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Review

Repair of wind turbine blades: Review of methods and related computational mechanics problems

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A R T I C L E I N F O

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A short overview of main repair techniques for wind turbine blades and the related problems of computational mechanics is presented. Computational models of the leading edge erosion of wind turbine blades, injection repair and viscous flow, patch/scarf repair as well as curing and adhesive development are reviewed. Both the degradation of wind turbine blades during service (caused by surface erosion, surface cracking, delamination, fiber failure) and the repair procedures (coating, patch and scarf attachment, injection and curing of adhesives) represent the multiscale processes, controlled by geometrical., blade, patch, scarf geometries), mechanical (strength of composite, strength of adhesive, coating, stress distribution) and physical/chemical effects (curing, viscous flow, humidity, temperature and UV effects). For the further optimization of repair technology and efficiency, multi-physical, multi-scale computational models should be employed.

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Contents

1. Introduction

Wind energy becoming one of the most important energy sources in Europe. In 2017, it was one of the quickest growing industrial segments in the world, with a total investment of USD

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107.2 billion [1]. By 2020, wind energy capacity expected to surpass 200 GW milestone and become Europe's largest renewable source [2].

Still, after past decades of the rapid wind capacity expansion, the majority of installed wind turbines are aging, which boosts the growth of the maintenance and repair market as well as the demand of the advanced maintenance and repair technology.

As an example, the Danish energy company Ørsted had to repair 2000 blades at the farm in Aholt [3]. Citing The Times," Hundreds of offshore wind turbines in UK waters need emergency repairs after they started eroding within a few years of being installed. Owners of the 175-turbine London Array wind farm off Kent, the biggest offshore farm in the world, and the 108-turbine West of Duddon Sands wind farm off Cumbria have applied to the Marine Management Organisation for permission to carry out urgent repairs" [4].

Wind turbine blade repair is typically quite expensive. Generally, operation and maintenance (O&M) costs make up 20–25% of the total levelised cost per kWh produced over the lifetime of the turbine, growing from be 10–15% for new to 20–35% by the end of the turbine's lifetime [5]. An out-of-service turbine can cost $800 to $1600 (USD) per day, with most repairs taking one to three days. If a crane is required to repair or replace a blade, the cost can run up to $350,000 per week. An average blade repair can cost up to $30,000, and a new blade costs, on average, about $200,000 [6]. The wind turbines built and established at the beginning of century, becoming old now. While most rotor blades carry post-installation warranties for one to two years, and with the expected service life of 15–20 years, this leaves much of the blade's maintenance outside the warranty window [6]. Typically, wind turbine blades require repair after each 2–5 years [8], thus, creating the permanent factor of costs increase for wind energy industry.

The wind operations and maintenance (O&M) market is expected to reach $27.4 billion by 2025 globally, with the compound annual growth rate of 8% [7]. With increasing part of off-shore technologies, high O&M costs are expected, due to higher turbine maintenance and higher logistics costs.

The philosophy of repair of large remotely installed moving structures is apparently different from approaches used for household appliances (where repair means often replacement) or cars (with its very dense, widely available network of repair stations), but also from aircraft industry (with, again, rather dense network of airports and repair services). Requirements toward the efficiency and costs of repair techniques for wind turbines are therefore rather high.

Fig. 1 shows the repair of wind turbines from rope, and makes clearly visible the challenges of the repair, even in on-shore location and relatively good weather.

Thus, the optimization of the wind turbine blade repairs is a very important task for the development of renewable energy in Europe. The repairs should become cheaper and more efficient, take less time, and, most important, the repaired structures should have performance at the same level as the initial structures. Further, the lifetime of repaired structures should in ideal case correspond to the lifetime requirements of the wind turbine blade (15–20 years, optimally even more).

In order to optimize and upgrade the repair technologies to the required level, computational modelling of the degradation, repair and post-repair service of the blades should be used. There are a number of studies, specific solutions and recommendations for the repair of wind turbine blades. In this paper, we seek to analyse **main directions of repair technology** for wind turbine blades and computational models of degradation and repair of turbine blades. The following aspects of the wind turbine repair are considered: general strategy, surface erosion and protective coatings, surface cracking and injection repair, patch repair and the optimal geometry and the adhesive material choice problems.

2. Repair of wind turbines: main steps

Investigations into technologies of repair of polymer composite structures has been intensified in the last decades, due to the growing application of lightweight polymer composites in structural applications, in aerospace and also thanks to the development of wind energy.

Technologies of repair of wind turbines are less mature than the repair of aircraft constructions, due to relatively recent launching of large wind energy projects, and also recent appearance of the blade repair problem [9]. On the other side, aerospace industry was based mainly on metallic structures over decades, and started to move over to composite parts recently [10]. As a result, some aerospace repair techniques for composites were inherited from metallic parts.

Among the main causes of wind turbine blade damage, one can list (following the lifecycle of wind turbine): manufacturing defects, transportation damage, assembly damage, installation damage, lightning strikes, environmental wear, rain, sand and contaminants caused erosion, bird impacts, thermal cycling, leading and trailing edge erosion, fatigue, moisture intrusion and foreign object impact, egress of moisture through the laminate skin structure, as a result of the surface damage, mechanical failure [11–13].

Fig. 1. On site repair of wind turbines. Courtesy of Mira Rope Access, http://www.mira-ra.com.

The repair techniques can be classified according to (a) severity of damage, and (b) region of damage, and (c) aerodynamic/flush requirements. According to the severity and kind of damage, the repair techniques can be grouped as follows:

1) Erosion repair and protection, typically by coatings, tapes, shields,
2) Non-structural matrix cracks, cosmetic repairs. Filling and sealing, resin injection for small surface cracks or small delaminations,
3) Structural damage: Plug/patch and scarf repair.

With view on the different regions of damage and structural repair (see Fig. 2), Heslehurst [14,15] identified four blade repair zones: zone 1 - leading edge (requiring flush repair), zone 2 - close to tip, behind leading edge, requiring aeroelastic semi-structural repair, zone 3- in the middle between tip area and root area, including trailing edge (which requires flush repair), zone 4 - near root and root, requiring semi-structural and structural repair. Heslehurst and colleagues also grouped the repair schemes into aerodynamic/aero-elastic/no-aerodynamic, and structural/semi-structural/non-structural (with aerodynamic structural repair as scarf repair, non-aerodynamic structural as patch repair).

The general algorithm of composite repair has been described in Ref. [11] as follows: 1. Finding damage, using visual inspection, observing the material property changes or NDI (non-destructive inspection) techniques, like ultrasonic methods, 2. Assess the degree and type of the damage, 3. Analyse the stress state in the damaged part and likelihood of crack growth, 4. Design the repair scheme, with view of availability of repair facilities, damage possible development, expected repair outcome and costs of repair, 5. Remove damage and prepare structure, 6. Fabricate repairing parts, 7. Apply/attach repairing parts, 8. Carry out post-repair inspection, 9. Document the repair, 10 Monitor repair zone.

3. Surface erosion: coating and surface protection

3.1. Types of defects and technological solutions

Leading edge erosion (LEE) is in fact the most common and expensive type of wind turbine blade degradation. Leading edge erosion is responsible for more than 5% reduction of annual energy production for wind turbines [16]. The impact of erosion on the rotor performance includes an increase in drag coefficient by 80–200% [17] and a decrease in lift coefficient for higher angles of attack. Further, even minor LEE can cause a potential lifetime loss of up to 7% [18].

The leading edge erosion of wind turbine blades depends on the loading conditions of the leading edge and surface of wind turbines (rain density, rain droplet size distribution, dust, flow velocity) as well as on properties of coating/gelcoat protection system (strength, stiffness, viscosity, damping) [19,20]. The removal and roughening of the leading edge surface takes place by the material fatigue and damage accumulation due to multiple liquid impacts by the raindrops [19]. Each rain droplet hits the surfaces, creating pressure on the surface, and wave propagation in the protective layers. This leads to the deformation and damage initiation, and fatigue and materials degradation over time. The surface erosion is realized as coating cracking, debonding, cracks in composite, material loss, roughening of surface (see Fig. 3a).

Other effects, which likely influence the leading edge erosion, are abrasion/cutting of coating surface (at low impact angle by raindrops), brittle fracture and plastic deformation of the surface (at high and medium speed of raindrops, respectively). Further, apart from direct deformation and stress wave propagation, lateral outflow jetting and hydraulic penetration are active erosion mechanisms [21].

Among solutions for repair of leading edge erosion [22], one can list protection tapes (from durable, abrasion-resistant polyurethane elastomers), protective coatings, applied with either a brush or casting, epoxy and polyurethane fillers. The specific solutions available on the market include the ProBlade Collision Barrier by LM Wind Power, KYNAR PVDF-acrylic hybrid emulsion coating by Arkema, 3M polyurethane coatings and W4600, polyurethane tape by Bergolin, Duromar, Enercon two component polyurethane coating system, Belzona 1331 and Belzona 1381 and many others [23]. ELLE (Ever Lasting Leading Edge), soft shell developed and marketed by Poly Tech, is a quite popular technique for surface repair (see Fig. 3b). Durable cover Blaid Protective Sheet, produced by IER Fujikura, is another solution for quick and seemingly reliable wind turbine blade surface repair [23,24]. However, the shells or shields, protecting the blades, may change the aerodynamics of wind turbine blades.

While most of these solutions indeed provide some protection for the leading edge, the solutions cant ensure the required lifetime for 15 … 20 years. Many coatings have the lifetime 6 … 8 years [25].

3.2. Computational modelling

Computational models of surface erosion of wind turbine blades are expected to provide both predictions of performance, lifetime and maintenance requirements of repaired structures, and serve as a tool for the optimization of the protection and repair technologies. While the degradation of structural parts, even with defects, can be relatively well described by the available tools of mechanics of materials and fracture mechanics, the description of surface degradation of wind turbine blades due to erosion is a separate, complex problem.

A number of quite complex multiscale and multi-physical models have been developed, from good phenomenological formulas (water hammer, damage threshold velocity, see Ref. [28]) to complex multistep models [19] including the full model chain from

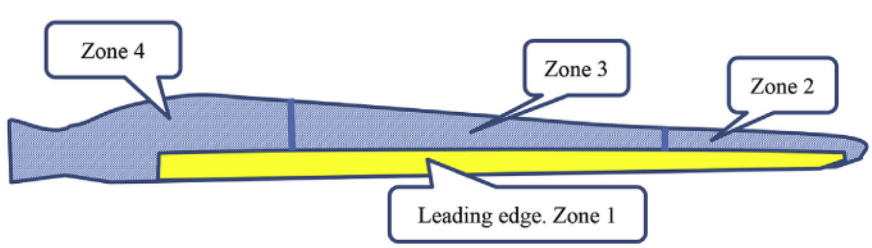

Fig. 2. Schema: four blade repair zones according to Heslehurst [14]. Zone 1. For both for aerodynamic and structural purposes. Always requires a flush repair. Zone 2. For aeroelastic purposes. Needs to be an aeroelastic semi-structural repair. Zone 3. Primarily for aeroelastic purposes. Not necessarily flush, but must not add significant weight. Zone 4. Not required to be aerodynamically smooth, but may need to the semi-structural or structural repair.

Fig. 3. Leading edge erosion and repair option. (a) Photo: Eroded wind turbine blade (Courtesy of Jakob Ilsted Bech, DTU) and (b) Application of coating on the eroded blade surface (from Polytech ELLE® - Leading Edge Protection, youtube).

turbulent flow, real rain statistics via the liquid impact [26] up to the fatigue damage studies [20].

Main steps of leading edge erosion modelling include the evaluation of loading (rain density, droplet size distribution, dust, flow velocity), modelling of impact contact between droplet/particle and surface (pressure on the surface, time, deformation and damage initiation; wave distribution, Rayleigh waves), modelling of materials degradation over time (coating cracking, debonding, cracks in composite fatigue, material loss, roughening of surface, estimation of lifetime).

Typically, the probability distribution of rain droplets proposed by Best [27] is used to describe the rain load [28]:

$$F = 1 - exp\left[-\left(\frac{d}{1.3I^{0.232}}\right)^{2.25}\right] \tag{1}$$

where d is the drop diameter in mm, I is the rain intensity in mm/h and F is the fraction of liquid water in air comprised of drops with a diameter smaller than d. In Ref. [19], a stochastic model of rain texture was developed. The number of rain drops in a given volume was supposed to follow the Poisson distribution (rain as homogeneous spatial Poisson process). A rain scenario (3D field of raindrops) was created.

For the estimation of pressure on the coating, the analytical water hammer equation, linking pressure on the surface with the liquid impact velocity and liquid density, is widely used. The water hammer equation in its classic and modified forms is as follows [28,29]:

$$P = \rho_0 c_0 V; \quad P = \frac{V\rho_l c_l \rho_s c_s}{\rho_l c_l + \rho_s c_s} \tag{2}$$

where P is pressure created during impact, ρ_0 is the density of the fluid, c_0 is the speed of sound in the undisturbed liquid and V is the impact velocity, and l and s as subscript refer to liquid and solid bodies, respectively.

Several more complex, finite element (FE) models of the **raindrop contact and wave propagation** in the coatings have been developed. Adler et al. [30] used FE analysis to simulate water droplet impacting thick compliant coatings. The deep craters development was observed in impacted polyurethane coatings which probably alters the evolving water drop shape. Further, it was shown that an impact by a single water droplet cannot initiate failure for polyurethane coating. Keegan et al. [31] used combined Eulerian/Lagrangian approach and Explicit Dynamics tool of the FE software ANSYS, to simulate the stresses in composite and the evolution of the droplet shape. Cho et al. [32] used Lagrangian approach to model the liquid impact and described thermodynamic states of the water by the Mie-Gruneisen equation. For the initial loading (first stage, the water drop behaves as a compressible body), water hammer pressure for estimated. For second stage, incompressible fluid behaviour, Bernoulli's stagnation pressure was used. In Ref. [19], FE transient stress analysis for various raindrop sizes was carried out. Entire layup structure and only gelcoat layer with rigid bottom were modelled and compared.

Fraisse et al. [33] developed a FE/Abaqus model of liquid (water) and solid (resin) impact into the coated laminate, and studied the internal transient stresses. The target laminate was modelled using the commonly used Eulerian domain. Water droplet specified in the Lagrangian domain, where the material was not fixed to the mesh but flew through it. It was observed that at the beginning (transient stage of the impact), the highest stress is localised under the contact surface, at the quasi-static stage the high stress region forms in the depth under the surface. Fig. 4 shows the deformation of droplet and stresses in the laminate under liquid impact loading.

For the fatigue damage and degradation of the coatings, again, there is a rather well justified analytical/phenomenological approach [28] and also a number of computational finite element models. In the empirical model by Eisenberg, Laustsen and Stege [28], a non-dimensional number of impacts required until erosion begins linked to erosive strength of the material that has been determined through rain erosion testing and the P is the pressure of the water droplet impact:

$$N_i = \frac{8.9}{d^2}\left(\frac{S}{P}\right)^{5.7}; \quad \dot{D} = \frac{qV_s\beta(d)}{N_i} \tag{3}$$

where S is the erosive strength of the material, P is the pressure of the water droplet impact on a coated material, and d is the droplet diameter, $\dot{D}$- rate of damage, q - is the number of droplets per cubic meter of air, V_s is velocity of the material in m/s, $\beta(d)$ is the impingement frequency as a function of droplet diameter.

Cortés et al. [27] modelled interface delamination, using a cohesive zone model of coating-substrate interface. In Ref. [19], fatigue damage at a given point was calculated as a superposition of damages from individual raindrops. The Miner-Palmer fatigue rule and the rainflow counting were used, and the damage accumulation was calculated as proportional to time. Slot et al. [20] presented a surface fatigue model as a removal of particles detached by fatigue arising from cyclic stress variations. Again, the Miner-Palmer fatigue rule and cumulative fatigue damage equation was used.

A number of very interesting anti-erosion protective coatings have been developed: for instance, nanoparticle reinforced polyurethane coatings [34,36], carbon nanofiber paper based coatings

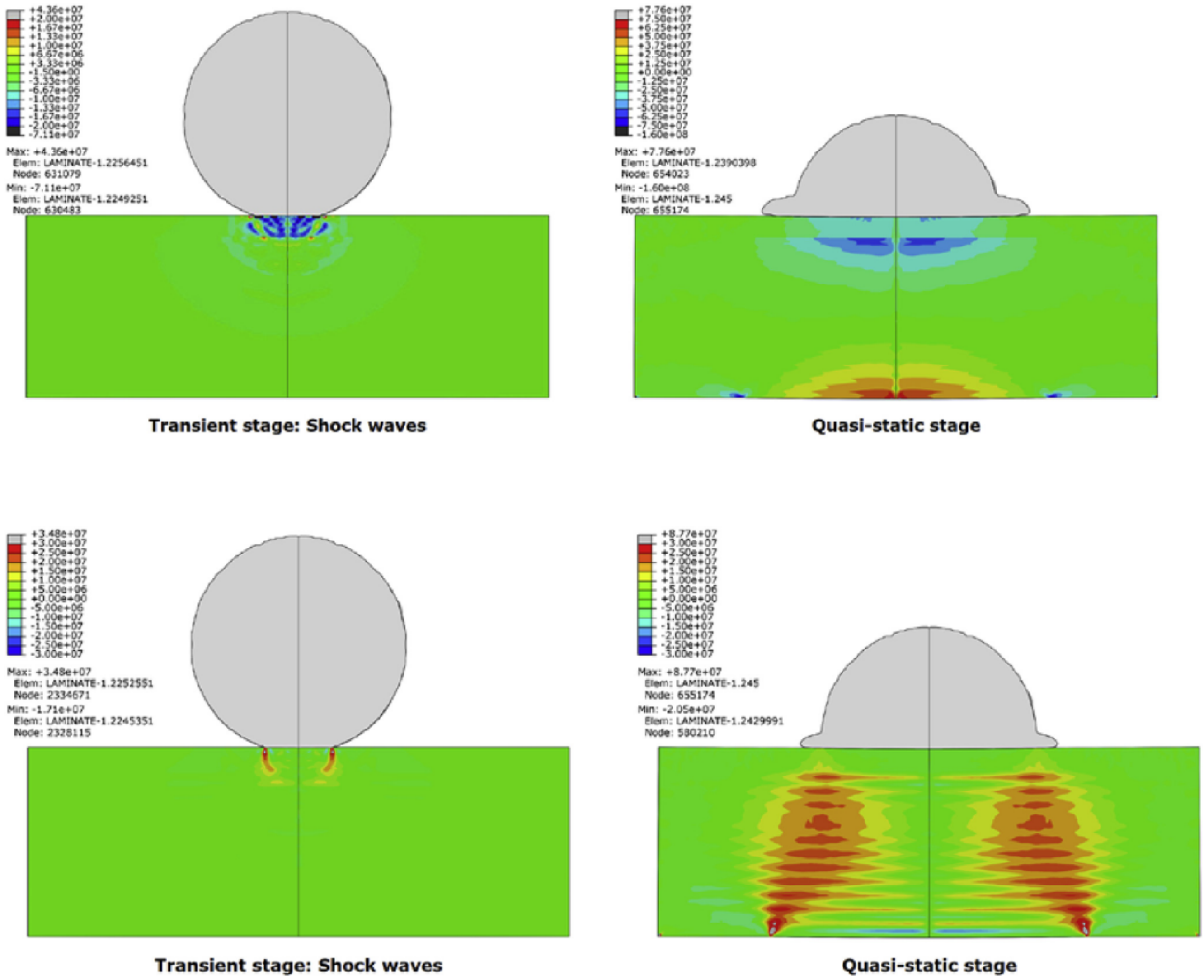

Fig. 4. Deformation of droplet and stresses in the laminate under loading (Reprinted from Fraisse et al. [33] with kind permission from Elsevier).

[35,38], organic-inorganic sol-gel produced hybrid coatings with nanoparticles [37], three-layered epoxy-polyurethane coatings [39]. Still, we are not aware that the above computational models of leading edge erosion have been used for the development and optimization of these or other protective systems. A new research project "DURALEDGE/Durable leading edges for high tip speed wind turbine blades" has started at the Technical University of Denmark, to optimize the structure of protective coatings of wind turbine blades on the basis of computational models [40].

Summarizing, one may see one common tendency with repair problems: the models should include both the scenario and mechanisms of wind turbine blade degradation (in this case, rain), materials aspects (viscoelastic and damping properties of coatings, in this case) and structural task (fatigue failure of the coating, debonding).

4. Surface and delamination cracks: injection repair

4.1. Injection repair

Another group of non-structural damage in composites are matrix cracks, minor delaminations and debonding. Fibers remain still undamaged and the structural integrity of laminates is not endangered. However, matrix cracks may be a source of further crack/delamination growth, also with moisture percolation.

The repair technology for such defects is realized by injection of resin into the cracks/holes. The low viscosity resin fills and seals the crack. Before injection, holes are drilled into the defect surface [11,47–51]. Then, the repair area is pre-heat, and the resin is injected; holes are temporarily sealed, pressure applied and resin is cured at room and then at higher temperature [11]. In Ref. [41], it is suggested to drill a fill and a vent hole to the opposite sites of the cracks, and then injecting resin into the fill hole until it flows from the vent hole.

For sandwich structures, as an example, potting repair is applied [11]. The damaged region (i.e., honeycomb) is filled with a potting compound (e.g., epoxy filled with hollow glass, phenolic or plastic microballoons, cotton, flox, or other materials [42]). The potting compound is heavier than the original core, and do not restore the full strength of the part.

In order to ensure full (or almost full) restoration of performance, external (doubler) patch can be applied on the sealed region in some cases [11], which can be either non-load-bearing, or fully or partially load-bearing.

4.2. Computational modelling

The formation of surface cracks, delaminations and debonding cracks is described in the framework of fracture mechanics and mechanics of composites [43]. The numerical methods of fracture mechanics of composites and layered structures are reviewed elsewhere [44–46].

The quality and efficiency of injection repair depends in fact on the resin flow properties, resin viscosity and bonding with the composites, but also on the design of drill holes [47,48]. Surprisingly, there is not many theoretical research works devoted to this subject.

Generally, resin infusion is modelled using Control Volume/Finite Element (CVFE) approach and the Volume of Fluid (VOF) method, and allows the simulation of resin flow behaviour, fill time and in some cases void formation [49,50]. The viscous resin flow is typically described by Darcy's law:

$$q = -\frac{k}{\mu}\nabla p \tag{4}$$

where q is the flux, k intrinsic permeability of the medium, μ-viscosity and ∇p is the pressure gradient vector. Hautier and colleagues [54] derived a formula for the time of infiltration of resin into a given delamination crack:

$$t = \int_0^L \frac{2\mu x}{K(x)\Delta P}dx \tag{5}$$

where L is delamination length, K is delamination permeability, $K \sim h^2(x)/12$, h is thickness of delamination,μ - resin viscosity, ΔP is pressure difference between injection pressure and pressure in non-injected zone. From pressure equilibrium (injection pressure plus capillary pressure is equal to residual pressure in non-injected zone), the resin front position was determined.

It is of interest to mention a related project at the Queen University of Belfast [51], which seeks to explore the potential of nanoreinforcements to enhance the injection repair performance by controlling the resin viscosity and bonding, as well as the effect of different drilling configurations on the performance of repaired structures. Pierce and colleagues [52,53] (the group, where this project is planned) developed a multi-physics process model for the simulation of infusion through a complex preform, based on combining a preform draping model with deformation-dependent permeability properties (based on Computational Fluid Dynamics package/FE software ANSYS FLUENT). The approach based on the VOF method, considered resin and air phases as interpenetrating continua. As a result, flow front profiles and shear stress distribution was obtained.

Summarizing, the computational tools for the simulation of infusion repair are available, and they are based on the viscous flow models, used in moulding analysis. The directions of improvement of infusion repair lie probably in the development of new low viscosity resins, controlling the adhesion and curing, but also nanoengineering of the resins, which can allow the better viscosity and adhesion control.

5. Structural repair, patches and scarfs

5.1. Repair techniques

Another group of repair techniques is applied when the composite fibers are damaged as well. Structural repair can be realized using bonded and bolted repair techniques.

In heavily loaded laminates with aerodynamic requirements, **bolted doublers** can be used, which are easy and faster to perform [55] (since no material removal is required), and ensure high level structural repair restoration [9]. Bolted doublers do not ensure aerodynamically smooth surfaces, create stress concentrations at the corners and edges. Still, according to Ref. [9], external doublers are suitable for wind turbine blade repairs (since a technician can access the damage regions only from one side).

Still, for the wind turbine blades, where aerodynamic properties are of critical importance, **flush repair** is the most common structural repair technique. Structural flush repair is realized by forming a joint between prepared repair area and the **repair patch**, which should fit exactly the area prepared for repair. The procedure includes the removal of damaged region, and bonding a patch with tapered (or stepped ends) to the parent laminate [11]. **Patches** are usually applied using wet lay-up technology and made often with unidirectional or biaxial uncured prepregs, usually, the same fabric, which is used in parent structure [55–57]. External patches are employed successfully to repair skins of thickness up to about 16 plies, can be easily applied under field conditions and recover strength to up to 50–100% of the parent material [11]. However, external patches can lead to eccentric load path, and, thus, bending in the patch and stresses in the adhesive and composite, and reduced buckling stability [11].

There exist several bonded repair configurations: scarf repair, stepped scarf repair (which both ensure aerodynamically smooth surface) and overlap repair [58]. For strength-critical applications, scarf joints are used [56]. Scarf repair can be the best choice for delamination in spar caps, other in-service damage, manufacturing defects (fiber waviness and dry spots).

Patches can be applied as **soft path** (composite patch co-cured with the adhesive at the same time), **hard patch** moulded (patch in pre-manufactured in mould and bonded), hard patch machined, and semi-hard patch (series of pre-cured composite laminates, each with several plies, interleaved with adhesives and bonded) [59]. In the case of hard patch (co-bonded pre-cured hard patch, bonded onto scarfed cavity using adhesive layer), the advantage is that patch is made from pre-processed high quality autoclave grade material. However, it is a two-step procedure (manufacturing of patch and bonding), and, thus, takes more time than the soft patch repair [58].

In Ref. [60], the authors proposed using pre-cured thin repair patches, with glue applied between them. These patches are formed to fit the area to be repaired, attached to the area, pressurized under atmospheric pressure. Then, the glue is heated and cured using a heater mat. This technology allows shortening the time to form and cure the repair patches.

The soft patch (in-situ co-cured soft patch configuration, with simultaneous curing the prepreg repair patch and adhesive) is one step procedure, however, it is more difficult to achieve high quality of the repair patch. For the soft patch repair, out of autoclave prepregs are used, and the patch is cured using vacuum bag in the presence of hear source [58].

Recently, several advanced repair technologies have been developed, which exploit **various heating or radiation effects,** to control the curing process in the composite. The requirement to control curing is related with the narrow time and temperature windows for blade repair. Wet resin systems need to be applied at temperatures above 15 °C and should be cured for at least 24 h [61]. Hardeners, heat blankets and infrared (IR) heaters can be used to ensure cure in cool weather.

In the company Gurlit [62], RENUVO™ Lapm Technology based on UV light from specially designed lamp equipment was developed to achieve full cure in just a few minutes. Further, the fibre reinforced prepreg (RENUVO PP) with a high performance matrix resin for outstanding laminate properties was developed. The plies of prepreg can be into the correct profiles, and then pre-consolidated to provide a required repair patch, or the prepreg can be applied in single plies to the repair. The UV curing resin is applied between the layers and between the patch and the substrate, and each patch is then cured using a high intensity UV source.

At the Iowa State University, the laser technology to improve wind turbine blade repair was proposed. The technology includes spraying glass powder into damaged areas, followed by laser heats to make them liquid and bond fibers [63].

In the EU project CORETO, on-site repair system was developed including combined heating-vacuum bagging system with heating blankets [64] and ultrasonic scanning system for defects detection. In another EU project, SkyServiceShop, mobile maintenance system Terra for wind turbines is developed, which includes special enclosure. This enclosure is sealed around the wind turbine blades, allowing to carry out repair independently on weather conditions [65].

5.2. Modelling

In the structural repair analysis, the following problems are often considered: stress distribution in repaired structures, effect of eventual defects and repair imperfections on the strength and/or lifetime of repaired structures, reliability and failure of repaired structures, optimization of patch and scarf joint configurations [66–71]. Typically, these problems are solved using the continuum and fracture mechanics methods. External patches can lead to eccentric load path, and, thus, bending in the patch and stresses in the adhesive and composite, and reduced buckling stability. Patch size and layup have strong influence on the stress concentration. Oversized patches can increase weight and also stress concentration [55]. Defected, partially bonded patches can lead to further destruction of the materials.

There is a number of analytical models of bonded repair. Generally, to analyse geometry of stepped and scarf joints, the so-called safe life and damage tolerance approaches are used [68]. In the framework of the **safe life approach**, the optimal scarf angle is determined from the maximum shear stress or strain as criteria for bond strength (for brittle and ductile failure of adhesives) [70]. Jones and Graves [72] considered the case of graphite/polyimide composites and of small scarf angles, and obtained from the stress equations a formula for the optimum scarf angle ensuring the maximum strength joints:

$$\theta = tan^{-1}\left(\frac{0.816\tau}{\sigma}\right) \tag{6}$$

where θ-optimal scarf angle, τ-adhesive shear strength, σ-laminate strength. The maximum stress failure criterion for small scarf angle is given as $S = \sigma/K_L = \tau/(K_A sin\theta)$, where K_L and K_A are stress concentration factors in the composite and adhesive. Wang et al. [68,73] proposed another formula $\theta = 0.5sin^{-1}\left(\frac{2\tau}{\sigma}\right)$.

Hartmann and Wang [75] derived and solved so called standard linear scarf joint equations, considering the equilibrium of an element of the adherend, and compared the results with finite element model. Effect of scarf angle on the adhesive stresses was studied in the simulations. Nishino and Aoki [76] developed an analytical model of patch on the basis of beam theory and concept of equivalent delamination, taking into account the delamination, large deflection and thermal stress, and validated the model by comparison with FEM model. Romilly and Clark [77] developed closed form analytical solution for one sided repair, to assess the effects of bending on failure of the repaired structure. Engels and Becker [78] studied the elliptical patch repair problem in the framework of the laminate theory, using the complex potential method.

In the framework of **damage tolerance approach**, a crack is assumed to be located in the scarf joint. Using the fracture mechanics approach, critical condition for the crack growth can be formulated, which allows the determination of the necessary scarf angle [68]. Fig. 5 shows the schema of scarf repair (a) and fracture mechanics idealization of scarf repair with disbond (following [68,73]). Wang and colleagues [73,74] derived the critical condition for the disbond growth for the parallelepiped part with inclined (angle θ) bonded line of length L, of which a part a is defect (crack, disbond). The condition, obtained on the basis of the Benzeggagh–Kenane (B–K) fracture criterion as the equation of strain energy release rate to a critical value is as follows:

$$G(a, \theta, L) = G_c \tag{7}$$

where $G(a, \theta, L) \sim a\sigma^2$ and $G_c = G_{Ic} + (G_{IIc} - G_{Ic})*const$, I, II, III mean fracture modes [44], G_c is critical value of energy release rate G.

Rose [79,80] developed an elastic model (isotropic plate with a one-sided bonded orthotropic elliptical patch), and evaluated the stress intensity for the repaired crack. Hart-Smith [81] presented an analytical models for analysis of tapered scarf and stepped-lap repair joints, which considers stiffness- and thermal mismatch of parts. Ratwani et al. [69] developed analytical techniques on the basis of complex variables method and obtained the stress intensity factors and crack opening displacements in plates with bonded repair patches. Ratwani [82] proposed a model of bonded repair as an infinite composite patch, adhesively bonded to an infinite cracked unstiffened sheet, with the adhesive considered as 2-dimensional shear springs. The model allows the estimation the stress intensity solution, for the repaired crack, the adhesive shear strain in the bond line and the load in the stiffened area [79]. Vlot et al. [83] implemented the model into software CalcuRep®, and extended it to include the thermal effects due to curing.

A number of **finite element models** of bonded joints have been developed [83–95]. The finite element models are used to find the location of highest stresses, to evaluate the effect of bonding defects on the stress distribution, to optimize the scarf angle and generally geometry of the patch/scarf on the stress distribution. The strength of composite scarf joints is analysed and predicted, using adhesive and composite failure criteria [89].

Bendemra et al. [91] developed 2D and 3D finite element models of tapered scarf and stepped-lap joints, and carried out parameter studies. The authors observed that the introduction of overplies (0° plies) improves protection and stiffness at joint tips, and an overply lap length was introduced to prevent further increasing peak stresses. Further, the authors demonstrated that stepped-lap joints exhibit higher stress concentration than tapered scarf joints. Campliho and colleagues [92] developed a 3D FE model of adhesively bonded single- and double-strap repairs. Damage in the adhesive layer was simulated, using the mixed-mode (I + II + III) cohesive damage model implemented with the interface finite elements. For stepped joints, Wang and colleagues [68] developed a finite element model of material behaviour under compression loading and impact. They observed that the multistep repairs exhibit higher stress concentration than scarf repairs.

Gunnion and Herzberg [90] studied the effect of the variations of the adhesive thickness on the stress distribution in the bind using 3D FE model. It was shown that the level of the peak adhesive shear decreases with increasing scarf angle. Raju et al. [94] developed 3D FEM model and characterized patch repair effectiveness by the stress intensity factor (SIFs), taking into account both thermal and mechanical load.

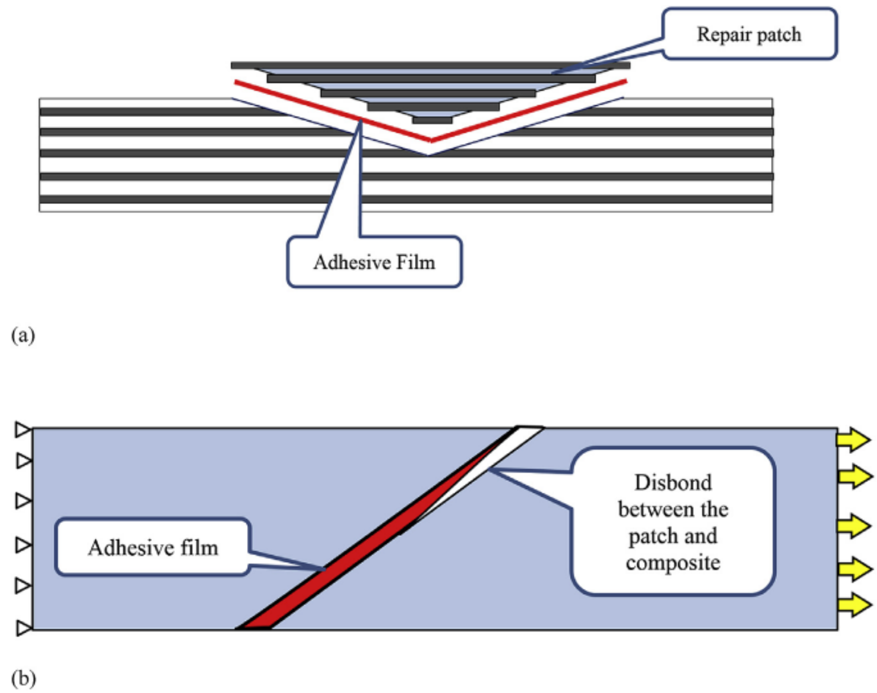

Fig. 5. Schema of scarf repair: General view (a) and fracture mechanics idealization of scarf repair with disbond (b) (following [68,73]).

There is a tendency to apply multiscale models to the repair problems, covering both the materials science aspects (adhesives, see section 6) and the structural/fracture mechanics aspects [44]. Apparently, this approach is promising, and can be a basis for comprehensive repair optimization (both at the materials and structural level).

Summarizing, one can state that the analytical and computational models of structural repair are rather well developed, thanks to the available strong computational and analytical tools (continuum mechanics, fracture mechanics, damage mechanics, laminate theory). Still, most of the models consider stress and strain distribution in bonded and bonded with defects structures. In typical case, it is enough, and the assumption that the repair creating too high stresses under single static loading is also unacceptable for 10 years service time, under high humidity, random cyclic loading and other physical service conditions, is well justified. Further development of these models will be the combination of the structural geometrical optimization with the materials design and development (e.g., new adhesives, new composites for patches) and taking into account the real service conditions.

6. Adhesives, resins and surfaces

6.1. Available solutions

Enhancing mechanical and physical properties of adhesives is an important source of improving the repair quality. As for now, the challenge with ensuring the required adhesive properties is one of the weak points of repair technologies of composites. The on-site repair of wind turbines is carried out under difficult weather conditions, on ropes, and under time pressure, and is limited to a rather narrow weather and time window [96]. As shown in section 5.2, the repair quality is very sensitive to the possible defects in the adhesives.

There are three major groups of adhesives used in composites bonding: urethanes, epoxies and methacrylates [97]. Epoxies demonstrate high strength, especially at elevated temperatures and in harsh environments. Urethanes are very adjustable, have wide windows of formulation variabilities, their adhesive properties don't degrade over time, can range from very ductile to relatively stiff (only 50% elongation), highly resistant to chemicals. Methacrylates cure very quickly, dissolve many contaminants, ensure excellent fatigue life under repeated impacts, and can reach the strength of epoxy, with greater ductility [97,98]. Methyl Methacrylate adhesive by the company SCIGRIP (USA) was demonstrated to have strength and high temperature performance (up to 66 °C) close to that of epoxy, but with better toughness at cold temperatures and drastic improvement in fatigue resistance [99].

Important **parameters for the development of adhesives** are bond strength, mixing method, surface preparation requirements (like special cleaning or conditioning), pot life, time to full cure, health and safety. Especially for wind turbine blades, the optimal adhesive application on very large surface areas and minimise labor intensive assembly processes has been identified as a key factor.

Traditional epoxy adhesives take 18 … 24 h to fully cure, which is surely too long. Several techniques to overcome the **problem of curing time** and to achieve required adhesive performance have been developed. Fast hardeners can be used to accelerate cure time at lower temperatures, but resin could gel quickly [96]. Here, it is of interest to mention activities on curing in aerospace industry. Several advanced developments are mentioned in Ref. [100]: rapid-cure resin system patented by TRI/Austin (Austin, Texas) and developed for the U.S. Air Force Research Laboratory (Wright Patterson AFB, Dayton) (with alternating layers of the acrylate resin and woven fiberglass fabric cures applied to fill the hole, and following bagging, cures in 20 min), electron beam (EB) or X-ray curing, deep-core curing method by Cornerstone Research Group Inc. (CRG, Dayton, Ohio) using photo-delivery system. These techniques allow the curing without (EB) or with acceptable level of heating [100].

Henkel developed two-component, structural polyurethane and MMA adhesive for blade bonding that cure at room temperature

[101]. Plexus offers two-part low viscosity resines, with single-step mixing/dispensing, to be used for drill-and-fill repairs (of internal debonding, delamination, or adhesive voids), lightning, transportation damage, with rapid curing and little surface preparation.

Another approach is to use **thixotropic materials** (in general two-component adhesives) for bonding the blades so that the resin and hardener develop 'non-slump' properties very quickly after mixing [101,102]. It can be achieved by using a thixotropic agent, such as fumed silica (so called 'physical thixotropy.'), or by using "chemical thixotropy concept" (when the protonation of a high molecular weight cationic polymer by acid entities present on the surface of special fillers occurs and the system develops almost instantaneously a physically cross-linked structure, when the resin and hardener are mixed together) [101]. The 'physical thixotropy' ensures a lower final viscosity than chemical one, and can be destroyed at high shear rate and is not recovered rapidly. Araldite developed Araldite AW 4856/Hardener HW 4856's chemical thixotropy based two-component structural adhesive for wind turbines, which ensures higher fracture resistance over standard epoxy wind turbine blade adhesives.

Further, the use of **UV cured adhesives** is considered as one of the ways for fast curing. Lu [55] developed new UV-based adhesives which included photoinitiator (PI), epoxy and different solvents, and applied them to pre-cured patch and soft patch repair, and VaRTM process. It was shown that UV adhesives can be efficiently used in in-field repair. Gurit proposed RENUVO Multi-Purpose System (MPS), a mono-component rapid UV curing resin, which is available in summer and Winter versions, to ensure the same low viscosity for cold and warm times. The resin has easy sanding characteristics and can be cured (as an example) within 180 s (for up to 10 mm thick sample) [62].

Another technologies of controlled curing is based on **electrical curing**, i.e. resistive heating of a steel mesh embedded between two layers of structural adhesive. The process can be adapted to field repairs of composites by using a low voltage power supply [103].

An important subject for the repair technologies is the **surface preparation**, to improve wettability, enhance surface free energy and chemical inertness [104,105]. The methods include manual polishing and mechanical abrasion, grit blasting, corona discharge, plasma modification, peel-ply and chemical etching techniques [106]. In Ref. [104], the authors proposed the surface pre-treatment by laser ablation, and demonstrated that this technology ensures higher roughness, more functional groups, increased surface free energy and wettability and enhanced bonding performance relative to the polishing surface treatment. Further, the cohesive failure mode was observed in this case, as differed from adhesive failure in polish-treated specimen.

6.2. *Modelling of adhesive curing*

One of the problems of optimization of the bonding repair at the materials level is the computational analysis of curing stages of adhesives. The differential equation model of curing developed by Kamal [107,108] is widely used to predict curing times and optimize curing cycles. The equation connects the rate of cure $d\varphi/dt$ to the temperature T and degree of cure φ (defined as heat generated up to time t divided by total heat of reaction at the end of cure cycle),

$$\frac{d\varphi}{dt} = \left[A\, exp\left(\frac{\Delta E_1}{TR}\right) + B\, exp\left(\frac{\Delta E_1}{TR}\right)\varphi^m\right](1-\varphi)^n \tag{8}$$

where *T*-temperature, *A, B, m, n* - constants of the material, ΔE_{12} —activation energies. This equation is solved together with the heat distribution equations. Martin and Salla [109] proposed an analytical model to simulate the curing process of unsaturated polyesters with both nth-order and autocatalyzed kinetics [110]. Tsamasphyros and colleagues [110] solved the Kamal equations analytically, and applied the results to predict and optimize the duration of curing in composite patch repair. More complex, physically-based curing models have been developed in works by Steinmann, Lion and others [111–123]. Hossain et al. [113] modelled the curing as a phase transition from a viscous fluid to a viscoelastic solid using a constitutive relation based on a temporal evolution of shear modulus and relaxation time. Klinger et al. [116] developed a continuum mechanical model for the curing of polymers, based on the free energy density functional with deviatoric and a volumetric part, and multiscale finite element method. Papathanassiou et al. [124] used Kamal equations and genetic algorithms to optimize the patch repair techniques, seeking to ensure temperatures high enough to initiate curing and still as low as possible, ensure sufficient degree of cure and maximum heat generation rate.

For the soft patch technology and out of autoclave, vacuum bag only curing, Bujun [58] simulated the transient heat transfer phenomena during the curing process of patches and adhesives. Using the cure kinetics model of the material developed by Kratz et al. [125] the author identified the cure cycle requirements.

A promising direction of improvement of adhesive performance is the **nanomodification of polymers** [126]. Addition of nanoparticles can enhance performance of adhesives [127], improve the mechanical properties, glass transition temperature, conductivity, resistance to the fracture, fatigue resistance, the peel and lap shear performance [127]. Scarselli et al. [128] developed epoxy adhesive with nano-graphite particles, and simulated the adhesive strength using the cohesive zone model, observing drastically enhanced performance. Prolongo et al. [129] proposed a modification of epoxy resin by the introduction of carbon nanofibers (CNFs), and demonstrated that CNFs addition slows down the curing reaction and lowers contact angle of adhesives.

In the more general sense, the development of adhesive polymers is carried out in the framework of **general computational design of materials**, which can be carried out using molecular mechanics, molecular mechanics and multiscale modelling approaches [44,130]. These approaches allow analysis of polymer chain behaviour, inter-chain sliding between polymer chains, hydrogen bonds, crosslinking and other basic effects [132–134].

7. Conclusions

Repair of wind turbine blades is an important task for energy technologies development, which at some stage can become decisive for the future of renewable energy. In order to optimize and to improve the repair techniques, the **scientific approach** to the repair is needed, which also includes the computational models of various aspects of the wind turbine blade repair and can be used as tools and basis for the repair optimization. In this paper, a short overview of main repair techniques for wind turbine blades and the related problems of computational mechanics is presented.

The current state of computational modelling of repair techniques includes the modelling of.

- wind turbine degradation and defects formation (typically done with mechanics of materials, fracture and damage mechanics),
- attaching new elements (shield, coatings, patches) (typically done, again, with mechanics of adhesively bonded structures),
- flow, distribution, curing and formation of adhesives (mechanics of viscous flow, phase transitions, but also molecular mechanics and polymer theory),
- behaviour and performance of repaired structures (again, mechanics of materials with defects and layers).

Apart from the traditional ideas of repair ("glue a patch to wounded place"), a number of new ideas for the repair of wind turbine blades developed and used now, among them:

- Structured, micro-architected patches and coatings (multilayered, particle reinforced, hybrid [34–39]),
- Structured, multielement patches, assembled during the repair [60],
- Physically controlled, fast adhesive curing (UV, electrically, by additives) [55,103].
- Nanoengineering and nanomodification of the coating, patches, adhesives to control their properties [35,37,128,129], and so on.

The main computational mechanics tools for the analysis of repair include:

- Contact and impact mechanics (for the estimation of the result of damaging interactions, like bird impact, rain erosion, others) [19,33],
- Fatigue and fracture modelling (reliability of bonded structures [92], lifetime prediction [20])
- Fluid dynamics (rain impact [33], adhesive curing modelling [113]) and phase transition theories [113] (curing), resin infusion [54],
- Laminate theory (patch modelling [78])
- Multiscale RVE (representative volume element) models (combining structural and materials aspects; nanoengineered constituents) [129,131].

Both the degradation of wind turbine blades during service (caused by surface erosion, surface cracking, delamination, fiber failure) and repair procedures (coating, patch and scarf attachment, injection and curing of adhesives) represent multiscale processes, controlled by geometrical (e.g., blade, patch, scarf geometries), mechanical (strength of composite, strength of adhesive, coating, stress distribution) and physical/chemical effects (curing, viscous flow, humidity, temperature and UV effects). Apparently, the best strategy would be the multiscale modelling, allowing optimization of both adhesive materials, regimes of their application, structures and geometries of new elements to be attached/replaced.

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