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A review of wind-turbine structural stability, failure and alleviation

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ABSTRACT

Advancements in materialistic life styles and at the same time increasing awareness about adverse climatic changes and its negative effects on human life have been the driving forces of finding new and clean sources of energy. Wind power technology has become technologically mature and commercially acceptable on a global scale. Saudi Arabia, though major producer and supplier of fossil fuels, has always been among front runners on renewable sources utilization. Recently, it has issued a white paper on wind and solar photovoltaic power projects development in the country. It is expected that around 450 MW of wind power installed capacity will be realized in the near future. Hence, to get ready to adopt this technology, various related aspects have to be understood by the scientific, engineering, utility, and contracting communities. This study is an effort towards the understanding of the (i) wind turbine blade and tower structural stability issues, (ii) turbine blade and tower failures and remedial measures, (iii) weather and seismic effects on turbine blade and tower failures, (iv) gear box failures, and (v) turbine blade and tower failure analysis tools.

1. INTRODUCTION

The cost of wind power generation has reduced to 4–7 US cents per kilowatt-hour. Generally speaking, as a rule of thumb, each MW of wind power installed capacity costs around one million USD. The wind farms require a minimum maintenance cost and attention of the skilled manpower. It is also evident from the fact that the cumulative global wind power installed capacity reached 539.581 GW with a new addition of 52.573 GW in year 2017 (GWEC - 2017). The annual growth of wind power installed capacity is shown in Fig. 1. Since 2014, more than 50 GW new capacities have been added every year (Fig. 1). The global cumulative annual wind power capacity increases almost linearly as shown in Fig 2. In year 2016, the wind power installed capacity was 488 GW while it increased to 540 GW in 2017, an increase of almost 11%. However in 2016, the wind power installed capacity was increased by 13%. At present, there are more than 90 countries contributing towards wind power capacity build-up including 9 countries with more than 10 GW and 29 more than 1 GW of installed capacities globally.

Modern wind turbine blades are mostly made of fiber-reinforced composites produced through a molding process. The most common blade manufacturing technique involves separate productions of the suction side and pressure side shells (Eder and Bitsche 2015). In the final assembly stage, the two halves are adhesively joined. One important adhesive joint occurs at the trailing edge, which refers to the downstream edge of a blade where the flow around the airfoil rejoins and leaves the blade (Fig. 3).

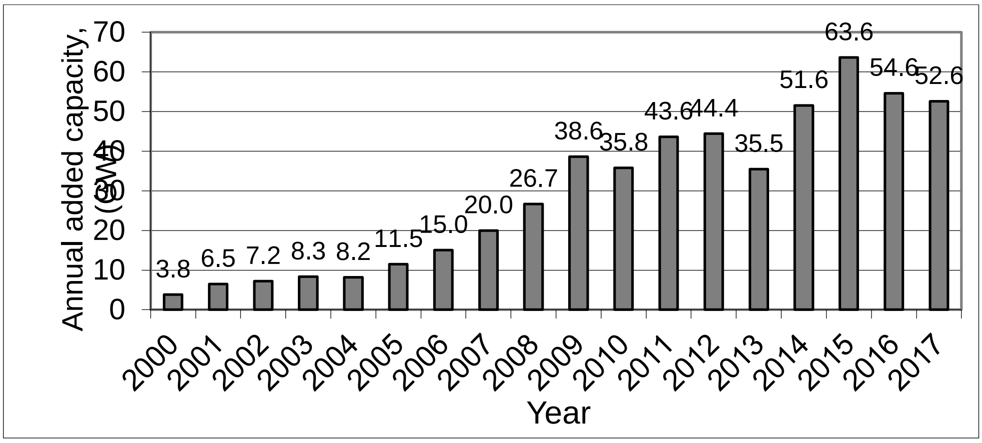


Fig. 1 Global annual growth of wind power installed capacity

The Kingdom of Saudi Arabia has embarked on restructuring its energy mix portfolio by supplementing the existing capacity through wind power and solar photovoltaic. With respect to wind power, the Kingdom is expecting to develop around 450 MW of capacity in the near future. Hence, as a consequence of it, large wind turbines of capacities ranging from 2 to 3.5 MW and even more will be installed in different operating areas of the Kingdom. Such large wind turbines are expected to have rotor diameters ranging from 80 to 120 meters and hub heights of 80 to 120 meters. This is the time that the researchers and the utility engineers come together and understand the physics and engineering behind holding and sustaining such huge infrastructure in the local environmental conditions. However, in the last 10 years, a great deal of research initiatives have been under taken on wind power related topics such as (i) understanding of the wind speed behavior and its prediction using artificial neural network and other techniques (Shoaib et al. 2017, Islam et al. 2017, Mohandes and Rehman 2016, Mohandes and Rehman 2014, and Mohandes et al. 2011), (ii) wind turbine selection and wind farm lay out design using fuzzy logic and multi-criteria methodologies (Rehman and Khan 2017, Rehman et al. 2016, Rehman and Khan 2016, Khan and Rehman 2013), (iii) wind power resource assessment, wind characteristics and feasibility (Zheng et al. 2017, Alam et al. 2014, Baseer et el. 2017, Himri et al. 2016, Bagiorgas et al. 2013, Rehman et al. 2016, Rehman et al. 2016, Baseer et al. 2016, Rehman et al. 2015, Baseer et al. 2015, Bassyouni et al. 2015, Rehman 2014, Rehman et al. 2013, Rehman 2013, Rehman 2012, Rehman et al. 2012, Rehman et al. 2012, Bagiorgas et al. 2012, McVicar et al. 2011, Bagiorgas et al. 2011, and Alam et al. 2011).

The present work emphasizes the need of studying the structural stability of wind turbine blades and towers, related failure issues, and prevailing remedial measures adopted internationally.

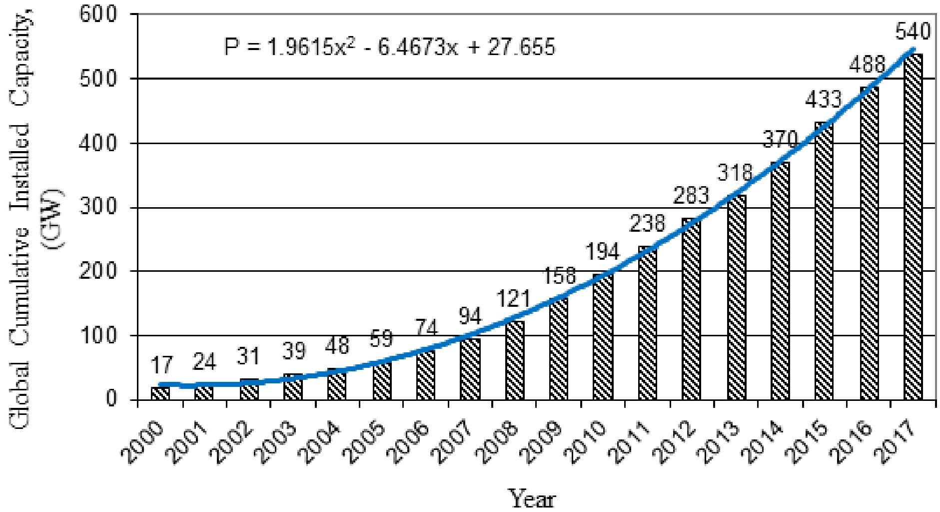


Fig. 2 Global cumulative annual growth of wind power installed capacity

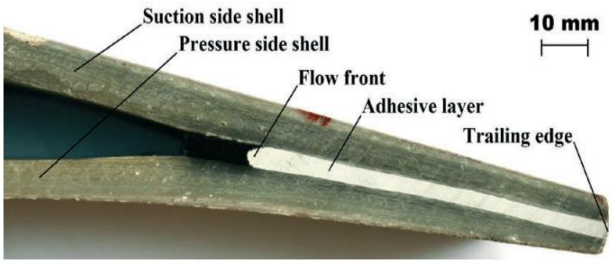
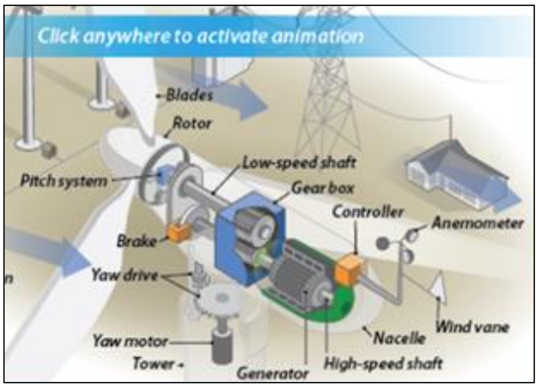


Fig. 3 Adhesive trailing edge joint of wind turbine blade as manufactured (Eder and Bitsche 2015)

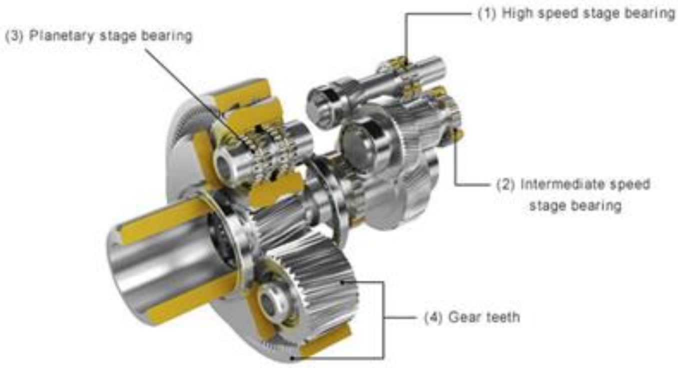
2. WIND TURBINE COMPONENTS

Wind turbines are used to extract the power of the wind and convert it to electrical energy through a generator. The energy in the wind turns two or three propeller-like blades around a rotor. The rotor of the turbine is connected to the main shaft of the generator through a high-speed gear box to create electricity. The three-bladed horizontal axis wind turbine illustration (Fig. 4a) provides a detailed view of the inside of the turbine, its components, and the functionality of different parts (Weblink-01 2018).
Wind flow induces lift on the blades, causing the rotor to spin around its axis of rotation. The breaking system (brake) stops the rotor electrically, mechanically, or hydraulically in emergencies and extreme weather conditions. The controller, provided at the rear portion of the nacelle unit, starts up the wind turbine at about 8 – 16 miles per hour (mph) and shuts it off at about 55 mph (Weblink-01 2018). Most of wind turbines do not operate above 55 to 60 mph wind speed to avoid the damage to the turbines. The gear box connects the low-speed shaft to the high-speed shaft and increases the rotational speed from about 30-60 rotations per minute (rpm) to about 1,000-1,800 rpm which is

the rotational speed required by the generators to generate electricity. Gear box is a very costly component of the wind turbine and is very heavy and hence researchers are working on making it more efficient in terms of weight and efficiency. An inside of a wind turbine gear box is shown in Fig. 4(b). It basically consists of four major parts i.e., high-speed stage bearing, intermediate stage bearing, planetary stage bearing and gear teeth.



(a)



(b)

Fig. 4 (a) Major parts of a commercial horizontal axis wind turbine (Weblink-01 2018), and (b) major parts of a wind turbine gear box (Weblink-02 2018).

3. WIND TURBINE BLADE and TOWER STRUCTURAL STABILITY ISSUES

The wind turbines are always located at sites where effective wind resources are available. Usually, these are the remote open locations away from the cities and inhibited areas. To keep these machines running safely continuously and being profitable is, therefore, a challenging task and has to be addressed well. The capacity and size of wind turbines increases rapidly to harvest more energy from wind. Fig. 5 shows existing and expected growth in turbine size and production for land-based and offshore turbines. The growth in size is larger for the offshore turbines because the offshore turbines produce more power per square meter than the land-based turbines. Different manufacturers have focused on different technologies to adopt the capacity and size, for example Enercon has developed 7 MW rated power wind turbine while Repower 3.4 MW, GE 4.0 MW, Gamesa 4.5 MW, XEMC Darwind 5 MW, and so on.

Control: Modern wind turbines are fitted with more intelligent control systems to work over a large range of wind speed, such as active pitch-regulated and variable-speed systems. Initially, the wind turbines used to work on passive stall-regulated load control, fixed-speed machines in a narrow wind speed range. The newly developed individual blade pitch control enables the modern turbines to deliver more power with smaller blades and towers (Leithead et al. 2009; Leithead and Chatzopoulos 2010). Today, more advanced blade control techniques and intelligent blades are being developed to allow the blades to measure wind speed and adapt automatically to wind conditions (Dvorak 2012).

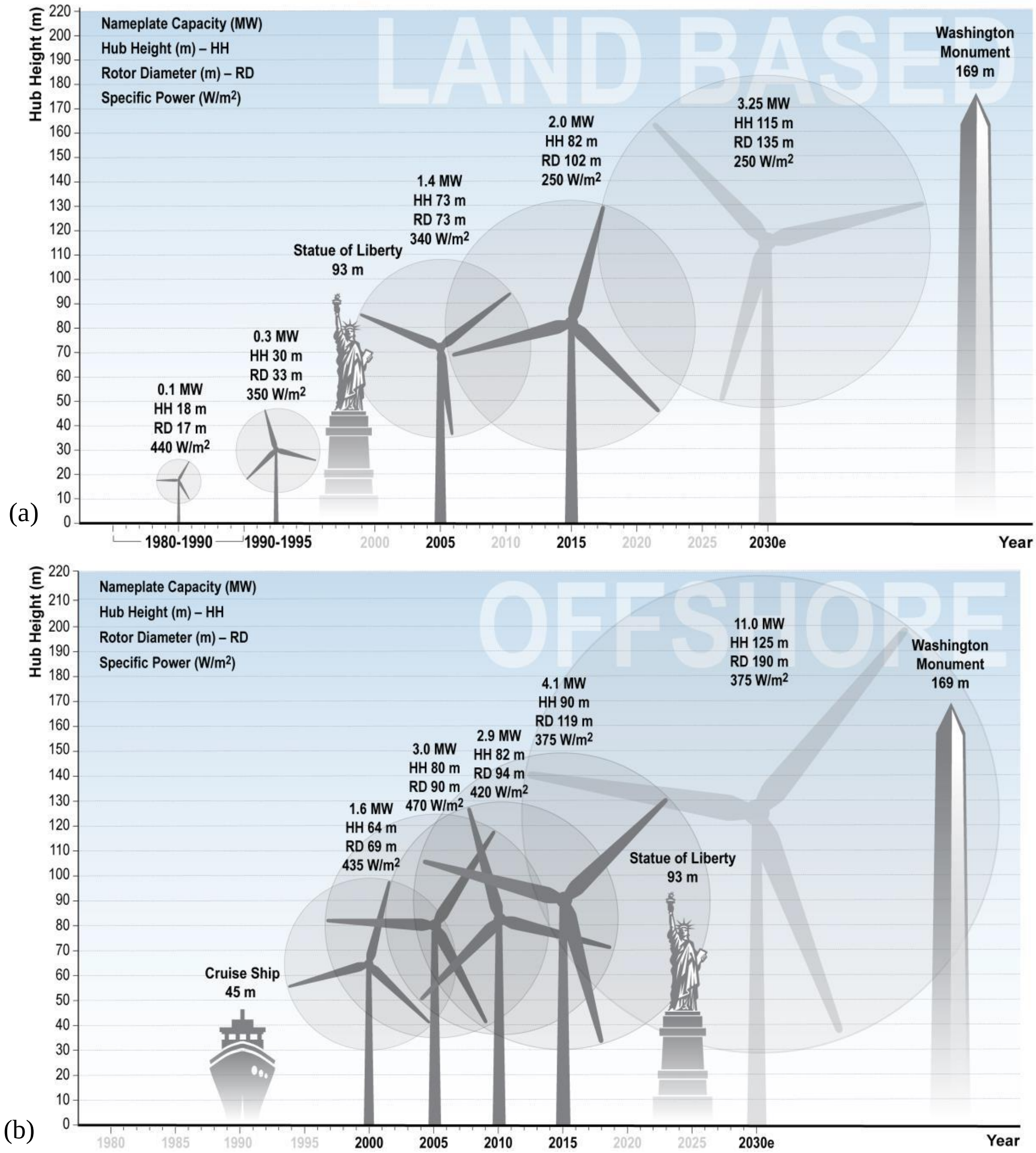


Fig. 5 (a) Existing and expected growth in turbine size and production for (a) land-based turbines in North America, and (b) offshore turbines around the world. Wiser et al. (2016).

It has been observed and reported that extreme winds are mainly responsible for the damage of the structural integrity of the wind turbine blades and towers. The extreme wind conditions are usually observed in the coastal and open areas. Fortunately, most of the wind turbines are located in the coastal areas due to high available wind resources. To validate the wind shear predictions used in load simulations for wind turbine design, Dimitrov et al. (2015) used wind speed data measured at two stations at heights ranging from 60 to 200 m for several years. They proposed a wind shear model for flat terrain which is capable of reducing the uncertainty associated with fatigue load predictions of the wind turbines. The model was used to evaluate the wind shear over different sections of the wind turbine with wind conditions provided in IEC 61400-1 ed. 3 standard. The results showed that, under moderate turbulence conditions, the effects of Woehler exponent and wind shear were pronounced on the blade flap loads but not on tower fatigue loads (Fig. 6a, c). An increase in the wind shear component leads to an increase in the fatigue damage load on the blades (Fig. 6b).

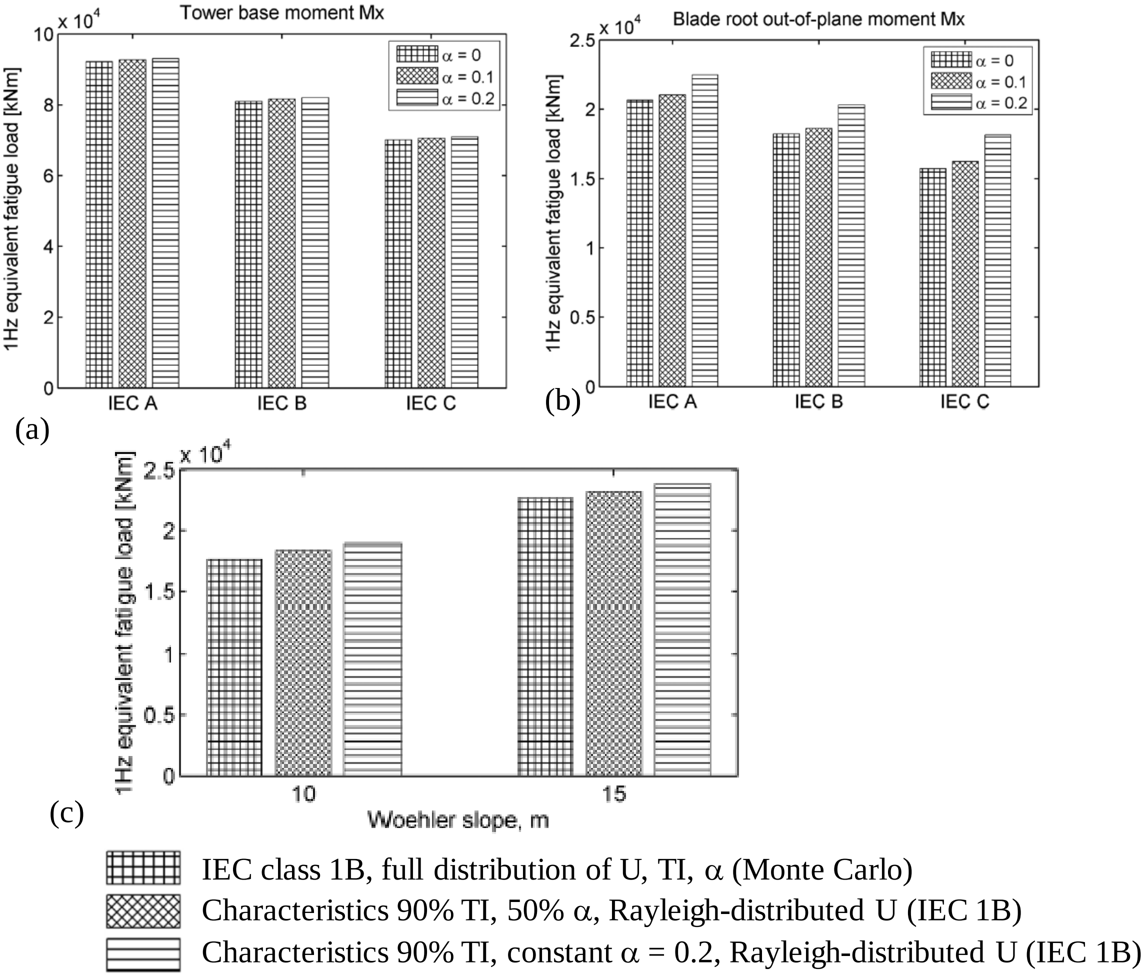


Fig. 6 Influence of wind shear exponent α on equivalent fatigue moment at (a) tower base and (b) blade root. (c) Effect of Woehler exponent m on flapwise fatigue load at blade root. Dimitrov et al. (2015).

Today's modern wind turbines have grown up in sizes, and the hub height often reaches somewhere between 80 to 120 m (Alam et al. 2011; Rehman et al. 2013). With such large hub heights, it has become almost must to design and develop towers of concrete or some other materials which can provide the improved dynamic properties (Kenna and Basu 2015). The transportation of long steel towers is a challenge in itself which can be addressed by using the concrete or other new material towers. Kenna and Basu (2015) proposed a finite element model for the description of the concrete as a continuum of four-noded, two-dimensional Reisser–Mindlin shell element. The effect of varying the magnitude of pre-stress and the time dependence of pre-stress forces has been investigated in the study. The impact of the compressive strength of the concrete on the stiffness of the tower was also studied.

4. BLADE and TOWER FAILURES, and REMEDIAL MEASURES

With passage of time, failures of wind turbine blade and tower have been reduced to a greater extent. It is the consequence of more reliable wind turbine blade manufacturing that has been possible due to continued efforts made in resolving and addressing the usual failure causes. However, with the ever-growing industrial volume of wind turbine installations, new problems and challenges emerge. Of these failures, some belong to aging of the turbines, reaching specified fatigue life limits; some are due to material defects and shortcomings in the manufacturing process; and lastly, some are new failure modes related to the increased rotor size and equally increasing hub heights. It is a fact that, as the number of turbines increases on the ground or ocean, the accidents are also expected to increase. Fig. 7 depicts numbers of wind turbine accidents occurred globally in different years, from 2000 till 2017 (Weblink-03 2018). It is very clear from these numbers that when the wind turbines were less in place, the number of accidents was also less (e.g. years 2000-2005), increasing according to the growing number of wind turbine installations. Between 2000 and 2005, the average number of accidents was 57 per year while during 2006-2010 this number reached 118 accidents per year. Between 2013 and 2017, the average number of accidents reached to around 167 per year.

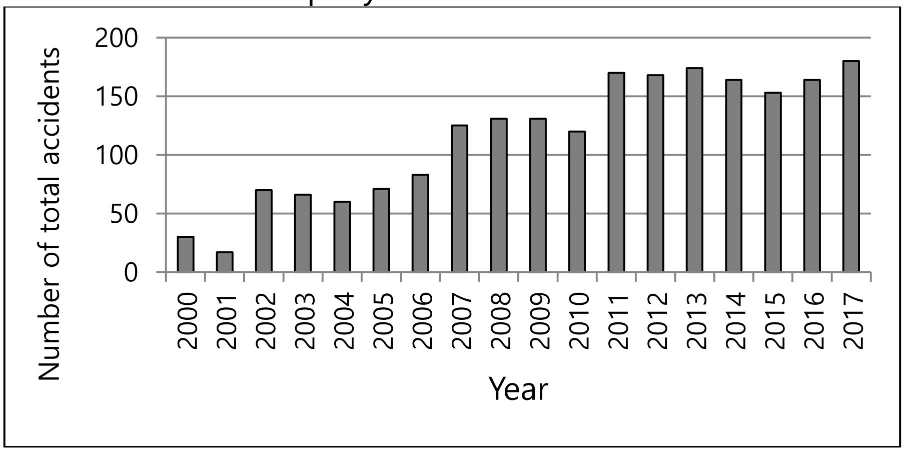


Fig. 7 Annual statistics of global wind-turbine accidents (Weblink-03 2018)

The numbers of blade and structural failures on the global level are shown in Fig. 8. It is evident from the figure that the number of structural failures is much less than the blade failures. The maximum number of wind turbine blade failures (35) occurred in 2013 while that of structural failures (16) in 2009. This means that more technological development is required in the area of wind-blade interaction, blade manufacturing techniques, and developing new materials to reduce the failures (Alam et al. 2010; Qin et al. 2017; Kim et al. 2018). Blade failures may cause the entire blades or pieces of blade being separated from the turbine. A piece of blades due to the centrifugal and Coriolis forces can travel upto 1.6 km, depending on the rotor size and speed. Some scraps of blades went through the roofs and walls of nearby buildings in an incidence in Germany, which suggests that wind turbines should be installed at least 2 km away from residential buildings. Some of the peculiar wind turbine tower and blade failure cases are shown in Fig. 9 (Weblink-04 2018 and Weblink-05 2018)**.**

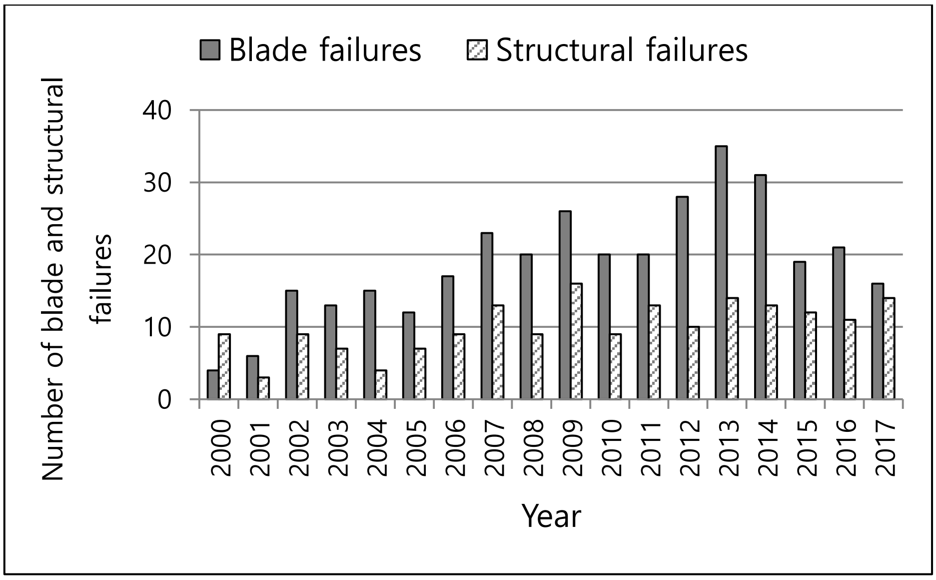


Fig. 8 Comparison of annual statistics between blade and tower failures (Weblink-03 2018)

Kress et al. (2015) in an experimental study measured and compared yaw stability of three different downwind rotors with corresponding upwind rotors by using a modular scale-model wind turbine allowing upwind or downwind operation. The investigation showed that at near full-scale Reynolds numbers the downwind rotor configurations have yaw stability while upwind turbines were either unstable or had significantly reduced yaw stability. Downwind configurations with 0°, 5° and 10° cone resulted in higher shaft power and rotor thrust than the corresponding upwind configurations. However, for zero yaw and 5° and 10° cone angles, the downwind configurations produced 5% more power and have only 3% higher thrust than the upwind configurations. Abdallah et al. (2015) proposed a rational stochastic model to quantify the uncertainty in airfoil static lift and drag coefficients based on field and wind tunnel data, aero-servo-elastic calculations, and engineering judgment. The results showed that the uncertainty in the static airfoil data has a significant impact on the prediction of extreme loads effects and structural reliability depending on the component, operating conditions and the correlations of aerodynamic variables along the span of the blades.

Lin et al. (2016) summarized the failures of wind turbine components; like blades, generators, gearboxes, frequency converters, pitch systems, yaw systems, braking systems and sub-synchronous machines based on the three primary configurations and failure statistics analysis data of wind turbines in China. The study revealed four primary reasons for failures; (i) lack of core technologies, (ii) inferior quality of the material used due to price competition, (iii) design standards and wind farm climate differences, and (vi) no mandatory quality certification and exterior factors. The study proposed a reliability management method with regard to the design, manufacturing and maintenance of wind turbines aiming to improve the reliability. Pascu et al. (2016) dealt with the problem of wind turbine tower damping control design and implementation in situations where the support structure parameters vary from their nominal design values and turbine's natural frequency. Authors designed an adaptive tower damping control loop using linear parameter-varying control synthesis.

(a)  (b) 

Fig. 9 (a) Wind turbine tower and blade failure example (Weblink-04 2018). (b) Wind turbine blade failure example (Weblink-05 2018)

4.1 Weather and Seismic effects on wind turbine failures

Tavner et al. (2012) provided an insight into the influence of weather on failure rate and downtime. A set of reliable Windstats data was used to find out the wind turbine failures and to correlate the weather conditions and the failures. The study found clear cross-correlations between wind turbine failures and weather data, in particular the wind speed, maximum temperature, and the humidity. The annual failure rates of wind turbine with daily average wind speed (Fig. 10) shows that as the wind speed increases the failure rates of control system, drive train, and the yaw system of the wind turbine tend to increase (Wilson and McMillan 2014). From this figure, it is observed that maximum failure rates of the above-mentioned wind turbine components occurred at mean wind speed of 12-14 m/s. Sathe et al. (2012) performed simulations of wind turbine loads for the NREL 5 MW reference wind turbine under diabatic conditions over wind speed range of 3 to 16 m/s for four cities. The study indicated that the atmospheric stability influences the tower and rotor loads but the blade loads were hardly affected by atmospheric stability. Furthermore, under stable conditions, loads induced by the wind profile were larger because of increased wind shear, whereas those induced by turbulence were lower because of less turbulent energy.

The global wind power growth suggests that wind turbines should be installed in seismically active regions, and entire arrays of similarly designed structures may become at risk of failing simultaneously under an extreme seismic event (Nuta et al. 2011; Myers et al. 2012). Only very few published studies appear to have considered the nonlinear dynamic response of a wind turbine support tower in the time domain (Nuta et al. 2011; Witcher 2005; Stamatopoulos 2013). Nuta et al. [3] performed an incremental dynamic analysis, investigating a 80-m-tall 1.65-MW wind turbine steel tower with the diameter to thickness (d/t) ratios ranging from 105 to 278 using suites of earthquake records representing North American seismic activity, including Los Angeles and Western Canada. Stamatopoulos (2013) performed a response spectrum, and a single time-history analysis on a 54-m tall ‘perfect’ hollow steel tower with d/t ratio ranging from 51 to 134 was modelled using nonlinear springs. The study found that the time-history analysis predicted almost 50% higher values of the base shear and overturning moment compared with a response spectrum analysis (Fig. 11).

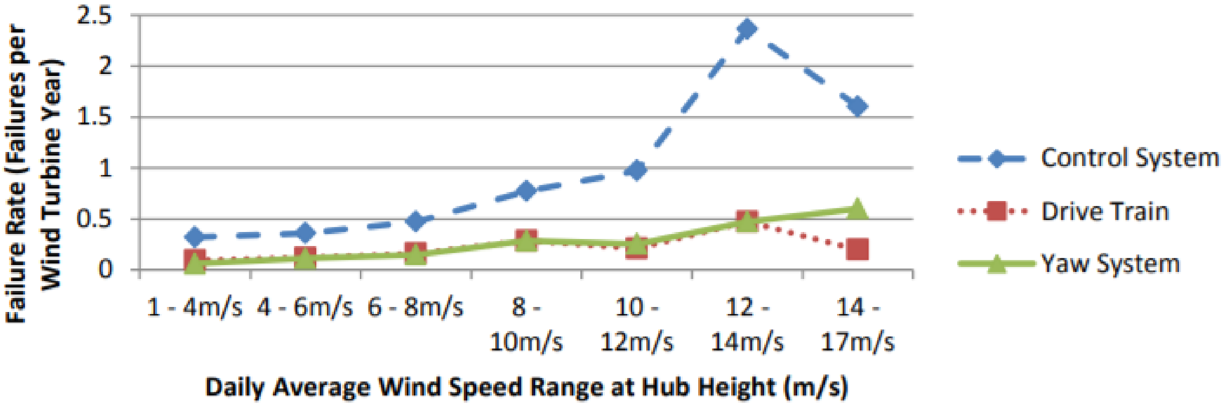


Fig. 10 Annual failure rates of wind turbine with daily average wind speed at hub height (Wilson and McMillan 2014)

Nebenführ and Davidson (2016) used Large-eddy simulations to predict the neutral atmospheric boundary layer over a sparse and a dense forest, as well as over grass-covered flat terrain. The impact of forest density, wind speed, and wind-turbine hub height on the wind-turbine fatigue loads was studied and showed that the equivalent fatigue loads increased significantly above the two forests (sparse and dense). Sadowski et al. (2017) presented a comprehensive analysis of the seismic response of a 1.5-MW wind turbine supported by steel tower modelled as a near-cylindrical shell structure with realistic axisymmetric weld depression imperfections. A selection of 20 representative earthquake ground motions, 10 ‘near- fault and 10 ‘far-fault, was applied. The tower was found to exhibit high stiffness through the development of a highly unstable plastic hinge under seismic excitations. The aggregate response was found to be significantly more damaging under near-fault earthquakes with pulse-like effects and large vertical accelerations than far- fault earthquakes without these aspects.

4.2 Wind Turbine Blade and Tower Failures

Chou et al. (2013) conducted a wind turbine blade failure analysis by examining the damage causes, specifically the delamination and cracking in the blades. They also critically studied the literature to identify the common causes of turbine blade failures. The structural mechanics of blades were then analyzed with behavioral models to identify the mechanisms of the damage. It is expected that the analytical results will help in reducing/preventing similar engineering incidents in the future. Extreme winds severely endanger structural integrity of wind turbines. Chen and Xu (2016) studied the structural failure phenomenon of wind turbines due to extreme wind conditions such as super typhoon Usagi in 2013 using post mortem analysis (PMA). The study concentrated on the effect of strong wind speed and frequently changing wind direction on tower collapse and blade fracture. The study suggested to modify the current IEC design standard and provided a few potential future directions to reduce the risk of wind turbine failures under extreme wind conditions such as typhoon and hurricane. The post mortem analysis has emerged as a commonly used approach in software engineering to determine and analyse elements of a completed project to be successful or unsuccessful (Collier 1996). This process involves identifying root causes of problems and successes that happened in the project, proposing process improvements which can help in mitigating the risks of future projects (Dingsoyr 2005; Bjornson et al. 2009). The PMA has been used successfully in analysing the failures of polyvinylidene fluoride pipes (Gacougnolle et al. 2006), power transformers by temperature distribution on surfaces (Carcedo et al. 2014), refractory linings (Queiroga et al. 2013), and compression of cast Al-Si alloys (Asghar and Requena 2014).

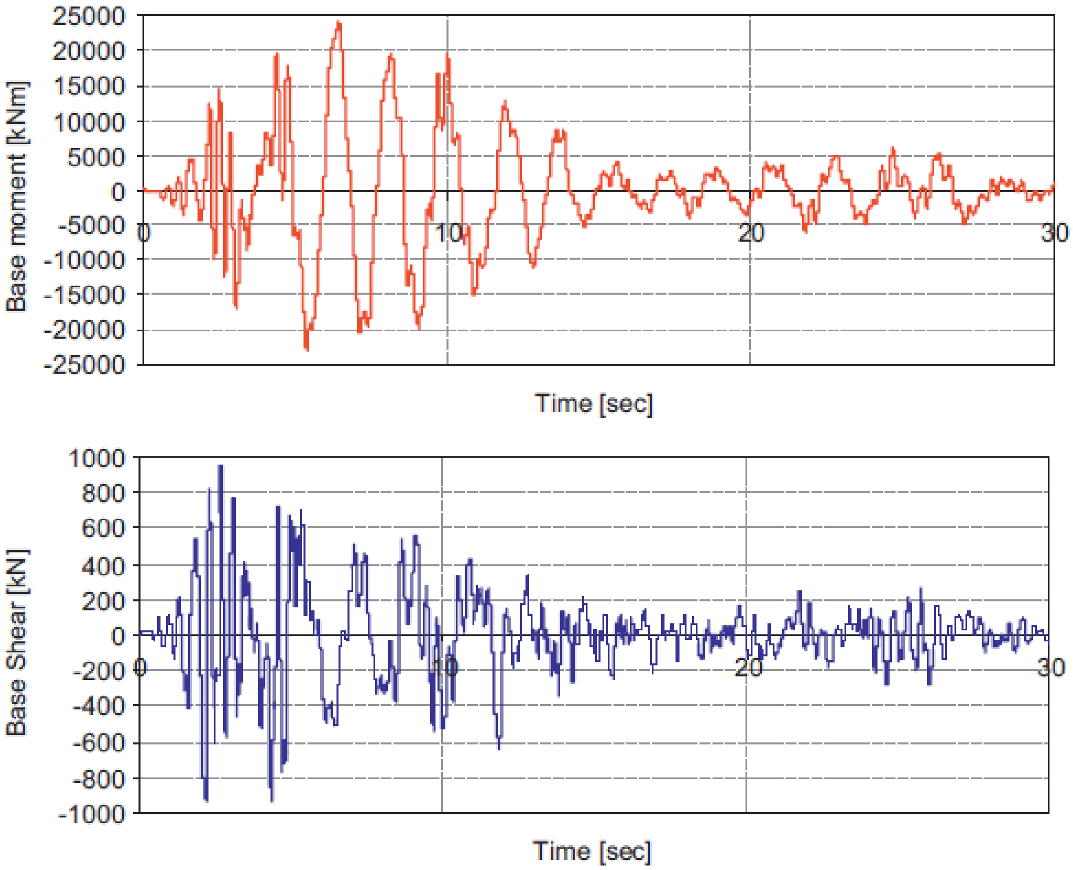


Fig. 11 Variation of the bending moment, shear force, peak displacement and peak acceleration vs time (damping ratio 1%, Stamatopoulos 2013).

Ishihara et al. (2005) investigated the collapse of two turbine towers caused by typhoon Maemi in Japan in 2003 and found that the maximum bending moment of the collapsed towers was larger than their ultimate bending moment during typhoon impact. Chou and Tu (2011) and Chou et al. (2013) examined the causes of tower collapse and rotor blade damage of a wind turbine during typhoon Jangmi in Taiwan in 2008. The study found that insufficient strength and poor quality of bolts were the causes of the collapse of tower during strong winds. On the other hand, in the case of wind turbine blade damages, poor blade material strength, wind frequency and resonance effects, and human errors during turbine installation were identified as the main causes. Zhang et al. (2013) conducted a series of experiments to find out the cause of shaft failure including the chemical composition and mechanical properties. The results showed that there were no significant differences in the material and mechanical properties of the main shaft compared to the Standard, EN10083-3:2006. The analysis revealed that stress concentration on the shaft surface coupled with high-stress concentration resulted from the change of the inner diameter of the main shaft were the main reasons of the main shaft fracture. Additionally, the theoretical stresses at the end of the shaft demonstrated that cracks can easily occur under the action of impact loads.

Jensen et al. (2006; 20011; 2012) conducted experimental investigations of a 34-m wind turbine blade and its load-carrying spar girder to failure and found that the Brazier effect induced large deformation in the spar cap and the further delamination buckling were the causes led to the blade collapse. In another experimental study, Overgarrd et al. (2010) and Overgarrd and Lund (2010) tested a 25-m blade to failure and concluded that the ultimate strength of the blade was governed by instability phenomena in the form of delamination and buckling effect. Yang et al. (2014) studied structural collapse of a 40 m blade and found that debonding of aerodynamic shells from adhesive joints was the main reason for the blade to collapse. Chou et al. [8] investigated a typhoon-damaged composite blade with a blade length close to 39.5 m and showed that the blade failed at a wind-speed of 53.4 m/s by delamination and cracking, although it was expected to resist forces at a wind speed of 80 m/s. Chen et al. (2014) presented the preliminary findings of a large composite blade (52.3 m) failure analysis. Static loads were applied to simulate extreme load conditions subjected by the blade. After blade failure, it was found that the blade exhibited multiple failure modes. Delamination of unidirectional laminates in the spar cap was found to be the root cause of the catastrophic failure of the blade.

The inspection of damages detected in some blades of 300 kW wind turbines revealed that the nature of damages was due to a fatigue mechanism (Marin et al. 2009). The failure causes (e.g. superficial cracks, geometric concentrator, and abrupt change of thickness) were studied and verified by simplified evaluation procedure of fatigue life of the “Germanischer Lloyd” (GL) standard. Lacalle et al. (2011) presented an analysis of the cracking cause in a wind turbine tower. Cracks were detected in the welded joint between the lower ring of the towers and the flange connecting the towers to their corresponding foundations. Furthermore, non-destructive tests were carried out on the base material, the weld bead, and the Heat Affected Zone (HAZ). To determine the stress state in the welded joints and the fatigue analysis in accordance to the Fatigue Module of the FITNET FFS Procedure, a Finite Elements (FE) simulation was conducted. The results demonstrated that the main cause of the cracking process was an inadequate design of the joint, with high-stress concentrations and an insufficient resistant section on the flange.

Karthikeyan et al. (2015) provided a detailed review of various blade profiles and aerofoil geometry optimization processes to achieve high power coefficient in small wind turbines that fall below Reynolds number 500,000. Chehouri et al. (2015) presented a review of the optimization techniques and strategies applied to wind turbine performance optimization through objective functions, design constraints, tools and models and optimization algorithms. Yang et al. (2016) presented a comprehensive review of non-destructive testing (NDT) techniques for wind turbine blade (WTB) inspection based on a concise literature survey. The review included typical flaw and damage occurring in manufacturing progress and in service of WTB, the developments of visual, sonic and ultrasonic, optical, electromagnetic, thermal and radiographic NDT for composite WTB, strengths and limitations of NDT techniques.

4.3 Wind Turbine Blade Extension

As the rotor diameter increases, the energy production improves. The concept of extending the size of the wind turbine blades is one of the convenient ways to achieve the higher energy output from the existing wind turbines (Burton et al. 2001). The blade extension can be obtained either by adhesively bonding technology (Kim et al. 2006; Song et al. 2010; Guo et al. 2017) and metal bolt connection (Whitworth et al. 2003; Kenche 2005; McCarthy et al. 2005). However, the adhesively bonded technology of extending blade size is simpler, provide better fatigue properties, and add less weight to the rotor compared to metal bolt connection. Adhesively bonding technology is an appropriate process for extending the wind turbine blades in service which increases the energy production (Wu et al. 2018). However, unsteady aerodynamic loads on the blades due to stochastic turbulent inflow may lead to fatigue damages and failures. The paper presented a study on strain response and fatigue life of adhesively bonded extended composite wind turbine blade suffering unsteady aerodynamic loads. The study confirmed the extendibility of the blades using adhesively bonding technology and achieving reduced risk of adhesively bonded structures (Wu et al. 2018).

4.4 Gear Box Failures

So far with the development of manufacturing technology, the reliability of wind turbine has been improved, but the gearbox problems still exist. According to the statistics (Hahn et al. 2007; Crabtree et al. 2010), in last ten years, gearbox, generator, low-speed shaft, high-speed shaft, blade, yaw system, pitch and control systems are the main failure components of a wind turbine. Generally, gearbox failure leads to the longest downtime and maximum economic loss compared to the losses associated with other failures of the wind turbines (Shen et al. 2018). The failure process of the planetary gear occurs in two stages, i.e. fretting wear and fatigue source generation. The fretting wear stage testing involves the measurements of the hardness difference between the inner surfaces of the gear and outer ring of the bearing, the influence of fit tolerance on fretting slip distance, and the influence of gear hub thickness on fretting slip distance. The experimental data and the pertinent analysis showed that the above measures were quite effective (Shen et al. 2018).

5. CONCLUSIONS

- The existing domestic expertise included the wind power rehouse assessment using historical data and data collected using 40 to 100 meter tall wind masts, wind farm design and optimization, wind-diesel and wind-photovoltaic-diesel hybrid power systems design and optimization with and without energy storage, wind turbine selection using multi-criteria approach, prediction of wind speed with time and vertical extrapolation using artificial neural networks and fuzzy logic techniques, and wind speed estimation in spatial domain using machine learning techniques to name some.

- The reported failure histories showed that extreme winds are largely responsible for the damage of the structural integrity of the blades and towers. The average number of failure incidents increases with turbine density. Among the incidents, the number of blade failures is much higher than the tower failures. This is because Woehler exponent and wind shear have pronounced effect on the blade flap loads but not much on tower fatigue loads. An increased shear component results in an increased fatigue load on the blades. Researchers thus need to pay more attention to wind-blade interaction, manufacturing techniques, and developing new blade materials to reduce the failures.
- The turbine size increases rapidly day-by-day, the increase is however larger for the offshore turbines than for the land-based turbines because the offshore turbines produce more power per square meter than the land-based turbines. As such, an increase in blade extension is required, where the extension of a blade is done by bonding technology or by metal bolt connection. The bonded technology to extend blade size is simpler and adds less weight to the rotor, but increases the chance of fatigue damage. Gearbox failure causes longer downtimes and hence needs more attention of engineering community to design more robust gearbox and develop lighter materials for its manufacturing. Fretting wear and fatigue source generation are the two main causes of gear box failures and must be addressed. Symmetrically arranged turbines may have a greater risk of failing all turbines simultaneously under an extreme seismic event. It is thus required to conduct experimental and theoretical modeling of turbine arrangement and to consider the nonlinear dynamic response of tower in the time domain.

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