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

Shafiqur Rehman[1], Md. Mahbub Alam[*2] and Luai M. Alhems

[1]*Center for Engineering Research, Research Institute, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia*
[2]*Institute for Turbulence-Noise-Vibration Interaction and Control, Harbin Institute of Technology (Shenzhen), University Town, Xili, Shenzhen 518055, China*

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Abstract. Advancements in materialistic life styles and increasing awareness about adverse climatic changes and its negative effects on human life have been the driving force of finding new and clean sources of energy. Wind power has become technologically mature and commercially acceptable on global scale. However, fossil fuels have been the major sources of energy in most countries, renewable energy (particularly wind) is now booming worldwide. To cope with this wind energy 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.

Keywords: wind power; wind turbine; turbine blade failure; structural stability; tower failure

1. Introduction

Exponentially growing population and even more rapidly increasing power demands have resulted in adverse effects on the environment due to the burning of fossil fuels to cope up with increasing power demands. However, the realization of unhealthy effects due to change in climatic conditions on the life of people has received efforts from all walks of life to overcome the adverse conditions of the climate and to meet the power demands. In this context, renewable and clean sources of energy are being developed and encouraged to be included into the existing energy mix on local and national levels around the globe. These sustainable sources of energy include wind, solar photovoltaic, solar thermal, geothermal, biomass, and ocean to name some. Among these clean sources, wind power receiving more attention because it is technologically developed and commercially accepted. The wind power plants or farms can be realized in a minimum possible time after the wind resource assessment exercise.

The cost of wind power generation has reduced to 4 - 7 US cents per kilowatt-hour. 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 to be maintained by capable 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 (Global Wind Report 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 monotonically 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 equipped 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. The wind power installed capacity can be represented by an equation fitted using the regression analysis of the data in Fig. 2 as

$$\begin{aligned} \mathrm{P} &= 1.961x^2 - 6.467x + 27.655 \qquad (x \geq 1), \\ &\approx 1.96(x^2 - 3.3x + 14) \end{aligned} \tag{1}$$

where P is the power in GW and x is the number of years starting with 1 at year 2000. When x is represented by actual year Y, Eq. (1) is reduced to,

$$P \approx 1.96[(Y - 2000)^2 - 1.3Y + 2611] \qquad (Y \geq 2000) \tag{2}$$

Modern wind turbine blades are mostly built-up of fiber-reinforced composites manufactured through molding process. The common blade designing technique comprises of independent productions of the suction and pressure side shells (Eder and Bitsche 2015). In the concluding stage, the two halves are adhesively connected. The most important adhesive joint appears at the trailing edge where the flow around the airfoil rejoins and exits the blade (Fig. 3).

The Kingdom of Saudi Arabia has embarked on restructuring its energy mix portfolio by supplementing the existing capacity through wind power and solar photovoltaic. Hence, because 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

*Corresponding author, Ph.D. Professor
E-mail: alamm28@yahoo.com; alam@hit.edu.cn

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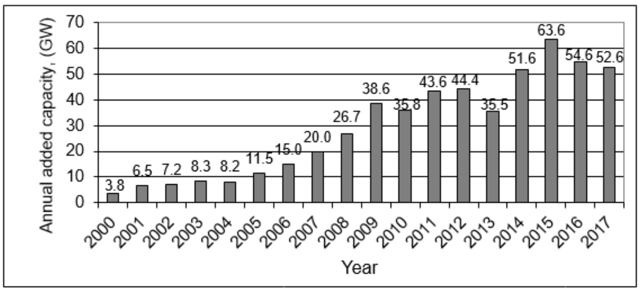


Fig. 1 Global annual growth of wind power installed capacity

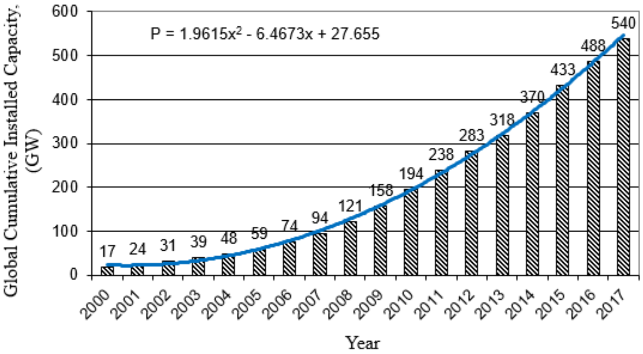


Fig. 2 Global cumulative annual growth of wind power installed capacity

meters. 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, 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); and (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).

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.

2. Wind turbine components

Wind turbines are utilized to extract the power of the wind and convert it to electrical energy through a generator. The wind energy turns two or three propeller-like blades around a rotor where the rotor is linked to the main shaft of the generator through a high-speed gearbox. The three-

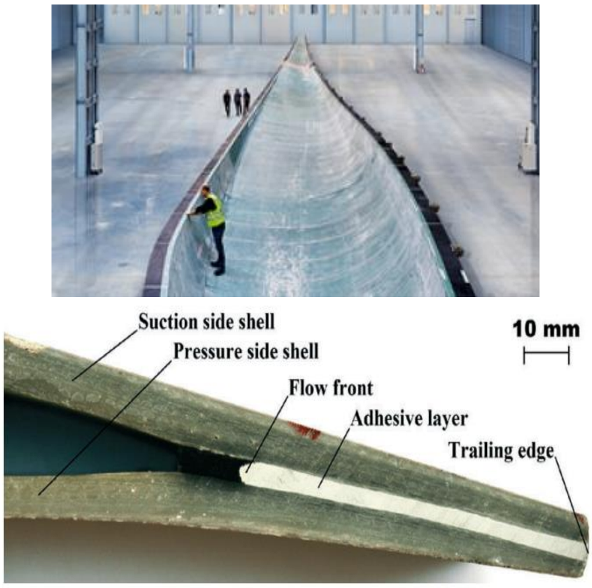
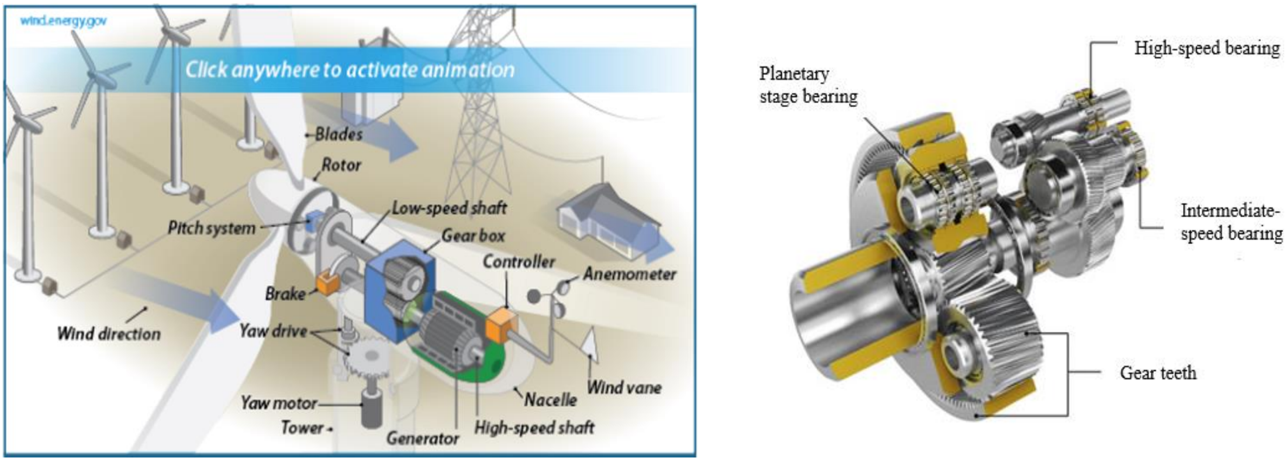


Fig. 3 Adhesive trailing edge joint of wind turbine blade as manufactured

bladed horizontal axis wind turbine illustration (Fig. 4(a)) demonstrates internal parts of the turbine and the functionality of different parts (Weblink-01 2018).

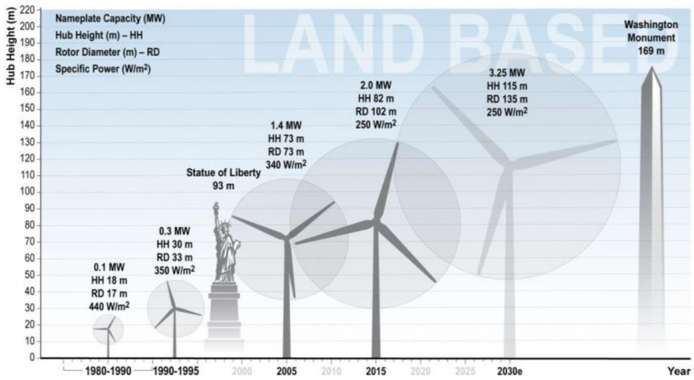
An anemometer, at the rear of the nacelle unit is installed to measure the wind speed and direction and transmit it to the controller to control/maneuver the wind turbine duringextreme conditions. Wind flow induces lift on the blades, causing rotor to spin around its axis of rotation. The breaking system halts the rotor electrically, mechanically, and/or hydraulically during emergencies and extreme weather conditions. The controller, provided at the rear portion of the nacelle unit, starts up the wind turbine at about 8 to 16 miles per hour (mph) and stops it at around 55 mph (Weblink-01 2018). Most of the wind turbines are not operated for wind speed more than 55 mph in order to avoid damage to the turbines. The gear box integrates the low and high-speed shafts thereby increasing the rotational speed from 30-60 rotations per minute (rpm) to about 1,000-1,800 rpm which is the rotational speed needed by the generators. As Gearbox is expensive and heavy, researchers are working to make it more efficient in terms of weight and efficiency. An inside view of a wind turbine gearbox is shown in Fig. 4(b). It consists of four major parts i.e., high-speed stage bearing, intermediate stage bearing, planetary stag bearing and gear teeth.

A generator is integrated with the gearbox shaft and generates 60-cycle alternating current (AC) electricity and usually available off-the-shelf. Nacelle unit rests on the top of the tower, containing the shafts, gearbox, generator, controller, cooling system, and braking system. The pitching system appears at the front of the nacelle unit. The blades of the turbine along with the hub form the rotor of the turbine. The tower is made up of tubular steel, or concrete, or steel lattice elements and it supports the dead and dynamic load of the turbine. The motor powers the yaw drive, which in turn aligns the turbines to track the incoming winds.

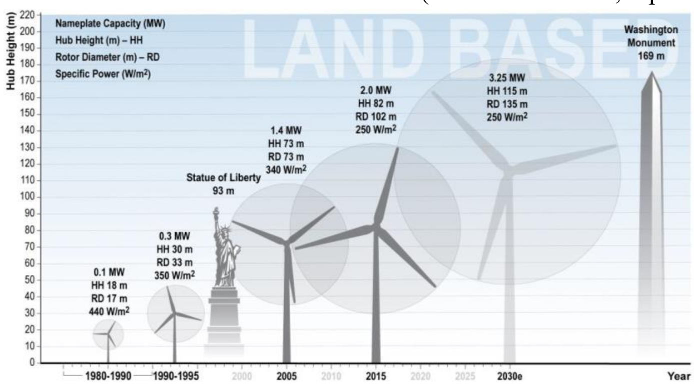


(a) (b)

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



(a) Major parts of a commercial horizontal axis wind turbine (Weblink-01 2018, reproduced with permission)



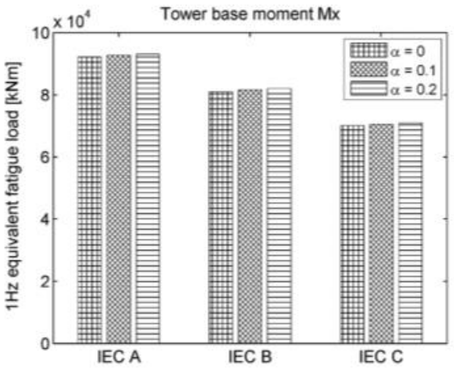
(b) major parts of a wind turbine gear box (Weblink-02 2018, open source)

Fig. 5 (a) Major parts of a commercial horizontal axis wind turbine (Weblink-01 2018, reproduced with permission), (b) major parts of a wind turbine gear box (Weblink-02 2018, open source)

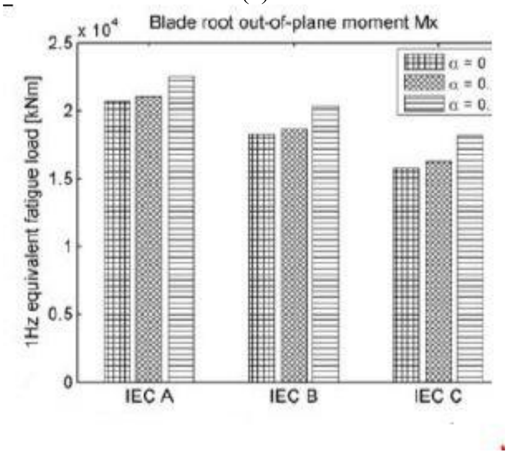
3. Wind turbine blade and tower structural stability issues

As stated earlier, the cumulative wind power capacity has reached around 540 GW by the end of 2017. This simply tells that there are around 350,000 large operational wind turbines around the world in the present time. 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 turbines in operation continuously and safely and being profitable is a challenging task and has to be addressed well. Furthermore, the operation and maintenance tasks of remotely located wind turbines becomes sophisticated due to the following wind resources dependent issues (Yang *et al*. 2014):

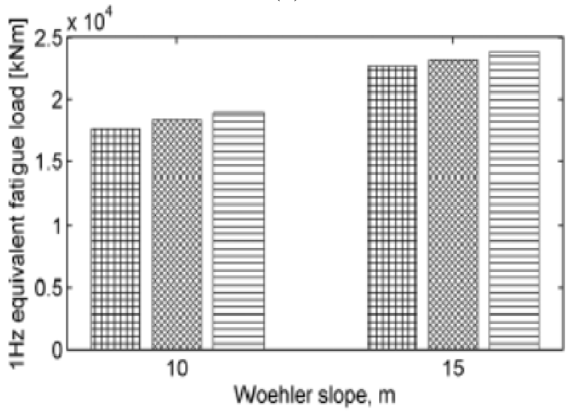
Sites: Wind turbines are installed largely in remote onshore areas and offshore locations with higher wind



(a)



(b)



(c)

Fig. 6 (a) Influence of wind shear exponent α on equivalent fatigue moment at tower base. (b) Influence of wind shear exponent α on equivalent fatigue moment at blade root, (c) Woehler exponent effect on flapwise fatigue load at blade root (Dimitrov *et al*. 2015, open source)

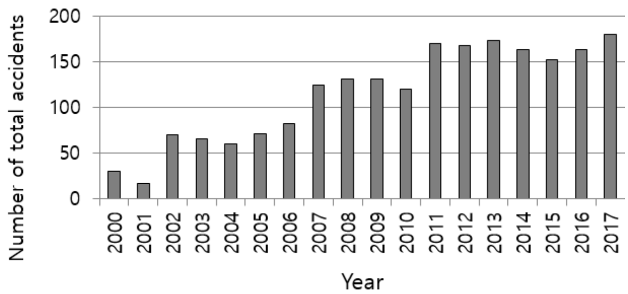


Fig. 7 Annual statistics of global wind turbine accidents (Weblink-03, reproduced with permission)

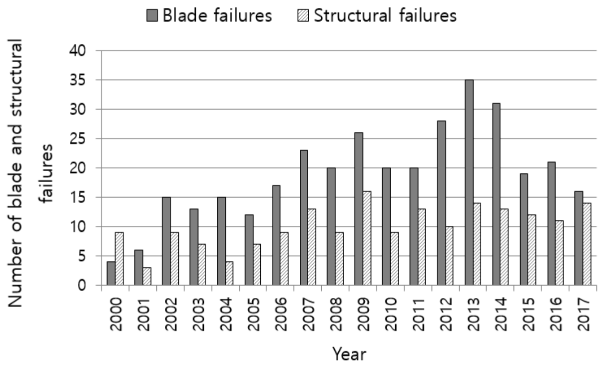


Fig. 8 Comparison of annual statistics between blade and tower failures (Weblink-03 2018, reproduced with permission)

resources.

Diversity: These days, wind turbines are manufactured based on different technologies such as geared-drive, direct-drive, variable geared, synchronous generators, permanent magnet generators, induction generators, and gearless wind turbines. Of these concepts, the gear based wind turbines drive the wind turbine market.

Sizes: The capacity and sizes of wind turbines are increasing rapidly to harvest more energy from wind. Fig. 5 shows existing and expected growth in turbine sizes and hub heights 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, wind turbines used to work on passive stall-regulated load control in a narrow wind speed range. The newly developed individual blade pitch control enables the turbines to generate more power with smaller blades and towers (Leithead *et al*. 2009, Leithead and Chatzopoulos 2010). Present day smart blade control techniques are being developed with built-in wind measuring sensors to allow the blades to follow the wind conditions (Dvorak 2012).

Economics: An increase in the wind turbine size directly reduces the cost of wind energy generation per kWh. However, in the case of offshore deployment it is not true, rather the energy generation cost increases due to installation and power cable laying complexities.

It reported that extreme winds are mainly responsible for the damage of the structural integrity of the blades and towers. The extreme wind scenarios are observed in the coastal and open areas. Fortunately, turbines are usually located in the coastal areas due to high available wind

(a)

(b)

Fig. 9 (a) Wind turbine tower failure example (Weblink-04 2018, Open source), (b) Wind turbine blade failure example (Weblink-05 2018, open source)

resources. To validate the wind shear estimations utilized in simulating the loads for the design of wind turbine, Dimitrov *et al*. (2015) used wind speed data measured at two stations at heights between 60 and 200 m for several years. They proposed a model for flat terrain, capable of reducing the ambiguity associated with fatigue load estimations. The model 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 was prominent on the blade flap loads but not on tower fatigue loads (Figs. 6(a) and 6(c). An increase in the wind shear component leads to an increase in the fatigue damage load on the blades (Fig. 6(b)).

Traditionally, the towers are tubular, made of structural steel. These towers are manufactured in large sections in factory environment and transported to the installation site. 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 must to design and develop concrete or some other material towers to facilitate improved dynamic properties (Kenna and Basu 2015). The transportation of long steel towers is a challenge in itself and can be addressed by using concrete or other new materials for towers. Kenna and Basu (2015) proposed a finite element model for the design of concrete as a continuum of four-noded, two-dimensional Reisser - Mindlin shell element. The authors studied the effect of changing the magnitude of pre-stress and related time dependence and the impact compressive strength of concrete on the stiffness of the tower.

4. Blade and tower failures and remedial measures

With passage of time, failures of wind turbine blade and tower have reduced to 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 related to bigger rotor size and increased hub heights. It is a fact that as the number of turbines grows on the ground or ocean; the accidents are also expected to increase. Fig. 7 depicts numbers of wind turbine accidents occurred globally from 2000 until 2017 (Weblink-03 2018). It is evident from these numbers that when the wind turbines were less in place, the number of accidents was also less (e.g., years 2000-2005), and increased 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.

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 incident 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). Furthermore, the weather conditions do play an important role in blade and tower failures.

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 wind turbine model allowing upwind or downwind operation. The investigation showed yaw stability for downwind rotor configuration at full-scale Reynolds numbers while upwind turbines were either not stable and/or had reduced stability. Downwind configurations with 0°, 5° and 10° cone resulted

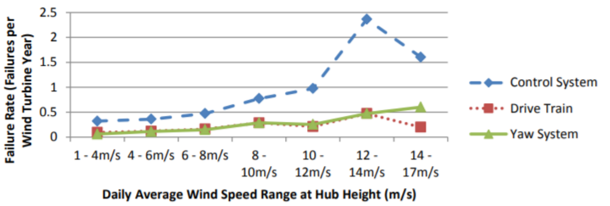


Fig. 10 Annual failure rates (Weblink-03 2014, reproduced with permission)

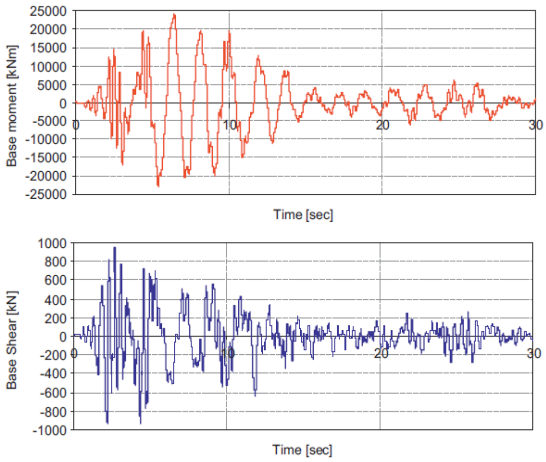


Fig. 11 Variation of the bending moment, shear force, peak displacement, and acceleration VS time (damping ratio 1%, Stamatopoulos 2013, reproduced with permission)

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 resulted in 5% additional power and have 3% higher thrust compared to upwind configurations. The study stated that the coned downwind configurations give easier yaw control and more power. 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 ambiguity in the static airfoil data has a significant impact on the prediction of extreme load effects and structural reliability. This depends on the component, operating conditions, and the correlations of aerodynamic variables along the span of the blades.

Lin *et al*. (2016) reviewed the failures of wind turbine parts; like blades, generators, gearboxes, frequency converters, pitch and yaw systems, braking systems and sub-synchronous machines based on the three primary configurations and failure statistics data of wind turbines in China. Four primary reasons were revealed by the study for failures; (i) lack of core technologies, (ii) compromised material quality, (iii) climatic conditions and design standards, and (vi) lack of certification and knowledge of exterior factors. The study proposed a management system for the design, manufacturing, and maintenance of wind turbines aiming at improved reliability. Pascu *et al*. (2016) investigated the tower damping control in situations when support structure parameters vary from nominal design values and turbine's natural frequency proposed an adaptive tower damping control loop utilizing linear parameter-varying control synthesis. The study demonstrated the fatigue load reduction performance relative initial tower damping control approach for horizontal axis wind turbine.

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 conditions. The annual failure rates of wind turbine with daily average wind speed (Fig. 10) show that as the wind speed increases the failure rates of control system, drive train, and the yaw system of the wind turbine also increases (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 turbine under diabatic conditions for wind speeds of 3 to 16 m/s for four cities. The study indicated that the atmospheric stability influenced the tower and rotor loads. Furthermore, under stable conditions the wind-induced load was higher due to the increased wind shear, whereas those induced by turbulence were lower due to less turbulent energy. Finally, the tower base loads are mainly affected by diabatic turbulence, whereas the rotor loads are affected by diabatic wind profiles. The blade loads are affected by both diabatic wind profile and turbulence.

The global wind power growth suggests that wind turbines should be installed in seismically inactive regions. Under extreme seismic events, there is a risk of simultaneous failure of entire arrays that have similarly designed structures (Nuta *et al*. 2011, Myers *et al*. 2012). Few published works in the literature have considered the nonlinear dynamic response of wind turbine support tower in the time domain (Nuta *et al*. 2011; Witcher 2005; Stamatopoulos 2013). Nuta *et al*. (2011) performed dynamic analysis of an 80-m-tall wind turbine (1.65-MW capacity)

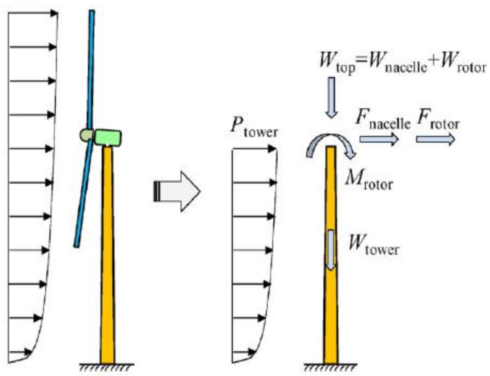


Fig. 12 External loads subjected on the turbine tower (Chen and Xu 2016; reproduced with permission)

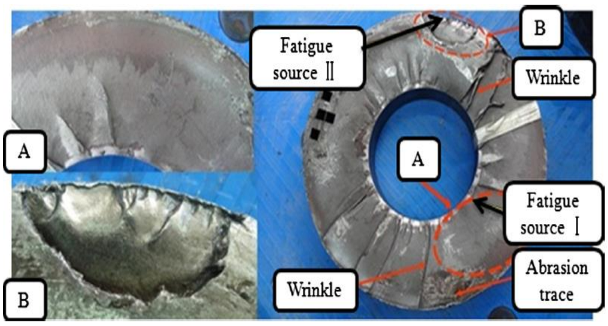


Fig. 13 Macro-photograph of fractured surface of the shaft (Zhang *et al*. 2013, reproduced with permission)

Fig. 14 Wind turbine blades under flapwise bending before failure (Chen *et al*. 2014, reproduced with permission)

steel tower with the diameter-to-thickness (d/t) ratios of 105 to 278 using earthquake records from Los Angeles and Western Canada. Stamatopoulos (2013) performed a response spectrum, and a single time-history analysis on a 54-m tall hollow steel tower with d/t ratio of 51 to 134 using nonlinear springs. The time-history analysis resulted in almost 50% higher base shear and overturning moment compared to response spectrum analysis (Fig. 11). A comprehensive review by Katsanos *et al*. (2016) concluded that the effects of near-fault records on wind turbines require further investigation.

Nebenführ and Davidson (2016) used Large-eddy simulations to predict the neutral atmospheric boundary layer over a sparse and a dense forest and over grass-covered flat terrain. The impact of these factors on wind-turbine fatigue loads showed that the fatigue loads increased significantly above the forests (sparse and dense). Sadowski *et al*. (2017) analyzed the seismic response of a 1.5 MW wind turbine supported by steel tower, modelled as a near-cylindrical shell structure with axisymmetric weld depression imperfections. Application of 20 representative earthquake ground motions, 10 near-fault and 10 far-fault, showed a high stiffness based on the development of a highly unstable plastic hinge in seismic excitations. The cumulative response was found to be highly damaging under near-fault earthquakes along with pulse-like effects and large vertical accelerations compared to far-fault earthquakes without these aspects (Nuta *et al*. 2011, Myers *et al*. 2012).

4.2 Blade and tower failures

Chou *et al*. (2013) conducted wind turbine blade failure analysis by examining the cause of damages, specifically the delamination and cracking in blades. They also critically studied the literature to point out the usual reasons for turbine blade failures. The structural mechanics of blades studied with behavioral models to understand the mechanisms of the damage. Chen and Xu (2016) studied the structural failure phenomenon of turbines due to very high winds (Fig. 12) such as super typhoon Usagi in 2013 using post mortem analysis (PMA). Typhoon Usagi caused failures of eight wind turbines inclusive of towers, rotor blades, generators, gearboxes, etc. Including cracked blades on the intact towers, the total number of the blade failures was 35 i.e., 46.7% of the total number of blades. The tower wall thickness was varied with the tower height and the steel shells were joined with butt-welding. Though failures of the towers were in buckling mode, the estimated elastic buckling strength, considering the stress concentration due to the butt joint, proved that the towers were strong enough to sustain steady loads by the wind (Fig. 12). It was inferred that the tower collapse was due to the elastic response to the wind. The study suggested modification of the current IEC design standard and provided some directions in order to minimize the risk of failures in wind turbines under severe wind conditions.

The post mortem analysis has emerged as a useful approach in software engineering to obtain and analyse elements of a completed project in order to be successful or unsuccessful (Collier *et al*. 1996). This process involves finding out the root causes of problems, proposing process improvements that 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).

Ishihara *et al*. (2005) investigated the failure of two turbine towers due to typhoon Maemi in Japan in 2003 and realized that the maximum bending moment was larger than their maximum bending moment. Chou and Tu (2011) and Chou *et al*. (2013) analyzed the reasons for tower collapse and blade damage of a wind turbine during typhoon Jangmi in Taiwan in 2008. The study found that lesser strength and poor quality of bolts were the reasons for the collapse of towers. On the other hand, in case of blade damages, poor blade material strength, wind frequency, 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 (Fig. 13) including the chemical composition and mechanical properties and showed that there were no noticeable differences in the main shaft's material and mechanical properties 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 for fracture. Additionally, the theoretical stresses at the end of the shaft demonstrated that cracks can appear due to the impact of the load.

Many studies have provided useful data to evaluate failure behaviour and the main causes of large wind turbine blades through full-scale structural tests. In this regard, Jensen *et al*. (2006, 2011, 2012) conducted experimental

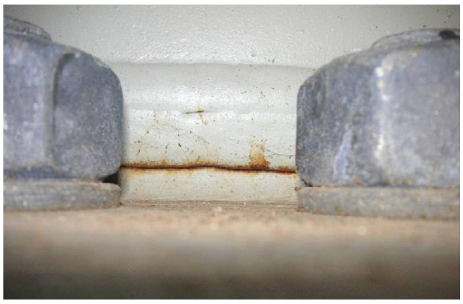


Fig. 15 Corrosion presence in welded joint on the inner side of tower (Lacalle *et al*. 2011; reproduced with permission)

investigations of a 34-m long wind turbine blade and its load-carrying spar girder to failure. It was learned that the Brazier effect induced large deformation in the spar cap and the blade was caused by delamination buckling. In another experimental study, Overgaard *et al*. (2010) and Overgaard and Lund (2010) tested a 25-m long blade to failure and found that the ultimate strength of the blade was caused due to the instability phenomena in the form of delamination and buckling. Yang *et al*. (2014) studied the structural collapse of a 40-m long blade and realized that the de-bonding of aerodynamic shells from adhesive joints was the root cause for the blade failure. Chou *et al*. (2013) investigated a typhoon damaged composite blade of 39.5 m long and demonstrated that the blade failed at a wind-speed of 53.4 m/s due to delamination and cracking. However, it was supposed to resist forces up to 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 (Fig. 14). Static loads applied to simulate extreme load conditions experienced by the blade. After failure, the blade exhibited multiple failure modes. Delamination of unidirectional laminates in the spar cap was found to be the primary cause of failure. Chen *et al*. (2014) revisited the structural collapse of a 52.3 m composite blade with a new approach to examine the chain of events captured in the video record of the blade collapse and provided direct phenomenological evidence of how the blade collapsed in its ultimate limit state. Lately, Chen (2018) carried out a forensic investigation of the fracture of two rotor blades taking into account interactive aspects associated with operational loads, materials, manufacturing processes, and structural design and recommended procedures to improve the structural integrity of the blades.

The inspection of faults detected in blades of 300 kW rated power turbines revealed that the failures were due to 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) analyzed the cracking cause in a wind turbine tower and observed cracks in the welded joint between the lower ring of the towers and the flange (Fig. 15) joining the towers with their foundations. To analyze the stress in the welded joints and fatigue analysis in accordance to the Fatigue Module of the FITNET FFS Procedure, a finite element simulation was

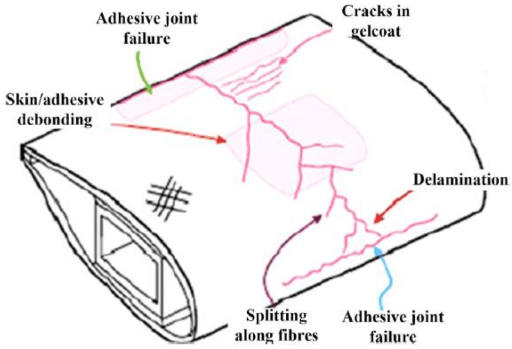


Fig. 16 Types of damages that may be sustained by wind turbine blades (Yang *et al*. 2016, reproduced with permission)

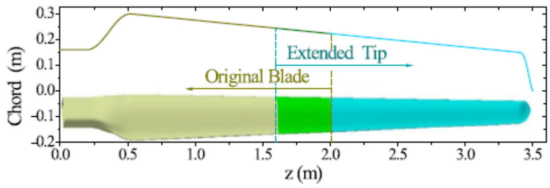


Fig. 17 Chord distribution of extended wind turbine blade (Wu *et al*. 2018, reproduced with permission)

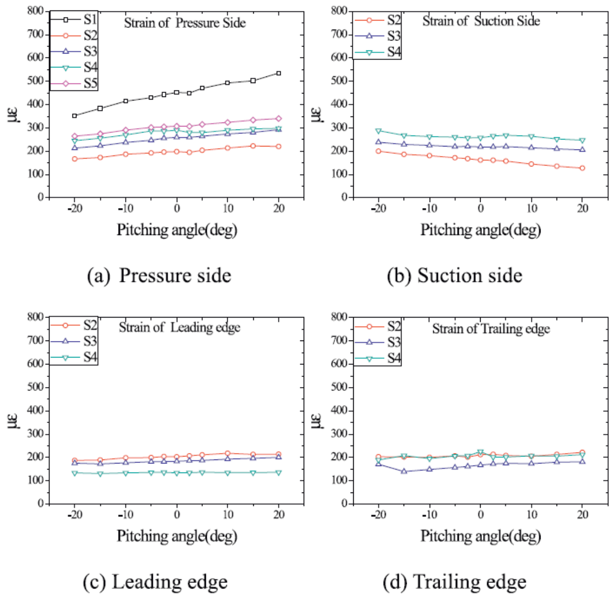


Fig. 18 Effect of pitching angles on the mean strain values at different locations of the blade length (Wu *et al*. 2018, reproduced with permission)

conducted, reporting that inadequate design of the joint with high-stress concentrations and insufficient resistant section on the flange is the main cause of failure.

Karthikeyan *et al*. (2015) reviewed cited blade profiles and airfoil geometry optimization techniques to increase power coefficient in small wind turbines (Reynolds number < 5×10^5). Chehouri *et al*. (2015) presented a review of published techniques and strategies used for performance optimization of turbines through objective functions, design constraints, tools, models, and algorithms. Yang *et al*. (2016)

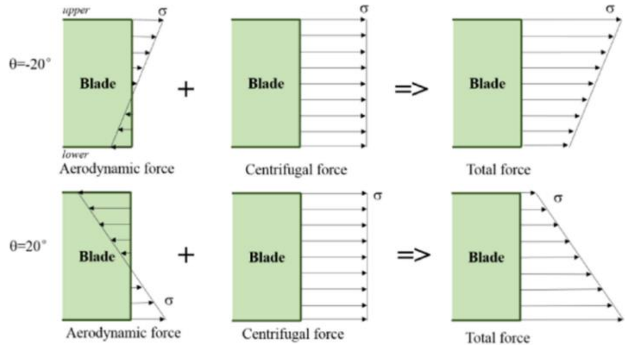


Fig. 19 Distribution of load on blade at different pitching angles (Wu *et al*. 2018, reproduced with permission)

presented a comprehensive overview of non-destructive testing (NDT) techniques for turbine blade inspection (Fig. 16) based on a concise literature survey. The review was based on studies focused on damages occurring during manufacturing and services and development of optical, sonic and ultrasonic, visual, thermal and radiographic nondestructive testing, and electromagnetic techniques. Wang *et al*. (2016) provided aero-elastic modelling, reviewed models for aerodynamic, analyzed structural and cross-sectional properties, and outlined the current implementations in the field of wind turbine blades.

Economic production of wind energy can be achieved by operating the wind turbines at/or near optimum efficiency during partial load operations, assuring reliability by fatigue load reduction, and regulating the power to rated value during rated wind availability. Njiri and Söffker (2016) reviewed control strategies, commonly used in wind turbines during low and high wind speed regimes focusing on multi-objective control schemes.

4.3 Turbine blade extension

It is well established that the power output of the wind turbine is proportional to the rotor swept area, air density, and cube of the speed. 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 higher energy from the existing 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 (Fig. 17) in service which increases energy production.[97] However, erratic aerodynamic loads on the blades because of the turbulent inflow can cause fatigue damages and failures. The study was focused on strain response and fatigue life of adhesively bonded extended composite turbine blade affected by unsteady aerodynamic loads. The effect of pitching angle on mean strain along various sections of the blades is depicted in Fig. 18. The strain linearly increases and decreases at the pressure and suction sides with increasing span-wise location. The strain does not obviously change at the leading and trailing edges at different pitching angles. An increase in lift causing flapwise moment, lead to an increase and decrease in strains at the pressure and suction sides, respectively. The blade undergoes not only aerodynamic force but also centrifugal force due to the rotation (Fig. 19). The aerodynamic force fluctuates with pitching angle, while centrifugal force remains almost constant. At a pitching angle of - 20°, the positive strain occurs on the pressure side, lower than that on the suction side. At the pitching angle of 20°, an opposite scenario prevails. 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 Gearbox failures

With the development of manufacturing technology till date, the reliability of wind turbine has been enhanced but the gearbox problems still prevail. According to the statistics (Hahn *et al*. 2007, Crabtree *et al*. 2010) in the past decade, gearbox, blade, generator, low- and high-speed shafts, pitch, yaw system, and control systems are seemingly the major 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 stage testing involves the measurements of the hardness difference between inner surfaces of the gear and outer ring of the bearing, the influence of fit tolerance and of gear hub thickness on fretting slip distance. The experimental data and the pertinent analysis showed that the above measures were quite effective.

5. Blade and tower failures analysis tools

The software tools developed for the analysis of wind turbine blades and towers are BModes, Modes and FAST (Bir 2005, Jonkman and Buhl 2005), HAWC2 and GH Bladed (Larsen and Hansen 2007, Bossanyi 2003). Most of these tools have been facilitated by National Renewable Energy Laboratory (NREL). BModes and Modes softwares are utilized to analyze the free-vibration properties of the wind turbine blades and the towers by modeling these components as a series of Bernoulli–Euler beam elements. On the other hand, FAST, HAWC2 and GH Bladed are tools used to study the wind turbine as a whole assembly. These tools allow the interaction among the blades, hub, and tower through coupled equations of motion. Additionally, there are some other general-purpose software tools available for designing the wind turbine blades, towers, and the complete wind turbine. These tools include the ANSYS and ABAQUS.

An asset model was developed for offshore turbine inspection, reliability, degradation, and maintenance processes evaluations. The model was based on the Petri net method which can capture the stochastic nature of the dynamic processes. The model outputs indicate the performance of the components in terms of probability of being in different conditions, the probable maintenance actions and finally the average number and duration of system downtime under any maintenance strategy. Ke *et al.* (2015) analyzed the wind field and wind-induced vibration characteristics of a 5 MW tower-blade coupled system (Fig. 20). The study developed a blade-nacelle-tower integrated finite element model with rotational blade induced centrifugal forces. Based on a harmony superposition approach and modified blade element-momentum theory, the fluctuating wind field of tower-blade coupled systems was simulated, which considered wind shear, tower shadow, rotational, blade-tower dynamic, and model interaction effects. The results indicated that wind-induced response of the tower-blade coupled structure produced modal and multimode coupling effects. The rotational effects tend to amplify aerodynamic loads on blades, wind-induced dynamic responses, and wind vibration coefficients. With increasing tower height, wind vibration coefficient first declines and then grows until the tower top. That on the blade tip is about 2.4, large than that on blade root.

Wang *et al.* (2015) proposed some alterations to the double multiple-stream tube model to include the component of wind speed parallel to the rotating shaft. Three dynamic stall models were integrated with Berg and the Beddoes–Leishman dynamic stall (BL DS) model. The study quantified the effect of tower tilting with respect to power, rotor torque, thrust force, normal and tangential force coefficients on the blades. The study also compared the simulation results of the Glauert and pure axial momentum theories to find the effect of the velocity on the accuracy of the model. A culture of root cause investigation and problem-solving has been penetrating in the wind power industry. This root cause analysis (RCA) helps in managing the cost of mechanical failures in the long run. The RCA methodology is a physics-based and data-driven analytical tool. The process starts by defining the problem followed by a review of existing documentation and machine data. Site-dependent information is obtained through tower inspection and measurement, and lubricant analysis. To further narrow down the failure causes, simulations and metallurgical testing were conducted to pinpoint the primary reason. Corrective measures are derived based on site inspection, laboratory analysis and expert opinion. This paper provided highlights of two wind turbine drivetrain failures to demonstrate the RCA process which can be obtained from the Weblink-06 (2018).

Ghaemmaghami *et al.* (2012) analysed the annular liquid tank as a tuned liquid damper in addressing the wind turbines vibrations. A hybrid wind tower model composed of a concrete shaft and a steel mast of 150 m high was simulated for a single-degree-of-freedom system. The structural domain (tank wall and a rigid mass) was modelled by finite element and fluid domain by finite volume method using CFX software. TLD was found to be effective for small amplitude of excitation. Soman *et al.* (2016) developed a decision level data fusion system for Structural Health Monitoring (SHM) of towers based on bi-axial tracking of change in neutral axis (NA) position. Bi-axial NA tracking based on data fusion was found to be necessary and sensitive for turbine tower damage assessment. Based on stochastic subspace identification, Dai *et al.* (2017) proposed an identification method for structural assessment towers. The proposed method could identify the modal parameters of structures under operating conditions with harmonic components in excitations.

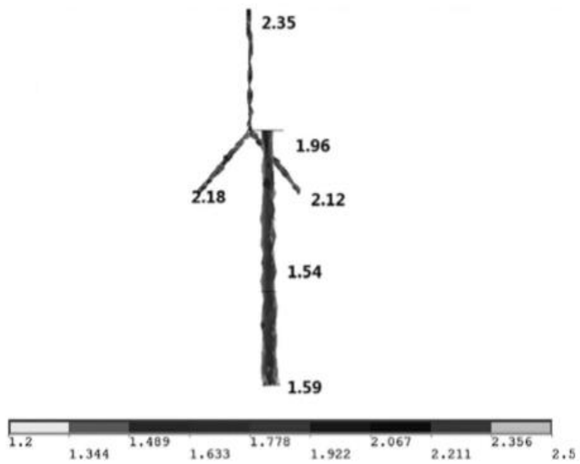


Fig. 20 Wind induced vibration coefficients of tower-blade system (Ke *et al.* 2015), open source

Jafari and Kosasih (2014) conducted CFD analysis of a small wind turbine with frustum diffuser shrouding. The analysis showed that the sub-atmospheric back pressure was an influential factor in power augmentation. The results of this study can be used for any type of turbine under nominal wind speed conditions. Hayat *et al.* (2014) studied the effects of the structural bend-twist coupling (BTC) on the flutter by considering the layup unbalances on the NREL 5-MW wind turbine rotor blade of glass fiber/epoxy [02/+45/-45] Slaminates. It was found that flutter speed may decrease by about 5 percent with unbalanced ply-angle only. The study also stated that the flutter performance of the blade can be enhanced through lighter and stiffer carbon fibers.

6. Conclusions

The present work aims at understanding various aspect of wind power technology for smooth implementation and adoption in the country. The study reviewed the existing understanding of the local expertise on the wind power subject and also focused on wind turbine blade and tower structural stability issues, blade and tower failures and remedial measures, weather and seismic effects on turbine blade and tower failures, gear box failures, and turbine blade and tower failure analysis tools. Some of the highlights of the present study are as follows.

- The existing domestic expertise includes the wind power resource assessment using historical and measured wind speed data collected using 40 to 100 meter tall wind masts; wind farm design and optimization, 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.

• 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. The failure of tower occurs largely in buckling mode due to the unsteady load generated by elastic response of the tower to the wind. To reduce wind turbine failure risk under extreme wind conditions (typhoon and hurricane), a modification of the current IEC design standard is thus suggested, incorporating the load due to the elastic response of the tower to the wind. The welded joint between the lower ring and the flange connecting the towers to the foundations, deteriorates rapidly particularly in the inner side of the shell, which should be paid attention when the tower base is designed. Gearbox failure causes longer downtimes and hence needs more attention of the 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 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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