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Impact threats and classification

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Review article

A review of impact loads on composite wind turbine blades: Impact threats and classification

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ABSTRACT

A fiber-reinforced composite wind turbine blade (WTB) is exposed to numerous impact threats during its service life causing damages that can be detrimental to its structural integrity. Currently, impact loads are not considered during blade design, so high safety factors are introduced, which result in a conservative design. However, as wind turbine blades become stiffer and lighter and health monitoring systems become more sophisticated, the design process is shifting toward damage-tolerant approaches. The design philosophy accepts damages to the structure, but it also requires that the damaged blade still meet structural and functional requirements. This design procedure requires a comprehensive understanding of different impact threats and their characteristics, which is currently unavailable in the public domain. This paper is a first attempt to review the impact loads on composite wind turbine blades. The aim of the current paper is to (a) identify different sources of impact threats on wind turbine blades during different stages of their service life, (b) describe their qualitative (causes and vulnerable regions) as well as quantitative characteristics (size, mass, and velocity of impactor), and to (c) provide modeling guidelines by comparing these impact threats using five different criteria - (i) relative deformability of projectile and wind turbine blade, (ii) impact velocity, (iii) kinetic energy of impact, (iv) repeatability of impacts and (v) nature of the impact. The review paper will be of special interest to researchers working on wind turbine blades and will serve as a baseline report for designing damage-tolerant blades. Recommendations are also provided for future research.

1. Introduction

1.1. Background

There is a great demand for utilizing renewable energy resources to reduce the carbon content in the environment. A growing focus is being placed on large-scale commercialization of sustainable energy sources such as solar energy, wind energy and hydropower energy. [1]. Among the different renewable resources, wind energy, due to its high potential and increased technological advances, has witnessed a rapid surge in its growth, both at onshore and offshore locations [2–4]. The current trend in the wind turbine (WT) industry is increasing turbine size with power ratings reaching in the order of 8–15 MW [5]. Large size turbines are profitable to the industry as (1) the power produced from the wind scales with the square of rotor diameter and cube of the wind speed, and (2) the power capacity of the wind farm is satisfied with fewer turbines, which reduces installation, operation and maintenance cost [6]. Fig. 1 shows the variation in the size and mass of rotor blades as well as hub height of the turbines with increase in power rating. A Senvion 5 MW wind turbine has a blade of length 61.5 m, blade mass of 20.8 tons. Meanwhile, a Haliade X 12 MW turbine has a blade length of around 107 m, and blade mass of 55 tons. Therefore, a typical characteristics of turbines with large power ratings are longer and heavier blades. Due to the increase in mass, wind turbine blade design has become dominated by gravity and inertia loads as compared to the aerodynamic loads [7–9]. These high gravity loads induce higher stresses in the blade materials, increase fatigue, along with transference of larger loads onto the rotor shaft and the turbine tower. It is therefore vital to reduce the weight of the blade by improving the existing design

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Nomenclature

CAA	Civil Aviation Authority
DSD	Droplet Size Distribution
FAA	Federal Aviation Administration
$F(t)$	Impact force at time t
k_1	Spring stiffness
k_2	Spring stiffness
KE	Kinetic Energy
m	Mass
m_1	Mass of projectile
m_2	Mass of target
NTSB	National Transportation Safety Board
QRA	Qualitative Risk Assessment
RPM	Rotations Per Minute
SEM	Scanning Electron Microscope
SiO_2	Silica
SPH	Smooth Particle Hydrodynamics
UAV	Unmanned Aerial Vehicle
UK	United Kingdom
US	United States
USD	United States Dollar
V_0	Projectile velocity
V_{imp}	Impact velocity
V_{tg}	Terminal velocity of particle
V_{tip}	Velocity of wind turbine blade tip
V_w	Wind speed
WT	Wind Turbine
WTB	Wind Turbine Blade
$x_1(t)$	Displacement of a projectile at time t
$x_2(t)$	Displacement of a target at time t
ρ_p	Projectile density
σ	Stress exerted by the projectile
σ_p	strength threshold of the projectile
σ_t	Strength threshold of the target

procedures [10,11]. A typical cross section of wind turbine blade and different material composition is shown in Fig. 2.

The current design philosophy of wind turbine blades is based on safe-life design concept [19–21] where a worst combination of in service damages that is likely to get undetected during the service life are considered. This design philosophy utilizes high safety knockdown factors that take into account uncertainty in material, structural and buckling failure strength of a wind turbine blade subjected to operational loads. In addition, these safety factors also take into account those failure loads and mechanisms which are not explicitly considered during the blade design. One such source of damage are those that arise due to out of plane impact loads on blades [17].

There are several sources of impact loads that could damage the wind turbine blade (Fig. 3) [17,22]. For example, bird and atmospheric particles collision strikes (e.g., hailstone and rain droplet impacts) during operation as well as impact with surrounding structures during transportation and installation [23,24]. Wind turbine blades are made of composite materials as well as sandwich sections (Fig. 2) that are weak in through the thickness direction, thus impact loads on blades can be detrimental to their structural integrity [8,25]. In addition, complex failure modes are obtained under impact loads that simultaneously interact and are sometimes visually undetectable [26]. For example, delamination of plies is barely visible but involves local separation of different lamina into sublaminates [27], thereby reducing the critical buckling loads and strength and stiffness of the structure. In addition, the impact threats due to rain droplets, hail impacts and sand collision can change the leading edge profile [28–30], which is detrimental to aerodynamic performance and causes significant loss in power production.

Currently, due to lack of understanding of all the possible impact threats, collision scenarios and their influence on blade's structural integrity, the blade design tends to become very conservative. Given that the blade industry aims to develop optimized wind turbine blades, this has led to a huge interest to transition from safe-life design philosophy to a damage-tolerant design philosophy [19,31,32]. The term damage tolerance refers to a structure's ability to sustain anticipated loads (e.g., limit loads) despite fatigue, corrosion, or accidental damage until the damage is detected and repaired [33]. In relation to damage tolerance analysis methodology, two terms are often used: fail-safe design and damage tolerant design [34,35]. Fail-safe designs ensure that damaged structures can continue to withstand design loads with reduced margins of safety. A damage-tolerant design on the other hand extends the concept of fail-safe to encompass damage growth and residual strength analysis necessary to allow continued system operation [36]. The damage tolerance analysis can be used throughout most phases of the structure life cycle, with early design life predictions during the design phase, a major update after manufacturing to take into account defects and flaws, and periodic updates during operation phases to take into account damage growth and identification using health monitoring system. Overall, rapid advancement in inspection and monitoring techniques in wind turbine blades have further boosted this transition from safe-life design philosophy to a damage-tolerant design philosophy. In this review, we explicitly focus on impact loads and impact damage-tolerant design. According to [37,38], the different steps involved in the development of an impact damage-tolerant design criteria of a typical composite structure include (1) an accurate characterization of sources of impact threats and identify critical locations of interests for the structure (2) modeling techniques for analyzing impact damages (3) adequate inspection systems/devices so the damage can be detected, and (4) post impact residual strength assessment. This research focuses on first aspect and discusses different sources of impact threats during different stages of blade service life as well as compare their characteristics. In addition, different vulnerable regions of wind turbine blades subjected to such impact threats are identified. The scope, target readers and novelty of the current review research are further elaborated below.

1.2. Scope, novelty and target readers of the review paper

It is crucial to understand that not all impact loads acting on the wind turbine blades are caused by accidents. Collision with impact threats such as rain, hail, sand and insect particles can be categorized as normal impact during service life. While a collection of accident events for different wind turbine components can be found in many online websites including recent review papers [39,40]. However, there is no systematic literature available that deals specifically with impact loads and damages of wind turbine blades during their service life. Other literature review on wind turbine blades deals with fatigue failure [41], failure due to extreme operational loads [42], failure due to erosion [43,44], damage detection and mitigation techniques [45–47]. This review paper is a first attempt to review different sources of impact threats on wind turbine blades and the structure of the paper is shown in Fig. 4. The main aim of the current paper is (a) identifying different sources of impact threats during different stages of blade's service life (b) describe their qualitative (causes and vulnerable blade regions) as well as quantitative characteristics (size, mass and velocity of impactor), and (c) provide modeling guidelines by comparing these impact threats using five different criteria - (i) relative deformability of projectile and wind turbine blade, (ii) impact velocity, (iii) kinetic energy of impact (iv) repeatability of impacts and (v) nature of impact. This work will be of special interest to researchers working on wind

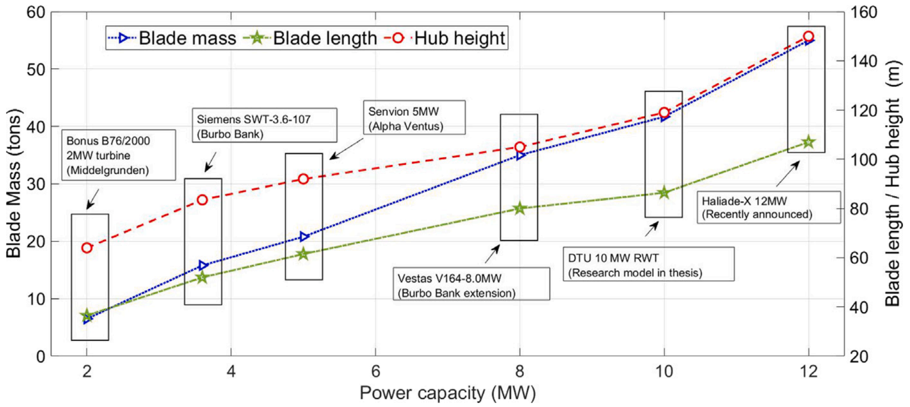


Fig. 1. Variation in the size and mass of rotor blade.
Source: Data taken from [12–16].

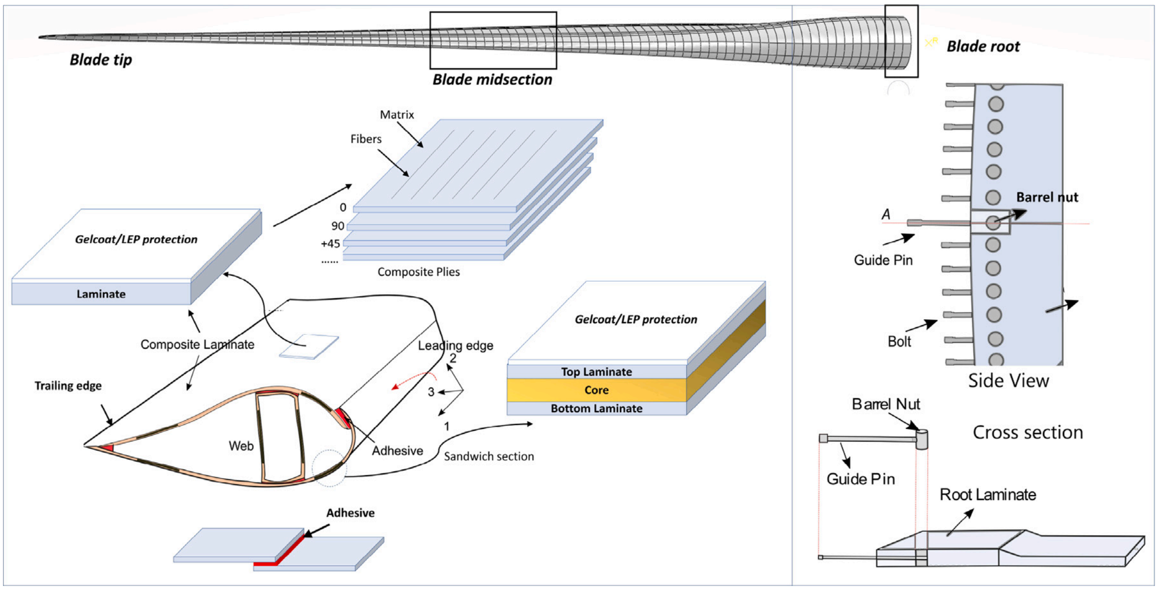


Fig. 2. A typical cross section of a wind turbine blade.
Source: Adapted from [17].

turbines, blades, thin walled composite structures, design and structural safety. The paper will also serve as a benchmark paper to industrial practitioners to refer to different aspects – sources and characteristics of impact threats, vulnerable impact region, factors that causes such collision etc – that will help them to design damage-tolerant blades.

1.3. Assumptions and limitation of the current review

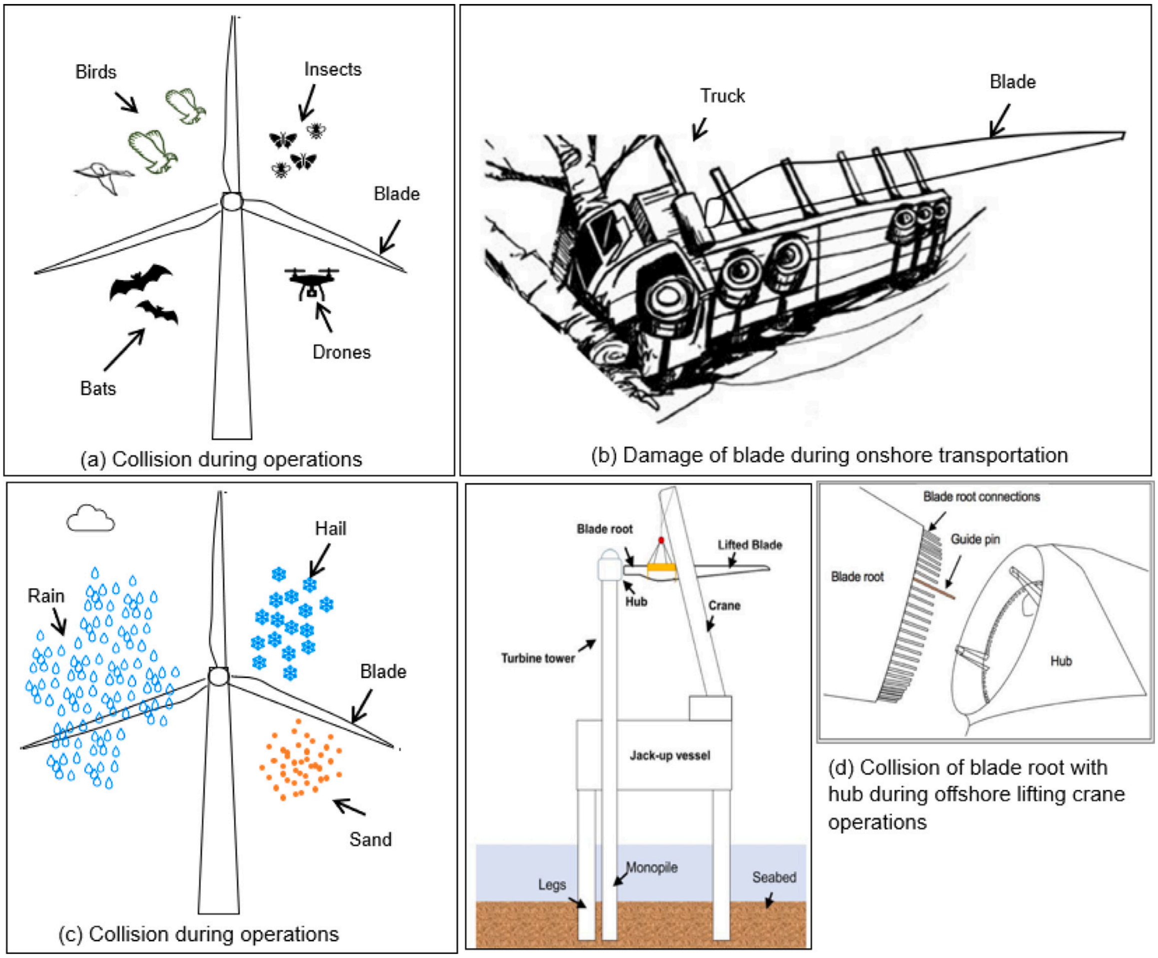
The focus of this review is specifically on mechanical impact loads on wind turbine blades. Other causes of wind turbine blade damage and faults, such as gust loads and lighting effects, have not been considered. In addition, the findings, comparisons, and conclusions are drawn from peer-reviewed published papers, each with its own limitations and assumptions. In addition, this review only analyzes what impact threats exist for wind turbine blades, how they can be classified and their comparison. This work does not explicitly discuss different numerical modeling strategies, their results, and types of failure modes in the blades associated with each of these impact threats. Instead, this review would provide essential modeling guidelines to engineers and scientists. As an example, this can include choosing the appropriate collision scenario, utilizing the right impactor properties such as mass, stiffness, diameter, among others, and selecting the right blade vulnerable region for investigation. All these efforts would contribute significantly to design future damage-tolerant wind blades.

2. Classification of impact threats on wind turbine blades

Wind turbine blades can suffer impact threats majorly during four stages of their service life, that includes (a) transportation stage (b) installation stage (c) operation stage and (d) maintenance and inspection stage (Fig. 5). A thorough literature review has been performed and different sources of impact threats are identified under each of the stages and described in Fig. 5. Note that for some of the impact threats as highlighted in Fig. 5, a quantitative description (e.g., mass, size and velocity of impactor) is not possible, given that these are associated with random accidental events with immense impact energy. Therefore, for such impact threats, only a qualitative description is provided that deals with factors which causes such accidents and vulnerable blade regions are indicated. A detailed discussion about different sources of impact threats during different stages of blade service life is elaborated below.

2.1. Impact during transportation stage

Increasing size and dimensions of wind turbine blades pose challenges during transportation, both for onshore and offshore wind industry [50]. For sites that are located onshore, wind turbine blades have to be transported either through roads, rail or a combination [50,51]



(a) Collision during operations

(b) Damage of blade during onshore transportation

(c) Collision during operations

(d) Collision of blade root with hub during offshore lifting crane operations

Fig. 3. Different examples of impact threats.
Source: Adapted from [18].

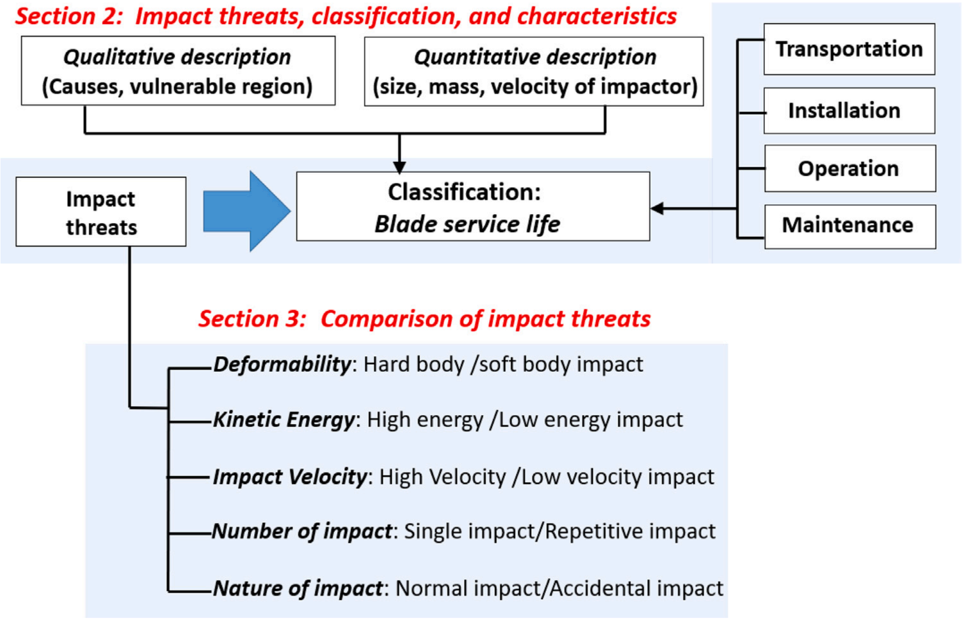


Fig. 4. Overview of structure of this paper.

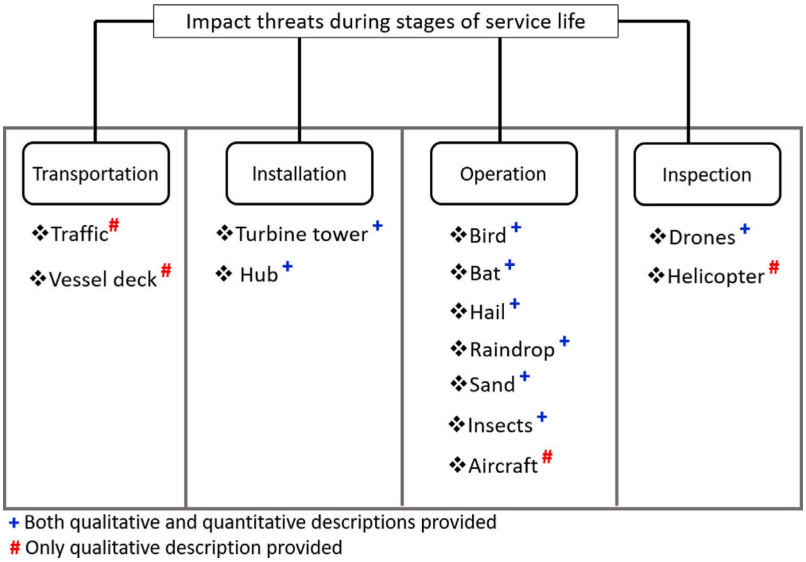


Fig. 5. Impact threats during different stages of blade service life.

Fig. 6. (a) Onshore transportation of blade (permission taken from Elsevier [48]) (b) Blade damage during offshore transportation (permission taken from Skuld [49]).

(Fig. 6(a)). Wind turbine blades have to be maneuvered through narrow passages, around sharp turns as well as overhead obstructions over long distances that pose impact threats from surrounding traffic and obstacles, requiring extensive planning [52]. Several reports of mild to severe damages to wind turbine blades from surrounding traffic and obstacles have been reported in news articles [39,53]. The damage can occur at any region of the blade especially at the region exposed to traffic (e.g., leading edges). On the other hand, offshore transportation of blades is equally challenging due to sensitivity of the vessel to dynamic excitation from wave loads along with high wind loads that can act on the blade cargo [54]. A number of blade damage cases have been reported due to collision with the vessel deck [55]. These are mainly caused due to (a) poor stowage plan of the blade cargo on the vessel (b) poor welding of stoppers, (c) handling errors during loading due to high winds (d) human error and (e) inappropriate securing of blade cargoes. Fig. 6(b) presents a situation where blade cargo has fallen overboard due to poor securing and bad weather, thus damaging the wind turbine blades. Note that offshore wind farms require several blades and premature blade damage during sea voyage can cause severe delay to the project as spare blades are generally not available. Further, since the traffic and vessel deck collisions are random accidental events and the blades cannot be designed against such loads, a quantitative description of impact threat (size, mass, or velocity of the impactor) is not provided.

2.2. Impact during installation stage

Here, the discussion is mostly focused on installation of offshore wind turbine blades where specialized crane vessels such as jack-up crane vessels or floating crane vessels [17] are used. These vessels are extremely sensitive to dynamic wave loads such as wave height, wave period and wind speed. Excessive crane tip motions can cause impact loads on wind turbine blades. Therefore, a quantitative estimate of impact velocity requires global motion response analysis of the installation system [56]. Analysis performed in [18] showed that blade can impact the surrounding structures with low velocity in the range of 1–2 m/s; nevertheless, impact energy during the collision of the blade is very high since a blade of a typical MW-sized WT can weigh several tons. Note that for collision scenario during installation, the blade itself can be considered a projectile as it collides with surrounding structures such as the turbine tower that are relatively stationary and stiff. It is also important to understand that wind turbine blades are installed in three distinct phases and each phase present different vulnerable blade region. The first stage is the lift-off phase where blade is close

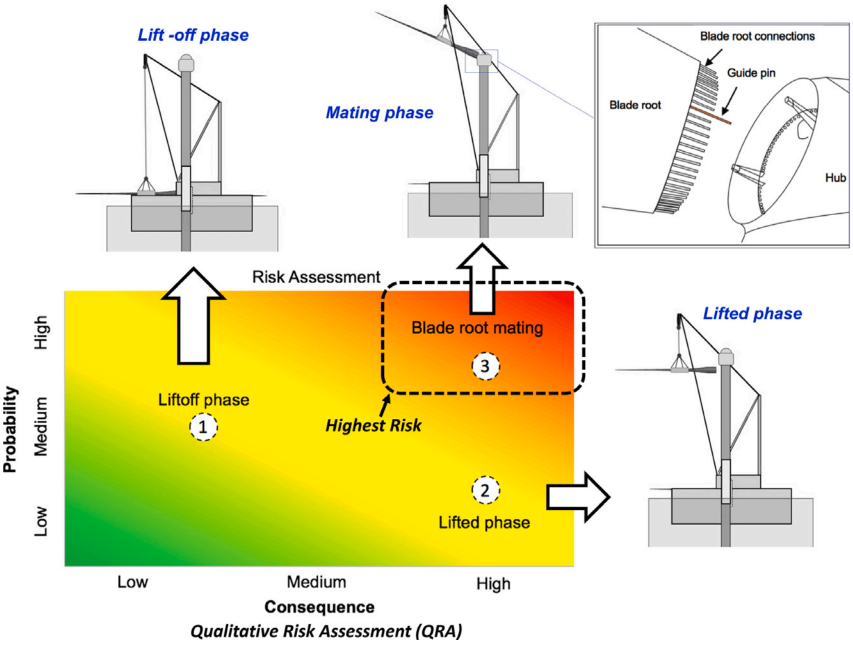


Fig. 7. Qualitative risk assessment chart during the installation phase.
Source: Adapted from [59].

to vessel deck, the second stage is the lifted phase where the blade is hoisted from the deck towards the hub height, and the last stage mating phase [57] where the blade root is docked in the hub. A qualitative risk assessment (QRA) was performed in [58] to identify and rank collision threats during these three stages and vulnerable blade regions were identified, see Fig. 7. During the lift-off phase, the blade leading edge can impact the surrounding structure, however, this stage is ranked the lowest on the risk assessment chart as such events have medium occurrence rate, and have low consequences. The lifted phase is ranked second as it has a low occurrence rate since structures are relatively spaced apart during controlled installations. However, due to large blade pendulum motions, the blade leading edge could hit the tower and can cause localized damages at the adhesive joints. Finally, during the mating phase sensitive blade root connections can get damaged. The impact during blade mating phase is ranked highest given that such events have high occurrence rate and are associated with high consequences.

2.3. Impact during operation stage

One of the important differences compared to the previous discussions, is that the blade during operation stage is rotating. Consequently, major part of kinetic energy of impact comes from blade rotational speed. Fig. 8(a) shows the angular speed of the blade for a typical 10-MW turbine. As seen from the figure, there are three important regimes—cut-in, rated and cut-off wind speed. The blade is in parked condition at wind speed below cut-in and above cut-off speed. The blade is at its highest angular speed between rated and cut-off wind speed. The angular speed can be translated to the linear speed of a blade section, the largest being at the tip. Fig. 8(b) shows the range of nominal tip speed for existing and future wind turbine blades, i.e between 60–110 m/s. Hence, a impactor itself with a low speed can be detrimental to the blade during the operational phase. A description of the different impact threats during the operational phase is discussed below.

2.3.1. Wildlife collisions

There are several reports that cite rotating wind turbine blade collisions with wildlife that mainly include flying birds and bats [22, 63–69]. Given the growth of the wind energy market, it is expected that wildlife fatalities due to collision with wind turbine blades will increase [62,70–75]. A comprehensive analysis based on 133 and 101 papers was performed by [76], where birds and bats collision rate with wind farms were analyzed. It is found in the paper that: (1) collision rates are higher for bats compared to the birds, (2) bird collision rate mainly depends on their migratory behavior, their spreading distance and habitat associations, (3) bat collision rate mainly depends on their dispersal distance, and (4) bird species accipitriformes (e.g., hawks, eagles, vultures, and kite) had the highest collision rates with wind turbines.

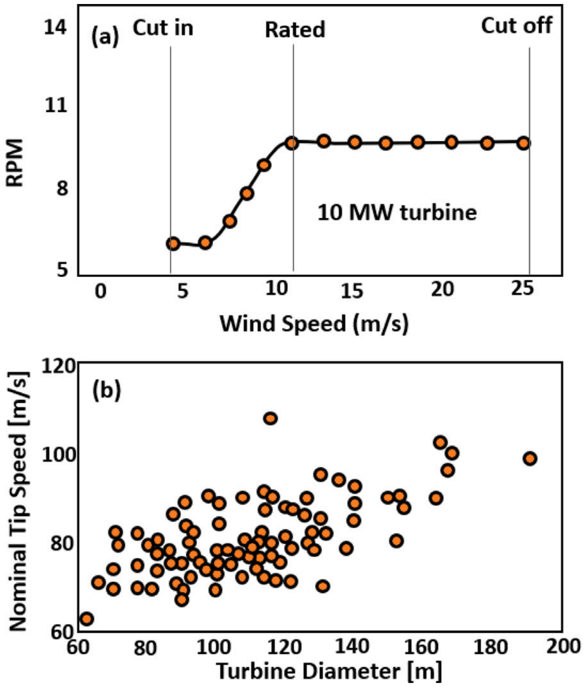


Fig. 8. (a) A typical RPM-wind speed curve for a turbine (adapted from [60]) (b) trend in the tip speed of wind turbine blades (adapted from [61]).

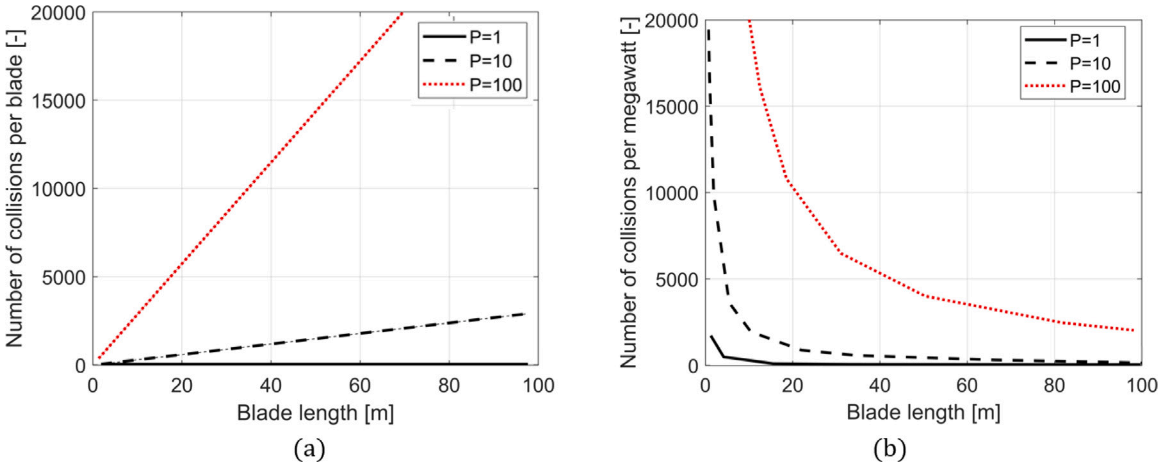


Fig. 9. Correlation between (a) number of collisions per turbine (b) number of collisions per MW and blade length.
Source: Adapted and data taken from [62].

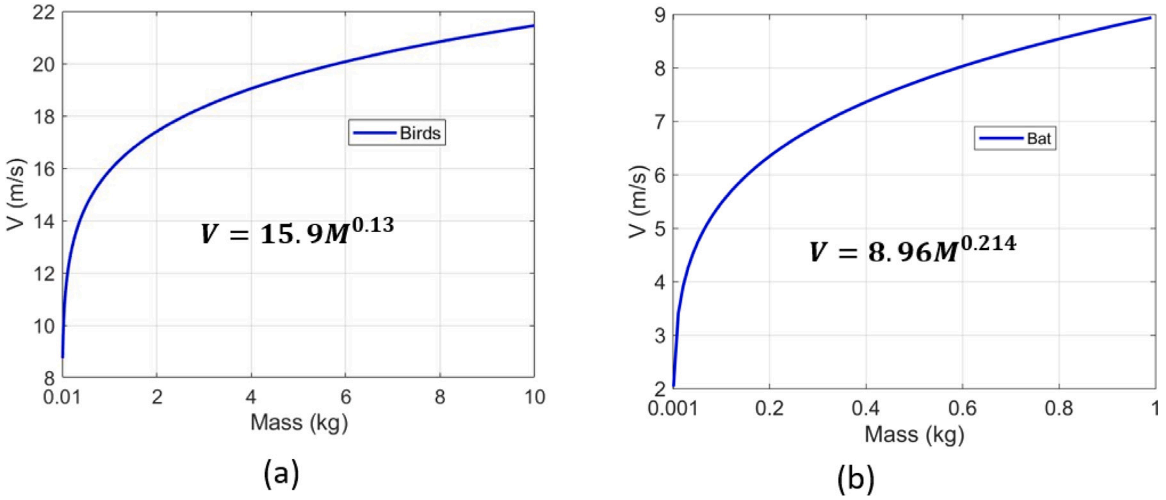


Fig. 10. (a) Bird flight velocity (b) Bat flight velocity and their dependence on their body mass.

Several collision models [70,72,73,77] have been developed to predict collision probability of birds with wind turbine blades. Also the effect of size of the wind turbine and the blade length on wildlife collision rates has been investigated in [62]. For birds and bats, larger power ratings of wind turbines increased the collision rates; however, deploying fewer, but larger turbines, can reduce bird collisions compared to having several smaller wind turbines. Further, number of collisions per turbine increased linearly with increasing blade length (Fig. 9(a)), although the collision rate per megawatt decreased as an hyperbolic function (Fig. 9(b)). It is therefore important to consider bat and bird impact loads on wind turbine blades. The bird and bat impacts often occur on the leading edge of wind turbine blades. The mass, and flight speed of birds and bats are important modeling parameters while analyzing their collision with blades. The mass of birds that are relevant for wind turbine blade collision is mainly distributed between 0.01 kg and 10 kg whereas the mass of bats is between 0.001 kg, and 1 kg. Further, flight speed of the birds and bats is related to their own mass, which can be expressed by functions as shown in Fig. 10(a)(b). It can be seen that the flight speed of birds and bats can range between 9 to 22 m/s and flight velocity of bat can range between 2 to 9 m/s. A comparison of impact energy will provided in Section 3.

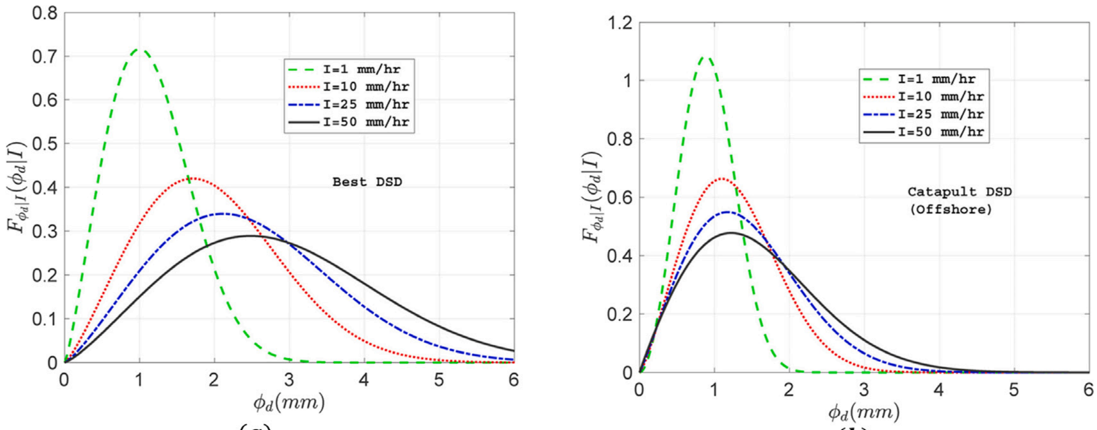
2.3.2. Hydrometeors collisions

Wind turbine blades can suffer collision with rain droplets and hailstones during rotation and are individually discussed below.

Rain droplet impact involves repetitive liquid particle impingement on the leading edges of wind turbine blades [24,79–82]. The droplet impact causes local pitting, progressive material loss and increases the local surface roughness of the leading edge, consequentially decreasing the overall aerodynamic efficiency [83–87]. The damage due to rain droplet impact can be found at several locations in blades, however most is found at the leading edge of the blade [60,78,88].

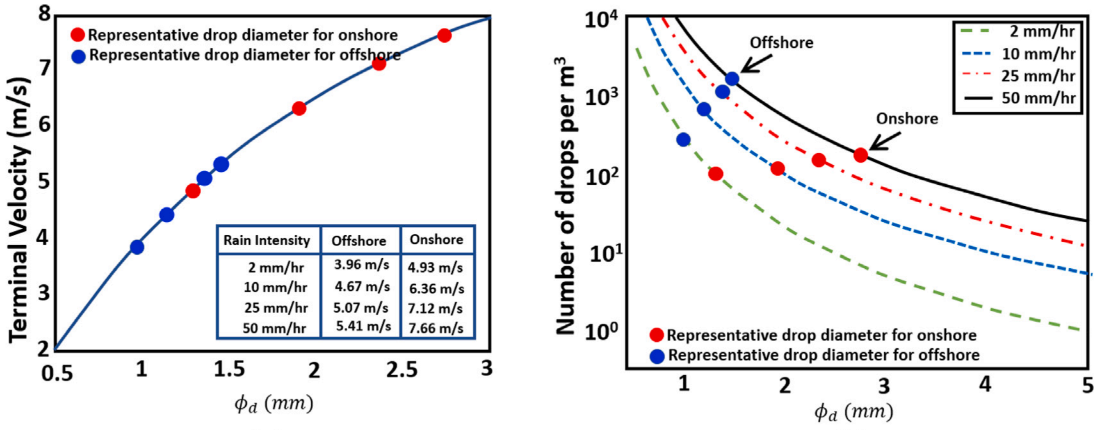
A typical rainfall has a site specific characteristics and their nature varies for onshore and offshore conditions [89–91]. The modeling parameters that are critical to analyze rain droplet impact are rainfall intensity, rain droplet size and number of droplets in a rainfall. The droplet size distribution (DSD) describes the range of droplet size at a given site and is dependent on the given rainfall intensity [92,93]. Depending on the rainfall intensity, the droplet diameters can vary in the range of 0.1 to 6 mm (Fig. 11). Further, the fraction of larger rain droplet sizes increases with increasing rainfall intensity and there are relatively larger droplet sizes at onshore location compared to offshore locations (Fig. 11(a)(b)). Further, the terminal falling velocity of raindrop can range up to 8 m/s depending on the droplet size (Fig. 12(a)). Based on Fig. 12(b), offshore rainfall produces more liquid droplets per volume of rainfall than onshore rainfall for the same rainfall intensity.

Hailstones, unlike rain droplets, are relatively larger, heavier and harder and can cause delamination, permanent indentations, surface



(*a*) (*b*)

Fig. 11. (a) Onshore DSD (b) Offshore DSD.
Source: Permission taken from [24].



Rain Intensity	Offshore	Onshore
2 mm/hr	3.96 m/s	4.93 m/s
10 mm/hr	4.67 m/s	6.36 m/s
25 mm/hr	5.07 m/s	7.12 m/s
50 mm/hr	5.41 m/s	7.66 m/s

(a) (b)

Fig. 12. (a) Terminal velocity of rainfall (b) Number of raindrops in a volume of rainfall.
Source: Data taken and adapted from [78].

cracking and in worst cases can also penetrate the composite laminate of wind turbine blades [42,97,98]. The damage from hailstones mostly occurs on the leading edge of wind turbine blades [61,99,100]. Hailstones in nature are not monolithic ice balls. Instead hailstones consist of a spherically layered structure owing to their complex formation [95,96,101]. As a result, hailstones have a large variation in their density. Hail with a diameter greater than 5 mm has a density range between 810 and 915 kg/m^3, whereas graupel has a density range between 50 and 700 kg/m^3.

In order to analyze wind turbine blade collisions, hail size, shape, and terminal falling velocity are important modeling parameters [94,102–104]. These parameters can vary according to the site. According to data collected from the United Kingdom (UK) from 1949 to 2013, Fig. 13(a) counts the number of incidents of hail classified based on the size [94]. As shown in the figure, Graupel, also called ice pellets, was observed the most, followed by hailstones with diameter between 5 mm and 9 mm. A variation in hail shape has also been observed [105]. Hails are oblate spheroids rather than perfect spheres with mean axis ratios ranging from 0.5 to 0.95. As hail size increases, the axis ratio decreases [105]. As an example, axis ratios decrease from 0.95 for hail diameter of 5 mm to 0.6 for hail diameter of 50 mm, raising questions about the validity of using spherical ice spheres for representing larger hail. Consequently, the mass of hail does not follow a relation based on volume of an ideal ice sphere, rather it deviates following a power curve as seen from Fig. 13(b). Hailstones typically weigh between 0–200 g, except for a few extreme events where there are hailstones measured over 870 g in mass.

A hailstone's terminal velocity is also a key model parameter, and depends on the hailstone's density, the air's density, the Reynolds number, the atmospheric environment, and the drag coefficient [95,96,101]. Fig. 14(a) shows terminal velocity for different hail sizes based on hail sizes 0–10 cm and drag coefficients 0.45–0.8. As can be seen from the figure, the terminal velocity can reach 45 m/s. The drag coefficient is also affected by the size and roughness of the hailstone. A drag coefficient of 0.6 is most commonly used in the literature. Recent observations have shown that the drag coefficient can vary from 0.4 to 0.8–1 for large non-spherical hailstones. The terminal velocity is also affected by air density, which varies with temperature, humidity, and pressure [106,107]. As altitude increases, air density decreases, and higher terminal velocity is associated with lower air density, according to Fig. 14(b).

2.3.3. *Airborne particle collisions*

Wind turbine blades are vulnerable to impact from two types of airborne particles: sand particles and insects. There is one common feature of airborne particle collisions: the particles have little or no velocity of their own, and their velocity depends mainly on wind speed. These are individually discussed below.

Sand frequently impinges with wind turbine blades in deserts and arid climates, especially during sandstorms [108–111]. The impact of

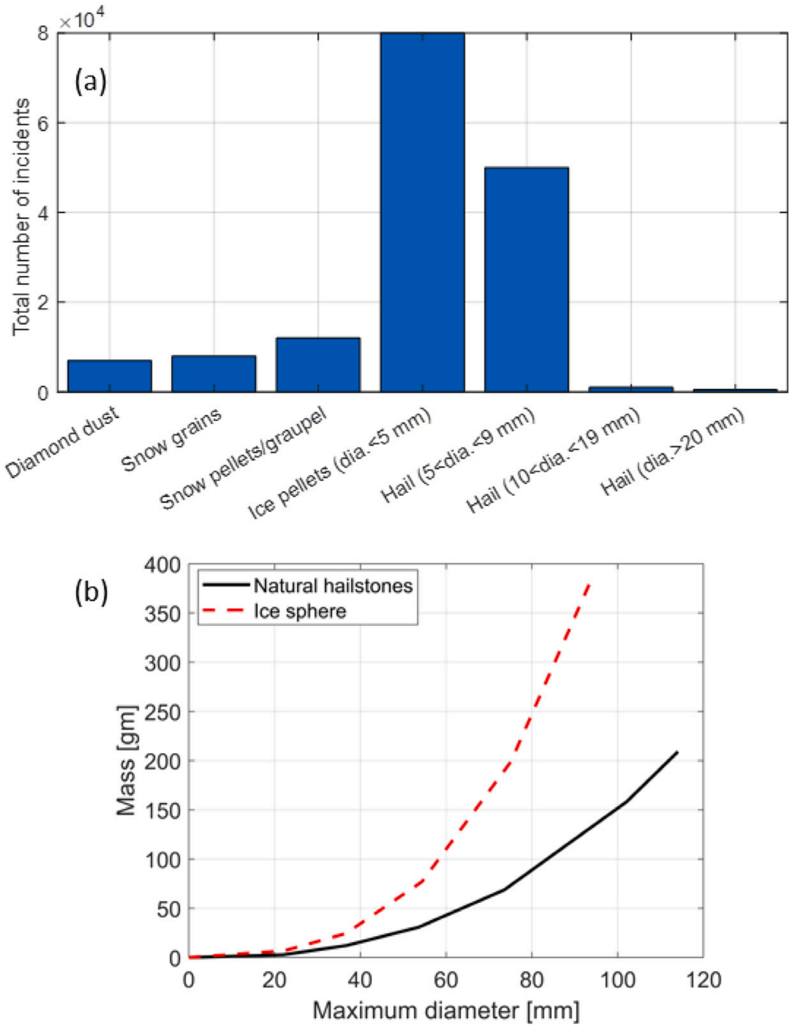


Fig. 13. (a) Types of hail sizes (b) Hail mass.
Source: Data taken and adapted from [94].

sand particles on wind turbine blades can cause erosion and material abrasion. The leading edge of the blade is the most vulnerable region subjected to sand impact [112,113]. The important modeling parameters for sand collision are particle size, density, impact angle, and shape of sand particles [114–116]. ISO 14688 standard categorizes sand particles into three sizes based on their diameters [117]: coarse (0.63 mm – 2 mm), medium (0.2 mm – 0.63 mm), and fine (0.063 mm – 0.2 mm). Al-Sanad et al. [118] analyze the chemical composition of sand collected from four desert sites in Kuwait. The results showed that the composition consists mainly of silica (SiO2). There were different sizes of sand particles collected from these sites, and the average value obtained was 297 μm (Fig. 15). A micrograph by scanning electron microscope (SEM) of the sand particles showed that the particles have mostly angular shape. Salik et al. [119] found that sharp-shaped sand particles cause a greater erosive shock than rounded particles, with an order of magnitude difference. Finally, in one of the studies in [110], the density of sand particle has been taken as 2200 kg/m^3.

Insects collision with wind turbine blades is one of the important reasons that causes contamination of leading edge resulting in power loss [121]. A collision between an insect and the blade surface can negatively affect the aerodynamic boundary layer, resulting in local flow separation if the residual debris thickness is equal to the boundary layer critical height [121–123]. Insect contamination was hypothesized to cause power losses up to 25% with two or more different power levels obtained for same wind speed [120] (Fig. 16(a)). This phenomenon is termed as double stalling. Flow visualization techniques were used to confirm the hypothesis [120]. The insects generally fly in low wind condition and stick to the leading edge and this contamination causes power losses at high wind speed. In addition, rainfall or manual maintenance cleans the leading edges, which further brings power to its maximum design values (Fig. 16(b)). There has also been evidence that insects are affected by the color of a wind turbine [124]. Turbine colors such as ‘pure white’ (RAL 9010) and ‘light grey’ (RAL 7035) were found to attract significantly more insects. Currently, the insect species most vulnerable to collision with wind turbines is a subject of ongoing concern [125]. According to some reports, mostly hill-topping, swarming, and migrating insects interact with wind turbines. Further, collision rates are highest during migration in the summer and autumn [125].

The important modeling parameter for insect collision with wind turbine blades include: insect body mass (Fig. 17(a)), their shape defined in terms of ‘sphericity’ (Fig. 17(b)) as well as rupture velocity. As shown in Fig. 17(a), the body mass varies greatly between four different species of insects and can range between 0.5 mg to 50 mg [123]. Fig. 17(b) shows variations in the sphericity, which determines whether or not the insects can be assumed spherical [123]. The shape of insects such as Coleoptera and Diptera is more spherical than that of other insect species such as Hymenoptera and Lepidoptera. An additional modeling parameter, rupture velocity, is defined as the minimum impact velocity at which an insect strike creates an excrescence. If the

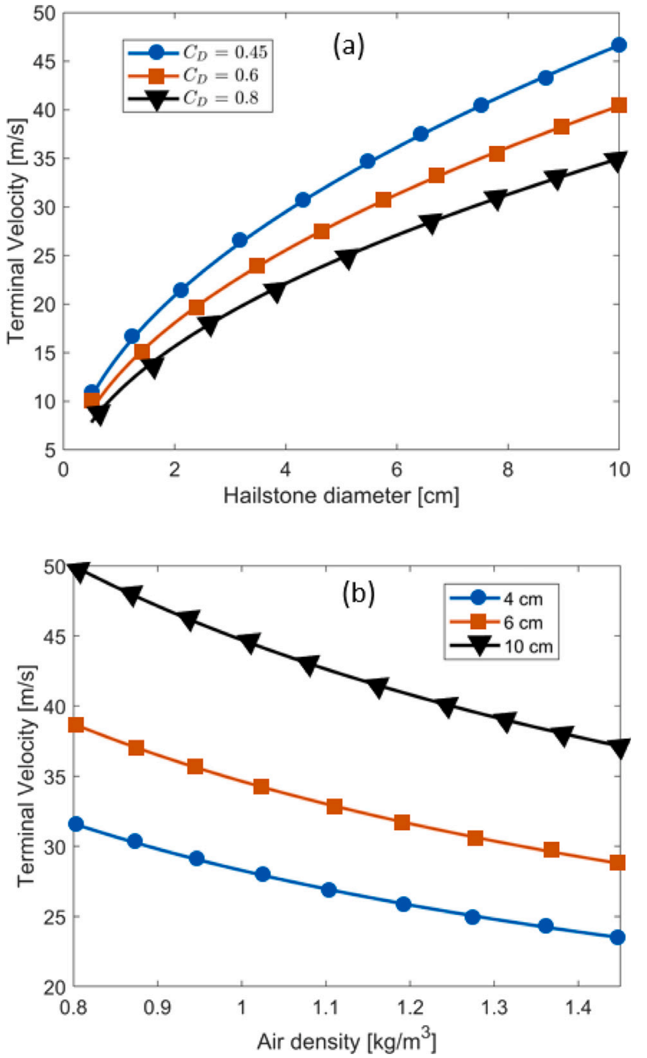


Fig. 14. (a) hailstone diameter and drag coefficient (b) air density and hailstone diameter.
Source: Adapted from [95,96].

impact is below the rupture velocity, there will be no excrescence and the insect will slide off after the collision. The rupture velocity is dependent on the type of insect and is taken as 12 m/s for houseflies and 14 m/s for fruit flies for collision with wind turbine blades [121]. More research is required to understand the interaction between the wind turbines and insects [125].

2.3.4. Aviation aircraft collisions

The risk of aircraft collision with wind turbine blades has first been mentioned in [126]. At the time of the writing of this review, there have been report of four cases where aircraft has collided with wind turbine blades causing loss of life, severe damage to the aircraft as well as blades. The risk of collision of wind turbine is more severe for small aircraft, planes that are involved in low level flying such as those used for agricultural purposes (e.g. spreading pesticides in the farm, providing medical air services) or those involved in aerial logistics for offshore wind energy parks [127]. According to [128], wind turbines are also of concern for those aircraft that arrives at airports situated in close vicinity of wind farms, especially due to disturbance caused by wakes and turbulence from wind farms (Fig. 18(b)). According to [128], around 40% of the wind turbines in the United States are placed within 10 km of a small airport and around 5% are placed in the range of 5 km of a small airport (Fig. 18(a)). The effect of wake from wind turbines on aircraft flight path, and flight trajectory is a subject of ongoing concerns [129,130]. Serious roll hazard exists to the aircrafts due to turbine wakes generated by the wind turbine [131,132]. Other than rolling hazards, yaw and pitching moments can also be of serious concern. Note that there are no clear recommendations from the Federal Aviation Administration (FAA) of the United States and the Civil Aviation Authority (CAA) of the United Kingdom on wind-turbine-induced roll hazards for aircraft. This poses serious concerns over interaction between aircraft and wind turbines making aircraft collisions with a blade a major source of impact threat. Fig. 18(c) shows a schematic of damage of the wind turbine blade caused due to collision of PIPER PA 32R-300 with wind turbine blades in 2014 in South Dakota. The incident also led to 4 fatalities. According to the national transportation safety board (NTSB) report [133], the main reason that contributed to the collision was low level flying due to bad weather and poor visibility including the turbine was not marked on the sectional charts and the lights on the wind turbine was not operational. The damage due to aircraft collision, depends on where the aircraft collides and is thus not specific for a certain blade location (random) and could even be complete turbine collapse. It is not feasible to design blades that can withstand such high impact loads caused by such accidents, however, efficient mitigation measures must be implemented to prevent them.

2.4. Impact during maintenance and inspection stage

Wind turbines require several maintenance activities, including inspections and repairs. In contrast to the operation stage, the wind turbine is generally parked and not rotating. Therefore, the impact velocity is solely contributed from the impactor speed. This section discusses the impact threats on wind turbine blades during this stage.

2.4.1. Helicopter collision

There is a rapid increase in demand for the use of helicopters for operation and maintenance activities. According to [136,137], helicopter fleet demand for the offshore wind market (Fig. 19) will increase by at least 100 aircraft valued at 1 billion United States dollar (USD) between now and 2030 [134]. Use of helicopters aids in quick maintenance and repair work as well as efficient transfer of technicians compared to ships. In addition, it has been mentioned that helicopter operations can be available for about 90 percent of the time in a year, compared to boats or ships which has availability 50 percent of the time in year [138]. However, helicopter operations are challenging for offshore structures due to poor visibility, bad weather, high dynamic motion of the structures, and therefore several accidents have been reported in the field. For instance, helicopter accidents have been reported during technician transfer on semi-submersible floating platforms in offshore oil and gas sector [138]. Additionally, helicopter operations are recommended to be used for search and rescue operations for offshore wind turbines [139]. In addition, offshore wind farms presents unique challenges such as generation of wakes and turbulence and its effect on helicopter navigation and control [140]. Report from [136] cites issues of blade collision with helicopter during search and rescue operations and recognizes three suitable blade configurations during parked conditions to avoid collisions: (a) Retreating blade horizontal (b) bunney ear configuration and (c) Advancing blade horizontal (Fig. 20). Aside from that, the blades and nacelle should be positioned, braked, and/or locked to stop wind-induced or rotor-induced movement. During this process, the anemometers and yaw motors in the nacelle will also be overridden/disabled. Similar to aviation aircraft collisions, the damage region of helicopter collision is random and suitable mitigation measures need to be in place to avoid collision with blades.

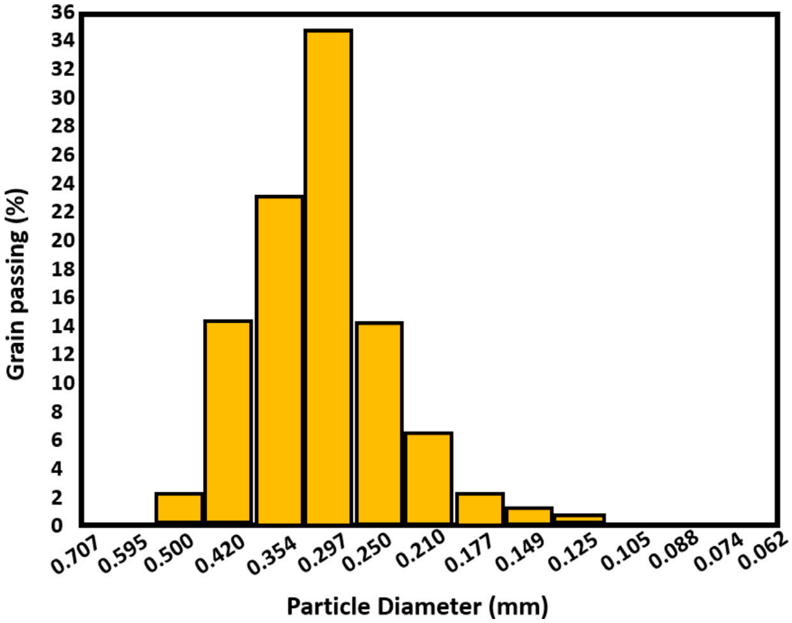


Fig. 15. Distribution of grain size in sand.
Source: Data taken and adapted from [109].

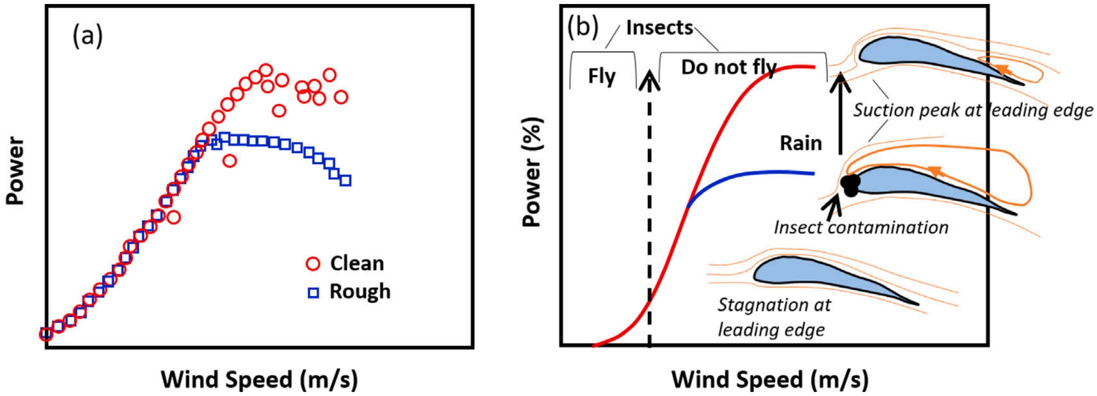


Fig. 16. (a) Production of multiple power levels at the same wind speed (b) Insect collision as an explanation for multiple power levels.
Source: Data taken and adapted from [120].

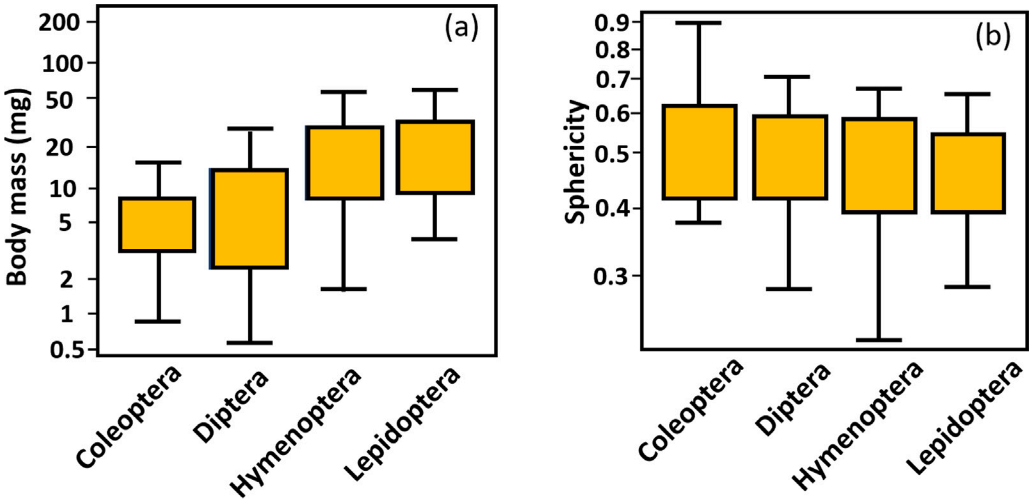


Fig. 17. (a) Insect body mass (b) Insect sphericity.
Source: Data taken and adapted from [123].

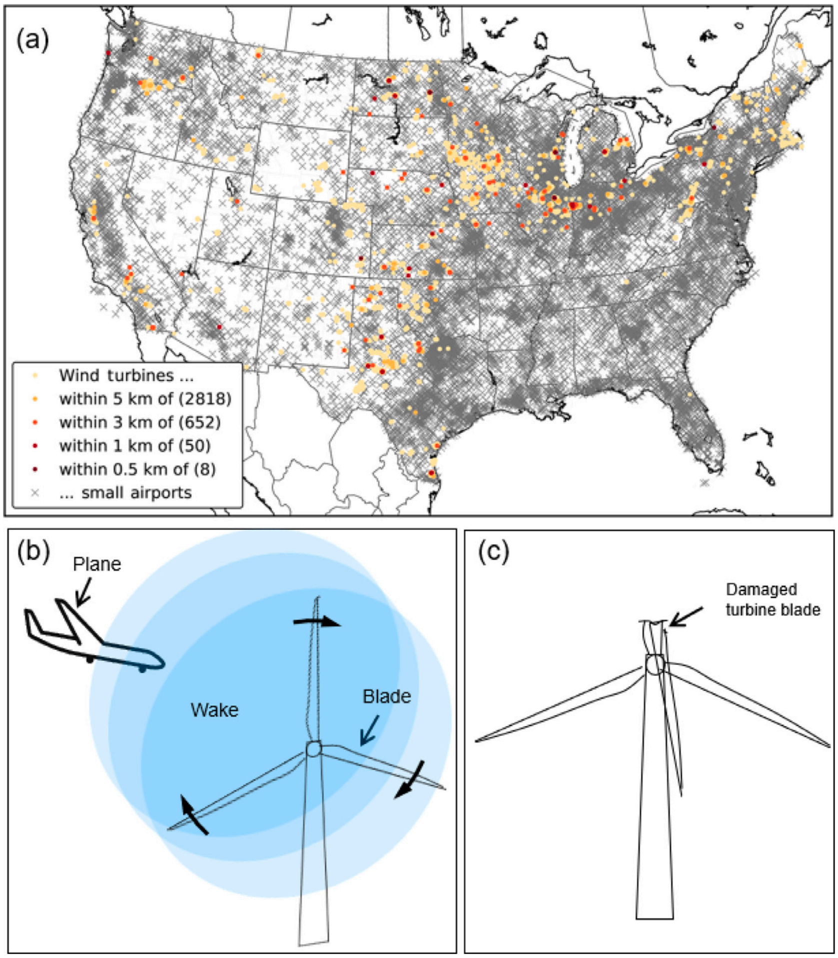


Fig. 18. (a) Map showing airports located in close vicinity of wind turbines in US [128] (b) Example of an airplane flying near wind turbine (c) wind turbine blade damage due to aircraft collision.
Source: Adapted from [133].

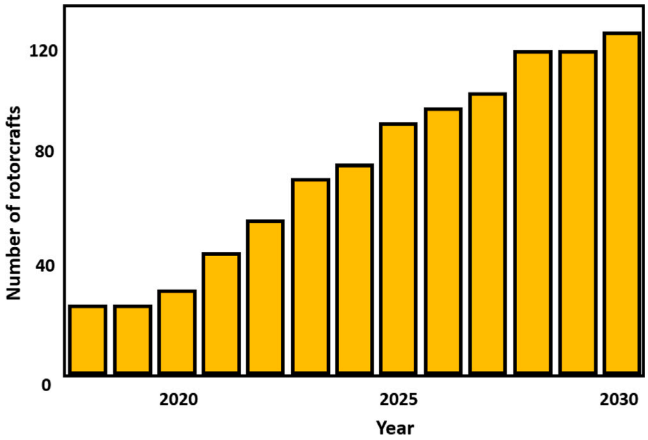


Fig. 19. Demand of helicopters for offshore WTs.
Source: Data taken and adapted from [134].

2.4.2. *UAV/drones collisions*

Unmanned aerial vehicles (UAVs) or drones can perform wind turbine inspections more efficiently and effectively than rope-based inspections, which are costly, infrequent and unsafe [141–143]. Research has shown that replacing rope access inspection with drones reduces costs by 70% and revenue lost due to downtime by 90% [143].

For offshore wind turbine inspections, drones are remotely operated from a boat or helicopter and are transported to the turbine asset by boat or helicopter [141–144]. The drone can hover near the blades of the wind turbine and capture high-quality images at different points and locations. After post-processing the images, the criticality of the defect is determined and maintenance strategies are designed accordingly [142]. Furthermore, drones are capable of carrying payloads such as thermal sensors, infrared sensors, and high-resolution cameras, near infrared sensors and hyperspectral sensors, depending on the target of the mission. As well as performing internal and external blade inspections, drones can also visually inspect turbine towers, nacelles, metmasts, and substations. There are three wide categories of drones that can be used for blade inspections: (a) multirotor (b) fixed wing and (c) hybrid system (Fig. 21). Multirotor or rotory wings drones are mostly widely used for industrial purposes given that these drones can hover at one location, less footprint required while operating as well as pilot skills required to fly these drones are less [141]. However, the payload capacity for these drones are small, have smaller flight times and are less stable in wind. Rotory wing drones can have one rotor (helicopter), three rotors (tricoptors), four rotors (quadcoptors), six rotors (hexacoptors) or eight rotors (octocoptors). Among all the rotory wing drones, the quadcopters are the most applied drones as these drones provide the best balance of lift, control, manoeuvrability, and cost. On the other hand, fixed wing aircrafts have longer range of flying, high endurance, and are stable in wind. However, the fixed wing aircrafts require large footprint area and cannot hover at one location in addition to requirements of specialized training. Nevertheless, drones

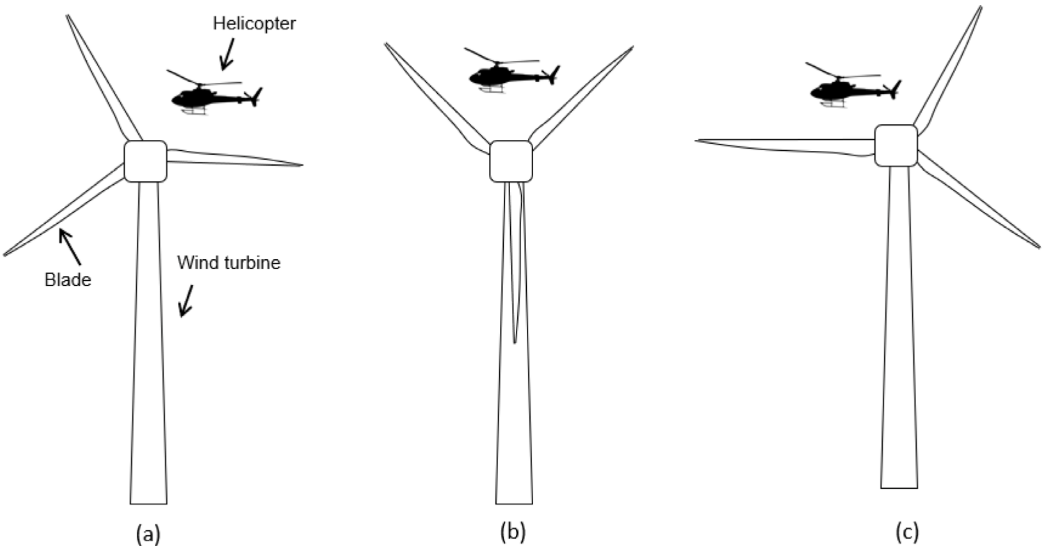


Fig. 20. Recommended configurations for helicopter landing on wind turbines during search and rescue operations.
Source: Adapted from [135].

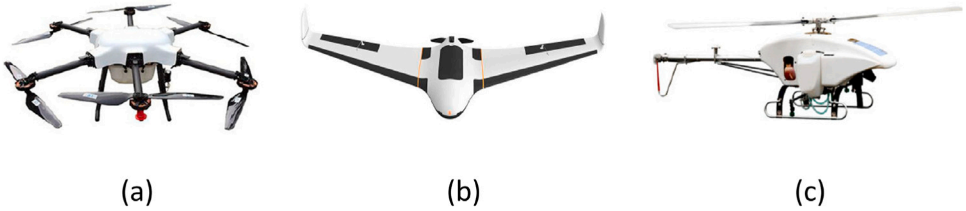
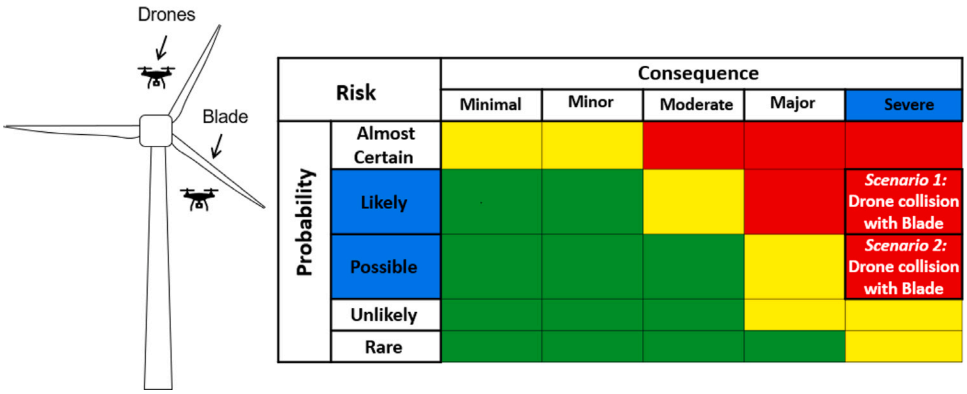


Fig. 21. Three wide categories of drones: (a) Multirotor, (b) fixed-wing, and (c) single-rotor drones [145].



Risk		Consequence				
		Minimal	Minor	Moderate	Major	Severe
Probability	Almost Certain	🟨	🟨	🟥	🟥	🟥
	Likely	🟩	🟩	🟨	🟥	🟥 *Scenario 1:* Drone collision with Blade
	Possible	🟩	🟩	🟩	🟨	🟥 *Scenario 2:* Drone collision with Blade
	Unlikely	🟩	🟩	🟩	🟨	🟨
	Rare	🟩	🟩	🟩	🟩	🟨

Fig. 22. Qualitative risk assessment for drone collision with wind turbine blade.
Source: Adapted from [146].

are still in the early stages of commercialization, and their reliability remains an issue.

The collision of drones with aerospace structures such as aircraft nose and windshields have been a question of ongoing concern [144, 146–152]. Collision analysis of drone with wind turbine blades have not been investigated so far in the literature but risk of their collision has been reported. For instance, the feasibility of the use of drone systems for ultrasound inspection of blades for delamination prediction was performed in [146]. A risk assessment was performed and two specific collision scenario were identified. (a) Scenario 1 involved drone collision with blade due to uncontrolled motion or error in navigation of UAV causing damages to drones as well as wind turbine blade. On the other hand, (b) Scenario 2 involved drone collision with blade due to unpredictable gust loads where the wind can cause drone to drift out of course causing collision and inducing significant damages to the blades. Both these scenarios were associated with a high risk as shown by red color in the qualitative risk matrix developed by [146](see Fig. 22) In addition, internal blade inspection using drones can cause collision with the blade due to wind-induced blade vibrations. There are many other reasons that can cause collisions of drone with blades e.g. high wind speeds, gusts, platform motions, and wake effects from turbines in a farm that can complicate the navigation of UAV systems at turbine sites. Therefore, the leading edge and spar both can be damaged by drones collision. A collision task force applied to the aviation industry [153] was established where risk assessment was performed for all the drones available in the market which has a mass of less than 25 kg and was termed as, 'open category', and the drones were categorized into large (greater than 3.5 kg), medium (between 1.5 kg and 3.5 kg), small

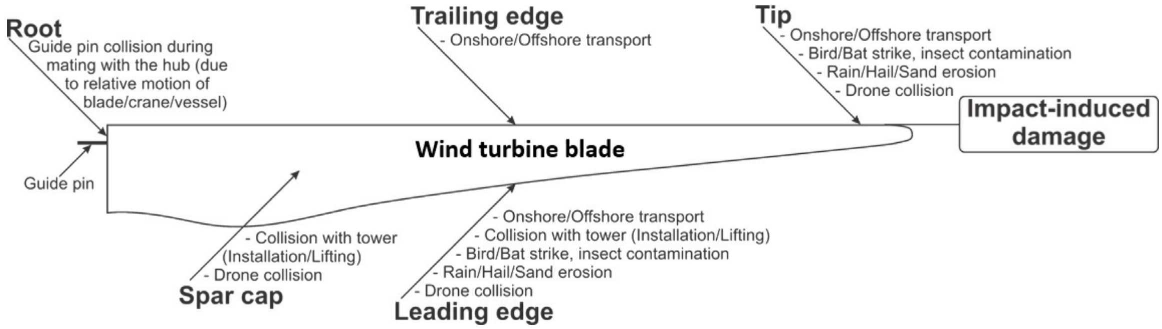


Fig. 23. The fishbone diagram of impact loads and impact-susceptible regions in wind turbine blade.

Table 1
Summary of impact threats for wind turbine blades.

Impact threat	Stage of occurrence	Blade region	Accidental	Normal	Single	Repetitive
Traffic	Transportation	Leading, trailing edge	✓		✓	
Vessel deck	Transportation	Random	✓		✓	
Lifting	Installation	Leading edge, spar	✓		✓	
Mating	Installation	Blade root		✓	✓	
Bird	Operation	Leading edge, tip	✓			✓
Bat	Operation	Leading edge, tip	✓			✓
Hail	Operation	Leading edge, tip		✓		✓
Rain drop	Operation	Leading edge, tip		✓		✓
Insect	Operation	Leading edge, tip		✓		✓
Sand	Operation	Leading edge, tip		✓		✓
Aviation aircraft	Operation	Random	✓		✓	
Drone	Inspection	Leading edge, spar, tip	✓		✓	
Helicopter	Inspection	Random	✓		✓	

(between 0.25 kg and 1.5 kg) and harmless (less than 0.25 kg). A similar classification for wind turbine blade inspection does not exist at present and will require further effort in the future. In addition, the horizontal flying speed of drones can be in the range of 20–25 m/s.

Summary of impact threats, stage of occurrence and vulnerable blade regions

Table 1 summarizes the impact threats, associated stage of occurrence as well as vulnerable blade regions for impact loads on wind turbine blades. In addition a fishbone diagram of impact loads and impact-susceptible regions in turbine blade is shown in Fig. 23.

3. Comparison of impact threats on wind turbine blades

In this section, the impact threats are compared based on the following five criteria: (a) relative deformability of projectile and wind turbine blades (b) impact velocity (c) kinetic energy of impact (d) repeatability of impacts, and (e) nature of the impact.

3.1. Relative deformability of projectile and wind turbine blades

The relative deformability of projectiles and wind turbine blades is determined by soft and hard impacts. The damage to turbine blades can vary depending on whether the impact is soft or hard. In addition to guiding the design of wind turbine blades, a classification of soft versus hard impacts will guide the modeling principles for collision analyses.

There are several qualitative definitions for soft and hard impacts [154–156]. Soft impacts are generally described as an inelastic shock of projectile without rebound, characterized by projectile's substantial displacement and deformation as compared to the target structure. In contrast, a hard impact involves a projectile that remains undamaged during impact, can rebound and exhibits low deformation compared to the target. Methods have been proposed in the aerospace industry to differentiate quantitatively between soft and hard impacts applied to aircraft collision analysis. Eibl et al. [157] proposed a method based on a mass–spring model (Fig. 24(a)) where relative displacements of target and projectile was considered as a key point for classifying an impact as hard or soft. Suppose there is a projectile of m_1 and a target of m_2, with spring stiffness k_1 and k_2, and $x_1(t)$ and $x_2(t)$ denoting the displacement of the projectile and target, respectively (Fig. 24(a)). The equation of motion is obtained as:

$$m_1\ddot{x}_1(t) + k_1[x_1(t) - x_2(t)] = 0 \tag{1}$$

$$m_1\ddot{x}_2(t) - k_1[x_1(t) - x_2(t)] + k_2x_2(t) = 0 \tag{2}$$

When the target displacement $x_2(t)$ is much smaller than the projectile displacement $x_1(t)$, that is, $x_2(t) \ll x_1(t)$, the above equation can be decoupled as:

$$m_1\ddot{x}_1(t) + k_1x_1(t) = 0 \tag{3}$$

$$m_1\ddot{x}_2(t) + k_2x_2(t) = F(t) \tag{4}$$

where $F(t) = k_1x_1(t)$. This situation is defined as a soft impact as the equation can be solved in an uncoupled manner. Thus, first displacement of projectile ($x_1(t)$) can be obtained separately, and can be used further to obtain $F(t)$. The output of this equation can then be used in the second equation to obtain the response of the target structure. On the contrary, when the equations cannot be decoupled, it is called a hard impact. However, this method has a limitation that it only considers relative displacement between projectile and the target as the key point, do not take into account the material strength of target and projectile, and can be applied only after observing the collision behavior.

Further, Pierre et al. [158] distinguished between soft and hard impact according to the material characteristics and projectile speed, and proposed to divide hard and soft impacts according to whether the projectile penetrates the target. The stress σ exerted by the projectile is compared to the strength threshold σ_t of the target. If the projectile is crushed then it is referred to as soft impact whereas if the projectile

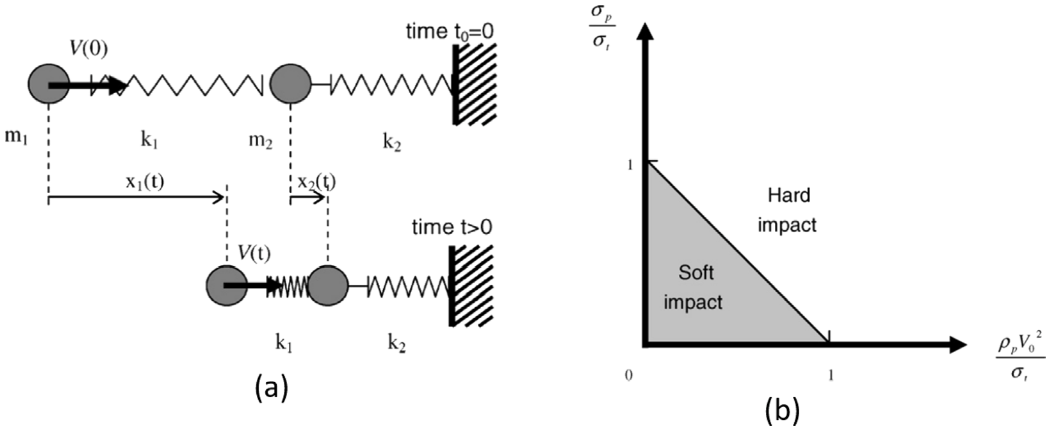


Fig. 24. (a) Spring mass model for projectile and target impact (b) Distinction between soft and hard impact based on material characteristics and projectile speed. *Source:* Permission taken from Elsevier [158].

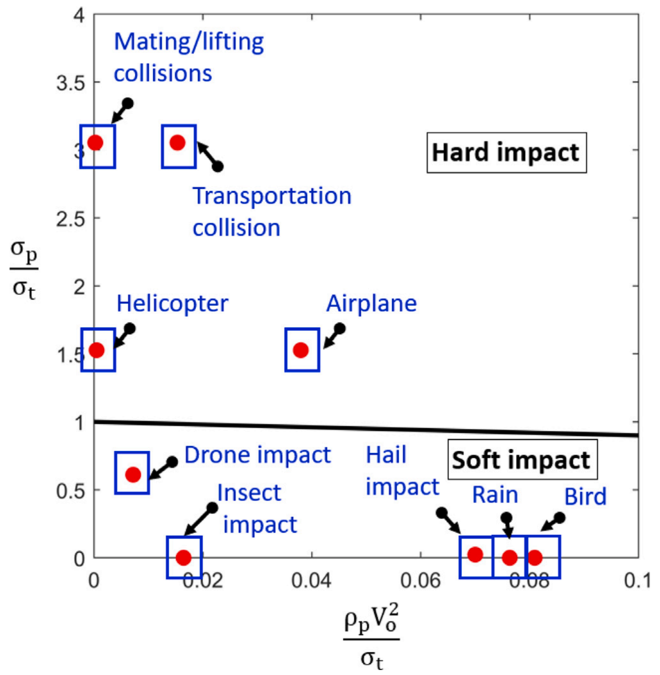


Fig. 25. Comparison of impact threats as hard and soft impact.

penetrates the target, it is a hard impact. Within these limits, a region of rebound and no rebound of projectile were also discussed and it was mentioned the exact area of impact with rebound is difficult to obtain. The total stress σ consists of two parts: the material strength threshold σ_p of the projectile itself, and the inertial impact stress generated by the mass and velocity:

$$\sigma = \sigma_p + \rho_p V_0^2 \tag{5}$$

where ρ_p is the projectile density (mass per unit volume) and V_0 is the projectile velocity. Substituting σ_t for σ, the limit for distinguishing soft and hard impacts can be defined as (and this is shown graphically in Fig. 24(b)):

$$\frac{\sigma_p}{\sigma_t} + \frac{\rho_p V_0^2}{\sigma_t} = 1 \tag{6}$$

This paper uses the second method and substitutes blade and projectile material properties as well as projectile speed for different impact threats to classify them as hard or soft. It should be noted that this is only a first attempt to classify such impacts for wind turbine blades and that further research is needed to distinguish them clearly. It can be seen from Fig. 25 that lifting collision, mating collision, transportation collision and aviation collision are obtained as hard impacts where the relative deformation in the wind turbine blade will be greatest. In contrast, soft impacts include hail, rain, bird/bat impacts, insect impacts, and impacts caused by drones. In this case, the relative deformation of a projectile will be greater than that of a wind turbine blade. It is advantageous to have a good understanding of these principles as they will influence the modeling strategy for analyzing blade collisions. The impactor can, for instance, be assumed as rigid for a hard body impact while, for a soft impact, modeling methods such as smooth particle hydrodynamics (SPH) can be used to represent the large deformation of the impactor.

3.2. *Impact velocity*

In this section, impact threats for wind turbine blades are compared according to their impact velocity. The impact can be classified [159] as low velocity impact ($V_{imp} < 30$ m/s); high velocity impact (30 m/s $< V_{imp} < 200$ m/s); ballistic impact ($V_{imp} > 200$ m/s) and hyper-velocity impact ($V_{imp} > 15\,000$ m/s). For wind turbine blades, only low velocity impact and high velocity impact are relevant. Table 2 compares impact threats according to low and high velocity impact. It can be seen from the table that all impact threats during transportation, installation and inspection stages of blade corresponds to low velocity impact. One common characteristic of wind turbine blade during these stages is that blade is not rotating. On the other hand, the impact threats occurring during the operation stage corresponds to high velocity impact. This is mainly due to the fact that the wind turbine blade during operation is rotating and the blade linear speed during rated conditions can reach up to 90–120 m/s. A more comprehensive discussion is provided below for describing impact velocity for collision during operation stages.

The impact velocity during operation stage will consists of combined contribution from the projectile velocity, the WT velocity (e.g. blade rotation speed) as well as the wind speed. Additionally, the size and mass of the projectile will have an effect on the projectile speed and the overall impact speed. The rotation speed of the blades, however, largely determines the impact speed. A blade's linear speed is also related to its position along its span, i.e., the blade's tip has the highest velocity compared to the blade's root. Since the impact velocity is the result of the superposition of multiple velocity vectors, the impact speed for the case of rain and hail collisions is given by:

$$V_{imp} = \sqrt{(V_{tip} + V_{tg})^2 + V_w^2} \tag{7}$$

where V_{imp} is the impact velocity, V_{tip} is the velocity of WT blade tip, V_{tg} is the terminal velocity of rain and hail particles, V_w is the wind

Table 2
Comparison of impact threats for wind turbine blades based on hard impact, soft impact, impact velocity and impact energy.

Impact threat	Stage of occurrence	Hard impact	Soft impact	Low velocity (<30 m/s)	High velocity (>30 m/s)	Low KE (<100 J)	High KE (>100 J)
Traffic	Transportation	✓		✓			✓
Lifting	Installation	✓		✓			✓
Mating	Installation	✓		✓			✓
Bird	Operation		✓		✓		✓
Bat	Operation		✓		✓		✓
Hail	Operation		✓		✓		✓
Rain drop	Operation		✓		✓	✓	
Insect	Operation		✓		✓	✓	
Sand	Operation	✓			✓	✓	
Drone	Inspection		✓	✓			✓
Helicopter	Inspection	✓		✓			✓

speed. Note that here effects of different blade azimuth angles are not considered and the impact velocity is assumed to be the maximum.

For the bird and bat impacts, the collisions usually takes place horizontally, so the impact speed can be defined as:

$$V_{imp} = \sqrt{V_{tip}^2 + (V_w + V_{tg})^2} \tag{8}$$

V_{tg} is the flight speed of bird and bats which is dependent on their masses. For sand and insect impact, the particles are mainly suspended in the air, and the impact velocity is mainly affected by the speed of the WT blade and the wind speed. So the impact speed can be defined as:

$$V_{imp} = \sqrt{V_{tip}^2 + V_w^2} \tag{9}$$

Fig. 26(a)–(f) compare the blade impact speed for rain, hail, sand, insect, bird and bat respectively corresponding to four different blade tip speeds. It can be clearly seen that for rain, hail, and bird the blade impact speed has a significant influence due to the projectile characteristics. For instance, the impact speed between hail and wind turbine blade can reach upto 160 m/s corresponding to a blade tip speed of 120 m/s and hail size of 80 mm. On the other hand, the projectile characteristics for sand, insect and bat do not have major significance on the overall impact speed. For instance, for a given tip speed of 120 m/s, the maximum value of impact speed can reach 121.49 m/s for bat, 120.60 m/s for sand, and 120.60 m/s for insect impingement with wind turbine blades.

3.3. Kinetic energy of impact

The kinetic energy of impact is influenced by the mass of the impactor as well as the corresponding impact velocity and is given by:

$$KE = \frac{1}{2} m V_{imp}^2 \tag{10}$$

where KE is the kinetic energy, m is the mass of impact particle, V_{imp} is the impact velocity. The impact can be considered as a low KE impact if impact energy is less than 100 J, otherwise it is considered as high KE impact. Using the mass and velocity of each impact described previously, the kinetic energy of the impact threats for wind turbine blades are categorized as low and high in Table 2. It can be seen from the table that collision during transportation and installation are associated with high KE impact, even though these collisions are associated with low velocity of impact. A wind turbine blade in such cases can be considered a projectile, and the excessive weight of the blade contributes significantly to impact energy. Further, impact energy for collisions during operations are shown in Fig. 27. The maximum impact kinetic energy of rain impact is 2.27 J, hail impact is 2.83e3 J, sand collision is 2.23e−4 J, insect collision is 0.65 J, bird collision is 7.76e4 J, and bat collision is 7.38e3 J. Overall, bird collisions have the highest kinetic energy, followed by bat collisions. Consequently, impacts with birds, bats, and hail are associated with high KE impacts. Impact of wind turbine blades with raindrops, insects, and sand are obtained as low KE impacts.

3.4. Repeatability of impacts

We compare impact threats according to whether they collide with blades once or repeatedly. The impact energy of one impact particle may be very small, but repeated impact can significantly damage the wind turbine blades. In Table 1, repetitive impacts include birds, bats, hail, rain drops, insects, and sand. Similarly, impacts during transportation, lifting, mating, aircraft impacts, drone collisions, and helicopter collisions are considered single impacts.

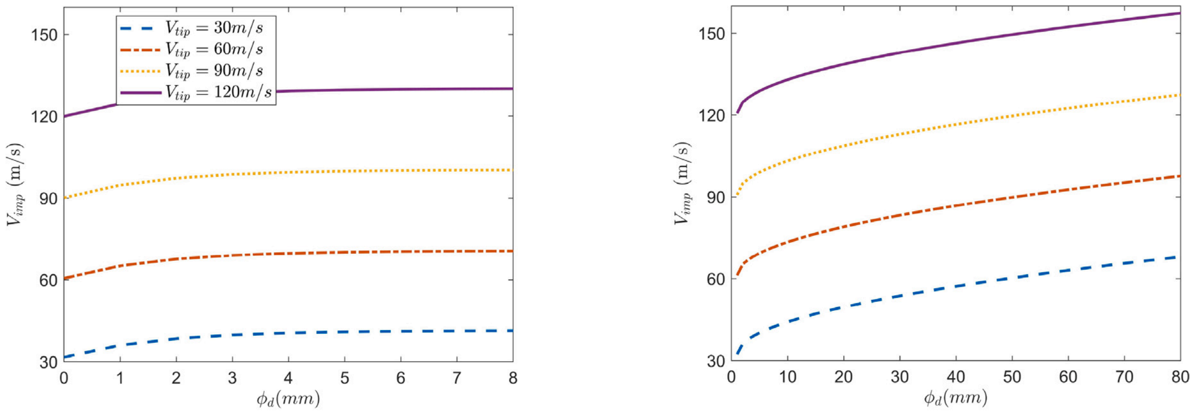
3.5. Nature of impact

In essence, wind turbines experience a variety of different impacts, and not every one will be affected in the same way. There are some impacts that are accidental and some that are normal. According to Table 1, accidental impacts include collision with traffic and vessel decks during transportation, collision during lifting, birds, bats, aviation aircraft, and drones impact during blade rotation. On the other hand, normal impacts include collision of blade root with hub during the root mating process, impact with hailstorms, raindrops, insects, and sand during operations.

Discussion on repeatability and nature of impact on damage tolerance design

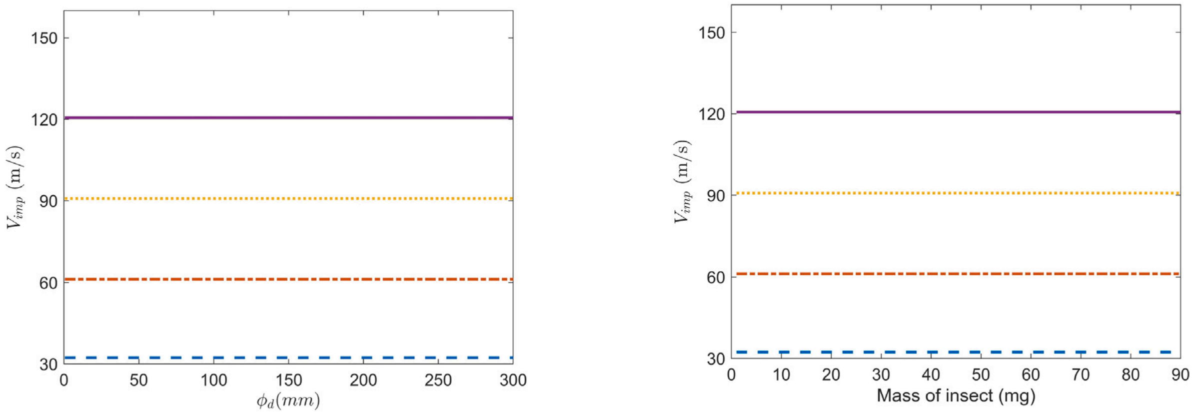
Repeatability and nature of impact together play a critical role in damage tolerance design. For instance, if an impact event has a high frequency and is associated with normal operational impacts that cannot be ignored or avoided, then it must be explicitly considered in the design of wind turbine blades. Table 1 explicitly lists such collision threats as ‘Normal’ as well as ‘Repetitive’. The most common examples are collisions between wind turbine blades and hydrometeors such as rain, hail, insects, and sand. Threats of this nature are highly frequent and cannot be avoided. Due to this, wind turbine blades are coated with specialized damage-tolerant coatings to minimize damage caused by such impact events.

On the other hand, for collision threats that have a relatively low frequency and are accidental in nature, historical data can be used to statistically determine the impact frequency and associated design kinetic energy for damage tolerance calculations. As demonstrated in Table 1, impacts with birds and bats are both repetitive and accidental. Consequently, a blade can be designed for a particular impact threat, if it is associated with a specific impact frequency and severity. In addition, mitigation measures must be implemented to reduce the collision probability and hence the risk involved. For instance, mitigation measures such as coloring blades with black paints [75], as well as bat deterrent techniques such as based on acoustics [160–162] and electromagnetic fields [163] are being developed. The repeatability of impacts can be determined by several scientific approaches, including field observations [39,40] and collision models that predict impact frequency. The data in field observations can be used to examine the frequency, location, and severity of impact events in the past.



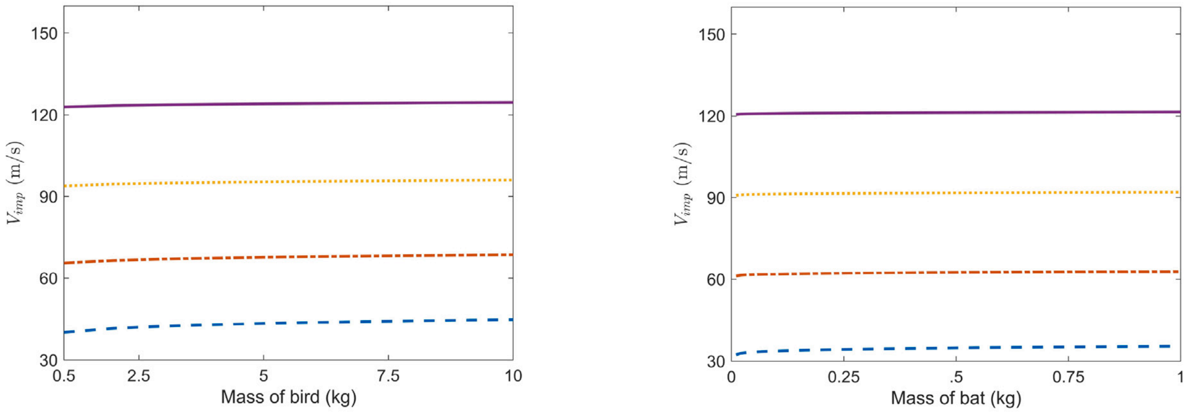
(a) Rain droplet

(b) Hail droplet



(c) Sand

(d) Insect



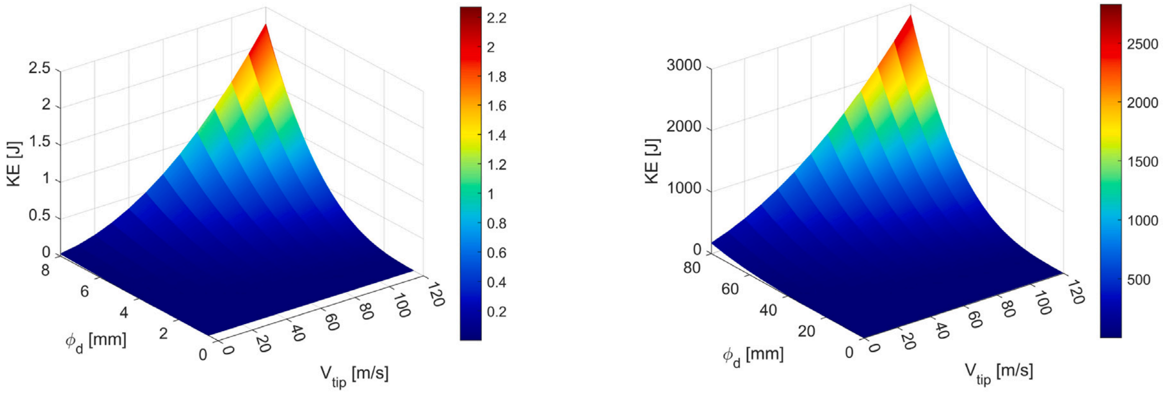
(e) Bird

(f) Bat

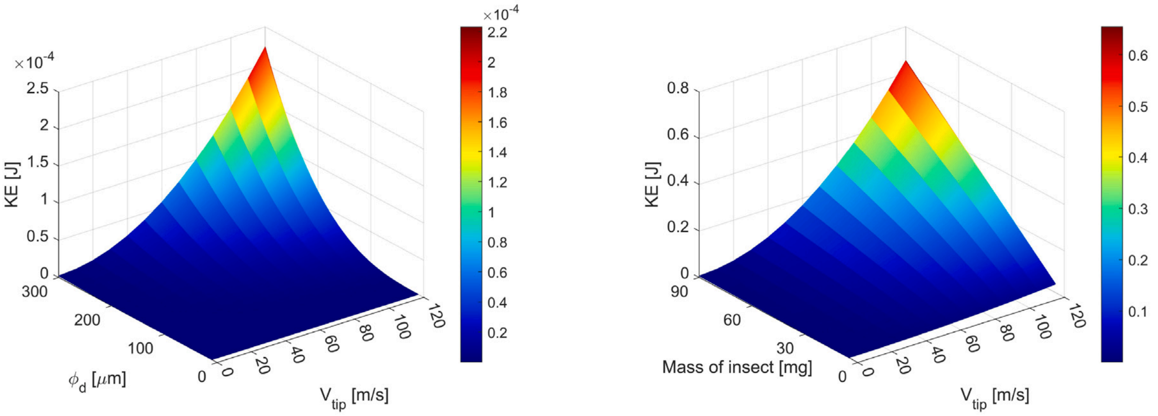
Fig. 26. Dependence of impact velocity on blade tip speed and impactor characteristics during operation stage.

Analyzing maintenance records over a long period of time will aid in determining how often the blade has been repaired or replaced due to impact damage. Data on environmental conditions, such as wind speed and direction, can also be collected to determine if any patterns correlate with impact events. These field observations are however rare and mostly confidential with wind turbine manufacturers and wind farm owners. However, several collision models [164–167] have been developed to calculate impact frequency using the collision model. Ultimately, the most effective approach for determining the repeatability of impacts will depend on the specific blade design, manufacturers, location as well as the available resources. By combining field observations, and numerical models, it is possible to develop a comprehensive understanding of the impact environment and design a blade that can withstand the expected range of impact events.

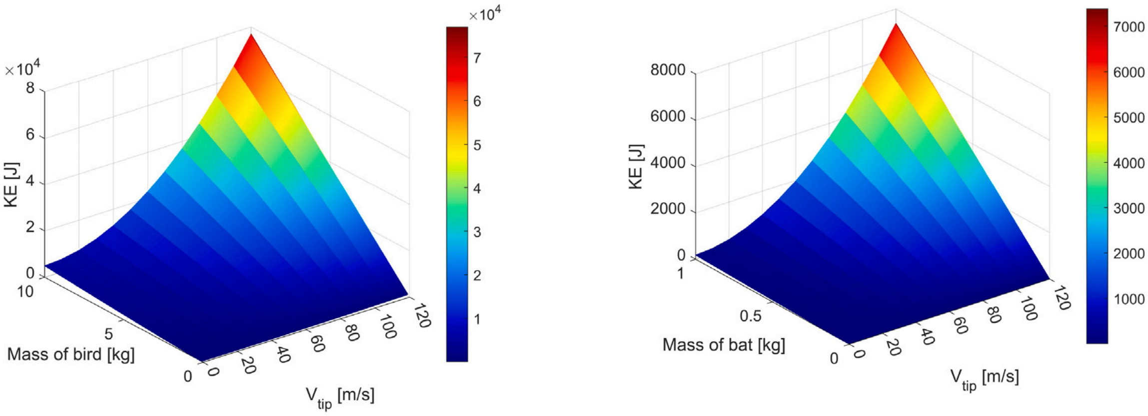
There are other impacts that are accidental and can occur once in a lifetime (marked as ‘single’ in the table). For instance, blade collisions during transportation and assembly are accidental in nature and can occur once during their service life. However, for such cases, it has already been discussed that the kinetic energy of impact can be very high. Therefore, a sound mitigation measure is of paramount importance and plays a crucial role in reducing the collision risk. For instance, proper stowage of blades during transportation must be arranged. In addition, automated tugger line control systems [168,169] and tuned mass damper systems have been developed to reduce blade



(a) Rain droplet ***(b) Hail droplet***



(c) Sand ***(d) Insect***



(e) Bird ***(f) Bat***

Fig. 27. Dependence of impact energy on blade tip speed and impactor characteristics during operation stage.

root motion during mating process. Similar approaches need to be implemented.

4. Recommendations for future work

Below is a list of recommendations for future research:

- Identify the insect species that are most frequently subjected to wind turbine blade collision: Insects are known to be particularly vulnerable to wind turbine blades, and a better understanding of which species are most frequently affected by collisions would help inform efforts to mitigate the impacts of wind turbines on local ecosystems. This research could involve a combination of field observations and lab studies to determine which species are most at risk, as well as investigations into the flight patterns and behaviors of different insect populations.
- Further investigate wake effects on airplane navigation caused by wind turbines: The wake generated by wind turbines can disrupt the flight paths of nearby aircraft, creating potential hazards for pilots and passengers. Future research could explore the effects of wind turbines on airplane navigation in greater detail, using simulations and real-world measurements to better understand how wind turbine wakes interact with planes and how best to mitigate the risks associated with these interactions.
- Establish a collision task force to specifically address drone collision with wind turbine blades: Drones are becoming increasingly common near wind turbines, and collisions between drones and

turbine blades can be dangerous and costly. To address this issue, a task force could be established to coordinate efforts among researchers, industry professionals, and regulatory agencies to better understand the risks associated with drone-turbine collisions and develop effective mitigation strategies. This could involve research into the types of drones most likely to collide with turbine blades, as well as investigations into technologies like sense and avoid systems that could help prevent such collisions.

- Develop a comprehensive classification system for differentiating between hard and soft impact: Currently, there is no widely accepted classification system for differentiating between hard and soft impacts on wind turbine blades. A better understanding of these impact types could help inform efforts to design more durable turbine blades and develop more effective mitigation strategies. Future research in this area could involve laboratory testing to identify the different characteristics of hard and soft impacts, as well as field studies to observe the effects of various types of impacts on turbine blades in real-world settings.
- Encourage more field observations of wind turbine blade collisions and share data publicly: Despite the importance of understanding the impacts of wind turbine collisions, there is still relatively little data available on the subject. Encouraging more field observations and sharing this data publicly could help researchers better understand the frequency and severity of wind turbine collisions, as well as inform efforts to mitigate their impacts. This could involve collaborations between wind farm operators and researchers to collect data on blade impacts and make this data available to the wider research community.
- Conduct drone collision analysis to study the extent of hard or soft impact on the blades: As mentioned earlier, drone-turbine collisions can be particularly costly and dangerous. Conducting detailed analyses of these collisions could help researchers better understand the characteristics of hard and soft impacts on wind turbine blades, as well as inform efforts to design more durable blades and develop more effective mitigation strategies.
- Investigate new modeling strategies for analyzing wind turbine blade collisions: Modeling wind turbine blade collisions is a complex task that requires accurate representations of both the blades and the objects they might collide with. Investigating new modeling strategies could help researchers better understand the dynamics of these collisions and develop more effective mitigation strategies. This could involve developing new computational models that can simulate the behavior of wind turbine blades under various types of impact, as well as incorporating data from real-world collisions to refine these models.
- Explore additional mitigation measures to reduce the likelihood and severity of accidental impact loads: Finally, future research could explore additional mitigation measures to reduce the likelihood and severity of wind turbine blade collisions. This could involve developing new sensor technologies to detect objects in the path of turbine blades and adjust their speed or direction accordingly, as well as investigating the use of damage tolerant materials that are more resistant to impact damage. Other potential strategies could include modifying the design of wind turbine blades to reduce their risk of collision, as well as exploring new approaches to site selection and wind farm layout to minimize the risk of collisions.

5. Conclusions

This paper is the first attempt to provide a comprehensive review of various impact threats on wind turbine blades during their service life. The impact threats are categorized based on the four stages of blade service life: transportation, installation, operation, and inspection. Different impact sources are elaborated in each stage, along with their quantitative and qualitative characteristics. In addition, five criteria are used to compare impact threats: relative deformability of impactors and turbine blades, kinetic energy, impact velocity, repeatability of impacts, and nature of impacts. The following are some interesting concluding remarks:

- As WTB sizes and dimensions increase, collisions between traffic and vessel decks are more likely during transportation, both for onshore and offshore wind farms. In spite of the unpredictability of these collisions, precautions can be taken to prevent them.
- WTB installation involves three phases: lift-off phase, lifted phase, and mating phase and each phase involves different scenarios for wind turbine blade collision. Based on qualitative risk assessments, lift-off, lifted, and mating phases are ranked from low to high risk.
- During the operation phase, WTBs are subject to wildlife collisions (e.g., bird and bat impacts), hydrometeor collisions (e.g., raindrops and hail impacts), and airborne particle collisions (e.g., sand and insects impacts), and aviation aircraft collisions.
- Helicopter and drone collisions are two of the most common impacts on WTBs during inspection and maintenance.
- There are two types of impacts: soft and hard, based on the relative deformability of WTBs and the impactor. According to this paper's analysis of soft and hard impacts, sand impact, collision during installation and transportation as well as helicopter collision during maintenance are obtained as hard impacts. In contrast, hail impact, rain impact, bird and bat impact, and drone impact are obtained as soft impacts.
- Impact threats were also compared based on impact velocity and impact energy. During operation, impact threats are associated with high velocity impacts, whereas during transportation, installation, and maintenance, impact threats are associated with low velocity impacts. Additionally, some scenarios such as installation impacts have high kinetic energy despite low velocity. A blade in such cases can be considered a projectile, and the excessive weight of the blade contributes significantly to impact energy.

The review paper will be of special interest to researchers working on wind turbine blades and will serve as a baseline report for designing damage-tolerant blades. This study makes three specific contributions:

- First attempt to identify different sources of impact threats and describe their qualitative (causes, vulnerable blade regions) and quantitative characteristics (mass, size, velocity etc.) during different stages of blade's service life;
- Quantify the regions of blade that are vulnerable to impact threats;
- Provide modeling guidelines by comparing the impact threats using the five different criteria.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] Ahrens Uwe, Diehl Moritz, Schmehl Roland. Airborne wind energy. Springer Science & Business Media; 2013.

[2] Pineda Iván, Tardieu Pierre. The European offshore wind industry – key trends and statistics 2016. https://windeurope.org/about-wind/statistics/offshore/european-offshore-wind-industry-key-trends-and-statistics-2016/, Accessed: -06-01.

[3] Jacobsen Henrik Klinge, Hevia-Koch Pablo, Wolter Christoph. Nearshore and offshore wind development: Costs and competitive advantage exemplified by nearshore wind in Denmark. Energy Sustain Dev 2019;50:91–100.

[4] Zhang Yu, Shi Wei, Li Dongsheng, Li Xin, Duan Yuanfeng, Verma Amrit Shankar. A novel framework for modeling floating offshore wind turbines based on the vector form intrinsic finite element (VFIFE) method. Ocean Eng 2022;262:112221.

[5] Sergiienko NY, da Silva LSP, Bachynski-Polić EE, Cazzolato BS, Arjomandi M, Ding B. Review of scaling laws applied to floating offshore wind turbines. Renew Sustain Energy Rev 2022;162:112477.

[6] Pishgar-Komleh SH, Keyhani A, Sefeedpari P. Wind speed and power density analysis based on Weibull and Rayleigh distributions (a case study: Firouzkooh county of Iran). Renew Sustain Energy Rev 2015;42:313–22.

[7] Jensen F Mølholt, Branner Kim. Introduction to wind turbine blade design. In: Advances in wind turbine blade design and materials. Elsevier; 2013, p. 3–28.

[8] Feng Dianshi. Simulation of low-velocity impact damage in sandwich composites (Ph.D. thesis), Universita'degli Studi di Cagliari; 2014.

[9] Hu Weifei, Choi KK, Zhupanska Olesya, Buchholz James HJ. Integrating variable wind load, aerodynamic, and structural analyses towards accurate fatigue life prediction in composite wind turbine blades. Struct Multidiscip Optim 2016;53(3):375–94.

[10] Lachenal Xavier, Daynes Stephen, Weaver Paul M. Review of morphing concepts and materials for wind turbine blade applications. Wind Energy 2013;16(2):283–307.

[11] Albanesi Alejandro, Roman Nadia, Bre Facundo, Fachinotti Victor. A metamodel-based optimization approach to reduce the weight of composite laminated wind turbine blades. Compos Struct 2018;194:345–56.

[12] Siemens. Siemens SWT-3.6-107 specifications. 2015, https://www.siemens.com/content/dam/internet/siemens-com/global/market-specific-solutions/wind/data_sheets/data-sheet-wind-turbine-swt-3-6-107.pdf, 2015.

[13] Alpha ventus. Alpha ventus offshore wind farm. 2015, https://www.alpha-ventus.de/english/, 2015. (Accessed on 12/12/2021).

[14] Vestas. V164-8MW specifications. 2012, http://www.homepages.ucl.ac.uk/~uceseug/Fluids2/Wind_Turbines/Turbines/V164-8MW.pdf, 2012. (Accessed on 12/12/2021).

[15] GE Renewable Energy. World's largest offshore wind turbine haliade-x. 2018, https://www.ge.com/renewableenergy/wind-energy/turbines/haliade-x-offshore-turbine, 2018. (Accessed on 12/12/2021).

[16] Bak Christian, Zahle F, Bitsche R, Kim T, Yde A, Henriksen LC, Hansen MH, Natarajan A. Description of the DTU 10 MW reference wind turbine. Progress report Report-I-0092, DTU Wind Energy; 2013.

[17] Verma Amrit Shankar, Vedvik Nils Petter, Haselbach Philipp Ulrich, Gao Zhen, Jiang Zhiyu. Comparison of numerical modelling techniques for impact investigation on a wind turbine blade. Compos Struct 2019;209:856–78.

[18] Verma Amrit Shankar, Jiang Zhiyu, Ren Zhengru, Gao Zhen, Vedvik Nils Petter. Response-based assessment of operational limits for mating blades on monopile-type offshore wind turbines. Energies 2019;12(10):1867.

[19] Hwang JS, Platenkamp DJ, Beukema RP. A literature survey on remote inspection of offshore wind turbine blades: Automated inspection and repair of turbine blades (AIRTuB)-WP1. 2021.

[20] Anisimov Andrei G, Beukema Ronald, Hwang Jason, Nijssen Rogier, Groves Roger M. AIRTuB: towards automated inspection of leading edge erosion of wind turbine blades by shape analysis. In: Multimodal sensing and artificial intelligence: Technologies and applications II, Vol. 11785. SPIE; 2021, p. 117850W.

[21] Nijssen Rogier, Manrique Emilio. Literature review of structural and non-structural wind turbine blade damage. In: TNO report, August. 2020.

[22] Nanami N, Ochoa OO. Bird impact study of a preloaded composite wind turbine blade. Energy 2013;15:2.

[23] Verma Amrit Shankar, Jiang Zhiyu, Ren Zhengru, Gao Zhen, Vedvik Nils Petter. Effects of wind-wave misalignment on a wind turbine blade mating process: impact velocities, blade root damages and structural safety assessment. J. Mar. Sci. Appl. 2020;19:218–33.

[24] Verma Amrit Shankar, Castro Saullo GP, Jiang Zhiyu, Teuwen Julie JE. Numerical investigation of rain droplet impact on offshore wind turbine blades under different rainfall conditions: A parametric study. Compos Struct 2020;241:112096.

[25] Pinto Thiago Henrique Lara, Gul Waseem, Torres Libardo Andrés González, Cimini Carlos Alberto, Ha Sung Kyu. Experimental and numerical comparison of impact behavior between thermoplastic and thermoset composite for wind turbine blades. Materials 2021;14(21):6377.

[26] Agrawal Sandeep, Singh Kalyan Kumar, Sarkar PK. Impact damage on fibre-reinforced polymer matrix composite–a review. J Compos Mater 2014;48(3):317–32.

[27] Haselbach PU, Bitsche R, Branner K. The effect of delaminations on local buckling in wind turbine blades. Renew Energy 2016;85:295–305.

[28] Mishnaevsky Jr Leon, Hasager Charlotte Bay, Bak Christian, Tilg Anna-Maria, Bech Jakob I, Rad Saeed Doagou, Fæster Søren. Leading edge erosion of wind turbine blades: Understanding, prevention and protection. Renew Energy 2021;169:953–69.

[29] Sareen Agrim, Sapre Chinmay A, Selig Michael S. Effects of leading edge erosion on wind turbine blade performance. Wind Energy 2014;17(10):1531–42.

[30] Han Woobeom, Kim Jonghwa, Kim Bumsuk. Effects of contamination and erosion at the leading edge of blade tip airfoils on the annual energy production of wind turbines. Renew Energy 2018;115:817–23.

[31] McGugan Malcolm, Pereira G, Sørensen Bent F, Toftegaard H, Branner Kim. Damage tolerance and structural monitoring for wind turbine blades. Phil Trans R Soc A 2015;373(2035):20140077.

[32] Lusty Ariel F, Cairns Douglas A. Alternative damage tolerant materials for wind turbine blades: An overview. 2021.

[33] Padmaja RK, Bhargav Y, Subramanya S. Fatigue and damage tolerance analysis of aircraft structural components. Technical report, East Hartford, CT (United States): Cyient; 2017.

[34] Hayman Brian. Approaches to damage assessment and damage tolerance for FRP sandwich structures. J Sandw Struct Mater 2007;9(6):571–96.

[35] Fan XL, Sun Q, Kikuchi M. Review of damage tolerant analysis of laminated composites. J Solid Mech 2010.

[36] Nielsen Jannie S, Sørensen John D. Bayesian estimation of remaining useful life for wind turbine blades. Energies 2017;10(5):664.

[37] Kim Hyonny, Halpin John C, DeFrancisci Gabriela K. Impact damage of composite structures. In: Long-term durability of polymeric matrix composites. Springer; 2012, p. 143–80.

[38] Shah SZH, Karuppanan S, Megat-Yusoff PSM, Sajid Z. Impact resistance and damage tolerance of fiber reinforced composites: A review. Compos Struct 2019;217:100–21.

[39] Ertek Gürdal, Kailas Lakshmi. Analyzing a decade of wind turbine accident news with topic modeling. Sustainability 2021;13(22):12757.

[40] Olabi Abdul Ghani, Wilberforce Tabbi, Elsaid Khaled, Sayed Enas Taha, Salameh Tareq, Abdelkareem Mohammad Ali, Baroutaji Ahmad. A review on failure modes of wind turbine components. Energies 2021;14(17):5241.

[41] Ravikumar Karthikeyan, Subbiah Rajkumar, Ranganathan Nalini, Bensingh Joseph, Kader Abdul, Nayak Sanjay K. A review on fatigue damages in the wind turbines: Challenges in determining and reducing fatigue failures in wind turbine blades. Wind Eng 2020;44(4):434–51.

[42] Katsaprakakis Dimitris Al, Papadakis Nikos, Ntintakis Ioannis. A comprehensive analysis of wind turbine blade damage. Energies 2021;14(18):5974.

[43] Herring Robbie, Dyer Kirsten, Martin Ffion, Ward Carwyn. The increasing importance of leading edge erosion and a review of existing protection solutions. Renew Sustain Energy Rev 2019;115:109382.

[44] Slot HM, Gelinck ERM, Rentrop C, Van Der Heide Emile. Leading edge erosion of coated wind turbine blades: Review of coating life models. Renew Energy 2015;80:837–48.

[45] Raišutis Renaldas, Jasiūnienė Elena, Šliteris Reimondas, Vladišauskas Alfonsas. The review of non-destructive testing techniques suitable for inspection of the wind turbine blades. Ultragarsas/Ultrasound 2008;63(2):26–30.

[46] Du Ying, Zhou Shengxi, Jing Xingjian, Peng Yeping, Wu Hongkun, Kwok Ngaiming. Damage detection techniques for wind turbine blades: A review. Mech Syst Signal Process 2020;141:106445.

[47] Shohag Md Abu S, Hammel Emily C, Olawale David O, Okoli Okenwa I. Damage mitigation techniques in wind turbine blades: A review. Wind Eng 2017;41(3):185–210.

[48] Ragheb Adam M, Selig Michael S. Multielement airfoils for wind turbines. In: Wind energy engineering. Elsevier; 2017, p. 203–19.

[49] https://www.skuld.com/topics/cargo/project-cargo/transportation-of-wind-turbines-as-cargo/. Picture.

[50] Cotrell J, Stehly T, Johnson J, Roberts JO, Parker Z, Scott G, Heimiller D. Analysis of transportation and logistics challenges affecting the deployment of larger wind turbines: summary of results. Technical report, Golden, CO (United States): National Renewable Energy Lab.(NREL); 2014.

[51] Carron William Scott, Bortolotti Pietro. Innovative rail transport of a supersized land-based wind turbine blade. In: Journal of physics: Conference series, Vol. 1618. IOP Publishing; 2020, 042041.

[52] Bortolotti Pietro, Johnson Nick, Abbas Nikhar J, Anderson Evan, Camarena Ernesto, Paquette Joshua. Land-based wind turbines with flexible rail-transportable blades–Part 1: Conceptual design and aeroservoelastic performance. Wind Energy Sci 2021;6(5):1277–90.

[53] Mooney Meghan, Maclaurin Galen. Transportation of large wind components: A review of existing geospatial data. 2016.

[54] Verma Amrit Shankar, Haselbach Philipp Ulrich, Vedvik Nils Petter, Gao Zhen. A global-local damage assessment methodology for impact damage on offshore wind turbine blades during lifting operations. In: ASME 2018 37th international conference on ocean, offshore and arctic engineering. American Society of Mechanical Engineers; 2018, V010T09A064.

[55] Skuld. Transportation of wind turbines as cargo. 2013, https://www.skuld.com/topics/cargo/project-cargo/transportation-of-wind-turbines-as-cargo/, 2013. (Accessed on 12/12/2021).

[56] Jiang Zhiyu. The impact of a passive tuned mass damper on offshore single-blade installation. J Wind Eng Ind Aerodyn 2018;176:65–77.

[57] Verma Amrit Shankar, Vedvik Nils Petter, Gao Zhen. A comprehensive numerical investigation of the impact behaviour of an offshore wind turbine blade due to impact loads during installation. Ocean Eng 2019;172:127–45.

[58] Verma Amrit Shankar. Modelling, analysis and response-based operability assessment of offshore wind turbine blade installation with emphasis on impact damages. 2019.

[59] Verma Amrit Shankar. Modelling, analysis and response-based operability assessment of offshore wind turbine blade installation with emphasis on impact damages. 2019.

[60] Verma Amrit Shankar, Jiang Zhiyu, Caboni Marco, Verhoef Hans, van der Mijle Meijer Harald, Castro Saullo GP, Teuwen Julie JE. A probabilistic rainfall model to estimate the leading-edge lifetime of wind turbine blade coating system. Renew Energy 2021;178:1435–55.

[61] Macdonald Hamish, Infield David, Nash David H, Stack Margaret M. Mapping hail meteorological observations for prediction of erosion in wind turbines. Wind Energy 2016;19(4):777–84.

[62] Shimada Yasuo. Reducing bird collision risk per megawatt by introducing longer wind turbine blades. Ornithol Sci 2021;20(2):253–61.

[63] Cryan Paul M, Gorresen Paulo M, Straw Bethany R, Thao Syhoune, DeGeorge Elise. Influencing activity of bats by dimly lighting wind turbine surfaces with ultraviolet light. Animals 2021;12(1):9.

[64] Horn Jason W, Arnett Edward B, Kunz Thomas H. Behavioral responses of bats to operating wind turbines. J Wildl Manage 2008;72(1):123–32.

[65] Norberg Ulla M, Rayner Jeremy MV. Ecological morphology and flight in bats (Mammalia; Chiroptera): wing adaptations, flight performance, foraging strategy and echolocation. Philos Trans R Soc Lond B Biol Sci 1987;316(1179):335–427.

[66] Tejas KS, Prashanth AS. Bird impact analysis of a composite wind turbine blade. 2017.

[67] Kong Changduk, Choi Suhyun, Park Hyunbum. Investigation on design for a 500 W wind turbine composite blade considering impact damage. Adv Compos Mater 2011;20(2):105–23.

[68] Nanami Norimichi. Structural and damage assessment of multi-section modular hybrid composite wind turbine blade (Ph.D. thesis), 2014.

[69] Nanami Norimichi, Ochoa OO. Damage assessment of a large-scale hybrid composite wind turbine blade. J Mech Eng Autom 2016;6(5):117–27.

[70] Tucker VA. Using a collision model to design safer wind turbine rotors for birds. 1996.

[71] Nizampatnam Lakshmi S. Models and methods for bird strike load predictions (Ph.D. thesis), Wichita State University; 2007.

[72] Diffendorfer Jay E, Stanton Jessica C, Beston Julie A, Thogmartin Wayne E, Loss Scott R, Katzner Todd E, Johnson Douglas H, Erickson Richard A, Merrill Matt D, Corum Margo D. Demographic and potential biological removal models identify raptor species sensitive to current and future wind energy. Ecosphere 2021;12(6):e03531.

[73] Hoge Alexander. Measures for mitigating avian collision rates with wind turbines-determining an effective technique regarding effort and effect. 2021.

[74] McClure Christopher JW, Rolek Brian W, Dunn Leah, McCabe Jennifer D, Martinson Luke, Katzner Todd. Eagle fatalities are reduced by automated curtailment of wind turbines. J Appl Ecol 2021;58(3):446–52.

[75] May Roel, Nygård Torgeir, Falkdalen Ulla, Å ström Jens, Hamre Øyvind, Stokke Bård G. Paint it black: Efficacy of increased wind turbine rotor blade visibility to reduce avian fatalities. Ecol Evol 2020;10(16):8927–35.

[76] Thaxter Chris B, Buchanan Graeme M, Carr Jamie, Butchart Stuart HM, Newbold Tim, Green Rhys E, Tobias Joseph A, Foden Wendy B, O'Brien Sue, Pearce-Higgins James W. Bird and bat species' global vulnerability to collision mortality at wind farms revealed through a trait-based assessment. Proc R Soc B: Biol Sci 2017;284(1862):20170829.

[77] Tucker VA. A mathematical model of bird collisions with wind turbine rotors. 1996.

[78] Shankar Verma Amrit, Jiang Zhiyu, Ren Zhengru, Hu Weifei, Teuwen Julie JE. Effects of onshore and offshore environmental parameters on the leading edge erosion of wind turbine blades: A comparative study. J Offshore Mech Arct Eng 2021;143(4).

[79] Ren Zhengru, Verma Amrit Shankar, Li Ye, Teuwen Julie JE, Jiang Zhiyu. Offshore wind turbine operations and maintenance: A state-of-the-art review. Renew Sustain Energy Rev 2021;144:110886.

[80] Verma Amrit Shankar, Noi Sandro Di, Ren Zhengru, Jiang Zhiyu, Teuwen Julie JE. Minimum leading edge protection application length to combat rain-induced erosion of wind turbine blades. Energies 2021;14(6):1629.

[81] Verma Amrit Shankar, Vedvik Nils Petter, Gao Zhen, Castro Saullo GP, Teuwen Julie JE. Bondline thickness effects on damage tolerance of adhesive joints subjected to localized impact damages: Application to leading edge of wind turbine blades. Materials 2021;14(24):7526.

[82] Verma Amrit Shankar, Jiang Zhiyu, Ren Zhengru, Teuwen Julie JE. Leading edge erosion of wind turbine blades: effects of environmental parameters on impact velocities and erosion damage rate. In: International conference on offshore mechanics and arctic engineering, Vol. 84416. American Society of Mechanical Engineers; 2020, V009T09A043.

[83] Leon Mishnaevsky, Fæster Søren, Rad Saeed Doagou. Mechanisms and computational analysis of leading edge erosion of wind turbine blades. In: IOP conference series: Materials science and engineering, Vol. 942. IOP Publishing; 2020, 012025.

[84] Hasager Charlotte, Mishnaevsky Jr Leon, Bak Christian, Bech Jakob Ilsted, Fæster Søren, Johansen Nicolai Frost-Jensen. How can we combat leading-edge erosion on wind turbine blades? In: DTU international energy report 2021: Perspectives on wind energy. DTU Wind Energy; 2021, p. 134–42.

[85] Mishnaevsky Jr Leon, Fæster Søren, Mikkelsen Lars P, Kusano Yukihiro, Bech Jakob Ilsted. Micromechanisms of leading edge erosion of wind turbine blades: X-ray tomography analysis and computational studies. Wind Energy 2020;23(3):547–62.

[86] Mishnaevsky Jr Leon, Thomsen Kenneth. Costs of repair of wind turbine blades: Influence of technology aspects. Wind Energy 2020;23(12):2247–55.

[87] Doagou-Rad Saeed, Mishnaevsky Leon. Rain erosion of wind turbine blades: computational analysis of parameters controlling the surface degradation. Meccanica 2020;55(4):725–43.

[88] Shankar Verma Amrit, Jiang Zhiyu, Ren Zhengru, Caboni Marco, Verhoef Hans, van der Mijle-Meijer Harald, Castro Saullo GP, Teuwen Julie JE. A probabilistic long-term framework for site-specific erosion analysis of wind turbine blades: A case study of 31 Dutch sites. Wind Energy 2021;24(11):1315–36.

[89] Elhadi Ibrahim Mohamed, Medraj Mamoun. Water droplet erosion of wind turbine blades: Mechanics, testing, modeling and future perspectives. Materials 2019;13(1):157.

[90] Keegan Mark Hugh, Nash DH, Stack MM. On erosion issues associated with the leading edge of wind turbine blades. J Phys D: Appl Phys 2013;46(38):383001.

[91] Keegan Mark Hugh, Nash David, Stack Margaret. Modelling rain drop impact on offshore wind turbine blades. In: ASME turbo expo 2012. 2012, p. Article–GT.

[92] Hu Weifei, Chen Weiyi, Wang Xiaobo, Jiang Zhiyu, Wang Yeqing, Verma Amrit Shankar, Teuwen Julie JE. A computational framework for coating fatigue analysis of wind turbine blades due to rain erosion. Renew Energy 2021;170:236–50. http://dx.doi.org/10.1016/j.renene.2021.01.094.

[93] Herring Robbie, Dyer Kirsten, Howkins Paul, Ward Carwyn. Characterisation of the offshore precipitation environment to help combat leading edge erosion of wind turbine blades. Wind Energy Sci 2020;5(4):1399–409. http://dx.doi.org/10.5194/wes-5-1399-2020.

[94] Macdonald Hamish. The infuence of hail on wind turbine blade leading edge erosion and damage. 2017.

[95] Dieling Christian, Smith Milton L, Peterson Stephen, Phelps Matthew, Norville H Scott, Beruvides Mario. Hail impact testing: Velocity effects of distance to target specimen. J Wind Eng Ind Aerodyn 2021;211:104554.

[96] Dieling Christian, Smith Milton, Beruvides Mario. Review of impact factors of the velocity of large hailstones for laboratory hail impact testing consideration. Geosciences 2020;10(12):500.

[97] Keegan Mark Hugh, Nash David, Stack Margaret. Numerical modelling of hailstone impact on the leading edge of a wind turbine blade. In: EWEA annual wind energy event 2013. 2013.

[98] Ivancevic D, Zakan I Badurina, Smojver I. Numerical methodology for aerostructures hail impact damage prediction. In: IOP conference series: Materials science and engineering, Vol. 1024. IOP Publishing; 2021, 012082.

[99] Macdonald JR, Stack MM. Some thoughts on modelling hail impact on surfaces. J Bio-and Tribo-Corros 2021;7(2):1–7.

[100] Prein Andreas F, Holland Greg J. Global estimates of damaging hail hazard. Weather Clim Extremes 2018;22:10–23.

[101] Dieling Christian, Smith Milton, Beruvides Mario. The importance of accurate terminal velocities for hail impact testing procedures. In: IIE annual conference. Proceedings. Institute of Industrial and Systems Engineers (IISE); 2021, p. 578–83.

[102] Soderholm Joshua S, Kumjian Matthew R, McCarthy Nicholas, Maldonado Paula, Wang Minzheng. Quantifying hail size distributions from the sky–application of drone aerial photogrammetry. Atmos Meas Tech 2020;13(2):747–54.

[103] Grieser Juergen, Hill Marc. How to express hail intensity—modeling the hailstone size distribution. J Appl Meteorol Climatol 2019;58(10):2329–45.

[104] Fiore Giovanni, Selig Michael S. Simulation of damage for wind turbine blades due to airborne particles. Wind Eng 2015;39(4):399–418.

[105] Shedd Laura, Kumjian Matthew R, Giammanco Ian, Brown-Giammanco Tanya, Maiden B Ross. Hailstone shapes. J Atmos Sci 2021;78(2):639–52. http://dx.doi.org/10.1175/jas-d-20-0250.1.

[106] Ćurić Mladjen, Zafirovski Oliver, Spiridonov Vlado. Meteorological and weather elements. In: Essentials of medical meteorology. Springer International Publishing; 2021, p. 39–62. http://dx.doi.org/10.1007/978-3-030-80975-1_4.

[107] Heymsfield Andrew J, Giammanco Ian M, Wright Robert. Terminal velocities and kinetic energies of natural hailstones. Geophys Res Lett 2014;41(23):8666–72. http://dx.doi.org/10.1002/2014gl062324.

[108] Alajmi Abdullah F. Characterization and modeling of the leading edge erosion of wind turbine blades due to sand particles impingement (Ph.D. thesis), University of Washington; 2021.

[109] Vera-Cardenas Edgar Ernesto, Mendoza-Mendoza Jesus Cornelio, Martinez-Perez Armando Irvin, Ledesma-Ledesma Saul, Rubio-González Carlos, Vite-Torres Manuel. Solid particle erosive wear study of polymer composite materials for wind turbine applications. Polym Compos 2021;42(4):1988–99.

[110] Liu GuangYou, Cen HaiTang, Zeng Qin, Tian WenLiang, Li Ling. Erosion mechanism and simulation analysis of wind turbine blade coating. In: 2019 4th international conference on mechanical, control and computer engineering. ICMCCE, IEEE; 2019, p. 1036–10364.

[111] Khakpour Yasmin, Bardakji Suheila, Nair Sudhakar. Aerodynamic performance of wind turbine blades in dusty environments. In: ASME international mechanical engineering congress and exposition, Vol. 43025. 2007, p. 483–91.

[112] Soltani Mohammad Reza, Birjandi Amir Hossein, Moorani M Seddighi. Effect of surface contamination on the performance of a section of a wind turbine blade. Sci Iran 2011;18(3):349–57.

[113] El-Din Ahmed Hossam, Diab Aya, Ghoneim Zakaria. Assessment of losses in annual energy production of wind turbines subjected to sand erosion. In: Proceedings of the international conference on fluid dynamics, Cairo, Egypt. 2016, p. 19–20.

[114] Fiore Giovanni, Selig Michael S. Optimization of wind turbine airfoils subject to particle erosion. In: 33rd AIAA applied aerodynamics conference. 2015, p. 3393.

[115] Fiore Giovanni, Selig Michael S. Simulation of damage progression on wind turbine blades subject to particle erosion. In: 54th AIAA aerospace sciences meeting. 2016, p. 0813.

[116] Bouhelal Abdelhamid, Guerri Ouahiba, Smaili Arezki, Masson Christian. Contribution to the aerodynamic study of the air-sand flow around a wind turbine blade installed in desert environment of Algeria. In: 2018 international conference on wind energy and applications in Algeria. ICWEAA, IEEE; 2018, p. 1–6.

[117] BSI. BS EN ISO 14688-1: 2002: Geotechnical investigation and testing. Identification and classification of soil. Identification and description. London: British Standards Institution; 2002.

[118] Al-Sanad HA, Ismael NF, Nayfeh AJ. Geotechnical properties of dune sands in Kuwait. Eng Geol 1993;34(1–2):45–52.

[119] Salik Joshua, Buckley Donald, Brainard William A. The effect of mechanical surface and heat treatments on the erosion resistance of 6061 aluminum alloy. Wear 1981;65(3):351–8.

[120] Corten Gustave P, Veldkamp Herman F. Insects can halve wind-turbine power. Nature 2001;412(6842):41–2. http://dx.doi.org/10.1038/35083698.

[121] Wilcox Benjamin, White Edward. Computational analysis of insect impingement patterns on wind turbine blades. Wind Energy 2015;19(3):483–95. http://dx.doi.org/10.1002/we.1846.

[122] Krishnan K Ghokulla, Milionis Athanasios, Loth Eric, Farrell Thomas E, Crouch Jeffrey D, Berry Douglas H. Influence of hydrophobic and superhydrophobic surfaces on reducing aerodynamic insect residues. Appl Surf Sci 2017;392:723–31. http://dx.doi.org/10.1016/j.apsusc.2016.09.096, URL https://linkinghub.elsevier.com/retrieve/pii/S0169433216319651.

[123] Kühsel Sara, Brückner Adrian, Schmelzle Sebastian, Heethoff Michael, Blüthgen Nico. Surface area-volume ratios in insects. Insect Sci 2016;24(5):829–41. http://dx.doi.org/10.1111/1744-7917.12362.

[124] Long CV, Flint JA, Lepper PA. Insect attraction to wind turbines: does colour play a role? Eur J Wildl Res 2010;57(2):323–31. http://dx.doi.org/10.1007/s10344-010-0432-7.

[125] Voigt Christian C. Insect fatalities at wind turbines as biodiversity sinks. Conserv Sci Pract 2021;3(5). http://dx.doi.org/10.1111/csp2.366.

[126] Manning PT. The environmental impact of the use of large wind turbines. Wind Eng 1983;1–11.

[127] Follett Andrew. Wind turbines create big problems for small planes. https://dailycaller.com/2017/04/21/wind-turbines-create-big-problems-for-small-planes/, Accessed: -06-01.

[128] Tomaszewski Jessica M, Lundquist Julie K, Churchfield Matthew J, Moriarty Patrick J. Do wind turbines pose roll hazards to light aircraft? Wind Energy Sci 2018;3(2):833–43.

[129] Wang Yaxing, White Mark, Barakos George N. Wind-turbine wake encounter by light aircraft. J Aircr 2016;54(1):367–70.

[130] Štrbac Alexander, Martini Tanja, Greiwe Daniel H, Hoffmann Frauke, Jones Michael. Analysis of rotorcraft wind turbine wake encounters using piloted simulation. CEAS Aeronaut J 2021;12(2):273–90.

[131] Visingardi Antonio, Pavel Marilena. Numerical investigations of the aerodynamics and handling qualities of a helicopter flying across a wind turbine wake. In: 44th European rotorcraft forum. 2018.

[132] Cormier Marion, Bühler Manuel, Mauz Moritz, Lutz Thorsten, Bange Jens, Krämer Ewald. CFD prediction of tip vortex aging in the wake of a multi-MW wind turbine. In: Journal of physics: Conference series, Vol. 1618. IOP Publishing; 2020, 062029.

[133] Hatch C, Hartley S, Roberto O, Alcala A. National transportation safety board aviation accident factual report. National Transportation Safety Board; 2015.

[134] Huber Mark. Offshore wind needs new helicopters worth 1 billion USD. 2021, https://www.ainonline.com/aviation-news/general-aviation/2021-01-26/offshore-wind-needs-new-helicopters-worth-1-billion. (Accessed on 12/3/2022).

[135] Energy Institute London. Good practice guidelines for offshore renewable energy developments. Technical report, London: Energy Institute; 2019.

[136] Horvat Bastian, Hajek Manfred, Rauleder Juergen. Computational flight path analysis of a helicopter in an offshore wind farm using a lattice-Boltzmann method. In: AIAA scitech 2021 forum. American Institute of Aeronautics and Astronautics; 2021, http://dx.doi.org/10.2514/6.2021-1827.

[137] Ramírez-Agudelo Oscar Hernán, Köpke Corinna, Guillouet Yann, Schäfer-Frey Jan, Engler Evelin, Mielniczek Jennifer, Torres Frank Sill. An expert-driven probabilistic assessment of the safety and security of offshore wind farms. Energies 2021;14(17):5465. http://dx.doi.org/10.3390/en14175465.

[138] Necci Amos, Tarantola Stefano, Vamanu Bogdan, Krausmann Elisabeth, Ponte Luca. Lessons learned from offshore oil and gas incidents in the Arctic and other ice-prone seas. Ocean Eng 2019;185:12–26. http://dx.doi.org/10.1016/j.oceaneng.2019.05.021.

[139] Stuhr M, Dethleff D, Weinrich N, Nielsen M, Hory D, Kowald B, Seide K, Kerner T, Nau C, Jürgens C. Notfallmedizinische versorgung in offshore-windparks. Der Anaesthesist 2016;65(5):369–79. http://dx.doi.org/10.1007/s00101-016-0154-7.

[140] Bühler Manuel, Weihing Pascal, Klein Levin, Lutz Thorsten, Krämer Ewald. Actuator line method simulations for the analysis of wind turbine wakes acting on helicopters. J Phys Conf Ser 2018;1037:062004. http://dx.doi.org/10.1088/1742-6596/1037/6/062004.

[141] Kulsinskas Andrius, Durdevic Petar, Ortiz-Arroyo Daniel. Internal wind turbine blade inspections using UAVs: Analysis and design issues. Energies 2021;14(2):294. http://dx.doi.org/10.3390/en14020294.

[142] Liu Y, Hajj M, Bao Y. Review of robot-based damage assessment for offshore wind turbines. Renew Sustain Energy Rev 2022;158:112187. http://dx.doi.org/10.1016/j.rser.2022.112187.

[143] Poleo Khristopher Kabbabe, Crowther William J, Barnes Mike. Estimating the impact of drone-based inspection on the Levelised Cost of electricity for offshore wind farms. Results Eng 2021;9:100201. http://dx.doi.org/10.1016/j.rineng.2021.100201.

[144] Shihavuddin ASM, Chen Xiao, Fedorov Vladimir, Christensen Anders Nymark, Riis Nicolai Andre Brogaard, Branner Kim, Dahl Anders Bjorholm, Paulsen Rasmus Reinhold. Wind turbine surface damage detection by deep learning aided drone inspection analysis. Energies 2019;12(4):676. http://dx.doi.org/10.3390/en12040676.

[145] Shafiee Mahmood, Zhou Zeyu, Mei Luyao, Dinmohammadi Fateme, Karama Jackson, Flynn David. Unmanned aerial drones for inspection of offshore wind turbines: A mission-critical failure analysis. Robotics 2021;10(1):26. http://dx.doi.org/10.3390/robotics10010026.

[146] Skaga Simon Kleppevik. Feasibility study of Unmanned Aerial Vehicles (UAV) application for ultrasonic Non-Destructive Testing (NDT) of Wind Turbine Rotor Blades. Preliminary experiments of handheld and UAV utrasonic testing on glass fibre laminates (Ph.D. thesis), Faculty of Science and Technology, Department of Engineering and Safety, The Arctic University of Norway; 2017.

[147] Franke Florian, Schwab Michael, Burger Uli, Hühne Christian. An analytical model to determine the impact force of drone strikes. CEAS Aeronaut J 2021;13(1):69–84. http://dx.doi.org/10.1007/s13272-021-00552-4.

[148] la Cour-Harbo Anders. Mass threshold for 'harmless' drones. Int J Micro Air Veh 2017;9(2):77–92. http://dx.doi.org/10.1177/1756829317691991.

[149] Wild Graham, Gavin Kellie, Murray John, Silva Jose, Baxter Glenn. A post-accident analysis of civil remotely-piloted aircraft system accidents and incidents. J Aerosp Technol Manag 2017;9(2):157–68. http://dx.doi.org/10.5028/jatm.v9i2.701.

[150] Man Mohd Hasrizam Che, Liu Hu, Low Kin Huat. Severity assessment of aircraft engine fan blades under airborne collision of unmanned aerial vehicles comparable to bird strike certification standards. Proc Inst Mech Eng G 2021;236(9):1817–35. http://dx.doi.org/10.1177/09544100211044909.

[151] Lu Xiaohua, Liu Xinchao, Li Yulong, Zhang Yingchun, Zuo Hongfu. Simulations of airborne collisions between drones and an aircraft windshield. Aerosp Sci Technol 2020;98:105713. http://dx.doi.org/10.1016/j.ast.2020.105713.

[152] Lu Xiaohua, Liu Xinchao, Zhang Yingchun, Li Yulong, Zuo Hongfu. Simulation of airborne collision between a drone and an aircraft nose. Aerosp Sci Technol 2021;118:107078. http://dx.doi.org/10.1016/j.ast.2021.107078.

[153] Collision Task force. 'Drone collision' task force'. 2016, https://www.easa.europa.eu/document-library/general-publications/drone-collision-task-force. (Accessed on 12/3/2022).

[154] Yankelevsky David Z. Local response of concrete slabs to low velocity missile impact. Int J Impact Eng 1997;19(4):331–43. http://dx.doi.org/10.1016/s0734-743x(96)00041-3.

[155] Li QM, Reid SR, Wen HM, Telford AR. Local impact effects of hard missiles on concrete targets. Int J Impact Eng 2005;32(1–4):224–84. http://dx.doi.org/10.1016/j.ijimpeng.2005.04.005.

[156] Sugano T, Tsubota H, Kasai Y, Koshika N, Orui S, von Riesemann WA, Bickel DC, Parks MB. Full-scale aircraft impact test for evaluation of impact force. Nucl Eng Des 1993;140(3):373–85. http://dx.doi.org/10.1016/0029-5493(93)90119-t.

[157] Eibl J. Soft and hard impact. In: Proceedings concrete for hazard protection. Edinburgh (Scotland): The Concrete Society, Concrete for Hazard Protection; 1987, p. 175–86.

[158] Kœchlin Pierre, Potapov Sergueï. Classification of soft and hard impacts—Application to aircraft crash. Nucl Eng Des 2009;239(4):613–8.

[159] Alagesan Praveen Kumar. Recent advances of hybrid fiber composites for various applications. Wiley; 2020, p. 381–404. http://dx.doi.org/10.1002/9783527824571.ch18.

[160] Arnett Edward B, Hein Cris D, Schirmacher Michael R, Huso Manuela MP, Szewczak Joseph M. Evaluating the effectiveness of an ultrasonic acoustic deterrent for reducing bat fatalities at wind turbines. PLoS One 2013;8(6):e65794.

[161] Weaver Sara P, Hein Cris D, Simpson Thomas R, Evans Jonah W, Castro-Arellano Ivan. Ultrasonic acoustic deterrents significantly reduce bat fatalities at wind turbines. Global Ecol Conserv 2020;24:e01099.

[162] Marques Ana Teresa, Batalha Helena, Rodrigues Sandra, Costa Hugo, Pereira Maria João Ramos, Fonseca Carlos, Mascarenhas Miguel, Bernardino Joana. Understanding bird collisions at wind farms: An updated review on the causes and possible mitigation strategies. Biol Cons 2014;179:40–52.

[163] Nicholls Barry, Racey Paul A. Bats avoid radar installations: could electromagnetic fields deter bats from colliding with wind turbines? Plos One 2007;2(3):e297.

[164] Dai Lijuan, Ehlers Sören, Rausand Marvin, Utne Ingrid Bouwer. Risk of collision between service vessels and offshore wind turbines. Reliab Eng Syst Saf 2013;109:18–31.

[165] den Boon Henk, Just Henning, Hansen Peter Friis, Ravn Erik Sonne, Frouws Koos, Otto Sven, Dalhoff Peter, Stein Jürgen, van der Tak Cees, van Rooij Jan. Reduction of ship collision risks for offshore wind farms–SAFESHIP. London: EWEC; 2004.

[166] Eichhorn Marcus, Johst Karin, Seppelt Ralf, Drechsler Martin. Model-based estimation of collision risks of predatory birds with wind turbines. Ecol Soc 2012;17(2).

[167] Kim Sang Jin, Seo Jung Kwan, Ma Kuk Yeol, Park Joo Shin. Methodology for collision-frequency analysis of wind-turbine installation vessels. Ships Offshore Struct 2021;16(4):423–39.

[168] Ren Zhengru, Jiang Zhiyu, Gao Zhen, Skjetne Roger. Active tugger line force control for single blade installation. Wind Energy 2018;21(12):1344–58.

[169] Verma Amrit Shankar, Jiang Zhiyu, Gao Zhen, Vedvik Nils Petter. Effects of a passive tuned mass damper on blade root impacts during the offshore mating process. Mar Struct 2020;72:102778.