تقييم أداء ريش طواحين الرياح المغلفة بالمواد المركبة تحت التأثيرات البيئية المختلفة

إعداد

مهندسة / هالة السيد طـاهر قطـاريـة

رسالة مقدمة إلى كلية الهندسة – جامعة القاهرة

كجزء من متطلبات الحصول على درجة **ماجستير العلوم**

في

هندسة التصميم الميكانيكي والإنتاج

كلية الهندسـة - جامعـة القاهرة

الجيزة - جمهورية مصر العربية

2018

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يعتمد من لجنة الممتحنين:

الأستاذ الدكتور: **طارق عبد الصادق عثمان** المشرف الرئيسي

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كلية الهندسـة - جامعـة القاهرة

الجيزة - جمهورية مصر العربية

2018

مهندســـــــة: هالة السيد طاهر قطـاريـة

تاريخ الميلاد: 1979/2/21

الجنسيـــــة : مصرية

تاريخ التسجيل: 10/ 2012

تاريخ المنـــح: 2018

القســـــــــم: هندسة التصميم الميكانيكي والإنتاج

الدرجـــــــــة: ماجستير العلوم

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عنوان الرسالة: تقييم أداء ريش طواحين الرياح المغلفة بالمواد المركبة تحت التأثيرات البيئية المختلفة

الكلمات الدالة: المواد المركبة ، ريش طواحين الرياح ، ألياف الكربون ، التآكل الميكانيكي علي الساخن.

ملخص الرسالة:

تهدف هذه الرسالة إلي دراسة أداء وتقييم ريش طواحين الرياح المغلفة بالمواد الاليافية المركبة تحت تأثير الأحمال المختلفة وذلك بغرض حمايتها من التعرض لعوامل الطقس المختلفة.

وقد تناولت الدراسة استعراض ثلاثة أنواع من المواد المركبة وهي: ألياف الكربون (HM-type) ، ألياف الزجاج (E-type) ، وألياف الكيفلر (Kevlar49 type) ، إضافة إلي عينات من الصلب المصلد بالكروم، وقد تم اختبار هذه العينات تحت تأثير أحمال جوية مختلفة لاختبار مدى تعرض الشفرات لظروف الطقس المختلفة.

قد تعرضت العينات المغلفة لعوامل بيئية مختلفة على النحو التالي ؛ التآكل والتآكل الساخن تليها الاختبارات الميكانيكية. أظهرت نتائج هذا البحث أن معدل تآكل الكيفلار أكبر من ألياف الكربون والألياف الزجاجية بنسبة 15.6٪ و 4.9٪ على التوالي.وكانت النتيجة ان معدل التآكل الساخن لعينات ألياف الزجاج بعد شهر واحد أكبر من ألياف الكربون والكيفلار بنسبة 17.3 ٪.

وأظهرت نتائج هذا العمل أن طلاء الكروم الصلب لا يمكن أن يتحمل عوامل الطقس التي لا تلائم حماية شفرات توربينات الرياح. لقد أظهر طلاء CRP (البوليستر المقوى بالكربون) (CRP) قدرة جيدة على تحمل التأثيرات البيئية المختلفة. تم التحقق من هذه المواد المركبة المناسبة من خلال بعض الاختبار التجريبي للتحقق من سلامة تصميمها تحت الأحمال البيئية المختلفة المطبقة على شفرات الرياح، وCRP يمكن أن يعزز أداء شفرات الرياح أكثر من أنواع أخرى من المواد المركبة.

الملخص

تعتبر طواحين الرياح احد أهم مصادر توليد الطاقة الجديدة والمتجددة . حيث تعتبر مصدرا هاما من مصادر توليد الطاقة النقية والغير ملوثة للبيئة والتي تتميز بقلة تكاليف صيانتها مع طول عمرها التشغيلي مقارنة بالمصادر الاخري لتوليد الطاقة الجديدة.
وتهدف هذه الرسالة إلي دراسة أداء وتقييم ريش طواحين الرياح المغلفة بالمواد الاليافية المركبة تحت تأثير الأحمال المختلفة وذلك بغرض حمايتها من التعرض لعوامل الطقس المختلفة.
وقد تناولت الدراسة استعراض ثلاثة أنواع من المواد المركبة وهي: ألياف الكربون (HM-type) ، ألياف الزجاج (E-type) ، وألياف الكيفلر (Kevlar49 type) ، إضافة إلي عينات من الصلب المصلد بالكروم ، وقد تم اختبار هذه العينات تحت تأثير أحمال جوية مختلفة لاختبار مدى تعرض الشفرات لظروف الطقس المختلفة، تم إجراء ثلاثة اختبارات، العينات هي الفولاذ المطلي بمواد مركبة مختلفة معززة بالإيبوكسي أو البوليستر.

أولاً: اختبار صدمات عاصفية رملية (الصفع) عن طريق دفع تيار من الرمال الناعمة من فوهة المسدس نحو العينات لفترة زمنية ثم قياس معدل تآكل التآكل الناتج. ثانيا: اختبار التآكل الساخن عن طريق تعريض العينات لأبخرة ماء البحر الساخن وبها نسبة املاح عالية عند 77-81 درجة مئوية لفترات زمنية مختلفة. وتم حساب التآكل الذي يحدث لهذه العينات نتيجة هذه الأحمال. كما تم إجراء اختبار شد لهذه العينات لقياس خواصها الميكانيكية باستخدام آلة الشد الميكانيكية (MTS-810) للحصول على قوة الشد لكل مادة مركبة . كل هذه الاختبارات تم إجراءها علي عينات ذات طبقة واحدة، وطبقتين وثلاث طبقات من المواد المركبة والتي تم مزجها بنوعين مختلفين من الراتنجات (Polymers) وهما البوليستر والايبوكسي. مع الأخذ في الاعتبار عدد الطبقات ، واتجاهات الألياف فيها.
وتناولت الدراسة أيضاً دراسة العوامل المختلفة المؤثرة على العينات وأداءها من حيث سمك طبقة الطلاء وعدد طبقاته.
أظهرت نتائج هذا البحث أن معدل تآكل الكيفلار أكبر من ألياف الكربون والألياف الزجاجية بنسبة 15.6٪ و 4.9٪ على التوالي.وكانت النتيجة ان معدل التآكل الساخن لعينات ألياف الزجاج بعد شهر واحد أكبر من ألياف الكربون والكيفلار بنسبة 17.3 ٪. وقد بينت الدراسة إن العينات المغطاة بعدد كاف من ألياف الكربون (High modules) قد أعطت أعلى تحمل لريش طواحين الرياح للظروف الجوية المختلفة والحرارة العالية.
وبينت الدراسة أيضا أن العينات المغلفة بالفولاذ المصلد بالكروم لم تستطع أن تتحمل عوامل الطقس المختلفة حيث انهرات كلياً، مما يبين ان استخدام هذه الخامة في تصنيع شفرات الطواحين الهوائية غير مناسب لحمياتها ضد التأثيرات البيئية المختلفة.
وبينت الدراسة أيصا أن استخدام ألياف الكربون (معامل عالي) يمكن أن يطيل عمر شفرات طواحين الهواء وخصوصا عند استخدام ثلاث طبقات فما فوق.

CHAPTER ONE

INTRODUCTION AND LITERATURE SURVEY OF WIND TURBINE BLADES

INTRODUCTION

As the need for renewable energy sources increases, the methods of design and analysis for the structures servicing these sources must be advanced to become more resilient when subjected to various loading conditions. The different sources of renewable energies include solar, geothermal, hydropower, ocean, hydrogen and wind.

The advantage of utilizing wind turbines for energy collecting is that wind is free and can be easily captured. It is necessary for the design of these structures accurately to account for the various types of loading that accurately could be experienced during a turbine's lifetime [1].

The technology used in manufacturing wind turbine blades has been improved over the past 20 years, to achieve a reduction in both cost and defects probability through evolving the materials of the main components of wind turbines.

The trend, nowadays, is directed towards the Automated Fiber Placement (AFP) for the following causes:

- To withstand severe weather conditions and improve quality.
- To reduce labour and to improve the quality of blades.

Another technique for improving the behavior of the wind turbine is by using advance polymers as polyester and epoxy on a broad scale with comprising skins of unidirectional and multi axial fabrics of composite materials. On the other hand, the spars of wind turbine blades have been manufactured with fiberglass roving and a combination of unidirectional multi axial fabrics.

In the design of a wind blade, a high performance fiber like carbon is realized in the tensile direction and most prevalent in the tensile properties and hence is the reason that it is used in parts that undergo high tensile stresses. In contrast, the compressive properties for carbon fiber reinforced laminates do not differ greatly from cost-effective alternatives like; E glass based composites. The industry is clearly moving towards larger turbines with longer blades. Larger blades produce more energy. This is a basic target for driving costs down.

This work is on developing materials that are appropriate for the technologies of blade coating.

New technology developments in: fiber reinforcements and resin systems

1.1 OBJECTIVE OF TURBINES AS POWER GENERATION MACHINES

A turbine [2] is a rotary mechanical device that extracts energy from a fluid flow and converts it into useful work. A turbine is a turbo-machine with at least one moving part called a rotor. This is a shaft or drum with blades attached. Air, gas, steam, and water work as a moving fluid acting on the blades so that the blades move and impart rotational energy to the rotor. Early turbine examples are windmills and waterwheels. A working fluid may be compressible or incompressible. They contain potential energy (pressure head) and kinetic energy (velocity head). Simon Joncas [3] mentioned in his paper that over the past three decades, wind turbines have been developed efficiently to increase power generation, so they were required to increase length of blades by a factor of 10 from the eighth of last century to date. Some blades currently measuring more than 60 meters in length, weight and length which caused many problems, did not previously exist. They proposed a structural design for large wind turbine blades using recyclable thermoplastic composites (TPC). Based on material properties , cost and processing, reactively processed anionic polyamide-6 (APA-6) after mechanically characterizing in situ polymerized APA-6/glass composites and assessing their recyclability. APA-6 composite material and processing: because of the very low viscosity of the anionic polyamide-6 resin system. Performance of fatigue in tension-tension was found low for APA-6 composites. Under moist conditions, fiber/matrix interface degradation causes a reduction in mechanical properties of APA-6 composites.

In Anthony Broad thesis [4], manufacturers employ the vacuum infusion technique to produce monolithic and sandwich cored components, Siemens has developed these products by creating three-dimensional internal structures by polymer matrix composite in both external faces and internal structures composite components in a single process complete with its internal structure. And the structural spar section forms as an integral part. Use the technique of resin infusion to develop a manufacturing process to allow a small wind turbine blade, and the manufacture of prototype 2.5 m fiber glass wind turbine blades.

In Abiy Alene thesis [5], he investigated the performance of bamboo and E-glass fiber reinforced epoxy hybrid composite (BGREC) with different unidirectional (UD) of bamboo to E-glass fiber fraction for wind turbine blade shell application.

After the manufacture of composite materials is done, he tested the tensile, in-plane shear, compressive, and flexural moments. He discovered that a bamboo to E-glass fiber ratio of 0:100 gives a higher tensile strength. Whereas ratio of 50:50 had given higher compressive strength, higher elastic modulus surface morphology of BGFRECs and higher tensile fractured surfaces with morphology and homogeneity of stress distribution. His results showed also that the bamboo fibers have experienced substantial changes during alkaline treatment, with good results with epoxy of 50:50 ratio. These outputs can have a potential to be used for wind turbine blade shell construction.

In BISMARK, thesis [6], he observed that bamboo is more sustainable than the current materials. It has good properties of low density, good strength and high modulus. He tried to design and manufactured 1m wind turbine blade using bamboo, he harvested fresh bamboo and split it into laminated strips into boards with a torque of 2MPa, .and then the board had the dimension 1.0 m x 0.18 m x 0.02 m. He recommended the use of bamboo to manufacture wind turbine blades and it should be employed in areas where the forest needs to be reserved and other wood. In Mishnaevsky Jr. [7], Blades represent the most important composite based part of a wind turbine, whose properties quite often determine the performances and lifetime of the turbine.

The first wind turbine for electric power generation was built by the company S. Morgan-Smith at Grandpa’s Knob in Vermont, USA, in 1941. In 1956 the turbine was produced with composite blades, built from steel spars, with aluminum shells supported by wooden ribs. The turbine (three blades, 24 m rotor, 200 kW) had run for 11 years without maintenance. After 1970s, most of wind turbines blades were manufactured from composite materials.

Tyler R. Fox [8] has selected glass fiber reinforced plastics (GFRPs) for manufacturing the blades of a wind turbine and showed a good material availability and well-documented processing technology. He also showed in his study that carbon fiber reinforced plastics (CFRPs) are now replacing GFRPs in large turbine blades due to their superior specific stiffness and strength properties. Moreover, he showed that a hybrid CFRP-spar /GFRP-skin design is the most widely established use. Finally, he has recommended performing an additional search in an irregular form of composite to enhance the total strength of the wind turbine blades.

1.2 TYPES OF TURBINES

The turbines are divided based on the working fluid into; hydro turbines, steam turbines, gas turbines and wind turbines. Based on the basis of the principle of operation, they can be classified into: Impulse turbines of high-head and low flow rate, Reaction turbines of low-head and high-flow rate and Impulse- reaction turbines [9, 10].

1.2.1 Impulse Turbines

An example of impulse turbines is the Pelton wheel; the drop in pressure of steam takes place only in nozzle, not in moving blades, which only transfers energy. Impulse turbines change the direction of flow of high velocity fluid or gas jet. The resulting impulse spins the turbine and leaves the fluid flow with diminished kinetic energy.
Impulse turbines have high-heads, low flow rate.

1.2.2 Reaction Turbines

The turbine must be fully immersed in the flowing fluid. Energy transformation takes place in rotor, and transfers only in rotor. Pressure drop takes place in rotor. Part of the pressure drop occurs across the guide vanes, part occurs across the rotor and part occurs across the rotor. It leaves the fluid flow with a decreased amount of kinetic energy. The fluid or gases in the turbine blades have no pressure change; it is accelerated using a nozzle, which changes its pressure head to velocity head [11]. This concept is used in most steam turbines including the Francis turbine

1.2.3 Impulse - Reaction Turbine

Energy transformation occurs and drop in pressure of steam takes place in both fixed blades and moving blades. The rotor blade causes energy transfer & energy transformation [11, 12].

1.3 WIND TURBINES

Wind turbines work by turning the kinetic energy of the wind into torque that causes the wind turbine to rotate driving an electrical generator and then it is converted into electrical energy [13, 14].

1.3.1 Types of Wind Turbines [15, 16]

A- Horizontal Axis Wind Turbines (HAWT)
B- Vertical axis Wind Turbines (VAWT)

1.3.2. Main Advantages and Disadvantages of Wind Turbines [17]

Advantages:

1. The wind is free and it can be captured efficiently by modern technology.
2. Building of wind turbines and energy produced does not cause any pollution or green house gases.
3. It takes up only a small plot of land.
4. Wind turbines can be used to produce power for remote areas.
5. Wind turbines are available in a range of sizes.

Disadvantages:

1. Wind turbine does not produce the same amount of electricity all the time because the strength of wind is not constant and it varies from zero to storm force.

2. Many people see that wind turbines are unsightly, and they feel that the countryside should be left in its natural form to enjoy, without these large structures being built.

1.3.3 Main Components of Wind Turbines

The rotor, and its blades, the hub assembly, the main shaft and the gear box system are the main parts of any wind turbine. The wind turbine also comprises the main frame, transmission, yaw mechanism, over speed protection, electric generator, nacelle, yaw drive, power conditioning equipment, and tower [16, 18].

1.4 MAIN TYPES OF WIND TURBINE BLADE MATERIALS

Older style wind turbines blades were designed of wood, but because of its sensitivity to moisture and processing costs, composite materials are now extensively used to design the wind turbine blades such as glass fiber reinforced plastic (GFRP) and carbon fiber reinforced plastic (CFRP). The most types of plastics used as matrix material of those composites are; polyester resin, a vinyl resin, and epoxy thermosetting matrix resin besides steel and aluminum as metallic matrices [18].

Selection criteria of materials for wind turbine blades

1. The most important factors affecting the selection of materials are the properties of the materials. The important properties of the materials are mechanical, thermal, chemical properties. Physical properties such as, size, weight, and appearance are also important factors of turbine performance.

2. The material must be reliable and must be available in a large enough quantity.

3. The material must perform its function safely.

4. The material processing must be of low costs.

5. The material must have high stiffness to maintain shape of performance with low density to reduce gravity forces

6- The material must be of long-fatigue life to reduce material degradation

1.5 DIFFERENT LOADS AFFECTING WIND TURBINE BLADES

TYPES OF LOADS

Wind turbines are generally subjected to two types of loading which affect their functions. These loads can be classified as [19]:

1- STATIC LOADING

The static load applied on the turbine blades is constant with time and the resulting deflection of their structure is also constant and proportional to its stiffness.

2- CYCLIC LOADING

Can be classified as:

- **Quasi static cycling**: the loading varies slowly, whereas the resulted deflection of the structure is proportional to the loading.
- **Dynamic cycling**: the dynamic cycling loading results in a deflection related to the damping forces of the structure.

3- STOCHASTIC LOADING

It varies in a random manner; it is caused by wind turbulence.

4. AERODYNAMIC LOADING

It is derived from the force of the wind. The rotor of a wind turbine converts the wind's kinetic energy into useful mechanical work through aerodynamic effects. The cyclic and stochastic loads can cause most structural failures. Figure 1.1 shows the direction of the wind flow around the wind turbine blade [19].

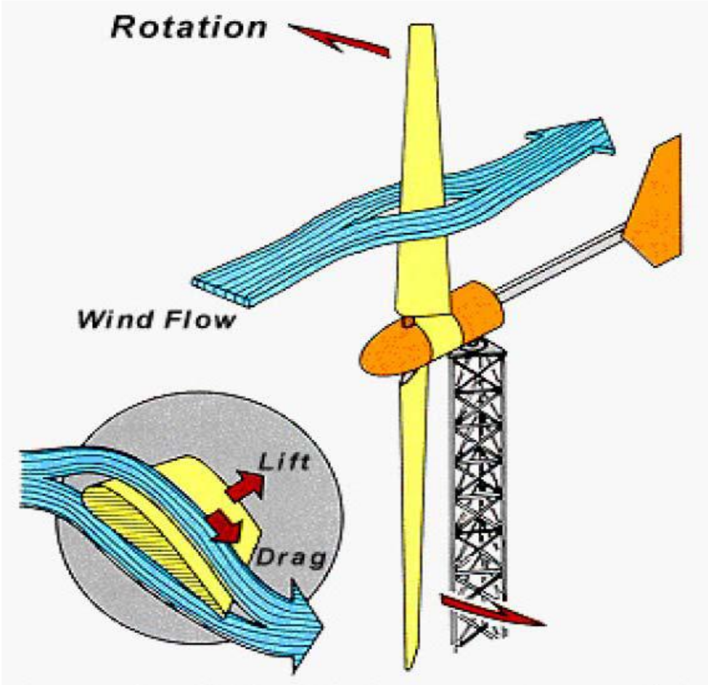

Figure 1.1: Wind flows around a wind turbine blade

5- OTHER MECHANICAL LOADING

The other mechanical loads result from the air momentum which acting on the wind structure blades can affect the performance of the wind turbine. These loads include:

1. Gravity loading which can impose large fatigue stresses on the moving rotor.
2. Bending of the rotor blades in high winds, thus reducing the mean blade loading.
3. Transient Loads which occur at the start up and shut down times.

1.6 FAILURE CRITERIA OF WIND TURBINE BLADES

Wind turbine blade failures are often catastrophic and can happen without warning. The main causes of blade failure can be caused due to one or more of the following causes [20]:

1- An excessive applied load acting on the blade due to extreme wind events.
2- Reduction of the blade strength which may be due to manufacturing defects.
3- Non-compliance with quality requirements lead to defects resulting in a failure.
4- Cracks which can be found in blades at the bonding resin, delaminating within the glass fiber reinforced plastics (GFR) or the sandwich, discontinuities on the sandwich, crack on web, excess of bonding resin [21, 22].
5- Failure criteria of wind turbine blades which occur by environmental conditions like rain, moisture, temperature change, ice, UV radiation and lightning.

1.7 COMPOSITE MATERIALS FOR WIND TURBINE BLADES

Today the trend is toward to new technology in composite manufacturing as Automated Tape Layup (ATL) or Automated Fiber Placement (AFP) [1] to reduce labor and to improve quality input materials in blade production .Resin technology includes both polyester and epoxy on a broad scale.

In the design of a wind blade a high performance fiber like carbon is realized in the tensile direction and most prevalent in the tensile properties and hence is the reason that it is used in parts that undergoes high tensile stresses. In contrast, the compressive properties for

carbon fiber reinforced laminates do not differ greatly from cost-effective alternatives like E glass based composites. The industry is clearly heading to toward larger turbines with longer blades. Larger blades produce more energy, and this is a basic target for driving costs down.
This work is on developing materials that are appropriate for the technologies of blade coating.

1.8 WIND TURBINE BLADE PROFILE SHAPE (HAWT)

A focus is being made on the HAWT because of its dominance in the wind turbine industry [23]. The tip speed ratio defined as the relationship between rotor blade velocity and relative wind velocity. Efficient, torque, mechanical stress, aerodynamics and noise should be considered when selecting the appropriate tip speed ratio **λ**, which is calculated from the following equation:

$$\lambda = \frac{\Omega . r}{V_w} \qquad (1.1)\ [23]$$

where:
λ = Tip speed ratio
Ω= Rotational velocity (rad./s)
r= Radius of turbine
V_w= Wind speed

A blade optimization method produces blade plans principally dependant on design tip speed ratio and number of blades [23]. Figure 1.2 shows the region classification of a wind turbine blade.

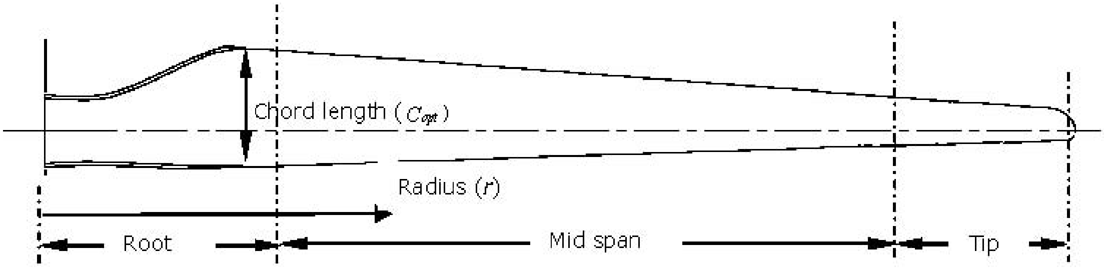

Figure 1.2: A typical blade plan and region classification [23]

The optimum length of chord of the wind turbine blade, which is illustrated in figure 1.2 could be calculated form the following equation [23]:

$$C_{opt} = \frac{2\pi r}{n} \frac{8}{9C_L} \frac{U_{wd}}{\lambda V_r} \quad \text{where } V_r = \sqrt{V_w^{\ 2} + U^2} \qquad (1.2)$$

Where;
C_{opt}. = Optimum chord length
r = Radius of turbine (m)
n = Blade quantity
C_L= Lift coefficient
λ = Local tip speed ratio
V_r = Local resultant air velocity (m/s)
U = Wind speed (m/s)
U_{wd} = Design wind speed (m/s)

The amount of energy produced by each turbine varies according to the size, height, specifications and number of blades. The differing aerofoil requirements relative to the blade region are apparent when considering airflow velocities and structural loads. The aerofoil requirements for blade regions are shown in table 1.1.

Table 1.1: The aerofoil requirements for blade regions [23]

Parameter	Blade Position		
	Root	Mid Span	Tip
Thickness to chord ratio (%)	>27	27–21	21–15
Structural load bearing requirement	High	Med	Low
Geometrical compatibility	Med	Med	Med
Maximum lift insensitive to leading edge roughness			High
Design lift close to maximum lift off-design		Low	Med
Maximum CL and post stall behaviour		Low	High
Low Aerofoil Noise			High

To make optimum blades, there are some simplifications must be considered in designing the wind blades as follows:

1- Reducing the angle of twist of the blade.
2- Linearization of the chord width of the blade
3- Reducing the number of differing aerofoil profiles.

Thickness and camber of the blade airfoil are very important parameters to describe the shape of an airfoil. Geometrical parameters defining an airfoil are shown in figure 1.3.

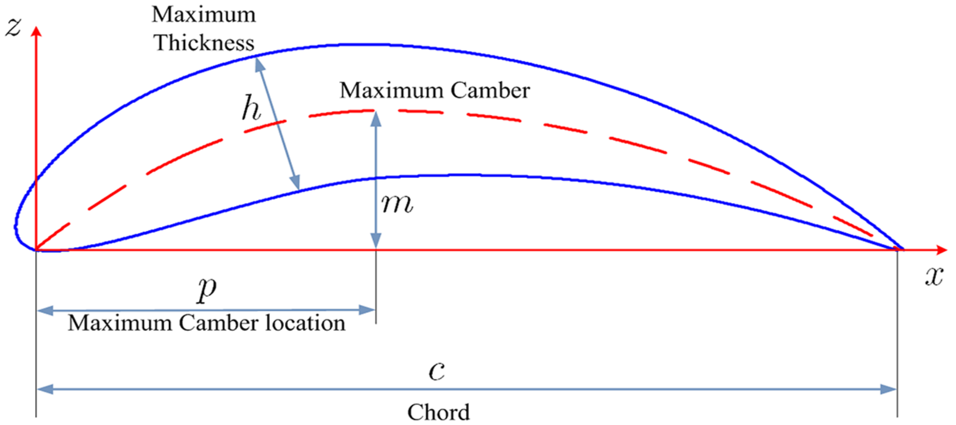

Figure 1.3: Wind turbine blade shape [24, 25]

Where:
h: Maximum thickness
m: Maximum camber
p: Maximum camber location
c: Chord length

Wind turbine blade design

The wind turbine blades have airfoil cross section varies from root to tip. The driving force of wind turbine is lift force, as shown in figure 1.4, is generated when wind flows over the airfoils. Lift force is perpendicular to apparent velocity and it increases with increasing the angle of attack. While, tangential component of lift force supports the blade rotation. The wind turbine can give maximum performance, when lift to drag ratio is maximum (at the angle of attack [24, 25].

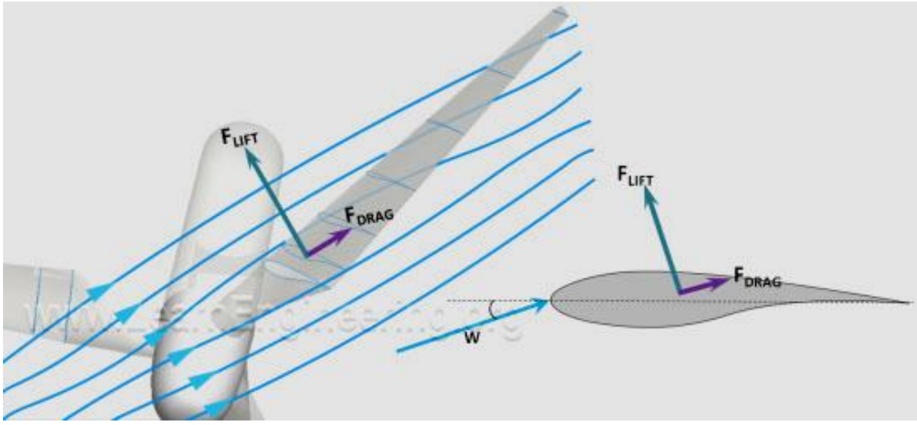

Figure 1.4: Forces on wind turbine blade [25]

1.9 LOADS AND STRESSES INDUCED IN WIND TURBINE BLADES

In large turbines (D > 70 m): it should be considered the mass of the blade when calculating loads resulting [23].

The main sources of blade loading are:

1. Aerodynamic
2. Gravitational
3. Centrifugal
4. Gyroscopic
5. Operational

The priority is given to the following loading conditions:

1- Emergency stop scenario
2- Extreme loading during operation

1.9.1 Aerodynamic Load

Aerodynamic load generated by lift and drag of the blades aerofoil section**,** which are resolved into useful thrust in the direction of rotation absorbed by the generator and reaction forces**.** It is dependent on wind velocity, blade velocity, surface finish, angle of attack (α) and yaw. Figure 1.5 [22, 23] shows an aerodynamic forces on blade element.

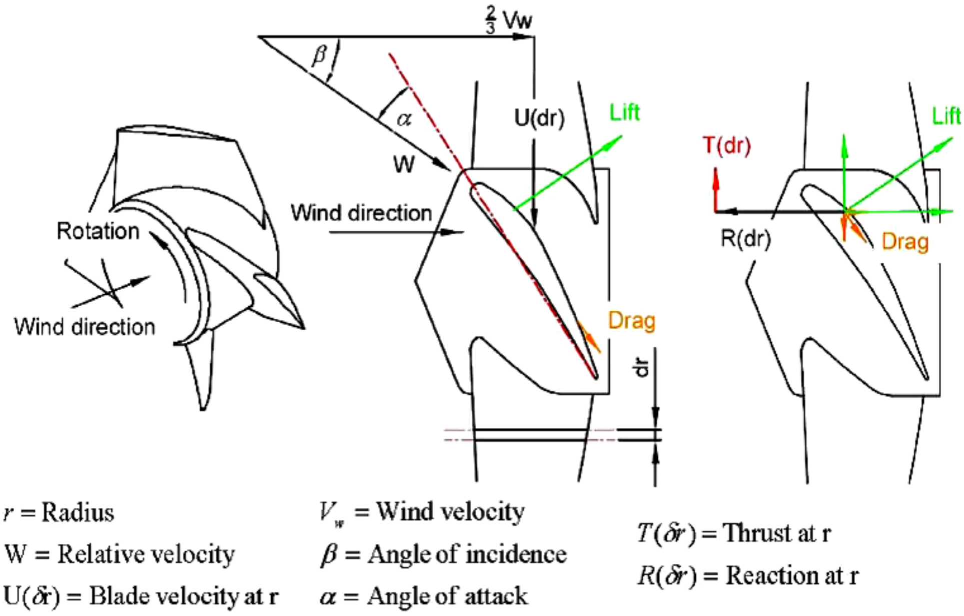

Figure1.5 [23] Aerodynamic forces generated at a blade element

1.9.2 Gravitational and Centrifugal Loads

1.9.2.1 The gravitational force

Become critical due to blade mass, they increase cubically with increase turbine diameter. So, turbines under ten meters diameter have negligible inertial loads. The inertia loads start to be critical at more than 70 meter rotors diameter. The gravitational force has constant direction acting towards the centre of the earth which causes an alternating cyclic load case.

1.9.2.2 The centrifugal force

The centrifugal force acting on the wind blades depends on its rotational velocity, mass and eccentricity (resulted from any out of balance).

1.9.3 Gyroscopic loads:

These loads result from yawing during operation.

1.9.4 Operational loads:

They are systems - dependants, resulting from pitching, yawing, breaking and generator connection.

1.9.5 Flap wise Bending

The flap wise bending moment is a result of the aerodynamic loads. It can be modeled as a cantilever beam with a uniformly distributed load. Figure 1.6 [23] shows how bending occurs about the chord axis creating bending stresses in the blade cross section**.**

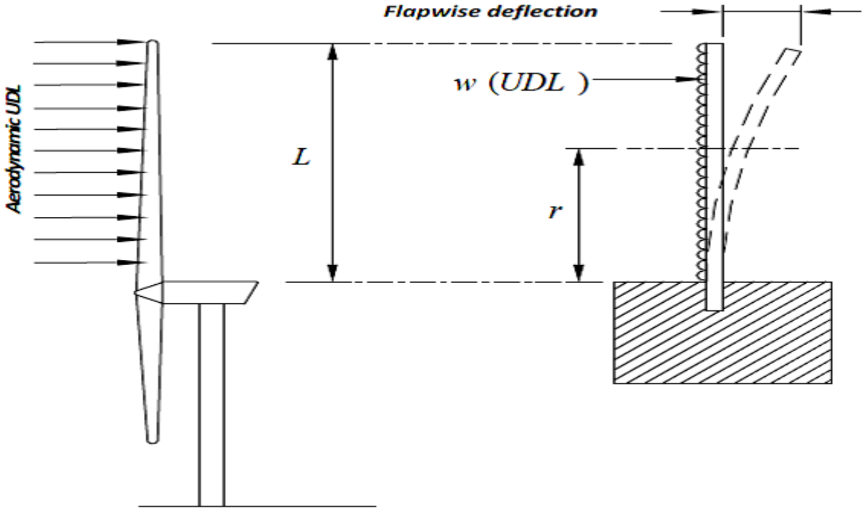

Figure 1.6 Blade modeled as a cantilever beam with uniformly distributed Aerodynamic load [23]

1.9.6. Edgewise Bending

It is a result of blade mass and gravity, this loading can be negligible for smaller blades with negligible blade mass, therefore for big turbine sizes excess of 70 m diameter. This loading is increasing critically.

The blade has a distributed load, as shown in figure 1.7, which increases in intensity towards the hub as the blade thicknesses increase.

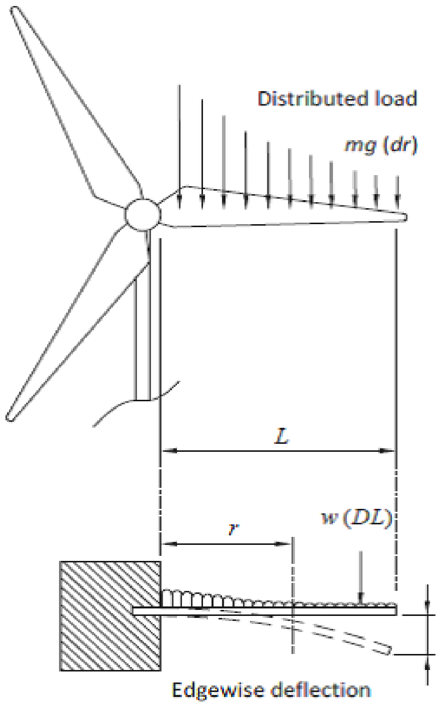

Figure 1.7: Gravitational load modeled as a cantilever beam [23]

1.9.7 Fatigue Loading

Fatigue loading can occurs when a material of blade is subjected to a repeated (cyclic) load which causes the fatigue limit to be exceeded. It is a result of gravitational cyclic loads [26]. The choice of materials and manufacturing process will have an influence on how thin the blade can be built.