side and compression side separately. Strain over the top surface and bottom surface were measured using bonded strain gages. Over the waviness induced area, two set of strains were measured at upper and lower region. Four set of specimens were tested separately by considering waviness at the top flange and at the bottom flange.

Figure 7.11: (a) Experiment set up with waviness at the bottom of the beam, (b) bonded strain gages.

The tests were conducted at a speed of 1 mm/min and the strains were measured using a datalogger. Both longitudinal and lateral strain were measured with a bonded strain gage. Over the waviness affected area, two strain gages were bonded as shown in Figure 7.11 (gage 1 and gage 2). In addition, the third strain gage (gage 3) was bonded at exactly opposite flange surface of the waviness region.

7.5.1 Result and discussion

In total, eight I - beams were tested by considering four beams each with fiber waviness at the top flange and at the bottom flange. Compared to the inner most layer (in compression), the outer most layer (in tension) strains more due to a larger radius of curvature at higher deflection. Hence, at a particular load, the outermost layer has larger strain value (see Figure 7.12) compared to innermost layer. It is clear from the measured strains 1 and 2 as shown in Figure 7.12, irrespective of waviness location (top or bottom), the strain rate at the upper

region (strain 2) of the waviness affected area is greater than the lower region (strain 1).

Figure 7.12: Measured longitudinal strain with applied load.

The Figure 7.13 shows the measured strain at the mid-section of the beam and the dash line represents the trend in strain across the section. It was found that, irrespective of waviness position (top or bottom) the zero-strain point in the beam section always shift towards the compression side. For a particular applied load, the wavy region would undergo additional strain at both tension side and compression side compared to a defect free region. By considering the strain 1 and strain 2 at the wavy region, it could be predicted that the localized damage always initiated from the upper region (strain 2 > strain 1) at extreme load conditions. In the previous chapter 6, it was evident from the static flexural analysis that the damage initiated at upper region of the wavy area. Hence, after damage initiation, more damage was found at the upper region of the waviness (Strain 2 location).

Figure 7.13: Strain along the cross section of the I-beam.

The simple bending theory is only applicable to small deflection. At larger deflection during bending, the outermost layer strain is greater than that of innermost layer and causes the neutral axis shift towards the compression side. For the present experiment, the beam is symmetric with a localized reduction in stiffness at the waviness effected region. When the waviness comes at top flange (see Figure 7.13(a)), the compressive strain at the waviness effected top flange region increases (more negative) and neutral axis shift away from the middle section. Similarly, when the waviness is at the bottom flange (see Figure 7.13(b)), the tensile strain at the waviness effected bottom flange region increases (more positive) and the neutral axis shift towards the compression side. Similar trend was observed in the cross-sectional strain of ABAQUS blade model (see Figure 7.9).

In Figure 7.14, the numbers 1, 2 and 3 are the measured strain location in the blade model and the strain gage number in the beam experiment. At compression side, the strain rate of model was higher than that of experiment, and was due to the difference in boundary conditions and the applied load. As both load and boundary conditions were different for model and experiment, the experimental flexural I - beam analysis helps to understand the strain deformation on a blade cross section under the influence of fiber waviness.

Figure 7.14: Comparison of strains obtained from the wavy middle region of the FE blade model and the I-beam experiment.

The present study considered an infrequent and neglected maximum size of the waviness defect to be expected at the spar-cap area in a blade. Thus, the I-beam experiment helps to identify the strain deformation occurs with a same size in-plane fiber waviness on a blade spar-cap under flap-wise flexure. While comparing the scale of the waviness defect in terms of beam span length, for the experiment it was 1:8.5 and for the blade model it was 1:44. Hence the impact of the defect over the reduction in laminate strength of I-beam and the FE blade model were incomparable. The above experiment helps to understand the behavior of localized in-plane fiber waviness under flexural loading condition. Also based on the waviness location, it would be possible to predict the regions of stress concentration and localized damage initiation.

7.6 Summary

A 6 m blade design was discussed with the help of an existing aero-elastic blade model and a shell blade model was developed using NuMAD. A flap-wise bending analysis of the blade shell form in ABAQUS software was done to understand the effect of waviness on spar-cap region. The strain deformation along blade section due to the waviness were studied. To validate the influence of fiber waviness under bending on both pressure side and suction side of the blade, a four-point bending experiment was performed on a composite I - beam

with fiber waviness on top and bottom flange. The flexural experiment helps to understand the strain deformation under the influence of in-plane fiber waviness along the cross section.

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Chapter 8

Conclusions and future work

In this chapter, a summary of the major contributions and conclusions from all the chapters of this thesis are presented followed by some recommendations on the future work.

8.1 Conclusions

The thesis was focused on investigating the effects of through thickness in-plane fiber waviness on the mechanical properties unidirectional FRP laminates. Coupon level analysis was used to study the various properties in numerical and experimental method. Finally, a static FE analysis on a blade model was carried out to understand the waviness effect at the structural level. The main conclusions from the present investigations are listed below:

- Among various types and sizes of waviness defect, a through thickness in-plane fiber waviness was selected and successfully introduced into unidirectional laminates. The intensity level of the waviness was represented with a term called fiber wave severity (W_s). Composite laminates were prepared with fiber wave severity ranging from 0.01 to 0.075.
 - Static compressive analysis of the waviness induced specimens confirmed that there is a significant reduction in compressive strength as compared to laminates without waviness defect. Further, the compressive strength reduced with increase in fiber wave severity. With a severity level of 0.075, a compressive strength reduction of approximately 75% were observed.
 - Failure characterization was performed on the failed samples using optical and scanning electron microscopes. As the fiber severity increases, a transition in failure modes was observed and with increase in fiber wave

severity the failure was purely due to micro-buckling followed by fiber kinking.

- Among various failure modes presented in FRP laminates, delamination is a major mode of failure observed under various loading conditions. The interlaminar fracture energy of laminates has greater dependence on the delamination failure.
 - A Double Cantilever Beam (DCB) experiment was conducted to understand the interlaminar resistance for the crack propagation and to calculate the fracture energy for the crack initiation and crack propagation under the influence of fiber waviness. For the same, two categories of specimens were prepared. On one set the waviness defect was at the crack initiation region and on another set the waviness was at the crack propagation region. A comparison study was performed with normal specimens having no waviness defect.
 - It was found that compared to normal unidirectional specimens, a considerable difference in the load-displacement data when the crack initiate at the waviness region. Fiber waviness causes increase in compliance of the specimen loading arm. However, no difference in load-displacement data was observed for specimens with waviness defect at the crack propagation region.
 - Irrespective of waviness defect and the location of defect (initiation region or propagation region), for the specimens with same geometrical parameters and initial crack length, unidirectional specimens have slightly higher average initiation fracture energy compared to waviness induced specimens.
 - Due to waviness, the crack propagation is not uniform along the width of the specimen. At the upper peak edge of the waviness, crack travels slowly and at the lower edge crack travels rapidly. There exist a few non-zero terms in the extensional and bending stiffness matrices due to waviness. These non-zero terms increase the delamination front curvature

compared to normal specimen. A bend-twist coupling exists at the waviness area due to the non-zero D_{16} term in the bending matrix. The non-uniform crack propagation at the waviness area was due to the presents of this coupling while bending the loading arm.

- An analytical model study was done with the help of constitutive relations and by considering the fiber waviness as a sinusoidal wave. Effective moduli were calculated with different fiber wave severity.
- The compression experiments were simulated with the help of an FE model using ABAQUS software. By considering LaRC02 failure criterion, the failure initiations and instantaneous degradation were successfully predicted with a final kink band failure. However, at higher fiber severity level, the FE model showed large differences in the predicted compressive strength.
 - A comparison study was done in between analytical, FE model and the experiment results of the compression analysis. In a compression failure, shear nonlinearity was one reason for the micro-buckling. A V-notch rail shear test was conducted to investigate the changes in shear non-linearity behavior due fiber waviness. The results showed that in-plane shear behavior does not have much impact on fiber waviness defect. Rather the failure mode greatly dependent on fiber misalignment.
- The major external loads on a wind turbine blade acts in the flap-wise direction, hence bending is a significant load condition for blades. Both static and fatigue flexural analyses were performed on standard specimens under the influence of waviness defect.
 - For static flexural analysis, fiber waviness was considered at the middle region of the standard specimen. The results showed that both bending stiffness and strength decreases with increase in fiber waviness. For static experiments at extreme loads, specimen compression side was more damaged compared to tension side. For waviness defect containing specimens, kink bands were observed at the compression side. At this case, the damage initiated at the upper region of the fiber waviness peak.

This was explained with the help of bend twist coupling at the waviness induced region. The twist moment while bending caused a stress concentration at the peak region of the 'wave' followed by damage initiation.

- Flexural fatigue analysis was performed on the waviness induced specimens at stress ratios of $R = 0.1$ and $R = 0.5$. when the stress ratio increases from 0.1 to 0.5, the fatigue life increases for both unidirectional specimen and waviness defect containing specimen. But for a specific stress ratio and a maximum load, the corresponding fatigue life of wavy specimen was less than that of unidirectional specimens. At fatigue loads, for both unidirectional and wavy specimens the observed damages were more on the tension side as compared to compression side. An X-ray tomography scanning was performed over the failed area to analyze the internal damages. For unidirectional specimen, the major damage was delamination at tension side. Nevertheless, there was no delamination failure on the defect containing specimen. The major failure were matrix cracks along the fiber direction and fiber strand debonding.
- From these experimental investigations, a specimen level dependency on waviness under various loading conditions is understood. For understanding the effects of fiber waviness manufacturing defect at structural level, a static flexural analysis was performed on an FE blade model. This was based on calculated design load at extreme wind conditions. Initially a basic wind turbine blade design was explained and with the help of NuMAD software, a blade shell model was developed and transferred into Abaqus software for the static flexural analysis. Based on the optimum tip deflection, the materials and the layup sequence were finalized from root to tip.
- A fiber waviness defect was introduced in the unidirectional laminates present at the spar cap region by rotating the elements at the wavy region along the wavy path. Both transition region and middle region of the blades at suction side and pressure side were separately analyzed by

considering waviness defect. It was found that, during flap-wise bending, the waviness over the pressure side has greater impact compared to the waviness over the suction side.

- To validate the above result a bending experiment has been performed on a composite I-beam with waviness defect at the top flange and bottom flange separately. The experiment result showed that, at large deflection conditions the outer flange had more strain deformation compared to the inner flange. Hence the waviness effected outer flange deform additionally due to the increase in compliance at the defected region. For the same load conditions, the strain deformation was lesser when the waviness presented at the inner flange. Nevertheless, the strain over the inner flange was more than that of normal unidirectional flange. While looking on to the strain values over the top and bottom region of the waviness effected area, the strain was high at the top region of the waviness peak compared to bottom region. For the blade model at the waviness effected spar-cap region, the cross-sectional strain trend was similar to that observed in the experiment.
- The present investigation helped to understand the influence of one kind of fiber waviness manufacturing defect under various loading conditions. The investigation helps to recognize both level and type of damage that can possibly happen in unidirectional laminates under compression and bending loads. Understanding the specimen level material behavior due to these types of defects is necessary to predict the reliability of a wind turbine blade in operation. As these defects are expected to be present in a localized region of a bigger structure, the chances of damage initiations will be high at these defected regions. The flexural fatigue analysis showed more internal damage at the waviness effected region. This understanding could help to take extra care for a future blade maintenance and repair. The static flexural analysis on blade model showed that additional tip deflection occurs due to waviness presence at the pressure side. This could be a threat situation for a blade to

hit the tower and several previous ‘tower hitting’ incidents were reported. The choice of downwind turbines over upwind turbines could help to reduce this issue up to an extent. For the present work, the scale of damage was not a factor. Depending on the percentage amount of damage upon the total size of structure, the effect of damage over the material properties of the structure will be less. That means for the same size of damage presented on a standard specimen and a blade structure will not make the same impact. However, the final expected failure modes due to the waviness defect would be the same as that investigated. The presence of fiber waviness during manufacturing of composite blade structure is unavoidable, yet an additional care provided while stacking the fiber fabric with the help of robots could help to minimize their inclusion up to a considerable amount. The recent advancement in composite repair technology would be another solution for this issue.

8.2 Contributions

- Understanding the effect fiber waviness with known features on failure behavior of unidirectional laminated composites under various mechanical loading.
- A reliable FE model to predict the compressive strength and failure modes at small fiber wave severity level.
- The behavior of crack during initiation and propagation in a pure opening mode under the influence of in-plane fiber waviness.
- An FE blade model to understand and predict the effect of waviness defect presented at various spar-cap locations under flap-wise loading.

8.3 Scope for future work

Further investigation related to current scope of the work are follows:

- Having a reliable three-dimensional FE model to predict the strength and failure behavior at all ranges of fiber wave severity. Presently, a single wave was considered, however it would also be useful to study the waviness defect with multiple peaks and non-uniform amplitudes.

- The effect of waviness under static tensile loads were not investigated, hence effect of different fiber wave severity waviness on both strength and stiffness need to be analyzed.
- Current investigation considered the effect of waviness on mode-I fracture energy and delamination onset. The effect of waviness on mode-II fracture energy could be another topic to consider.
- A progressive failure model should be developed to understand the influence of fiber waviness under various fatigue loads.
- From the specimen level, flexural fatigue analysis of both unidirectional and wavy specimens, a difference in failure modes were observed in between them. Hence a fatigue flap-wise bending FE analysis on the blade model should be performed to understand the failure modes.
- Current investigation focused only on unidirectional laminates with waviness. It is necessary to understand the effect of waviness on multidirectional laminates with 0° laminas having fiber waviness defect.
- For the present investigation, the existence of other defects was not taken into consideration. The influence of various other defects along with the fiber waviness could be another topic to consider.

Appendix A

Let the fiber waviness be represented as a sinusoidal wave,

$$y = A \sin\left(\frac{2\pi x}{L}\right)$$

Let θ be the angle of deviation from the x – direction.

Differentiate with respect to x

$$\tan \theta = \frac{dy}{dx} = \frac{2\pi A}{L} \cos\left(\frac{2\pi x}{L}\right)$$

$$m = \cos \theta = \left[1 + \left(\frac{2\pi A}{L} \cos\left(\frac{2\pi x}{L}\right) \right)^2 \right]^{-1/2}$$

$$n = \sin \theta = \frac{2\pi A}{L} \cos\left(\frac{2\pi x}{L}\right) \left[1 + \left(\frac{2\pi A}{L} \cos\left(\frac{2\pi x}{L}\right) \right)^2 \right]^{-1/2}$$

The Generalized Hook's law for the material coordinates,

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{13} \\ \gamma_{23} \\ \gamma_{12} \end{bmatrix} = [s] \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{13} \\ \tau_{23} \\ \tau_{12} \end{bmatrix}$$

where $[s]$ is the compliance matrix and its constituents are calculated from the material properties.

$$[s] = \begin{bmatrix} s_{11} & s_{12} & s_{13} & 0 & 0 & 0 \\ s_{12} & s_{22} & s_{23} & 0 & 0 & 0 \\ s_{13} & s_{23} & s_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66} \end{bmatrix}$$

$$s_{11} = \frac{1}{E_1}, s_{12} = \frac{-\nu_{12}}{E_1}, s_{13} = \frac{\nu_{13}}{E_1}, s_{22} = \frac{1}{E_2}, s_{23} = \frac{-\nu_{23}}{E_2}, s_{33} = \frac{1}{E_3}, s_{44} = \frac{1}{G_{23}},$$

$$s_{55} = \frac{1}{G_{13}}, s_{66} = \frac{1}{G_{12}}$$

$$\bar{s}_{ij} = \frac{1}{L} \int_0^L s_{ij} dx$$

where,

$$s_{11} = s_{11} \cos^4 \theta + (2s_{12} + s_{66}) \cos^2 \theta \sin^2 \theta + s_{22} \sin^4 \theta$$

$$S_{12} = s_{12} \cos^4 \theta + (s_{11} + s_{11} - s_{66}) \cos^2 \theta \sin^2 \theta + s_{12} \sin^4 \theta$$

$$S_{22} = s_{22} \cos^4 \theta + (2s_{12} + s_{66}) \cos^2 \theta \sin^2 \theta + s_{11} \sin^4 \theta$$

$$S_{23} = s_{23} \cos^2 \theta + s_{13} \sin^2 \theta$$

$$S_{33} = s_{33}$$

$$S_{44} = s_{44} \cos^2 \theta + s_{55} \sin^2 \theta$$

$$S_{55} = s_{55} \cos^2 \theta + s_{44} \sin^2 \theta$$

$$S_{66} = s_{66} (\cos^2 \theta - \sin^2 \theta)^2 + 4(s_{11} + s_{22} - 2s_{12}) \cos^2 \theta \sin^2 \theta$$

$$S_{55} = s_{66}$$

$$S_{13} = s_{13} \cos^2 \theta + s_{23} \sin^2 \theta$$

After integration

$$S_{11} = s_{11} I_1 + (2s_{12} + s_{66}) I_3 + s_{22} I_5$$

$$S_{12} = s_{12} I_1 + (s_{11} + s_{22} - s_{66}) I_3 + s_{12} I_5$$

$$S_{13} = s_{13} I_6 + s_{23} I_8$$

$$S_{33} = s_{33}$$

$$S_{44} = s_{44} I_6 + s_{55} I_8$$

$$S_{55} = s_{55} I_6 + s_{44} I_8$$

$$S_{66} = s_{66} (I_6 - I_8)^2 + 4(s_{11} + s_{22} - 2s_{12}) I_3$$

$$I_1 = \frac{1 + \alpha^2/2}{(1 + \alpha^2)^{3/2}}$$

$$I_3 = \frac{\alpha^2/2}{(1 + \alpha^2)^{3/2}}$$

$$I_5 = 1 - \frac{1 + 3\alpha^2/2}{(1 + \alpha^2)^{3/2}}$$

$$I_6 = \frac{1}{(1 + \alpha^2)^{1/2}}$$

$$I_8 = 1 - \frac{1}{(1 + \alpha^2)^{1/2}}$$

$$\alpha = 2\pi \frac{A}{L} = \tan \theta_{max}$$

The stress and strain tensor along the coordinate axis can be represented as,

$$[\bar{\sigma}] = \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xz} \\ \tau_{yz} \\ \tau_{xy} \end{bmatrix} = [T]^{-1} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{13} \\ \tau_{23} \\ \tau_{12} \end{bmatrix}, \quad [\bar{\varepsilon}] = \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xz} \\ \gamma_{yz} \\ \gamma_{xy} \end{bmatrix} = [R][T][R]^{-1} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{13} \\ \gamma_{23} \\ \gamma_{12} \end{bmatrix}$$

Let $[T]$ be the transformation matrix and $[R]$ be the Reuters matrix.

$$[T] = \begin{bmatrix} m^2 & n^2 & 0 & 0 & 0 & -2mn \\ n^2 & m^2 & 0 & 0 & 0 & 2mn \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & m & n & 0 \\ 0 & 0 & 0 & -n & m & 0 \\ mn & 0 & -mn & 0 & 0 & m^2 - n^2 \end{bmatrix}$$

$$[R] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2 \end{bmatrix}$$

The global compliance matrix can be written as

$$[S] = [T]^{-1}[s][R][T][R]^{-1}$$

And the global stiffness relation can be written as,

$$[\bar{\varepsilon}] = [S][\bar{\sigma}]$$

$$E_x = \frac{1}{S_{11}} = \frac{1}{s_{11}I_1 + (2s_{12} + s_{66})I_3 + s_{22}I_5}$$