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A Critical Review of Damage and Failure of Composite Wind Turbine Blade Structures

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Abstract. Advancing beyond the historic feasibility limits deemed by designers, wind turbine rotor blades have eventually surpassed the 100m milestone, making them reside among the largest single components in the world made of fiber composite materials. In the development of wind energy, aerodynamics has been an essential field of research, just as it will still be, the recent two decades witnesses structures becoming more critical due to the ever-increasing size of the rotor blades. The fact is simple: for wind turbines to operate continuously and cost-efficiently, rotor blades must maintain their structural integrity and reliability. This study reviews recent advances in the field of the structural integrity of large scale composite wind turbine blades. A particular focus is placed on damage and failure in such structures from the triad of field observations, laboratory experiments and numerical modeling. This study also identifies the established knowledge, the latest achievements, the topical research fields and the current challenges for future research and development.

1. Introduction

Wind turbine blades are surprisingly simple structures from a construction point of view, c.f. Figure 1. They are either manufactured by adhesively joining a few structural sub-components, i.e., aerodynamic shells, spar caps and shear webs, or by virtue of an infusion process as a single component in one shot. Four primary materials are commonly used to build wind turbine blades: fiber fabrics (glass, carbon), resin (epoxy, polyester), sandwich core material (e.g. PVC foam, Balsa wood), and adhesives (e.g. epoxy, polyurethane). The blades are manufactured by a vacuum-assisted resin infusion process, unavoidably introducing defects of different types and sizes distributed at different locations. Before the blade is cleared to leave the factory, nondestructive testing (NDT) is carried out to detect major defects located in critical regions such as spar caps and trailing edge bondlines, which are typical for the prevailing production process. During their designated 20 to 25 years of operation in the field, the blades are expected to withstand high cycle fatigue and environmental degradation. Already born with various manufacturing defects and imperfections, (typically in the form of small air bubbles any ply waviness in the laminates) some of these remain latent while others act as damage initiators potentially leading to catastrophic structural failure.

The manufacturing-induced defects are only one of many other additional culprits responsible for the damage and failure of blades: operational loads, environmental effects (e.g. erosion, thermal cycles, lightning), structural design, material properties, manufacturing processes and their interplay determine the destiny of a blade in terms of how, why and possibly when it fails c.f. Figure 2. These circumstances



indeed pose a highly complex and multidimensional problem whose severity is soaring with the ever-increasing demand for longer blades that compel a multi-disciplinary approach in order to fulfill the reliability requirements. The considerable research effort of the past two decades has provided deep insights and a broad understanding of damage mechanisms and fracture processes in composite materials and adhesive bondlines.

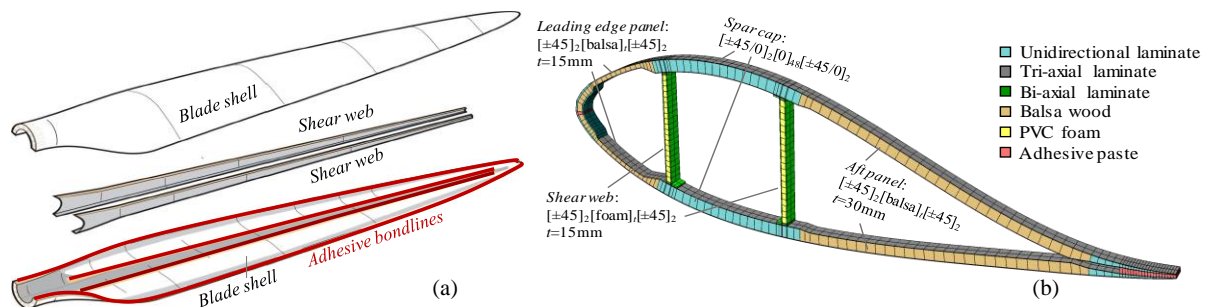


Figure 1. A typical structural construction of wind turbine blade. (a) A sketch showing a blade is assembled by adhesively joining four parts, adapted from [1]. (b) A cross section of a commercially available large utility wind turbine rotor blade [2]. Four adhesive bondlines are used to join two shear webs with a pair of spar caps. Two adhesive bondlines are used to join two lift generating shells at the leading edge (left end) and the trailing edge (right end). Two spar caps comprise a considerable amount of unidirectional laminates responsible for carrying bending moment in the flapwise direction (i.e. bending around the minor axis). Sandwich constructions are used to build the complex geometry of the aerodynamic shells that need to be lightweight and simultaneously resistant towards buckling.

Building on this bedrock on a microscopic material level, a variety of advanced experimental and numerical analysis methods evolved with the aim to more closely approach realistic test scenarios and to predict failure more accurately on an intermediate and large scale. Despite the enhanced methodology, the fierce time-to-market requirements put a strong emphasis on the development of more efficient experimental and numerical methods in terms of full-scale testing time and computation time. Both, the improved fidelity as well as the gain in efficiency facilitate the development of longer blades with a high strength-to-mass utilization ratio, which eventually leads to more cost-efficient blades for the wind energy industry.

This study is dedicated to reviewing the most recent research advances in the structural integrity of large scale composite wind turbine blades. A particular focus is placed on damage and failure of such structures from the perspective of field observation, laboratory experiments and numerical modeling. Also identified in this study are the state-of-the-art knowledge, the latest achievements, the current understanding, the on-going topics and the remaining challenges associated with this research field for future work. An overview of the research status is shown in Figure 3 and consequently discussed in detail in the following sections.

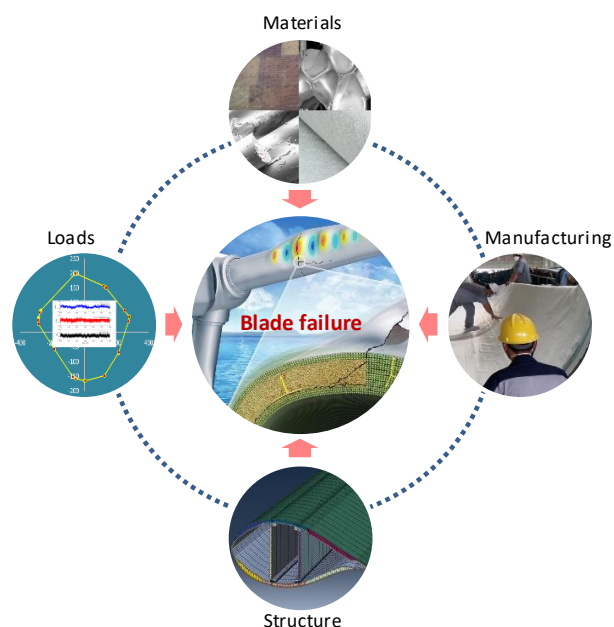


Figure 2. Interactive aspects affecting rotor blade failure [3]. The interplay among material properties, manufacturing processes, structural designs and operational loads (and environmental conditions) are essential to be considered in their collectivity if the structural integrity of composite rotor blades should live up to the designated service life of 20 to 25 years.

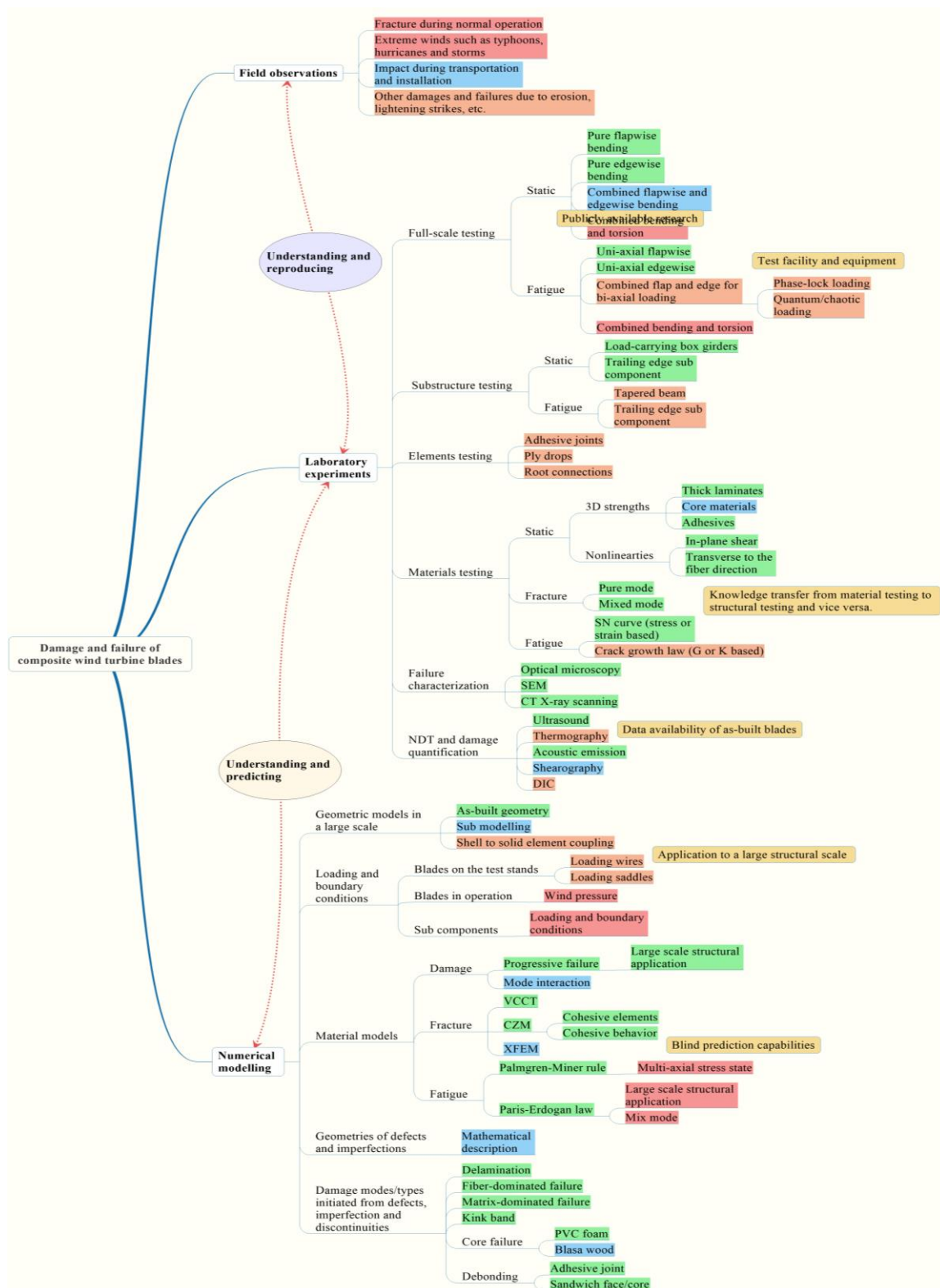


Figure 3. An overview of research status in damage and failure of composite wind turbine blades. Color codes: **green** – well studied with considerable understanding achieved; **orange** – ongoing studied with a few recent research publications; **red** – remaining challenges with a few or limited research publications; **blue** – less studied with a few or limited research publications; **yellow** – key issues to be addressed; Note that the color categorization may be debatable as continuous and interlinked research usually blurs boundaries between different categories.

2. Field observations

It is reported that with an estimated 700 000 blades in operation globally, there are, on average, 3800 incidents of blade failure each year [4]. Based on this report [4], blades are susceptible to a number of different failures caused by one or a combination of the following incidents:

- Failure of control system to detect vibration, imbalance or insufficient power
- Failure at root connection leading to blade throw (entire blade becomes separated from the hub at the metal to metal root joint)
- Extreme load buckling
- Lightning damages, including subsurface effect and moisture ingress thereafter
- Manufacturing defects leading to debonding (deterioration of the bonding agents used at the interface between the various structural elements of a blade)
- Blade overspeed striking the tower
- Environmental events, including natural perils, outside design envelopes
- Incorrect design for fatigue loads
- Crane impact during scheduled maintenance or on-site repair
- Poor manufacturing quality control/assurance leading to delamination (air traps between the piles of a blade or poor infusion of resin in a given area that causes poor or no bonding)
- Nacelle fire spreading to blades
- Human error (making an unauthorized adjustment during construction/maintenance)

These failures are rarely published in academic literature, mainly because relevant companies are reluctant to disclose such issues and technical data is hardly available due to commercial confidentiality. This inaccessibility of course deprives others from the opportunity to improve blade design and manufacturing processes in order to avoid similar blade failure from happening in the future. Nevertheless, a few available studies [5-9] are shedding light on the structural failure of rotor blades under extreme wind conditions such as typhoons, Figure 4. These incentives provide useful information on the different root causes of blade failure and can be used to infer recommendations for possible improvements in blade design and control strategies to reduce the risk of failure. This valuable knowledge contributes to the successful development of wind energy in regions prone to the impact of typhoons and hurricanes.



Figure 4. A wind farm located on a coastal island is impacted by a typhoon in 2013 [5]. In total, 35 out of 75 22.9-meter long blades are totally fractured in the wind farm. The fracture location is from 6 to 11 m from the blade root. The estimated wind speed during the typhoon is higher than the design survival wind speed of the turbine.

In surprisingly frequent cases rotor blades fail during normal operation when deemed structurally safe due to a presumably large safety margin. A recently conducted comprehensive study [3] scrutinized the reasons for rotor blade failure during normal operation in a wind farm. Another notable study published in [10], investigates fatigue damage, i.e., laminate cracks, of operational wind turbine blades by examining the slices of the damaged area with an abrupt thickness transition of laminates at the blade

root. Field investigations concerning damages inflicted by erosion and lightning strikes are scarce and mostly limited to experimental work under laboratory conditions [11-14].

The bottleneck concerning the availability of field observation data is the restricted accessibility due to proprietary rights preventing the dissemination to the public domain. The quality of a field failure investigation is a strong function of the availability of high-quality data and reliable information that needs to be collected, verified and analyzed before conclusions can be drawn on a rational basis. In particular material data, manufacturing processes, structural design details and loads represent crucially important elements giving credence to the root cause analysis, but are closely guarded secrets with highly restricted accessibility.

3. Experimental investigation

Experimental investigation on damage and failure of the blades can be categorized into full-scale testing, substructure/subcomponent testing, elements testing and materials testing. Complimentary utilization of material and failure characterization (e.g. scanning electron microscopy, X-ray tomography), nondestructive testing (e.g. ultrasound, thermal imaging) and experimental campaigns at different length scales provide indispensable information on a holistic level necessary to advance the understanding of failure mechanisms and their emergence at increasing length scales under controlled conditions (load magnitudes, loading frequencies, moisture, temperature, etc.).

3.1. Full-scale testing

The damage and failure modes of full-scale blades under monotonic ultimate loading conditions, in particular under pure flapwise (i.e. bending around the weak axis) and edgewise bending (i.e. bending around the strong axis), have been studied extensively over the past two decades. Full-scale structural tests enable an in-depth apprehension of the structural response of composite blades to quasi-static loads. Such tests can be used to validate the blade strength and serve the purpose to probe for necessary modifications in order to improve the structural performance and/or to reduce the blade weight. Prominent studies have been carried out by [15-26] and - despite the variance in structural design and material properties - came to a few common conclusions, notably:

- The governing failure phenomenon is primarily buckling driven whereby structural (geometric) nonlinearity plays an important role in the failure process.
- The ultimate failure is typically characterized by a sequence of multiple failure modes, in which three-dimensional stresses/strain states may play an important role.

These conclusions agree well with the general behavior of an imperfection sensitive thin-walled shell-type structure that can undergo a tip deformation of 25% of its span. The three-dimensional stress state stems from 1) thick laminates and sandwich panels; 2) material and geometric discontinuities; 3) the doubly curved lift generating shells (airfoil shape curvature in-plane and the taper curvature along the blade axis direction) which are prone to fail in a cascade of buckling modes.

In reality, however, the blades are subject to highly complex combined loading conditions which include the simultaneous action of flapwise-, edgewise bending and/or torsion. A full-scale blade test under the combined flapwise and edgewise bending is reported in [27], where the buckling of trailing edge panels subject to critical levels of compressive stress initiated the failure of the blade. The full-scale blade collapse tests under combined flapwise bending and torsion bending are pioneered by [28] are shown in Figure 5 and were later continued by [29]. In [28], failure was caused by crushing of the spar cap laminates under compressive bending stress leading to delamination that is driven by local buckling. Note that all publicly available studies use blades made of glass fiber composites. It is practically unavoidable though, to employ (hybrid) carbon fiber composites in order to compete in the global blade upscaling battle. The failure behavior of such large-scale carbon fiber composite blades is to date not publically available although a previous experimental study [30] has been carried out on three small scale (9 m) blade, showing the failure of two blades due to panel buckling near the max chord and good buckling resistance of the blade using a flat back airfoil feature.



Figure 5. Setup of a full-scale blade test under combined flapwise bending and torsion [28]. The desired state of combined bending and torsion is achieved by shifting the loading lines (force action lines) in such a way that they do not pass the shear centers of blade sections. The step-wise static load is applied to collapse the blade.

In the same vein as static tests, fatigue tests of full-scale blades are traditionally conducted under pure flapwise and pure edgewise bending, respectively. This testing mode is commonly referred to as uniaxial fatigue testing. Some notable studies [2, 31-34] report on the damage progress inspected during the fatigue test. It can be inferred from literature, that the observed damage is highly blade-specific and catastrophic structural failure did not occur during these tests. A categorization and consequential generalization of the observed damage mechanisms is strongly exacerbated by the limited number of publicly available test results reported in the literature. The most popular approach for uniaxial testing is the equivalent force approach, in which the first natural mode of the blade is excited and additional tuning masses are mounted on the blade in order to fit a prescribed equivalent bending moment distribution at maximum amplitude. Operating blades are exposed to a vast number of cycles in the order of $\sim 10^{10}$ during their lifespan of 20 - 25 years. For monetary reasons, blades are typically tested to approx. 2×10^6 cycles where the amplitude is artificially amplified with the intent to induce a damage level equivalent to $\sim 10^{10}$ cycles. It is noteworthy to mention that the validity of the uniaxial testing approach is questionable for two principal reasons: First, an operating blade is exposed to multiaxial loading conditions and operates at an entire frequency spectrum. Second, it is to date not scientifically corroborated that the equivalent force approach indeed induces the same damage levels and failure modes at the same location after 2×10^6 cycles the same blade would exhibit under operating conditions after $\sim 10^{10}$ cycles.

The key limiting factor associated with full-scale blade testing is the exorbitantly high cost, primarily caused by the testing time of up to six months (e.g., for a 90 m long blade) and the energy consumption due to aerodynamic damping effects. The full-scale blade testing in the industry was mainly concerned in developing methods able to reduce the cost of uniaxial testing using aerodynamic drag breakers (fairing) and by developing excitation methods in which the exciter mass is relocated from the blade to the ground. A method for significantly reducing the testing time was proposed by [35] which utilizes a multi-frequency excitation approach allowing to accumulate the desired cycle count in a shorter period of time. Moreover, the multi-frequency approach is a closer approximation to the operational loading conditions. Another limiting factor inhibiting the availability of publically available fatigue damage data pertains to current blade certification procedures driving the incentive to demonstrate that the blade does not show any damage e.g. after 2×10^6 cycles. While the pursuit of such an approach is intelligible from an economical perspective, it evenhandedly foils the fundamental idea of testing which relies on the observation of damage for the sake of knowledge gain.

More recently, research focused on the development of multi-axial fatigue testing methods in which the blade is simultaneously excited in two different (e.g. orthogonal) directions. This approach represents a major advancement in fatigue testing technology. The reports on the damage of the full-scale blades under multi-axial fatigue are scarce although the multi-axial fatigue tests themselves are reported frequently [36-38] and demonstrated such as shown in Figure 6. The development of improved full-scale blade testing methods is a very active field with an international research effort. A substantial investment in test facilities, equipment, instrumentation and time sets the bar rather high for most research organizations to enter this field if without close collaboration with industry.

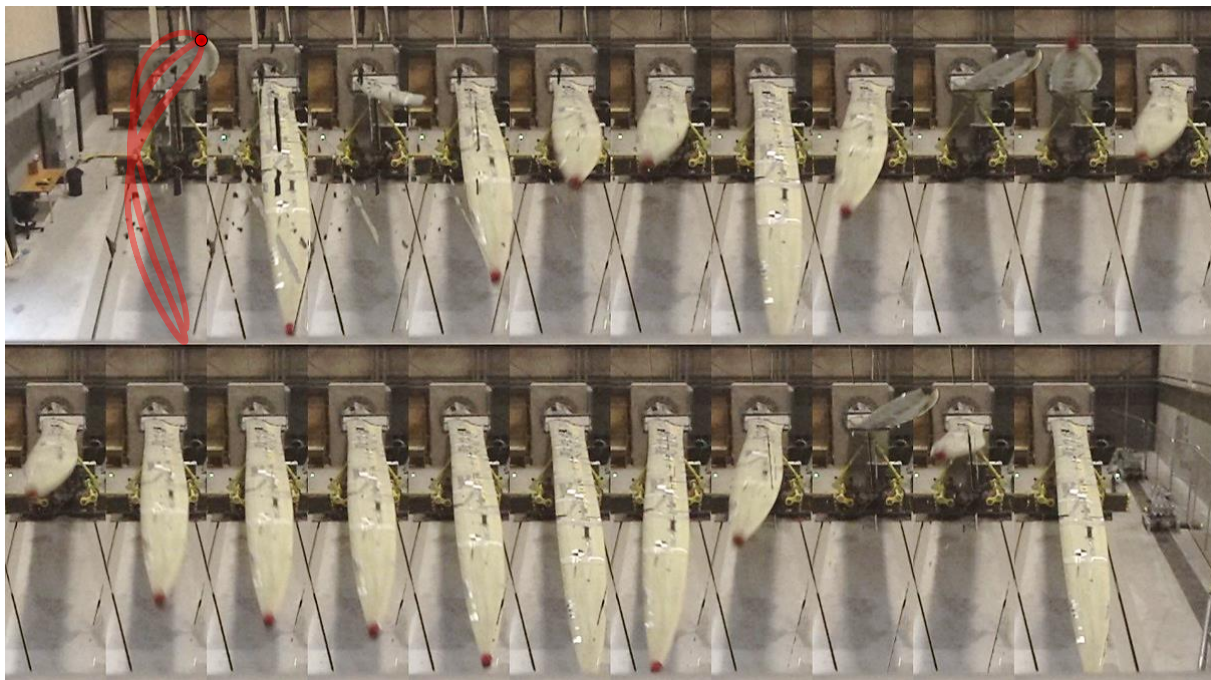


Figure 6. A 14.3 meter long blade under biaxial fatigue that is excited by a ground-based backlash constrained dual-axis exciter developed by R&D A/S within the BLATIGUE project (Fast and Efficient Fatigue Test of Large Wind Turbine Blades, 64016-0023) funded by the Danish Energy Technology Development and Demonstration Program (EUDP). A clown's nose is mounted at the tip of the blade to visualize its trajectory under bi-axial fatigue. The trajectory of the tip over 1 second of period is superposed to the figure.

3.2. Substructure and element testing

Considering the dominating burden of the cost involved in full-scale blade testing, it appears natural to develop a more cost-efficient trade-off. Equally important to consider is the distinct level of scattering inherent to fatigue test results. It is, therefore, desirable to establish statistically significant datasets by testing a sufficiently large number of identical specimens that permits the application of statistical methods. In this light, the high cost involved in full-scale tests alas prevents the acquisition of the required sample size. Testing a part of the blades – a subcomponent – is a cost-effective alternative solution to experimentally evaluate the structural integrity of the potentially critical regions. Subcomponent testing or a.k.a. substructure testing can be conducted at a fraction of the time and cost of a full-scale test. Consequently, a larger sample size can be tested endowing the data with lower uncertainty levels. Subcomponents lend themselves to experimentally investigate a wide range of different design details, e.g., load-carrying beams [39-43], buckling-prone trailing edge segments [44-46], and elements such as ply drops and adhesive connections in various parts of the blade to name a few. Subcomponent tests provide valuable insights into local structural behavior that are difficult and/or costly to investigate via full-scale blade testing and hardly possible to gain on a smaller scale by virtue of e.g. coupon tests.

The biggest challenge of developing meaningful subcomponent test methods is to emulate the force and displacement boundary conditions along the free body cut of the very same component as-integrated in the blade. A well-known hurdle in the development of subcomponents is failure initiation in the load application points and the restraints. It is natural that in these particular regions stress concentrations arise (e.g. high stiffness gradients due to local reinforcements) which precipitate failure in regions remote from the gauge area. Moreover, the stress state in the boundaries and local force application points (e.g. three-point- or four-point bending tests) is typically largely at a variance of the stress state present in the real blade. The critical question which arises pertains to the value such subcomponent test data provides if a failure occurs outside the designated region at unrepresentative load levels in an

unrepresentative failure mode. When it comes to fatigue, the challenge may be worsened as the effects of both loading and boundary conditions on the premature damage are more significant compared to the static loading. The first step towards meaningful subcomponent testing was done by [43]. Later it was shown that topology optimization can be used to develop a subcomponent geometry that satisfies the failure location and facilitates the investigation of a specific failure mode [47]. One further application of this approach is shown in Figure 7 where the hourglass-shaped subcomponent was developed to test the web-to-spar-cap adhesive bondline under fatigue loading. By utilizing a finite element optimization-based approach, it was possible to successfully investigate the desired shear failure mode inside the desired gauge region [48]. The other possible solution would be to reinforce the boundaries during (not after) the infusion/manufacturing of the specimens.

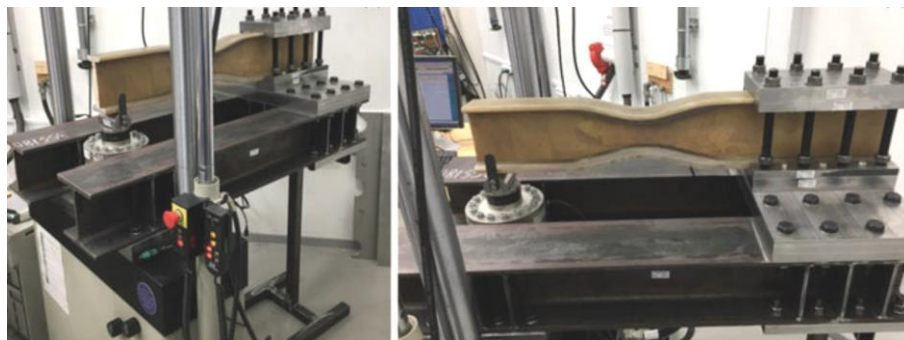


Figure 7. A tapered beam with adhesive joint interfaces [48]. The adhesive failure initiates in the gauge area remote from boundary conditions and load application points.

Testing the so-called elements is one additional way to evaluate structural details of composite blades. The difference between the element and substructures and the subcomponents is that the elements are smaller in size, allowing a larger number of specimens to be tested more cost-effectively. The element test usually focuses on rather local structural details with two or more failure modes although its distinction from materials testing is not yet uniquely defined in the current research community. A typical element test is shown in [49] where thick adhesive joints used in wind turbine blades are tested under static and fatigue loads.

3.3. Materials testing

This section only focuses on materials testing that is directly relevant to damage, failure and fracture of composite wind turbine blade structures. Four primary materials commonly used to build wind turbine blades include fiber fabrics, resin, cores, and adhesives. Their ultimate strength, fracture toughness and fatigue resistance are key material properties relevant to the structural integrity of the composite blades. A few notable studies have been published. They include a) three-dimensional static strength parameters of a thick glass/epoxy unidirectional laminate [50, 51] where stress-strain curves are also reported; b) bi-axial static strength [52] and fatigue strength [53] of thick adhesives using tubular specimens; c) composite fatigue test database SNL/MSU/DOE [54], FACT [55], and OptiDATA [56] with the SNL/MSU/DOE database recently updated and remain publicly available. A short review of these databases can be found in [57]; d) material strength of PVC foams under multiaxial static loading [58, 59] and fatigue [60]. A short review [61] on sandwich materials for wind turbine blades identified a few challenges, some of which, such as NDT methods, are still valid nowadays.

The availability of publically accessible databases is highly celebrated and constitutes an endeavor that should under all circumstances be carried forward. However, it is noteworthy to mention that both resin systems and fiber fabrics underwent soaring developments in the past decade, outdating large parts of existing material data available in these databases. State-of-the-art composite materials used in modern wind turbine rotor blades exhibit distinctly elevated fatigue strengths as compared to previous systems. Another aspect concerns the size effect (especially the thickness effect) of fiber composite materials under fatigue loading. Additional experimental research is required to shed more light on the

size effect of composite materials under high cycle loading conditions. Other topics that can only be briefly be touched upon in this work concern the influence of fiber architecture and curing induced residual stress on fatigue performance as well as the effect of the load cycle sequence dependency [62].

In the context of wind turbine blade damage and failure, the future trend of material testing will be not only continuing advanced tests in the on-going topics such as multiaxial strength, high cycle fatigue beyond tension and material degradation due to environmental effects but also will focus on establishing knowledge to close the gap between failure mechanisms observed in a material scale and those found in a structural scale; discontinuities between different materials, as well as within one material; the new failure modes due to the application of new materials such as hybrid and bio-materials in large wind turbine blades.

3.4. Damage detection and failure characterization

When damages and failures occur in the field or the laboratories, they should be detected, identified and preferably quantified to help understand the failure phenomena. Damage detection and failure characterization are a huge topic themselves. Regarding the application in wind turbine blades, ultrasound, thermography and acoustic emission are among the most widely used NDT methods, while shearography is less common but promising. A recent work by the lead author uses thermography to detect fatigue damage during the full-scale blade test, see Figure 8. Note that each NDT method has its advantages and shortcomings, the choice depends on the purposes of the testing. A trend is to enrich test results thus enhance the detectability and accuracy by either combining different methods in the test campaign or utilizing digital techniques such as machining learning and computer vision.

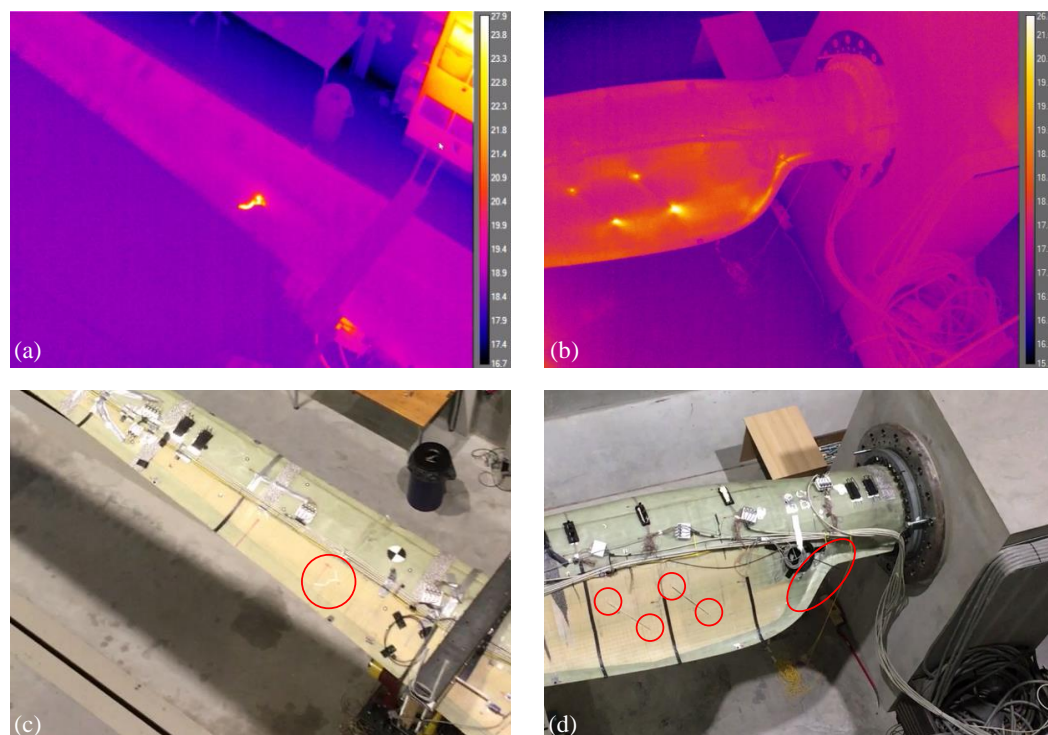


Figure 8. Remotely detecting fatigue damage of a 14.3 meter long blade under bi-axial fatigue using infrared thermography. (a) thermal footprints of progressive surface cracks in the sandwich panel with a pre-cut in the trailing edge. (b) thermal footprints of multiple damage sites in the max-chord sandwich panels and in the root transition region. (c) the regular RGB image of the progressive surface cracks in the sandwich panel marked with a circle. (d) the regular RGB image shows surface damages at the tips of two pre-cracks in the sandwich panel marked with four circles and subsurface delamination damage in the root transition region marked with an ellipse. A detailed study to be published in a separate work coined by AquaDa. The study is supported by the DARWIN Project (Drone Application for pioneering Reporting in Wind turbine blade INSpections, 6151-00020B) funded by Innovation Fund Denmark.

For failure characterization, the widely used techniques regular cameras, optical microscopy, Scanning Electron Microscopes (SEM), computer tomography (CT) scanning. Notable literature include fractographic analysis of composite materials [63] is systemically introduced; fatigue damage characterization using micro CT scanning images [64]; post-mortem investigation on two large blades collapsed during normal operation [3] and a subcomponent specimen after a collapse test [65], establishing the relationship between microscale material failure characteristics and macroscale structural failure behavior.

Driven by the field application aiming for the cost-effective operation and maintenance (O&M) in the wind energy industry, the future trend in this area will be more automated damage detection and characterization to evaluate damage criticality of the structures under concern. The data-driven approach will be gaining more and more popularity simply due to the overall trend of digitalization in the industry [66].

4. Numerical modeling

This section only focuses on numerical modeling of damage and failure in full-scale blades and their substructures and subcomponents. Modeling damage and failure of composite wind turbine blades on a large scale is challenging and it is worthwhile to briefly elaborate on the gravity of this statement. It is abundantly clear that damage and failure are distinctly local phenomena which for the sake of argument can be said to occur on a characteristic length scale range of 10^{-3} - 10^{-6} m for all practical purposes in the fiber composites world. Now unlike e.g. plasticity phenomena, the characteristic length e.g. of a fracture process zone does unfortunately not scale with the characteristic macroscopic length – which for a modern wind turbine blade is in the order of $\sim 10^2$ m. This illustrates the dilemma of numerical damage and failure analysis of large scale blades and the ordeal to bridge an overwhelming length scale gap of several orders of magnitude whilst simultaneously struggling to maintain reasonable computation times – even on modern supercomputers. Literature shows that high fidelity modeling approaches such e.g. as cohesive zone models are predominantly applied on manageable macroscopic length scales such as coupons where the scale bridging dilemma is significantly less apparent. Therefore, numerical modeling of test elements and coupons are not discussed here to maintain this section at a manageable level.

Naturally, research has developed methods to close this gap from both sides. On the macroscopic side, e.g. sub-modeling techniques are deployed providing the opportunity to limit the high mesh discretization levels to comparatively small areas of the blade. Sub-modelling requires prior ad-hoc knowledge about the location and size of the damage zone rendering this approach increasingly inapplicable to the simulation of operating wind turbine blades with multisite damage distributions. That is to say, resolving the blade with different sub-models like a jigsaw compromises the computational advantage. On the microscopic side, e.g. continuum damage models utilize a phenomenological approach to smear over microscopic length scales enabling the adoption of comparatively coarse mesh discretization levels. In other words, instead of modeling the discrete fracture process, the material softening effect caused by the fracture process is implicitly considered by modifying the local element constitutive matrix as a function of the prevailing damage index. Continuum damage approaches represent indeed a computationally efficient alternative. However, their inability to accurately resolve the physical crack, makes them less compatible with full-scale experimental observations and inspection based repair frameworks. Other approaches such as the celebrated extended finite element family are better suited for this purpose but despite significant software developments still suffer to a considerable degree from the wide applicability to anisotropic materials, numerical instability (i.e. convergence issues) and crack-path mesh-size/ element-type dependency.

While the aforementioned circumstances can be reasonably dealt with under monotonic loading conditions, the situation faces a game changer when it comes to high cycle fatigue analysis of full-scale blades. In the latter case the burden of spatial discretization is aggravated by the temporal discretization of a highly time-dependent process (note that load cycles can be considered as a pseudo-time parameter). It needs to be borne in mind that blades under operating conditions are subject to dynamic multiaxial loading conditions contained in an entire frequency spectrum. These variable amplitude (quasi-

stochastic) loads containing vast cycle numbers are typically non-proportional and inherent nonlinearities (see below) let the superposition principle break down. The latter was often used as a lifeline inasmuch it enabled the analysis of complex loading situations by applying linear combinations of finite element model runs with unit forces. This approach does not hold anymore if large scale blades are concerned.

In a nutshell, the main focus of future research on numerical modeling strategies will need to focus on not only further improvements of their fidelity but also, maybe more importantly, drastic improvements of computational efficiency capable of dealing with the challenges outlined above.

It should be noted that any numerical model is essentially a mathematical representation of a physical process on a specific characteristic length scale underlying certain simplifications and assumptions. Depending on the objectives of the simulation, different modeling techniques can be used. Nevertheless, to perform reliable numerical simulations on damage and failure of large-scale blades, a few points need to be addressed:

- (1) Geometric models that are detailed enough at least in the regions of interest where damage and failure may occur. In this context, ‘detailed’ does not only refer to mesh refinement but also more importantly thorough consideration of the damages to be simulated. For example, finer shell element meshes alone are not able to capture debonding and delamination that require through-thickness stresses/strains. Imagine the modeling effort if the detailed geometric modeling pertains to a predominant portion of the blade and even through its wall thickness. Typical examples for such cases are the adhesive bondlines running along the entire span of the blade with varying geometry. Adhesive web foot joints feature local stress concentration zones and singularities in corners caused by the adhesive flow front and the substrate [67]. Figure 1 only shows one slice of a blade that is modeled with solid elements and with different elements representing different materials, e.g., the outside skin of the sandwich laminate, the PVC foam core, the inside skin of sandwich laminate, through the wall thickness. Obviously, there is a balance between the level to which details are resolved and the time spent on the modeling i.e. the modeling effort. Automated modeling tools for research purposes are built in-house, e.g., Figure 9. Some software is commercially available for general industrial applications such as [68, 69] and they mainly focus on completing the entire aerodynamic-aeroelasticity-structure design loop for a blade and a wind turbine, respectively. One open-source software is NuMAD [70] developed by Sandia National Laboratories as a general blade modeling tool.
- (2) Publicly available data of the blade details that are needed to model blades is another challenge in this area. Although some blade models such as the DTU 10 MW wind turbine blade [71], the NREL 5 MW wind turbine blade [72], and the Sandia 100 m wind turbine blade [73] are publicly available, they are artificially created and do not necessarily reflect the actual blade details used in the industry. Due to the proprietary data, existing publications are only able to partly disclose the information when the commercial blades are modeled, making the reproduction of simulation results difficult or even impossible. A set of publicly available data of real modern blades are highly valuable to the entire research community.
- (3) Loading and boundary conditions. For the simulation of full-scale blade tests, it is sometimes important to model the loading wires in order to consider the change of load directions during static loading. Moreover, it may be also necessary to model loading saddles [74] if they may affect the failure of the blades. It is challenging to model proper loading and boundary conditions of substructure and subcomponent tests when the connections between specimens and loading points affect the failure behavior [44, 45, 75-78].
- (4) Structural nonlinearities. The consideration of geometric nonlinearity (i.e. large deformation theory) is straightforward in commercially available finite element software packages. Material nonlinearity is usually considered when the specific damage types are under concern. The importance of contact nonlinearity has not received a great deal of attention but proves to have a considerable influence on the failure sequences [44, 76] and needs to be assessed. A unified modeling approach that

considers all three types of nonlinearities, Figure 10, will be a valuable advancement in this field. A step towards this approach is presented in [79].

- (5) Highly sophisticated material models have been developed to predict the damage and failure of composites, core materials, and adhesives used in wind turbine blades. The current challenge is to apply these models to the damage prediction of large-scale blade structures. The widely used modeling technique is continuum damage mechanics for progressive damage analysis of the blades or their subcomponents. The fracture mechanics based approach is also used but primarily limited to small regions, e.g., trailing edge bondline and spar cap. The future trend will be a combination of two approaches in one single simulation to capture different damage modes and their interaction.
- (6) Fatigue simulation of rotor blades is mainly based on phenomenological models and usually the distribution of equivalent damages over the blades is calculated as damage indexes. Arguably the most popular method foresees the computation of the damage index according to the Palmgreen-Miner rule and to superimposing it as a scalar field on the blade model. Despite the convenience of using such an – arrantly speaking – intelligent post-processing scheme, the biggest drawback manifests itself in the negligence of the damage evolution since all predictions are based on the initial undamaged configuration. Strictly speaking, such approaches are only valid to predict fatigue damage initiation which can be a useful tool to screen blades for potential hot-spots e.g. for mitigation at an early design phase. For a more faithful prediction of fatigue crack growth in a large-scale blade requires overcoming the challenges outlined at the beginning of this section by radically new approaches and a shift of paradigm. A recent work [80], coined as FASTIGUE, is a first attempt to thrust forward and presents an efficient discrete fatigue crack growth simulation approach for the large-scale blade application. It is done by outsourcing the computationally demanding fracture analysis into a pre-processing module whereas the crack-growth simulation is conducted subsequently and independently in a separate fatigue analysis module, see Figure 11.

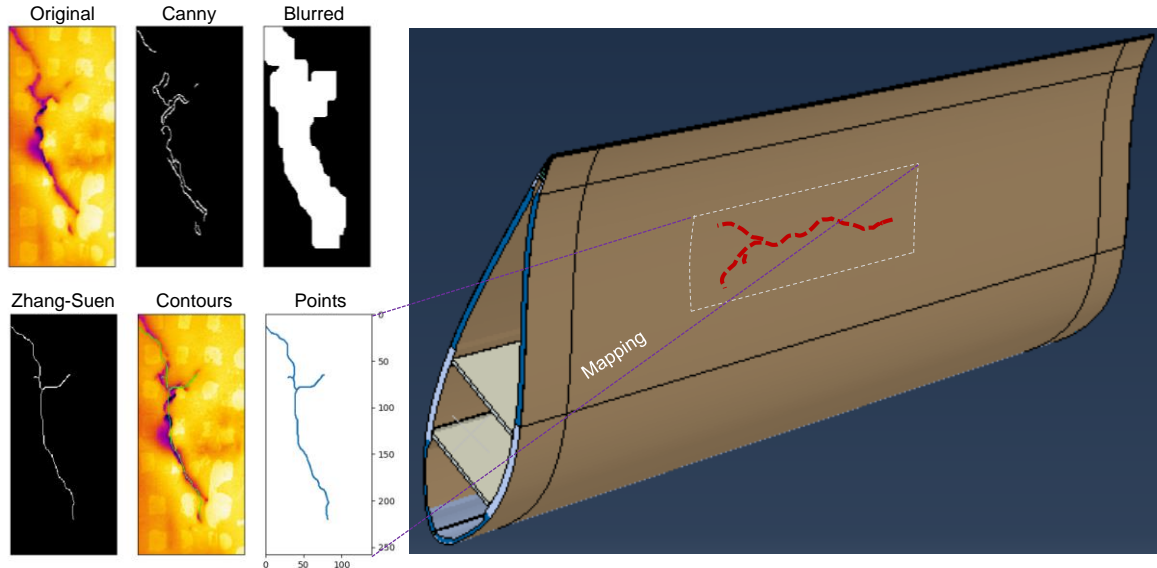


Figure 9. Automated damage identification and modelling (AUDIN) tool developed by X. Chen and S. Semenov. The tool first digitalizes complex crack geometries based on images from regular RGB cameras, thermography and other NDT methods, and then automatically imports the information into the FE model through mapping and scaling. The structural integrity of the damaged blade can be analyzed online via cloud-computing. The evaluation results can be sent back to inspectors in near real time who may work in the field, facilitating fast and reliable decision making for cost-effective O&M strategies. The work is supported by the DARWIN Project (Drone Application for pioneering Reporting in Wind turbine blade INspections, 6151-00020B) funded by Innovation Fund Denmark and the RELIABLE project (Improving Blade Reliability through Application of Digital Twins over Entire Life Cycle, 64018-0068) funded by the Energy Technology Development and Demonstration Program (EUDP) of Denmark.

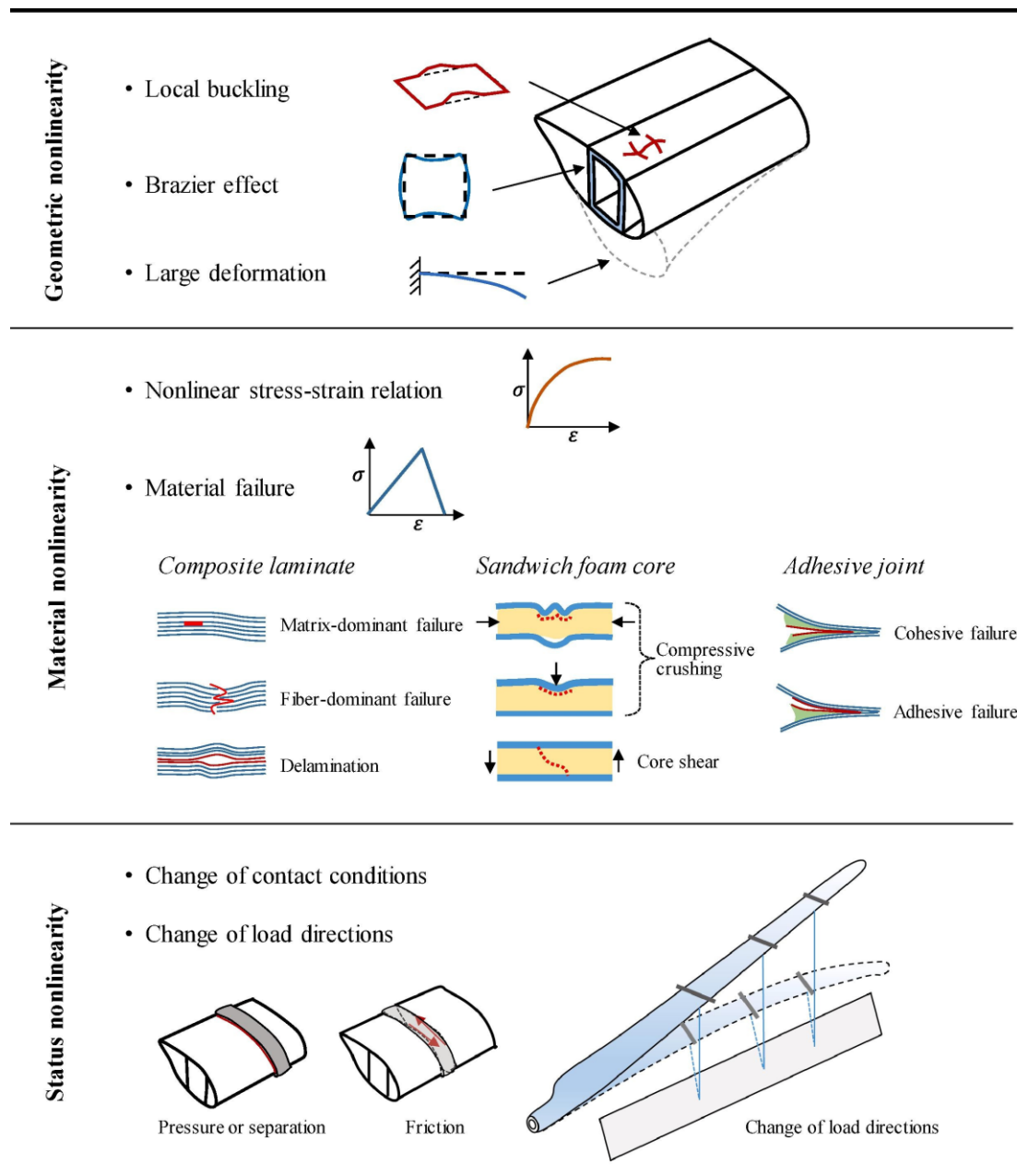


Figure 10. Examples of three types of structural nonlinearities that might be experienced by composite wind turbine blades [79]. Depending on the purpose of the simulation, relevant nonlinearities have to be modeled to capture damage and failure of the blades.

(7) Numerical modeling of damage and failure has been mainly focused on understanding failure behavior and reproducing experimental observations of the as-designed blades in their pristine state without pre-existing damage. The future trends are towards focusing on scenarios in which it is accepted that blades are born with major defects and imperfections in their as-built state and to predict and trace the damage evolution under service conditions. How these defects, imperfections and damages behave in the large-scale blades and their influence on the overall structural integrity are essential and of practical importance for the life-cycle performance evaluation of wind turbine blades. Instead of considering the faith of individual blades, future numerical modeling strategies need to be fit for the integration of all the blades of a wind turbine into interconnected digital twin systems.

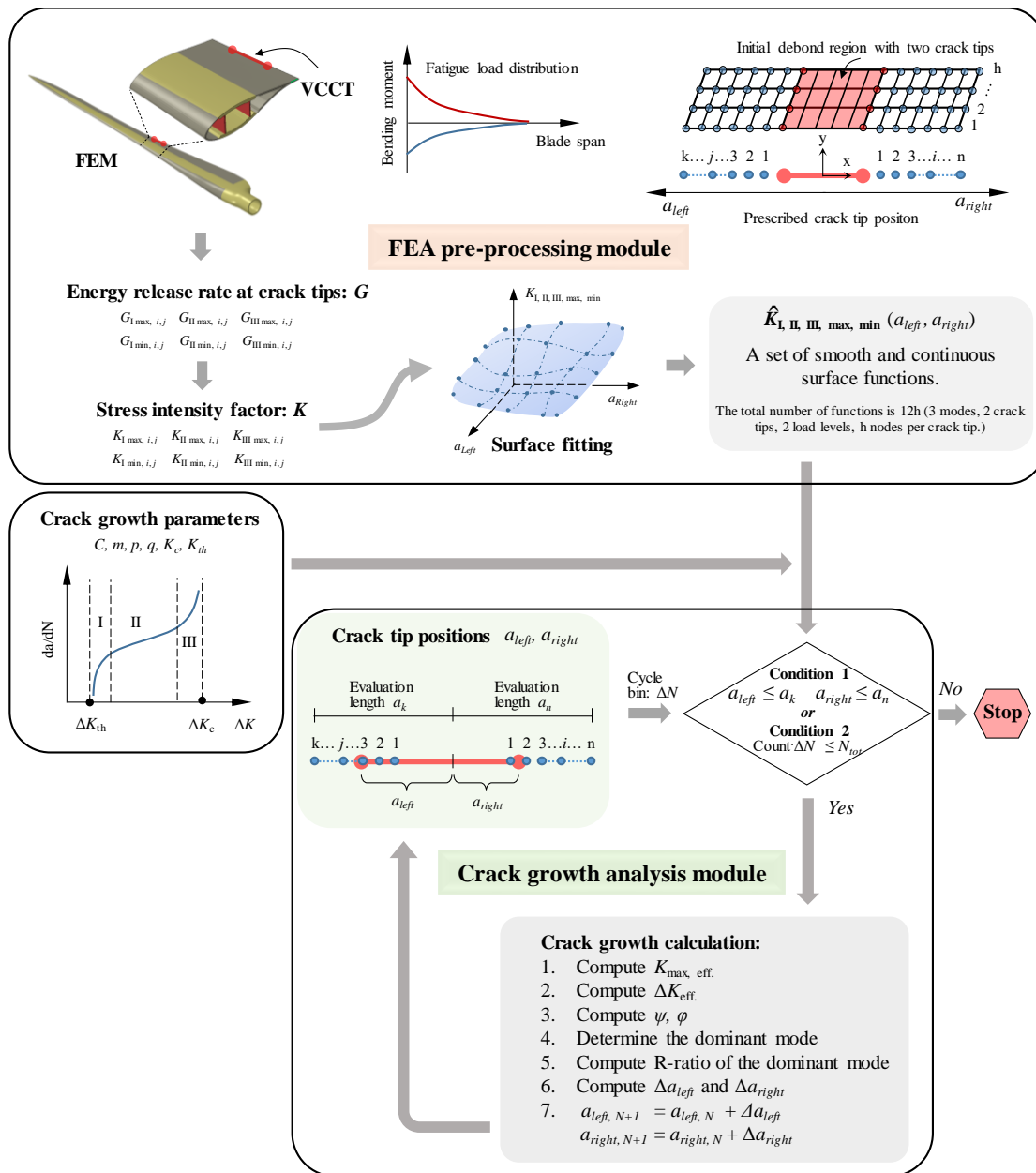


Figure 11. The flow chart of the FASTIGUE [80] approach comprising an FEA pre-processing module (top) and a crack growth analysis module (bottom); the grey arrows indicating the computational flow show that a feedback between the FEA preprocessing module and the crack growth analysis module is avoided, resolving heavy computational demands of fatigue crack simulation for composite wind turbine blades.

5. Concluding remarks

The recent two decades of research show significant advances in the understanding of damage and failure of composite rotor blades for multi-megawatt wind turbines, particularly in the case of ultimate loading situations. Important macroscale failure modes in blades observed in the large-scale experiments have been categorized and entrenched in the underlying theory. Numerical methods capable of predicting these structural damage and failure modes have been developed and successfully vindicated. The remaining challenges associated with the damage and failure prediction in large utility wind turbine rotor blades are identified as follows:

(1) Damage and failure under complex static loads: Structural failure mechanisms under combined complex (multiaxial) loading, in conjunction with failure phenomena associated with the advent of rather novel material systems, e.g., carbon/glass hybrid fiber fabrics and bio-materials whose utilization become increasingly popular. A missing keystone for quasi-static ultimate loading situations is a general/unified numerical modeling approach capable of predicting key failure modes in large scale structures. The success of these modeling strategies available in the literature should be measured and ranked objectively using blind tests during which experimental results are only disclosed in retrospect.

(2) Efficient (and maybe radically novel) methods to predict fatigue damage in large structures: The supreme discipline of predicting high cycle fatigue damage in composite rotor blades for multi-megawatt wind turbines is still a very active field of research and will remain so for decades to come. Conventional stress/strain-based methods hinging on damage accumulation, such as using the linear Palmgren-Miner rule, are well established for historic reasons and owing to their simplicity. However, as blades grow in size, structural behavior and failure modes gain complexity and become less intuitive. In fact, the apparent speed of the design evolution combined with the relentless time-to-market demands increase the risk of experience-based designs. Large scale fatigue tests and fatigue failure cases observed in the field provide ample evidence for the need of deploying more sophisticated fatigue prediction tools. Especially local damage modes such as delamination and debonding mostly inherent to the regions of geometric and material transitions/discontinuities (e.g. adhesive bondlines, ply drops) require more advanced modeling formulations on the basis of fracture mechanics and continuum damage mechanics.

It needs to be conceded that such methods are partially readily available albeit, do not enjoy great popularity for application on large scale because of two reasons: First, computational efficiency is compromised by high discretization demands and poor numerical stability rendering them impractical for high cycle fatigue analysis in practice. Secondly, many advanced fatigue prediction models require a comprehensive set of material parameters that might simply not be available for the desired material system. Even worse, testing methods to obtain these parameters might be inexistent. Large as it is, nowadays philosopher's stone is to integrate available material models into large scale systems such as digital twins which will be only achievable with research effort dedicated to a significant improvement of their computational efficiency. The recently developed FASTIGUE [80] approach shows one promising application of fracture mechanics based fatigue prediction to large scale structures.

(3) Interfacing the boundary between experiments and simulations: The development of improved numerical models goes hand in hand with the advancement of reliable experimental methodologies more accurately emulating prevailing stress/strain states, reproducing relevant failure modes and considering more realistic loading scenarios. More sophisticated fatigue test methodologies at full-scale, substructure, subcomponent and element levels have to be devised with a particular emphasis on reproducing damage and failure of the blades in operation and proper documentation to benefit reproducibility.

In contrast to other fields such as e.g. the automotive industry or earthquake engineering, it comes at a surprise that well established test methodologies on intermediate sub-component level for blades are scarce. This emphasises a strong research demand for novel sub-component testing techniques in the wind turbine blade industry. In particular an approach known as 'hybrid testing' craves for application in experimental blade research. Hybrid testing refers to a subcomponent of a structure that is loaded by an arrangement of different actuators in such a way that forces and displacements are closely emulated. An array of sensors enables real time feedback communication between the subcomponents response with a numerical full-scale model that is run in parallel. In this way, the cyclic global response is provided by the full-scale model and the force output consequently applied to the subcomponent. In turn, the stiffness degradation of the subcomponent due to fatigue damage is fed back into the numerical model in terms of the displacement. Such a versatile hybrid-testing approach offers a striking time and cost efficient alternative to full-scale tests. In the future, driven by digitalization, the historic sharp boundaries between experiment and simulation will strongly interlink and the two paradigms will become indistinguishable. To take it a step further, the real world wind turbines will become an integrated part of the digital world simply because the control of such complex systems and the decision

making process will not be possible without the aid of machine learning. These research efforts will continue to be the trend in the foreseeable future.

(4) **Operational damage and failure in the real world:** The importance of public accessibility of real-world failure incidents for the greater good of research cannot be overemphasized. Previous experience has shown that the formation of consortia between universities and key players of the industry successfully facilitates broader dissemination of research data with the shared incentive to make existing design guidelines less conservative (i.e. reduction of manufacturing cost) through public research. The research on the structural integrity of rotor blades under extreme winds such as typhoons, hurricanes and tornadoes will be still conducted by researchers outside of calm Europe. With the increasing development of coastal and offshore wind farms in typhoon/hurricane-prone regions, the necessity to boost the research in this area is still urgent for the industry.

As the wind energy industry moves towards digitalization, the research activities in the topic structural integrity of composite blades in recent years have involved more and more industry 4.0 technologies such as big data, internet of things, cloud computing and drone technology [81]. These technologies not only facilitate the development of more reliable and accurate testing and modeling of the rotor blades but also may change the way the structural performance is evaluated through the entire life cycle of the blades using digital twins [82]. This digital trend will be undoubtedly long-lasting and profound for the entire wind energy industry and beyond.

Author contributions

X. Chen conceived this study with inputs from M.A. Eder. X. Chen wrote the draft of this manuscript. M.A. Eder contributed significantly to modifications and revision of the draft.

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