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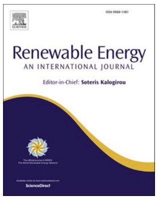

Fatigue reliability of wind turbines: historical perspectives, recent developments and future prospects

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ABSTRACT

Wind, as a sustainable and affordable energy source, represents a strong alternative to traditional energy sources. However, wind power is only one of the options, together with other renewable energy sources. Consequently, the core concerns for wind turbine manufacturers and operators are to increase its reliability and decrease costs, therefore enhancing commercial competitiveness. Among typical failure modes of wind turbines, fatigue is a common and critical source. Given the significance of fatigue reliability in wind turbine structural integrity, reliable probabilistic fatigue theories are necessary for design scheme optimization. By reducing the expenses on manufacturing, operation, and maintenance in reliability- and cost-optimal ways, the cost of energy can be significantly reduced. This study systematically reviews the state-of-the-art technology for fatigue reliability of wind turbines, and elaborates on the evolution of methodology in wind load uncertainty modelling. In addition, fatigue reliability assessment techniques on four typical components are summarized. Finally, discussions and conclusions are presented, intending to provide direct insights into future theoretical development and methodological innovation in this field.

1. Introduction

Energy shortage and environmental degradation are two major challenges to social development and human survival. As reported in the British Petroleum Statistical Review of World Energy 2019 [1], renewable resources account for less than 20% of global energy consumption. Currently, fossil fuels, including coal, oil, and natural gas, are dominant; however, they are non-renewable and bring air pollution. To avoid problems such as energy depletion and environmental pollution, it is imperative to develop efficient and sustainable clean energy sources to replace the traditional ones. For realizing sustainable development, extensive efforts have been made by governments to develop and promote clean energies; the new energy industry is undergoing a long transition from a supportive to a lead role.

Among non-conventional resources, wind energy exhibits the advantages of being clean, pollution-free, and sustainable [2–4]. It is a renewable energy source with the greatest scope for large-scale development and utilization in the future, and the global installed gross capacity of wind power has been steadily increasing each year [5], see Fig. 1. However, according to the Global Wind Energy Outlook presented by the Global Wind Energy Council, the utilization rate of wind resources is still generally low [6].

In addition, the development of offshore wind turbines didn't attract enough attention. As is illustrated in Fig. 1, it only accounts for a negligible fraction of the gross capacity; nevertheless, with the shortage of land resources with good wind fields, a surge in offshore wind turbines is expected and bound to happen [7]. According to the report of the government of the Netherlands, the costs of offshore wind energy have fallen significantly in recent years, making it the cheapest large-scale source of sustainable energy [8].

Besides the installed wind power capacity, also the size of the wind turbines has been continuously growing [9], see Fig. 2. Facing the pressing energy shortage, wind turbines of higher power ratings (bigger

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Nomenclature

ABS	American Bureau of Shipping
BSH	Federal Maritime and Hydrographic Agency
BV	Bureau Veritas
CTE	coefficient of thermal expansion
DCB	direct copper bonded
DNV	Det Norske Veritas
FAROW	fatigue and reliability of wind turbines
FORM	first-order reliability method
FWD	freewheeling diode
GFRP	glass fiber reinforced material
HAWT	horizontal axis wind turbine
IEC	International Electrotechnical Commission
IGBT	insulated gate bipolar transistor
ISO	International Organization for Standardization
LCOE	levelized cost of electricity
LDD	load duration distribution
MCS	Monte–Carlo simulation
MLE	maximum likelihood estimation
PDF	probability density function
RBDO	reliability-based design optimization
SLS-SVM	sparse least squares support vector machines
SRF	stress reserve factor
ULS	ultimate limit state
VAWT	vertical axis wind turbine

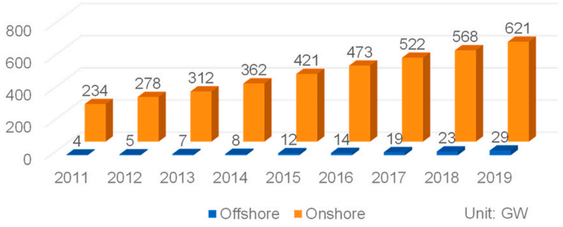


Fig. 1. Global installed gross capacity of wind power [6].

turbines, especially the offshore ones) are needed. Accordingly, fatigue lifetime modelling of future large wind turbines is needed to make reliability predictions early in the design phase [10]. Unscheduled repairs of components would lead to greater downtime, especially for offshore wind turbines located in areas inaccessible for portions of the year [11]. Maintenance is a critical element in the levelized cost of energy (LCOE), given the practical constraints imposed by offshore operations and the relatively high costs. The effects of maintenance on the life cycle of an offshore wind farm are highly complex and uncertain [12]. Accordingly, conducting reliability prediction in the design phase can ensure that the long service lives of newly developed wind turbines.

The structural block of a typical wind turbine system is shown in Fig. 3. Based on their axis of rotation, they can be divided into two generic groups: horizontal axis wind turbine (HAWT) blades rotating about a horizontal axis, and vertical axis wind turbine (VAWT) blades rotating about a vertical axis [14].

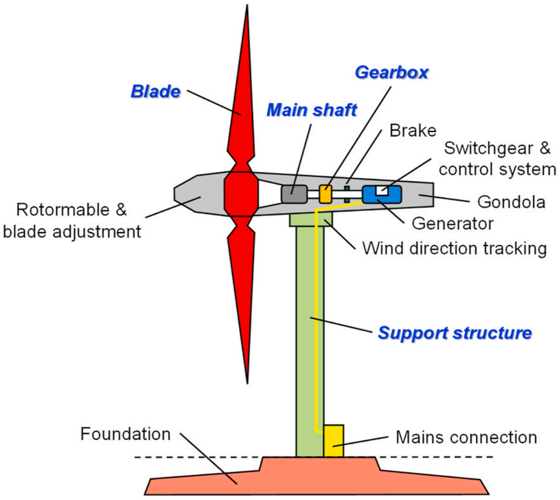
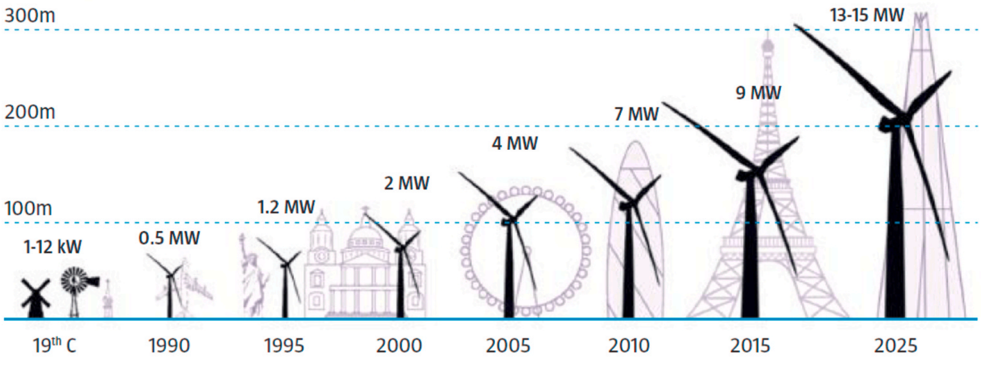


Fig. 3. Structural block of a typical HAWT system.

Wind turbines have been used in the generation of electrical power for the past 20–25 years [15]. Statistically, the operation and maintenance costs of wind turbines account for approximately one-fourth of the cost of wind power generation. During operation, wind turbines must withstand harsh and unrelenting environments that induce stress cycles in components, driving the materials to their fatigue endurance limits [16]. In particular, rotating machines are subjected to combinations of highly irregular wind, gravity, and gyroscopic loading [14]. Consequently, in the development of wind turbines, it is extremely critical to accurately predict and effectively increase their service lives [17,18]. The wind turbine industry has seen reliability improvements in recent decades but also continues to exhibit higher failure rates in relation to



Source: Bloomberg New Energy Finance

Fig. 2. The evolution of wind turbine height and capacity [13].

other industries [19]. Recently, the first international standard on the probabilistic design of wind turbines — IEC/TS 61400-9 Wind energy generation systems – Part 9: Probabilistic design measures for wind turbines was set up, demonstrating the industry's attention on this topic.

Smith–Putnam megawatt-scale HAWT — the first modern wind turbine — was built in New England during World War II [14]. Unfortunately, due to limited design experience, it experienced problems throughout its operation with blade fatigue and never achieved promised productivity. In addition, a large fraction of wind turbines installed in California in the early 1980s and operating under mean wind speed $\geq$7 m/s also experienced fatigue problems [20]. According to the statistical result of wind turbine failure cases, fatigue-induced fracture is a major contributor and has been a critical issue for several decades [20–24].

Fig. 4 shows typical wind turbine failure under fatigue. Until now, the rapid development of the wind power industry has led to the development of a wide variety of fatigue assessment methods for wind turbines [28–30], with generally deterministic outputs. However, the fatigue damage evolution process cannot be modelled with concise expression; instead, it is a complex phenomenon affected by many factors.

Owing to the existence of aleatoric and epistemic uncertainties, accurate life prediction is difficult, as the computation is sensitive to small changes in the input parameters [31–34]. Ashwill et al. [35] studied fatigue of the blade joint of a VAWT, in that case, when varying the input quantities over reasonable ranges, the calculated fatigue lives range from 6 months to 600 years.

As is given in Table 1, multi-source uncertainties contribute to wind turbine fatigue scatter [36–39]; under that circumstance, the distribution characteristic of fatigue strength must be properly considered to provide a reasonable service reliability evaluation [40,41]. In view of this, designers employ traditional deterministic fatigue rules together with conservative safety factors (i.e., partial safety factors method) to compensate for the large degree of uncertainty involved and to ensure the safety of structures [20]. However, this solution has significant drawbacks, evident from continuous turbine failure accidents. In principle, safety factors are either empirical or derived from specific cases; they cannot provide the influences of multi-source uncertainties on fatigue process quantitative descriptions; therefore, a definitive reliability description cannot be made.

To summarize, traditional methods are dedicated to the accurate prediction of fatigue strength/lifetime. However, if the problem statement is rephrased as: "Whether the component can reach its expected service life?" or "What is the failure probability that the component operates until a given service time?", a blind alley suddenly leads to open space. The formulation lends itself naturally to a structural reliability method in which uncertainties are appropriately modelled; moreover, the outputs of fatigue reliability analysis can help designers to define appropriate partial safety factors under specific safety requirements [42].

Table 1
Fatigue scatter sources of wind turbine components.

Types	Contents
Material property	Inherent dispersion of material's fatigue properties (e.g., fatigue strength and *S–N* curve), internal initial defect distribution (e.g., porosity, type, size, location and shape), crack interference, inherent material inhomogeneity
Geometry and Scale	Size (scale) effect and notch effect (stress concentration)
Manufacturing and Processing	Heat treatment caused microscopic structural heterogeneity, manufacturing process (e.g., surface roughness, manufacturing tolerances and residual stress)
Load and Environment	Working conditions, operating environment (environmental media, temperature, humidity, salinity, corrosion, wind speed and direction, turbulence intensity, significant wave height, and wave period), service time, installation and commissioning, maintenance and repair differences, stress distribution difference caused by assembling

In recent decades, probabilistic design methods accounting for characteristic distributions of material properties, loads, geometries, etc., have been proved to provide reasonable and consistent strategies for fatigue strength design [43], whose superiority lies in the logical framework for dealing with uncertain design variables and the quantitative basis for evaluating structural performance in the form of the hazard or probability of unfavorable properties [20].

Veers is a pioneer in wind turbine fatigue reliability study, who first reported on this topic in 1990 [44]. In his report, the basic procedure for reliability estimation is demonstrated by a blade joint case; in addition, a method for selecting proper distribution functions for random and uncertain parameters modelling was elaborated. Based on the LIFE2 package, he developed a tool for fatigue and reliability of wind turbines (FAROW), which can output premature failure probability, average lifetime, order of importance of random parameters, and results' sensitivity to input variables. However, due to the technical limitation at that time, it cannot solve all turbine designers' fatigue problems but provide important information about the state of the design and the value of additional data. Later, Lange [20] developed a computer program, called CYCLES, for fatigue reliability assessment on structural components, see Fig. 5. Within it, there is nothing that limits the analysis to considering wind speed and/or turbulence intensity, and other wind parameters could in principle be propagated through the analysis in a similar way.

So, should all our efforts be devoted to the promotion of wind turbine fatigue reliability? Apparently, the answer is "No". In contrast to critical components such as aero-engines and nuclear reactor vessels, as a commercial product, the failure or stoppage of a wind turbine is acceptable. So, the question becomes "How likely it is that the component will last sufficiently long to be safe and economically effective?". Accordingly, Veers [45] addressed the economic impacts of uncertainties on fatigue life by assessing the projected costs of replacing

(a) blade [25]
(b) drivetrain (gear) [26]
(c) support structure (tower) [27]

Fig. 4. Typical wind turbine fatigue failure cases [25–27].

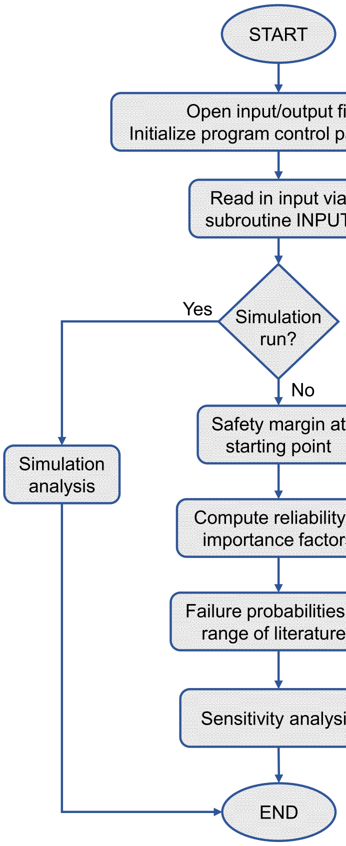


Fig. 5. Flowchart of general CYCLES code execution [20].

failed components in a turbine fleet. After dividing the probabilities into the total number of failure parts every year, a variable cost model for describing risk variation was developed. In particular, the FAROW tool for the first time provides a detailed economic analysis concerning the impact of uncertainty on fleet costs.

For the next 20 years, driven by the rapid growth of the wind power industry, research on the fatigue reliability of wind turbines is sure to experience a gold time [1,46]. Accordingly, to correlate existing technologies with future requirements in this area, this study reviews the recent advances in wind turbine fatigue reliability study and summarizes the advanced ideas and imperfections on this topic. In particular, it emphasizes the significance of developing multi-scenario applicable models, the accumulation and application of big databases, the introduction of advanced fatigue theories, the development of simulation tools with high precision and efficiency, updating the fatigue reliability theory from a local to a global view, building cost and reliability-integrated closed-loop optimal design framework, etc., therefore promoting theoretical and technique innovation.

The remainder of this paper is organized as follows: First, as the most important input in the fatigue reliability assessment of wind turbines, the latest developments in wind load uncertainty modelling are presented. Then, fatigue reliability analysis strategies for blades, drivetrains, support structures and power electronic components are reviewed. Finally, discussions and conclusions are presented.

2. Wind load uncertainty modelling

Wind turbines are generally subjected to a large number of extremely random cyclic loadings due to wind, gravity, and gyroscopic effects, which renders the turbines vulnerable to fatigue damage [20]. These loadings are stochastic and fluctuate in both the global intensity and cyclic amplitude [16], causing progressive damage which ultimately leads to structural failure of wind turbines [20]. Owing to the complexity of the service environment, wind turbines rarely experience constant-amplitude wind loads during operation; instead, normally, variable-amplitude loads or more complex random loads [47].

As mentioned previously, accurate fatigue damage evaluation of wind turbines is a challenging task, as it is a long-term stochastic process under various uncertainties originating from material properties, manufacturing processes, environmental loads, etc. [31]. Among these uncertainties, the fluctuating wind load is the most significant factor affecting its fatigue performance. Therefore, for a better description of wind turbine fatigue strength, efficient and effective statistical methods for wind-wave spectrum during its lifespan were developed in succession (see Table 2).

During the early years of wind turbine development, the designed structures were prone to premature failure, as even the most experienced designers belittled the wind load fluctuation [14]. They assumed that the loads could be approximated with a spatially uniform incoming wind with very slow variations in the average; however, unlike aircrafts flying in approximately uniform flows high above the ground, wind turbines operate in the earth's turbulent boundary layer, where the incoming wind fluctuates significantly in both time and space.

Turbulence was initially assumed to produce fluctuating loads at sufficiently low frequencies to be ignored; actually, blades can produce comparatively large shift forces when rotating in wind, thus the turbulence-induced loads are magnified and shifted to higher frequencies [54]. In addition, the broadband nature of turbulence also excites turbines' natural frequencies more than expected [55]. Moreover, in a wind farm, wind turbines experience varying airflow caused

Table 2
Representative literature findings concerning wind load uncertainty modelling.

Studies	Methods	Key findings	Limitations
[42, 48]	Partial safety factor	A method to determine the required partial factors, and the values of partial factors corresponding to different components	Empirical nature, difficulty in determining appropriate partial safety factor (even taking from other industries), unapplicable for structural optimal designs
[49, 50]	Probability density function (PDF) of wind speed	Flexibility, simplicity and usefulness of the PDFs in the description of different wind regimes (high frequencies of null winds, unimodal, bimodal, bitangential regimes, etc.)	Not good enough to capture null, low and high wind speeds, unable to explain tails, the influences of ordering and turbulence intensity were not considered
[51]	Mean wind distribution and turbulence intensity distribution	A procedure for realizing the inherent fluctuation among turbulent wind field	Can not characterize wind load distribution variation under wide spatio-temporal variability
[52, 53]	10-min mean wind speed and turbulence intensity factor	First using log–logistic distribution to represent the distribution of 10-min turbulence intensity factor, a hierarchical expanded wind uncertainty representation method	Can not characterize wind load distribution variation under wide spatio-temporal variability
[36]	Local wind measurements and speed-up factors	The impact of uncertainty in the site-specific wind climate parameters on total uncertainty in structural reliability analyses	Currently based on engineering judgement and await further research

by other wind turbines as well, which brings additional incentive to the studied object, which further complexes the loading condition [56]. For instance, a turbine servicing at approximately 30–70 rpm for 4000h each year would experience more than 10^8–10^9cycles over a 20-year lifespan [52], not to mention the advanced wind turbines built later. Under such a long-term service, it is a challenging task to compute the fatigue damage because of fluctuating loads.

Perhaps the simplest way to render the wind load uncertainty is to use partial safety factors [42,57]. Nevertheless, as pointed out in Section 1, empirical and fixed safety factors unchanging with specific service conditions cannot comprehensively consider spatio-temporal wind load variations. To overcome this problem, probabilistic models were developed to describe the annual wind load fluctuation, in which the mean wind speed was set as a stochastic quantity (the percentages of time of different average wind speeds experienced by the wind turbine are counted) [49,58]; accordingly, the distributions of total damage and fatigue lifetime can be evaluated using appropriate fatigue models.

Unfortunately, these models generally show poor capabilities, as they simply use specified probability distributions (Rayleigh or Weibull distribution) of average wind speed to characterize fatigue damage frequency. Since a specific distribution with defined parameters was utilized, the computational results are also deterministic [31]. In addition, a fixed distribution cannot reasonably model the wind load uncertainty over a larger spatio-temporal range, for example, at distinct places and in different years.

When studying the statistical uncertainty of wind loads, Ronold et al. [59] found that, in addition to the average wind speed, turbulence intensity (for describing the degree of wind speed variation over time and space) also exerts a significant influence. Later, this concept was widely accepted in wind turbine reliability analysis [51,52]. By combining the average wind speed and turbulence intensity distributions, the wind loads can be properly characterized based on the generated or measured 10-min realizations of the studied load [58,60,61].

However, a 10 min span is not representative, as wind turbines are supposed to survive under wind load over a wide turbulence intensity factor range. Since wind fluctuation is a natural phenomenon, whose distribution changes at different wind farms over different years and no control can be exercised [52]. Toft et al. [36] classified wind climate parameter uncertainties into three types:

a) short-term uncertainties — over 10 min periods;
b) mid-term uncertainties — over days, months, and seasons;
c) long-term uncertainties — over years.

It is a general observation that the influence of wind turbulence on fatigue lifetime has not been accurately considered in previous approaches. Accordingly, Hu et al. [31] developed a novel model for dynamic wind load uncertainty description (the hierarchical expanded wind uncertainty representation method), where the wind load fluctuation at a specific spot in a year is characterized by the joint distribution of 10-min mean wind speed V_{10} and 10-min turbulence intensity I_{10}. In detail, low-level wind uncertainty considers the distribution types identification of both the 10-min mean wind speed and 10-min turbulence intensity factor, while high-level wind uncertainty includes over a vast spatio-temporal range and provides wind load variation a comprehensive and systematic description.

Particularly, in their study, the Weibull distribution was found to provide a valid description of the fluctuation in the 10-min mean wind speed V_{10} over a year under typical circumstances [62]. The corresponding cumulative distribution function, F_{V10}, and PDF, f_{V10}, can be, respectively, given by:

$$F_{V10}(V_{10};c,k)=1-\exp\left[-\left(\frac{V_{10}}{C}\right)^k\right], \tag{1}$$

$$f_{V10}(V_{10};c,k)=\frac{k}{C}\left(\frac{V_{10}}{C}\right)^{k-1}\exp\left[-\left(\frac{V_{10}}{C}\right)^k\right], \tag{2}$$

where the scale parameter C and shape parameter k can, respectively, be derived from the mean μ_{V10} and standard deviation σ_{V10} of the V_{10} as follows:

$$\mu_{V10}=C\Gamma(1+1/k), \tag{3}$$

$$\sigma_{V10}^2=C^2\left[\Gamma(1+2/k)-\Gamma^2(1+1/k)\right], \tag{4}$$

where $\Gamma(x)$ is the gamma function of x.

The 10-min turbulence intensity factor I_{10} was set as the ratio of the wind speed standard deviation to the average wind speed, determined from the same set of extracted data samples of the wind speed, and considered over 10 min as:

$$I_{10}=\frac{\sigma_v}{V_{10}} \tag{5}$$

The evolution of methods for wind load uncertainty modelling is presented in Fig. 6.

In addition, there are certain characteristic studies on wind load uncertainty quantification [63]. Considering that previous studies were primarily performed based on given load spectrums, while a few of them consider actual service conditions. To link theoretical models to engineering requirements, Veers and Winterstein [64] analyzed the measured loads, and applied them to fatigue life assessments and reliability estimations, where the rain-flow counting method was used to identify significant cycles causing fatigue damage.

Veldkamp [42] investigated the critical stochastic parameters affecting fatigue loads and estimated their distributions. In particular, a strategy for the estimation of accurate structural component failure probability under fatigue loading was outlined.

For failure judgment, the stress–strength interference method was employed. In the analysis, a component's failure was judged by examining the limit state function $Z\left(\underline{x}\right)$, which was defined by the difference between the resistance $R\left(\underline{x}\right)$ and the load $S\left(\underline{x}\right)$ as follows:

$$Z\left(\underline{x}\right)=R\left(\underline{x}\right)-S\left(\underline{x}\right) \tag{6}$$

To further include the influences of multiple uncertainties on fatigue resistance, various parameters were included, and Eq. (6) was reformulated as:

$$Z\left(\underline{x}\right)=q_0x_{dim}x_{\Delta\sigma_A}SRF\gamma_f\gamma_mS\left(\underline{x}_{char}\right)-S\left(\underline{x}\right), \tag{7}$$

where q_0 is the parameter describing the change in fatigue strength due to load sequence effect; x_{dim} is the parameter characterizing the variation in material dimensions; $x_{\Delta\sigma_A}$ is the parameter modelling the variation in fatigue strength under constant amplitude; SRF is the stress reserve factor; γ_f and γ_m represent the load factor and the material factor for additional safety, respectively; and $\underline{x}_{char}$ denotes the characteristic load effect.

Recently, Toft et al. [36] presented a probability-based framework for evaluating the structural reliability level of wind turbines under

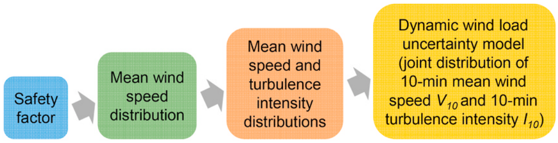


Fig. 6. Evolution of methods for wind load uncertainty modelling.

fatigue loading. The uncertainty of the site-specific wind climate parameters at every turbine location was assessed based on local wind monitoring, speed-up factors, and the length between the wind turbine and the measuring position. However, its applicability for wind turbulence, as well as wind shear, currently, was based on engineering judgment, which requires further validation.

To conclude, with the increasing attention on wind load fluctuation on wind turbine fatigue reliability, methods for wind load uncertainty modelling are becoming more efficient. The next tasks are to build a general analysis procedure, popularize it and further check its validity.

After determining an appropriate manner to model wind load uncertainty as an input, the next step is to output stress–strain response for fatigue lifing. Aeroelastic simulation is an essential part of the wind turbine design process, in which stochastic loadings are assessed through a number of simulations of the wind turbine under normal operating conditions within a prescribed turbulent wind field [65]. Aeroelasticity studies the coupling effects between the inertia, elastic, and aerodynamic forces, which occur as an elastic body exposed to a fluid flow, see Fig. 7. Various commercial and research-based simulators are available to compute the wind turbine aeroelastic loads (see Table 8), and a detailed comparison of aeroelastic codes for wind turbines can be found in Ref. [66].

The interaction of fluid flow and structural dynamics of the system is a critical aspect for machines operating under their coupling [67]. In classical aeroelastic approaches, the fluid–structure interaction is uncoupled and treated separately, their interaction is ignored without explanation [68]. With improving computing power, several integrated approaches including inherent fluid-structure coupling were developed in recent decades [69]. Future works are expected to include: expanding the input space to higher dimensions, introducing complex structural loading conditions, and running full-scale aero-servo-elastic simulations.

3. Fatigue reliability on blades

Wind turbines are generally installed in locations with strong and durable wind fields [70]. While a large wind load drives their fast rotating for higher power generation, it also causes fatigue damage accumulation on the wind turbine components. Wind turbine blades, as the first phase of wind power generation, are critical for driving large-scale wind turbine systems. They are exposed to harsh environments, withstanding extremely harsh dynamic loads, and are inclined to fail due to fatigue accumulation [71]. Research suggests that the service life of a blade depends very much on its fatigue performance [72].

As one of the key components of wind turbines, the cost of blades is approximately 15–20% of the total cost, and its quality of design will directly and significantly affect the performance and benefits of wind turbines [73]. In a large part, the ability to design blades with acceptable reliability levels determines the energy costs and technical success. To reduce the LCOE, developing cost-effective and reliable wind turbine blade design schemes is one of the key factors in wind turbine manufacturing.

Except for some details made by metal materials (like the connection), the major parts of wind turbine blade are manufactured from composite materials, owing to their excellence in strength, stability, lightweight, easy molding, corrosion and high-temperature resistance, as well as other advantages [74]. According to the statistics, composite material accounts for more than 90% of the gross weight [75]. In addition, at present, most commercial large-scale wind turbine blades are made of glass fiber reinforced materials, which are mainly glass fiber reinforced polyester or epoxy resin [76]. Through fatigue campaign, fatigue properties of composites are found to be superior to those of many other materials, by virtue of their 'flat' *S*–*N* curve; however, the scatter in fatigue life is typically higher than for metals, and can only partly be explained by variations in test conditions [77].

Fatigue of composites has presented researchers and designers with considerable modelling difficulties. Different from the fatigue damage of metal structure with the nucleation and propagation of one or several cracks, composite parts get global damage fields and present distinctly different, interacting damage types (including transverse cracks, delamination, debonding, edge effects, thickness and staking sequence) increases with the number of loading cycles, which hampers modelling [78,79].

The current composite fatigue performance analysis models can be classified as fatigue life model, phenomenological model and progressive damage model [80]. However, the studies on fatigue life of composite materials are mainly conducted by describing overall damage from macroscopic phenomenological perspectives, despite the physical nature and microscopic mechanism. More details on fatigue life prediction and damage analysis model of fiber reinforced composite were presented in two recently published review papers [81,82].

For fatigue damage modelling of composite wind turbine blades, with the increasing understanding on its failure mechanism and damage evolution process, methods keep updating. Initially, composite wind turbine blades were designed according to the procedures for metal components, which combine *S*–*N* curve, the Palmgren–Miner rule (usually referred to as Miner's rule) and sometimes the Goodman diagram (or constant life diagram [72]) [83,84]. Hereafter, considering the difference of damage evolution with the number of cycles among composites and metals (see Fig. 8) [85], Shokrieh and Rafiee [62] developed a new flowchart of accumulated fatigue damage modelling, in which a generalized material property degradation-based damage rule is utilized. In particular, to accurately describe the nonlinear fatigue damage development of composites in the three periods (matrix crack, delamination, interfacial debonding and fiber breakage), Liu et al. [86] presented an improved composite fatigue damage model considering stiffness evolution.

Recently, Rubiella et al. [74] published a review paper on the state-of-the-art in fatigue modelling of composite wind turbine blades. In their work, the methods for composite blade fatigue modelling were categorized into life-based failure criterion models, residual property calculation models, and progressive damage models. Specifically, a timeline of fatigue models' elaboration was summarized. After a comprehensive comparison, they suggested progressive damage models as the best solution, for their quantifying and qualifying physical damage growth to a reasonable extent during fatigue. Progressive damage models were further divided into two groups: progressive property degradation (covering matrix cracking, fiber failure, plane shear failure, and delamination growth) and alternative sub-continuum models (including micromechanical, mesomechanical and generalized residual material property degradation models). More details can be found in Ref. [74], while the later parts of this section will focus on the fatigue reliability modelling of blades.

The wind speed causing blade bending shows its variable nature, rendering the load amplitude to be stochastic, and the limited load knowledge on load fluctuation makes it difficult to interpret its statis-

Fig. 7. Collar's triangle: interaction of different forces [66].

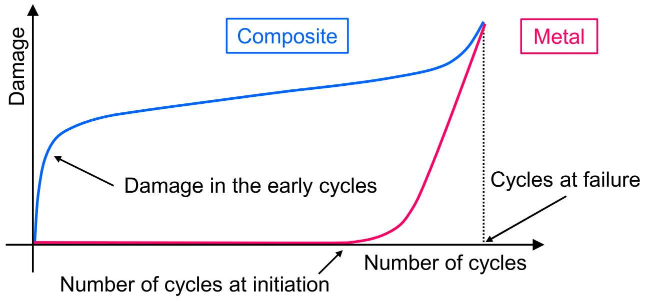


Fig. 8. Damage evolution trends: composites vs. metals [85].

tical uncertainty. In addition, owing to the limited number of test samples and variability from one sample to another, the *S*–*N* curve, which links the stress level and fatigue lifetime, becomes uncertain [59].

In addition, it deserves our attention that for blade fatigue, a short period of high loading cycles may determine the fatigue life. As a consequence, not only wind fluctuations, but also atmospheric and environmental phenomena, such as coastal storms, lightings and gusty winds which caused many downtimes to wind turbines should be considered in fatigue reliability design and evaluation [87,88]. Recently, both variable wind and gust conditions were combined in the fatigue life analysis of a 2 MW offshore wind turbine [89]. Under extreme conditions, above-rated wind speed for instance, pitch control will be used to control the aerodynamic power generated by the turbine rotor, regulating the aerodynamic power and loads produced by the rotor so that design limits are not exceeded [90]. The extreme load under these situations should be paid special attention as well.

To describe the sobering variability of the input parameters, Veers et al. [71] pioneered the use of the LIFE2 sophisticated numerical analysis package to estimate the probability of premature blade failure, in which Miner's rule and a linear-crack propagation rule were utilized for fatigue lifetime computation. Later, Ronold et al. [59] built a probabilistic framework for the fatigue assessment of a wind turbine blade against flap-wise bending. In the model, Miner's rule is employed for accumulated damage calculation, *S*–*N* curve for fatigue resistance formulation, and a new "distorted Weibull" distribution for wind-induced bending moment ranges modelling. The limit state function was defined:

$$g(\boldsymbol{X}) = 1 - F_M D(\boldsymbol{X}) = 1 - F_M \sum_{i=1}^{k} \frac{n(S_i)}{N(S_i)}, \tag{8}$$

where *D* is the assessed cumulative fatigue damage expressed using Miner's rule; ***X*** represents the vector of stochastic variables, which

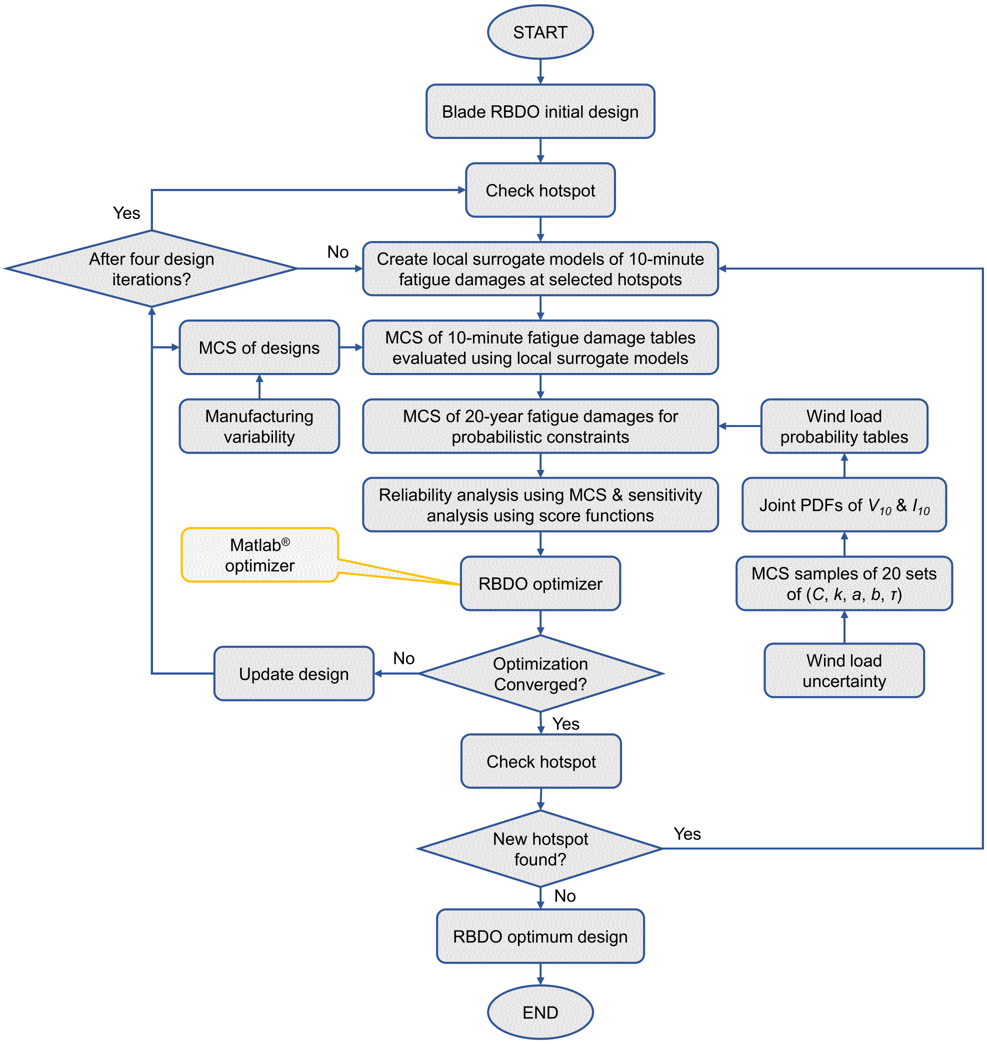


Fig. 9. Flowchart of the fatigue reliability-based design optimization process, incorporating wind load uncertainty and manufacturing variability [31].

includes the uncertainties in loading and resistance; F_M denotes the bias and uncertainty in cumulative damage evaluations; n and N are the loading cycle number and expected lifetime at stress range S, respectively. The reliability analysis results can help to set appropriate partial safety factors for loads and resistance in traditional deterministic anti-fatigue design; however, this strategy is after all site- and wind-turbine-specific and only suitable for blade flap-wise bending, which cannot model the wind load uncertainty over a large spatio-temporal range mentioned in Section 2.

In addition to the linear cumulative fatigue damage model (Miner's rule) utilized in Eq. (8), there are also some improved models (double linear or non-linear) with higher prediction accuracy. For instance, Pavlou [91] used the *S*–*N* fatigue damage envelope theory in fatigue-based structural health monitoring of an offshore wind turbine structure. More details about the advances in cumulative fatigue damage can be found in Refs. [92–94].

Toft and Sørensen [95] developed a probabilistic framework for the design of wind turbine blades. By combining the maximum likelihood estimation (MLE) method and Bayesian statistics, the physical, model and statistical uncertainties for wind turbine blades were determined from tests. With the stochastic model, partial safety factors for conventional deterministic design can be assessed. However, owing to a very limited amount of data, wind load uncertainty was not considered in their research.

Recently, using the hierarchical expanded wind uncertainty representation methodology, Hu et al. [52] studied the effect of spatio-temporal wind uncertainty on the fatigue reliability of 5-MW wind turbine blades. Furthermore, concerning the demands on both design cost reduction and blade performance improvement, they presented an extensively automated optimization procedure by combining an evolutionary algorithm with finite element analysis. Finally, based on these two studies, a reliability-based design optimization (RBDO) method for wind turbine blade fatigue under wind load fluctuation was established [31], see Fig. 9, which can characterize wind load variation over a large spatio-temporal range as well as the manufacturing variability. This work creates a closed-loop between fatigue reliability analysis and RBDO, which is an important step toward a reliable and cost-effective design scheme for wind turbine blades.

For assessing the fatigue reliability of wind turbine blades, combining full-scale fatigue testing data and performance degradation theory, Kou et al. [96] presented an inverse Gaussian process-based stochastic degradation model concerning the randomness and monotonicity of the degradation path. This strategy provides a method to deduce the unknown model parameters with MLE, and can enable fatigue reliability assessment of wind turbine blades without failure life data.

Recently, taking an offshore HAWT blade as an example, Zhang [73] presented a general fatigue damage assessment and optimized maintenance strategy. The comprehensive approach can describe the stress along the span of the blade, predict the fatigue damage development, estimate the fatigue failure probability, determine an optimum maintenance policy, and calculate the life cycle cost for the optimized strategies. Five models were presented to solve these critical issues and meet diverse user requirements: stress–loading, fatigue prediction, stochastic-probabilistic, decision-making, and cost-benefit models. However, their ability requires further verification on working blades in practice.

To sum up, in fatigue reliability assessment of wind turbine blades, various methods for uncertainty modelling (see Table 3), reliability analysis and optimal design were developed; in addition, regarding the significant cost of blades, some improved frameworks further considering cost optimization were put forward, devoting to minimizing the cost under the premise of meeting required fatigue reliability requirement. So, the next step is to popularize the idea and approaches, and validate and improve them with practical engineering cases.

Table 3
Representative literature findings concerning fatigue reliability on blades.

Studies	Key findings	Limitations
[71]	A sophisticated numerical analysis package (LIFE2) to illustrate the variability in fatigue performance caused by change of inputs	Log-normal formulation used in close form solution is highly non-conservative
[59]	A probabilistic model for wind-turbine rotor blade against fatigue failure in flapwise bending, method to perform reliability-based calibration on partial safety factors	Cannot model the wind load uncertainty over a large spatio-temporal range
[95]	A method to determine physical, model and statistical uncertainties for wind turbine blades from tests using MLE and Bayesian statistics	Wind load uncertainty was not considered
[31]	A RBDO method for wind turbine blade fatigue under wind load fluctuation	Limited number of wind data were used for model validation
[96]	A stochastic process degradation model based on the inverse Gaussian process	Derived fatigue reliability index only suitable for the studied case
[73]	A reliability-based fatigue damage assessment and optimum maintenance strategy	More experimental and field investigations are required to evaluate the nature of fatigue-prediction model products formed subject to different conditions

4. Fatigue reliability on drivetrains

The drivetrain in a wind turbine nacelle typically consists of multifarious heavily loaded parts, such as the main shaft, main bearing, gearbox, and generator [56], as shown in Fig. 10. During operation, the wind turbine drivetrain suffers significant impact load, which severely influences its reliability and safety [97]. The fluctuating environmental load poses a challenge to the fatigue resistance of all elementary units of the drivetrain [98,99]. As a series system, failure of any component will result in substantial economic losses, including disrupted energy production, repair, labor, and transportation expenses [100]. Thus, the fatigue reliability of wind turbine drivetrain components is critical for both manufacturers and operators.

Fatigue reliability modelling of the drivetrain component is crucial for assessing its life expectancy — a critical index in formulating operation and maintenance strategies. To accurately evaluate the failure probability of drivetrain components, meticulous modelling of multi-source uncertainties is fundamental [102]. To date, fatigue reliability analyses of drivetrains were primarily focused on two critical components, the main shaft and gears, as their failures generally accompanied by high repair costs and lengthy downtime.

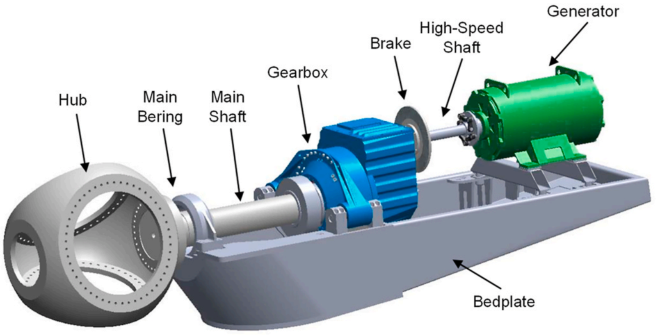


Fig. 10. Modular drivetrain configuration [101].

4.1. Main shaft

Currently, the main shafts of wind turbines are generally manufactured through casting [103]. In this process, owing to technical factors, some inevitable defects are randomly distributed in the components. The fatigue lifetime is quite stochastic, depending on the number, type, location, and size of these defects, and needs to be modelled using probability-based approaches. Research shows that cracks generally initiate from defects such as shrinkage cavities, and gas pores, which are the major controlling factors of fatigue life [104]. Accordingly, recent works on fatigue assessment of main shafts mainly focus on modelling defect-induced scatter. Considering the large volumes of main shafts, it is difficult to obtain the defect information inside the body with three-dimensional micro tomography visualization; instead, the fatigue strength shift caused by the population difference inside the body was interpreted and modelled with size effect.

To describe the size effect on fatigue strength of ductile cast iron on wind turbine parts, Shirani and Härkegård [105,106] employed Weibull's weakest-link method, where *P–S–N* curves corresponding to different fatigue probabilities were derived. However, as a phenomenological model, the description of the influence of defect location on the fatigue lifetime should be strengthened.

Later, Rafsanjani and Sørensen [107,108] developed a probabilistic framework considering manufacturing defects and their impacts on the structural fatigue performance of wind turbine components, which divided the defects into several groups according to their size, origin, orientation, etc. For every group, a Poisson distribution was used to describe the defect distribution. In particular, the defects were distinguished as interior or surface defects, which matches reality. Then, the failure probability of the entire structure was computed according to a series system probability of sub-volume failure. Test results indicate that the probabilistic model could accurately locate the actual failure site, but it failed to consider crack evolution.

4.2. Gears

The gearbox is one of the costliest parts of a wind turbine system, and generally shows higher-than-expected failure rates in the wind energy industry [109,110]. Contact failures in gears have been the sources of costly repairs and downtime of the turbine drivetrain [111].

Qin et al. [112] studied the time-dependent reliability of a gear transmission system for wind turbines under stochastic wind loads. First, the wind speed of the true wind field was modelled using the sparse least squares support vector machine (SLS-SVM) algorithm. A dynamic model of the coupling of gears and rolling bearings in the transmission system under random wind was then established, and the dynamic meshing forces of each gear pair as well as dynamic bearing forces of each bearing were obtained. Based on this, the actual load effect was treated as a random process, the dynamic reliability model of the planetary gear transmission system of the wind turbine was established using the stress–strength interference model, and the reliability of gears, bearings, and systems were analyzed. This work presented a general procedure for reliability analysis of gear transmission system, laying the theoretical foundation for dynamic reliability analyses of the drivetrain of a wind turbine and its components; but the employed stress–strength interference model is too simple to characterize the complex fatigue damage evolution and accumulation process.

Regarding the significant impact of load variation on fatigue reliability, drafting a strategy to represent the long-term distribution of gear contact pressures with some analytical functions (e.g., Weibull or the

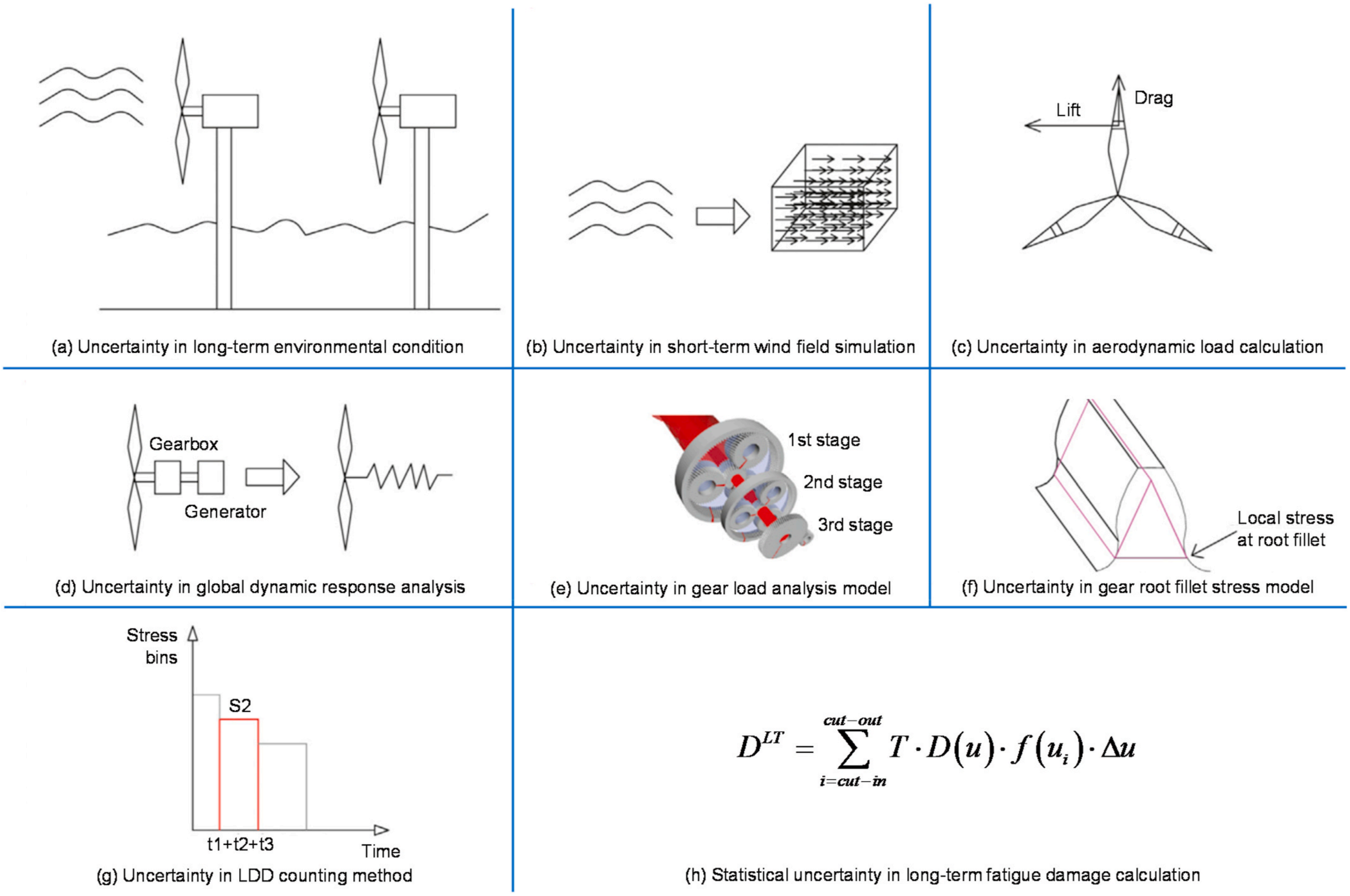


Fig. 11. Illustration of the load effect uncertainties [114].

generalized Gamma distribution) is critical. Focused on this, Dong et al. [113] analyzed the time domain-based gear contact fatigue under dynamic environmental conditions. An improved predictive pitting approach for service lifetime estimation was proposed and verified using abundant datasets taken from literature. The pity is that the input spectrum is deterministic rather than stochastic although wind load variation was considered; therefore, the calculated fatigue life is constant instead of being random.

Nejad et al. [114] proposed a long-term fatigue damage computing method for gears in wind turbine drivetrains, in which the load duration distribution (LDD) approach was employed to obtain the short-term stress cycles from the input load–time series of the global response evaluation. Then, the long-term fatigue damage was computed by combining the Miner's linear damage rule and the gear's *S*–*N* curve, considering all short-term damages and long-term wind speed distribution. Finally, the probabilistic fatigue life distribution and fatigue reliability were derived using the first-order reliability method (FORM) incorporating eight load effect uncertainties (see Fig. 11):

a) long-term environmental conditions,
b) short-term wind field simulation,
c) aerodynamic load calculation,
d) dynamic response of the turbine,
e) simplified model for the gear transmitted load,
f) gear root stress model,
g) LDD counting method,
h) long-term fatigue damage.

The procedure was applied to the fatigue reliability analysis of a 5-MW gearbox developed for a bottom-fixed offshore wind turbine; nevertheless, it is site-specific and can only be combined with gear tooth root stress. Later, based on this study, Nejad et al. introduced a reliability-based maintenance strategy for wind turbine gearbox components [115]. A "vulnerability map" was plotted to display global fatigue reliability, which improves operators' convenience to perform fault detection during routine maintenance, meanwhile reducing the downtime and effort required for the maintenance group to identify the point-of-failure.

Recently, Ding et al. [116] proposed an integrated strategy for the evaluation of wind turbine gearbox fatigue lifetime, considering instantaneously fluctuating loads. It focuses on fatigue crack growth and integrates gear physical models and documented health condition data. By comparing the proposed model and existing constant-load approximation approaches, the results show that the proposed varying-load model yields statistically improved predictions; however, the load randomness was not reflected.

In conclusion, among the existing literatures on the fatigue reliability of gears, generally, only the wind load dispersity has been considered, while its stochastic nature was overlooked (see Table 4). As a result, the evaluation results are deterministic, which deviates from the actual situation. Therefore, in future work, efforts should be made to apply the wind load uncertainty models in Section 2 to the fatigue reliability of gears, as the dynamic random loads on gear transmission systems are directly related to wind load.

Except for geared variable-speed wind turbines, there are also direct-drive (ungeared, fixed-speed) wind turbines without a speed-increasing gearbox [117], see Fig. 12. Direct-drive systems for wind turbines are potentially a more reliable alternative to gearbox-driven systems, which can eliminate gearbox failure and downtime effects (gearboxes are liable to significant accumulated fatigue torque loading with relatively high maintenance costs), although it gets the shortcomings including low energy yield, poor power quality, significant audible noise and difficulties in braking the turbine [118,119].

Table 4
Representative literature findings concerning fatigue reliability on gear transmission systems.

Studies	Key findings	Limitations
[112]	A SLS-SVM algorithm for simulating wind speed of true wind field, and a cumulative distribution function of equivalent load under random loads	Stress–strength interference model is too simple to characterize the complex fatigue damage evolution process
[113]	A method to represent the long-term distribution of gear contact pressures by analytical functions	Only the torque loads in the main shaft under normal operating conditions were considered
[114]	Identification and characterization of 8 load effect uncertainties, utilization of the LDD method to obtain the short-term stress cycles from the input load time series of global response analysis	Site-specific and can only be combined with gear tooth root stress
[115]	A vulnerability map based on global component fatigue reliability ranking	Only presents short-term fatigue damage estimation
[116]	An integrated varying-load approach for predicting wind turbine gearbox remaining useful life	Load randomness was not reflected

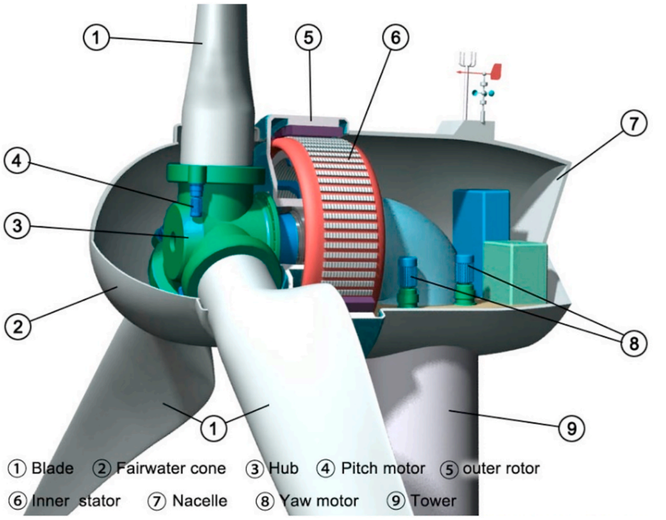


Fig. 12. Schematic diagram of external rotor permanent magnet direct-drive wind turbine [120].

In a direct-drive wind turbine system, the blades spin a shaft that is connected to the generator directly [121]. The bearings are arranged at both front and rear of a main shaft to support rotating parts of a rotor and generator [122]. Axial load (or thrust load) is carried by the front bearing, and perpendicular radial load is carried by the both front and rear bearings. Generators and other drive-train components in wind turbines experience significantly varying loads, which may lead to a bearing failure [119].

Multitudes of researches show that the main bearings are the most critical components of direct-drive wind turbine systems, whose failure accounts for a large proportion of wind turbine malfunctions and faults [123,124]. Accordingly, special attention should be paid to the main bearing when evaluating the fatigue reliability of direct-drive wind turbines. In addition, it was observed that both the average and variability of the damage rate vary substantially with the mean wind speed. Therefore, besides the mean, also the variability of the estimated damage should be considered [124]. Moreover, additional cases concerning turbulence characteristics should be explored, as well as the other conditions (start-up and shut-downs, ice on blades, etc.).

5. Fatigue reliability on support structures

As the capacity and height of wind turbines continue to increase, the safety problems regarding support structures increase [125]; accordingly, structural integrity analysis and evaluation of support structures have become an important technical subject in this field [126]. In the past, intensive efforts were exerted on the design and optimization of wind turbine support structures, while little attention was paid to their safety and reliability assessment [127]. Fatigue, as the dominant cause of structural failure of wind turbine support structures, is raising increasing concern [128].

The load acted on the support structures of onshore and offshore wind turbines are different [129]. For the onshore one, the cyclic load originates mainly from wind load. By using the orthogonal expansion method and the numerical-theoretical method of random dynamic action, Fu et al. [130] expanded the random fluctuating wind field into a set of scattered points to calculate wind load. Then, a fatigue probability model based on the probability density evolution method was proposed and later utilized in a 1.5 MW wind turbine tower case. Mankar and Sørensen [131] further used probabilistic fatigue theory for optimal design and found that, in general, the fatigue load reduction resulting from the application of lower equivalent turbulence could potentially lead to lighter structures, saving material and installation costs on large scales.

For offshore served wind turbines, apart from wind fluctuations, wave-induced load variation also exerts a significant influence on structural integrity, see Fig. 13. Owing to the high level of fatigue loading and a number of cycles of combined wind and wave loads, the fatigue resistance of welded connections is a critical indicator for performance checking of offshore wind turbine support structures. In a recent review by Tan and Qi [133], the research progress of the support structures of offshore wind turbines, including the methods of fatigue analysis, selection of the load combination and wave model, and fatigue reliability analysis methods, were systematically summarized. It is concluded that reliability-based philosophy is indispensable for the design specifications of wind turbine support structures, guiding their design, manufacture and inspection.

Accompanying with the tide to develop and utilize the ocean, methodologies for structural integrity assessment of offshore wind turbines were intensively studied, see Table 5. Considering the statistical turbulence intensity distribution and preservation of wave-induced resonant responses, Velarde et al. [134] conducted a reliability-based calibration of fatigue design factors, a minimum fatigue design factor was given and the sensitivity of fatigue reliability to stochastic input parameters was quantified as well. Rocher et al. [135] developed an incremental two-scale damage model for time-dependent damage evolution under both wave and wind fluctuations, dedicated to structural optimization and the consideration of time-variant hazards. Ivanhoe et al. [33] constructed a novel generic framework for reliability assessment of offshore wind turbine jacket support structures under stochastic and time dependent variables.

In addition to external loads, some researchers tried to further include the influence of inspection on fatigue reliability. Dong et al. [136] developed a decoupled procedure of high precision to compute the dynamic response of the jacket support structure to the wind and wave load fluctuations, in which both the effects of corrosion and inspection were quantified, which helps engineers in decision-making and achieving an optimal balance among different safety measures by design and inspection planning in an early phase. Similar studies were conducted by Márquez-Domínguez and Sørensen [137] and Yeter et al. [138] by linking fatigue reliability with inspection planning to find an optimal balance between design and inspection with diverse safety measures.

For reliability analysis, computational costs are a significant problem. To simplify the calculation required for structural fatigue design, Teixeira et al. [139] established a methodology, incorporating Kriging surrogate models to model the uncertainties, which achieves the decoupling of the diverse exterior contributions for fatigue lifetime with high effectiveness. However, before its engineering application, the joint action of multiple-source variables must be properly addressed.

Finally, as mentioned in the Abstract, reducing manufacturing costs is a key factor in improving the competitiveness of wind turbine products in the energy market [137]. In view of the demand for improving the cost-effectiveness of support structures, Colone et al. [138] studied the fatigue reliability of offshore wind turbine pile foundations involving the impact of turbulence loads and kinematic waves. It was discovered that, the fatigue load reduction resulting from the application of lower equivalent turbulence could in general lead to lighter structures, saving material and installation costs on large scales.

In short, concerning the fatigue reliability of wind turbine support structures, the influences on wind and wave loads as well as inspection were comprehensively considered; in addition, efficient computation and cost-effectiveness design were also studied. Further works should be conducted on reducing computational cost and considering the joint action of multi-source uncertainties.

6. Fatigue reliability on power electronic components

Wind turbines operate at variable speeds due to changes in wind conditions, causing their generators to produce electricity that varies in frequency and voltage [19]. Power electronic components are used in wind turbines to convert variable voltages and frequencies produced by the generator to fixed voltages and frequencies compliant with an electrical grid with minimal losses [11]. Researches investigating wind turbine failures of modern wind turbines observed that the power

Fig. 13. Typical support structures of offshore wind turbines [132].

Table 5
Representative literature findings concerning fatigue reliability on support structures.

Studies	Scenes	Components	Key findings	Limitations
[130]	Onshore	Tower flange and bolt	An evolution probability density curve clusters	Combination with other limit states related to fatigue of reinforcement and ultimate failure due to extreme loads were not included
[131]	Onshore	Reinforced-concrete foundations	An approach to optimize the design in a reliability- and cost-optimal way	The employed fatigue cumulative damage theory ignores the load sequence effect
[134]	Offshore	Large monopiles	Reliability-based calibration of fatigue design factors considering the statistical distribution of turbulence intensity and the preservation of wave-induced resonant responses	The effects of nonlinear wave modelling, wind-wave misalignment, wind farm wakes and fatigue inspections were not considered
[135]	Offshore	Steel foundations	A two-scale probabilistic time-dependent fatigue model	The computation time which can be significant
[136]	Offshore	Welded multi-planar tubular joints	Quantifications of corrosion and inspection effects, sensitivities of 7 stochastic inputs on reliability index	The rational quantification of different uncertainties
[137]	Offshore	Welded details in steel substructures	Calibration of partial safety factors/fatigue design factors, significance of conducting inspections	The effect of wakes in wind farms increasing the turbulence level was not considered
[138]	Offshore	Monopiles	Impact of turbulence and wave loads on fatigue reliability	The employed fatigue cumulative damage theory ignores the load sequence effect
[139]	Offshore	Tower components	Decoupling the different external contributions to fatigue life	The coupled influence of variables was not addressed

converter counts for 15% of all failures [140].

The power electronic system is based on a series of three-phase pulse width modulated power modules consisting of insulated gate bipolar transistors (IGBT) power switches and associated diodes [11]. As a power switch device, IGBT has the advantages of a big current carrying density and low saturation voltage, so have been widely used in power transformation and power electronic equipment [141]. But with the increase of switching frequency and power density, the power loss and junction temperature fluctuations of IGBT cause the fatigue damage of the power device with the action of electro-thermal-mechanical coupling [142], see Fig. 14.

For IGBT, there are two major types of packaging technologies, wire-bonded (see Fig. 15) and press-pack. A comparative overview of the failure mechanisms of standard wire-bonded and press-pack IGBT modules is shown in Table 6.

Three well-known weak points inside a standard wire-bonded IGBT module are the bond wire–Si chip interconnection, the Si chip–direct copper bonded (DCB) solder joint and the DCB–base plate solder joint [9]. One of the most common failure mechanisms of standard wire-bonded IGBT modules is the bond wire lift off, see Fig. 16a. The reason behind this failure mechanism is the combination of the coefficient of thermal expansion (CTE) mismatch with temperature variation. Another dominant failure mechanism of the standard wire-bonded IGBT modules is the solder joint fatigue under shear stress, see Fig. 16b [147].

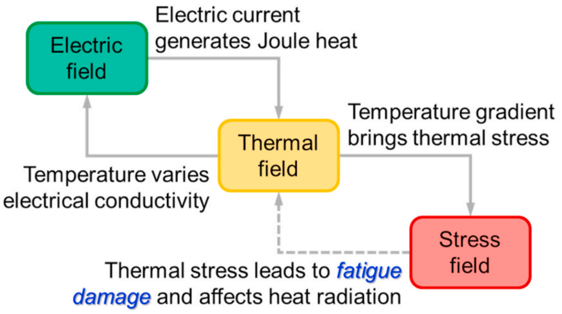


Fig. 14. Electric-thermal-stress fields of power electronic components [143].

Press-pack IGBTs eliminate the dominant failure mechanisms of standard wire-bonded IGBTs but introduce also new failure mechanisms characteristic to press-pack IGBTs like fretting damage, spring fatigue, spring stress relaxation, etc. [150]. One of the main driving forces behind the degradation of the press-pack IGBT is the same as for the standard wire-bonded IGBT modules — the CTE mismatch between the different layers of materials are used to build the device [9].

So far most of the fatigue reliability researches were focused on the standard wire-bonded IGBT modules [9]. Lu et al. [151] detailed a physics of failure approach to reliability predictions of IGBT modules. The impact of design variables on fatigue reliability of solder joint as well as wire bond are discussed respectively. In particular, a user-friendly design tool for power module design was developed, where all the numerical techniques are tailored to suit the needs of the power module optimal design and fatigue reliability analysis.

Kostandyan and Sørensen [152] performed a fatigue reliability assessment of solder joints in power electronic modules by crack damage model for wind turbine applications. The temperature variations and temperature ranges will be used to predict the best model for the accumulated plastic strain per cycle. Specifically, a cost-benefit model for fatigue reliability-based optimal decision making was established in which the decision problem of identifying the cost optimal inspection and maintenance plan may be solved. Later, Kostandyan and Ma [153] estimated the fatigue reliability of the high-power IGBTs in a 2.3 MW wind turbine converter system under uncertainties using FORM.

Recently, Wan et al. [154] proposed an operational reliability model for the power electronic components based on modular multi-level converters, where the effects of the fatigue accumulation and short-term operating conditions of IGBT modules were considered. The contributions of different time-scale junction temperature variations on the IGBT module failure rate were analyzed based on IGBT failure mechanisms and reliability guidelines. Finally, the Markov state space for fatigue reliability of power electronic components was established, and the validity of the operational reliability model was verified by a case study, which shows that their method could effectively predict the time-varying equipment reliability performance in the short-term operation. Similar work was conducted by Lai et al. [142], the innovation point is that different impacts of failure sites on power module remaining lifetime under different health conditions were considered.

By reviewing the advances in fatigue reliability on power electronic components, it is noticed that related works are still limited although the fatigue damage mechanisms were well-found. Sincerely, some concepts regarding fatigue reliability were developed, but none of them attaches an effective strategy for thermal coupling analysis [155], which directly influences the final evaluation result. In addition, the effectiveness of the

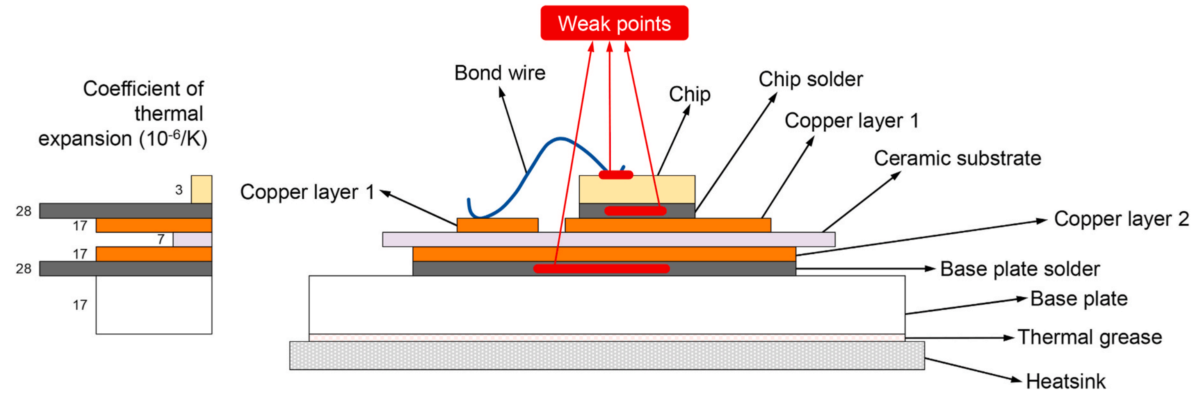


Fig. 15. Cross-sectional view of typical wire-bonded IGBT module indicating fatigue weak spots [144,145].

Table 6
Comparative overview of IGBT failure mechanisms [9,146].

IGBT module types	Failure mechanisms
Wire-bonded	Bond wire fatigue (lift off and heel cracking), solder joint (fatigue and voids), corrosion of the interconnections, cracking and fatigue crack propagation of brittle materials, aluminium reconstruction, burnout failures (latch up and cosmic ray)
Press-pack	Fretting damage, spring fatigue, spring stress relaxation, cracking and fatigue crack propagation of brittle materials, micro ablation, burnout failures (latch up and cosmic ray)

utilized fatigue models corresponding to different failure types were not validated by adequate test data. Lastly, more research is needed to be done about the failure reliability analysis of press-pack IGBTs together with new lifetime models for these new failure mechanisms like spring fatigue, etc. [9].

7. Discussions

Wind power is an important clean energy source that can conserve freshwater without the emission of greenhouse gases or air pollution during electricity generation. However, wind energy is not the only solution; there are other renewable energy sources, such as solar, hydro, ocean, and geothermal energy sources. As a result, it is essential to reduce relevant costs (including manufacture, operation, and maintenance) to promote its competitiveness among renewable energies. The possible strategies are summarized as follows [42]:

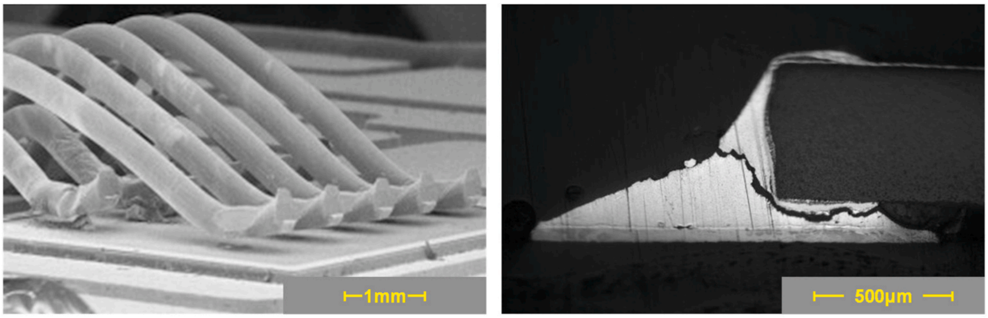
a) reduction in the sum of investment and maintenance costs, as cheaper products are more attractive.
b) calculation of failure cost with high precision, and estimation of the maintenance cost in advance.

In both strategies, an accurate estimation of the component failure probability is required. Among the failure modes of wind turbines, fatigue plays a predominant role. Accordingly, relevant studies to reduce costs were anti-fatigue design-based and -centered. To date, fatigue design criteria have been developed based on semi-probabilistic approaches in which partial safety factors are used to consider relevant uncertainties [134,156]; nevertheless, due to their empirical nature, optimal solutions cannot be achieved in the real sense.

Table 7 summarizes some commonly-used standards/guidelines for wind turbine fatigue design (in serial number or title). Some of them are specified for wind turbines, while the others were developed actually for offshore structures but were utilized by some scholars or institutes in offshore wind turbine designs as they endure similar loads. Looking back

Table 7
Standards/guidelines related to wind turbine fatigue design.

Institutes	Specified to wind turbines	Specified to offshore structures
International Electrotechnical Commission (IEC)	IEC 61400-1, IEC 61400-2, IEC 61400-4, IEC/TS 61400-9	IEC 61400-3
International Organization for Standardization (ISO)	Consistent with IEC standards	ISO 19900, ISO 19902, ISO 19903, ISO 19904-1, ISO 19904-2
American Bureau of Shipping (ABS)	Floating offshore wind turbines	Guide for the fatigue assessment of offshore structures
Federal Maritime and Hydrographic Agency (BSH)	Design of offshore wind turbines	/
Det Norske Veritas (DNV)	DNV-OS-J101, DNV-OS-J102, DNV-OS-J103, DNV-ST-0126	DNV-RP-C203
Bureau Veritas (BV)	NI 572 DT R02 E	/



(a) wire bond lift off [148]

(b) solder joint cracking [149]

Fig. 16. Pictures of wire-bonded IGBT module fatigue failure cases [148,149].

Table 8
Collection of simulation tools for wind turbine fatigue analysis.

Tools	Applications	Functions	Institutes
Ashes	Dynamic simulation	An analysis and design tool for offshore HAWTs using an integrated model of an offshore wind turbine.	Norwegian University of Science and Technology
Bladed	Dynamic simulation	A computer-aided engineering tool that builds wind turbine models, runs calculations and processes the results.	Det Norske Veritas
FAST	Dynamic simulation	A medium-complexity code for nonlinear aero-servo-elastic analysis of horizontal-axis wind turbines (both land-based and floating).	National Renewable Energy Laboratory
HAWC2	Dynamic simulation	An aeroelastic code for wind turbine response calculation in the time domain.	DTU Wind Energy
Simo-Riflex	Dynamic simulation	A nonlinear time-domain numerical program.	Norwegian Marine Technology Research Institute
TurbSim	Wind modelling	A stochastic, full-field, turbulence simulator primarily for use with inflow wind-based simulation tools.	National Renewable Energy Laboratory
WAMIT	Wave modelling	A computer program for computing wave loads and motions of offshore structures in waves.	Massachusetts Institute of Technology

at these standards/guidelines, all of them stress the significance of anti-fatigue design and fatigue reliability for ensuring wind turbine structural integrity; however, none of them provide a clear and detailed flow path for wind turbine fatigue reliability analysis.

As proposed by Sørensen and Toft [157], to avoid conservative designs and material wastes with the overall goal of minimizing the installation and ultimate energy costs, it is crucial to refine the wind turbine structures to a target reliability level. In this process, the rational quantification of different uncertainties, especially their conjoint modelling, is the basis [136]. Then, by combining fatigue reliability analysis results and design requirements, the optimal design scheme (safe and economically effective) can be determined; additionally, the maintenance and component replacement periods can be accurately planned.

Fig. 17 shows that uncertainties emerge throughout the manufacturing and usage periods [158]. For an accurate reliability calculation, apart from accounting for these uncertainties, they should be combined with reasonable numerical models to form a multidisciplinary analyzing framework [172–174]. In addition, the treatment of correlated input variables in a probabilistic analysis is also crucial. But now, many of the probabilistic tools and codes readily available to the industry cannot provide valid solutions for correlating input variables [173,174]. Also, in the fatigue reliability analysis of wind turbines, this issue is not discussed and can be a striving goal later.

In recent years, led by some top universities and institutes with rich experience in wind turbine fatigue analysis, some multi-functional and user-friendly simulation tools are developed [159–161]. In Table 8, some popular simulation tools that appeared in related publications are listed out, which can enable stochastic wind or load input and provide critical insight into wind turbine dynamics and optimization. In future work, it is a promising direction to develop a fatigue reliability-based closed-loop optimal design framework.

Finally, a key issue that requires emphasis is the utilization of the fatigue model. The fatigue reliability analysis of wind turbines consists of aspects other than the mathematical problem, and it should always be considered that the core theory supporting this procedure comprehensively considers the fatigue damage mechanism, rather than just the mathematical aspect. If the rationality and accuracy of the fatigue models cannot be guaranteed, the fatigue reliability analysis will be meaningless. Unfortunately, the models frequently used in the fatigue reliability analysis of wind turbines are over simple, such as Basquin/Coffin–Manson/Coffin–Manson–Basquin equations for fatigue life prediction, Miner's rule for damage accumulation, and Paris–Erdogan

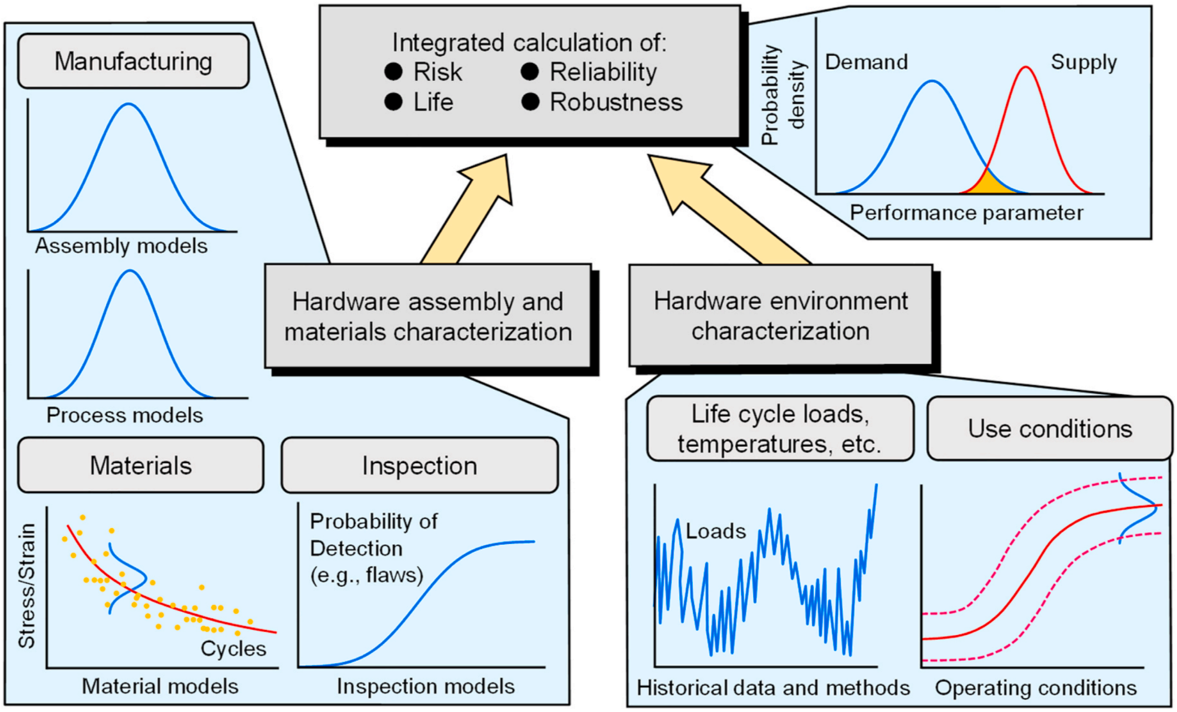


Fig. 17. End structural reliability is affected by uncertainties originating from manufacturing and service environments.

Table 9
A survey on fatigue models frequently used in wind turbine analysis.

Studies	Fatigue models	Components
[73]	$\sigma_e = A_1 - A_2 \log N$ (S–N curve with Goodman mean stress correction), Miner's linear or Reifsnider's nonlinear fatigue damage rule	Blade (offshore)
[95]	$\log N_f = \log K - m \log\Delta\sigma + \varepsilon$ (S–N curve), Miner's rule	Blade
[159]	S–N curve, Miner's rule	Blade
[91, 162]	S–N fatigue damage envelope theory	Blade and support structure (offshore)
[114]	S–N curve, Miner's rule	Gears (offshore)
[137]	S–N curve, Miner's rule, Paris–Erdogan equation	Support structure (offshore)
[131, 138]	S–N curve, Miner's rule	Support structure (offshore)
[9,146]	$N_f = a(\Delta T)^{-n}$ (temperature swing based Coffin–Manson equation), Miner's rule	Power electronic component (bond wire lift off, IGBT)
[146, 163]	$N_f = A(\Delta\varepsilon)^{-b}$ (visco-plastic strain increment based Coffin–Manson equation), Miner's rule	Power electronic component (bond wire heel cracking, IGBT)
[10, 146]	$N_f = 0.5\left(\frac{L\Delta\alpha\Delta T}{\gamma x}\right)^{1/c}$ (Coffin–Manson-like power law)	Power electronic component (solder fatigue, IGBT)

equation for crack propagation, see Table 9.

$$\text{Basquin equation}: \sigma_a = \sigma_f'(2N_f)^b \tag{9}$$

$$\text{Coffin–Manson equation}: \sigma_{a,p} = \varepsilon_f'(2N_f)^c \tag{10}$$

$$\text{Coffin–Manson–Basquin equation}: \varepsilon_a = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c \tag{11}$$

$$\text{Miner's rule}: \mathrm{D} = \sum_{i=1}^{k} \frac{n_i}{N_{f,i}} \tag{12}$$

$$\text{Paris–Erdogan equation}: \frac{da}{dN} = C(\Delta K)^m \tag{13}$$

In recent decades, with rapid advancements in mechanical engineering, fatigue study also experienced rapid growth. Certain unsolved fatigue issues have been extensively studied, and a multitude of models with better prediction accuracy has been proposed. However, they were not utilized in the fatigue reliability analysis of wind turbines, whereas the original models, such as Eqs. (9)–(13), proved with poor performance, are still widely used. Although there are new interpretations of multiaxial fatigue [164], notch effect [165], mean stress [166], size effect [167], and damage accumulation (load sequence effect) [168], which also influence the fatigue strength of wind turbine components, they are all generally neglected.

Sincerely, those newly developed fatigue models are more complicated in form than the ones, thus are difficult to calculate, and from simple to complicated is a common way to deal with a complex issue. However, by reviewing recently published literature on fatigue reliability analysis of wind turbines, most attention was paid to uncertainty quantification and reliability computation, while very few of them care about the advances in fatigue modelling. Undoubtedly, this is a bizarre scenario having the order reversed. Comparatively, the situation is significantly better in aero-engine turbine development [169,170,172]. To further optimize wind turbine fatigue reliability analysis, introducing advanced fatigue models to existing analysis frameworks is a necessary step. Right now, the fatigue reliability evaluation results based on the original models with poor accuracy are not convincing and cannot be used for high-confidence decision-making.

8. Conclusions

This study investigates the state-of-the-art technology and contentious research topics on fatigue reliability of wind turbines, and summarizes the methodology innovations, thereby providing reference and guidance for researchers, especially novices, focusing on this topic. The Introduction section reviews the development of fatigue reliability research; Section 2 introduces the historical evolution of wind load uncertainty (the most important scatter source) modelling strategy in detail; Sections 3–6 present the analytical techniques for determination of fatigue reliability of blades, drivetrains, support structures and power electronic components; Section 7 initiates some discussions regarding the imperfections concluded from a literature survey.

It is noteworthy that, both in policy and technology, increasing attention is being paid to the offshore wind turbine. On the sea, there is larger space for installation and stronger wind for electric power generation; however, challenges like harsh service environment, high maintenance cost, etc. come as well, which call for effective solutions for fatigue reliability design and monitoring of offshore wind turbines. Overall, although there is considerable progress in this field, there are still some aspects that require further investigation or extensions, which are presented successively. In particular, comments or solutions to these issues are supplied.

(1) *Establishment of a wind turbine fatigue failure database.* Although there are many cases on wind turbine fatigue reliability modelling now, engineers generally focus on solving individual cases (specific wind turbines and/or specific wind fields) and neglect their responsibility for the development of this industry. Actually, limited data may lead to the deviation between the fact and the observed phenomenon. Governments and associations should play active roles, encouraging researchers to collect and analyze the statistical characteristics of related parameters (especially combined wind and wave loads) as well as the failure modes and regions. As time goes on, more data will be documented; then, based on big databases, a more reasonable description of the random variables can be achieved and updated, and the locations inclined to fail can be paid special attention; as a result, the fatigue reliability of wind turbine can be assessed with a higher confidence level. Specifically, data science (including machine learning and data science) can be a good tool to summarize rules.

(2) *Development of a universal model under distinct environments.* A general framework for wind turbine fatigue reliability analysis suitable for different load conditions should be established. Most existing fatigue reliability analyzing frameworks are developed based on specific load environments, not suitable for different wind fields and user-unfriendly; accordingly, efforts should be made to summarize a universal analyzing procedure, in which designers can select the corresponding load modules according to the load condition.

(3) *Development of high-precision simulation tool considering the interaction of different fields and components.* Simulation tool is a critical medium to connect stochastic multiple-source uncertainties with uncertain stress–strain response for later fatigue lifing and reliability analysis. To date, some simulation tools were developed and applied to dynamic response analysis considering the interaction of different fields and components. Future works are expected to include: i) complex inflow, including wind shear; ii) hydrodynamic effects in the offshore application; iii) higher dimensional input space expansion; vi) nonlinearity due to large deflection, geometric and material distribution, and manufacturing methods; and v) application of smart rotor and control methods and their coupling to the full-scale system.

(4) *Advancements to match with the development of modern fatigue theories.* Among studies on the fatigue reliability of wind turbines, traditional fatigue models still play a major role. The

combination of the Basquin equation and Miner's linear damage rule was frequently used. However, they are only qualitative, which has already been proved with experimental evidences with poor prediction ability, as factors including multiaxial fatigue, notch effect, mean stress, load sequence, etc. were not considered. In subsequent studies, advanced fatigue models with better performance are supposed to be used; in addition, the joint action of multiple damage mechanisms such as corrosion, wear, and scuffing can also be considered.

(5) *Transformation from local components to global system (fatigue) reliability.* At present, the fatigue reliability assessment of wind turbine is centered on components. In the future, new methods should shift toward considering the overall structure (i.e., system-level fatigue reliability analysis), to enable the accurate evaluation of the global structural fatigue damage during service. In addition, fatigue reliability, as an important branch of the wind turbine reliability index, can be integrated with other elements using system reliability theories, contributing to assessing the comprehensive reliability of the wind turbine product [171].

(6) *Increasing and developing offshore wind turbines.* Owing to the lack of suitable sites for land and continuously increasing energy consumption, offshore wind turbines have become a contentious research topic in recent studies. Accordingly, it is necessary to introduce reliability-based engineering ideas into the design specifications of offshore wind turbine structures to guide their design, manufacturing, and testing, especially for the burgeoning floating offshore wind turbines under more complex loads.

(7) *Fatigue reliability of composite wind turbine components.* To increase the fatigue reliability and life of their components, especially blades, the use of composite materials is becoming popular, which boast attractive mechanical performances. Composite fatigue models develop at pace with the progresses of test technology and fundamental theory. Most of the existing fatigue models of composite materials have been tested and proved with ideal accuracy, and future works will focus on reducing implementation costs and improving universality. Applying the fatigue model to complex service conditions (such as random load spectrum, damp-heat environmental conditions, etc.) and complex structures will be a main challenge.

(8) *Fatigue reliability of power electronic components.* Fatigue reliability of wind turbine power electronic components is facing great challenges under increasing current density and heat generation. Further attention should be paid on the development of advanced thermal coupling analysis of high accuracy, the establishment of advanced fatigue models under the multiple environmental factors (heat, vibration, humidity, etc.) and the proposal of analyzing framework suitable for novel failure mechanisms of press-pack IGBTs.

(9) *Cost and reliability-integrated closed-loop software for wind turbine fatigue design.* As a civilian industry product, the guiding ideology of wind turbine design in practice is to minimize the overall cost of manufacturing, operation, and maintenance under the premise of meeting the required safety targets. This requires the organic integration of fatigue reliability analysis, structural optimization design, and cost management techniques to form an effective closed-loop, through continuous iteration and finally determine a both safe and economically competitive optimal solution. Developing cost management software applications for wind turbine systems and linking them with fatigue reliability design and structural optimization tools are sure to accelerate the healthy development of the wind energy industry.

Data availability statement

All materials data for model validation used during the study are available from the corresponding author by request.

Credit authorship contribution statement

Ding Liao: execution of the study, data analysis, writing; **Shun-Peng Zhu:** data analysis, writing, validation, supervision; **José A.F.O. Correia:** data analysis, writing, validation, supervision; **Abílio M.P. De Jesus:** data analysis, validation, supervision, writing - review; **Milan Veljkovic:** data analysis, writing - review; **Filippo Berto:** data analysis, writing - review.

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.

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