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Repair of Wind Turbine Blades: Costs and Quality

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Abstract. Repair and maintenance operations of wind turbines constitute a significant part of costs of wind energy. In this paper, technologies of structural repair of damaged wind turbine blades are reviewed. Costs of repair, and technological contribution to the costs are discussed. Technologies of repair are compared, including hand layup lamination, vacuum repair with hand layup and infusion, ultraviolet curing and high temperature thermal curing systems. Computational models of repaired blades, and curing as kinetic process are presented. Void formation during repair and curing, and the void influence on the post-repair reliability of blades is discussed.

1. Introduction

In order to realize the renewable energy transition, large expansion of wind energy generation is planned in next decades. Wind energy is one of the fastest growing renewable energy technologies. At the same time, wind turbines installed at the beginning of this millennium approach the end of their lifetime in 2020-2030. Operation and maintenance (O&M) costs for ageing wind turbines increase with time [1], [2]. Especially, the maintenance costs are 2 to 3 times higher for offshore wind turbines, than for onshore wind turbines.

The often observed damage mechanisms include leading edge erosion [3], [4], adhesive joint degradation, trailing edge failure, buckling and blade collapse phenomena. Critical areas of wind turbine blades include the outstanding and high velocity region (blade tip, leading edge), transitional and tapered areas (plydrops, root region) and interface regions (adhesive joins in spar/shell, trailing edge) [5], [6].

In [7], a survey was carried out among the wind turbine service teams, about frequency of observed damage mechanisms in different regions, in Europe and India. Figure 1 shows results of survey of blade service companies, presenting frequency of wind turbine blade failure mechanisms [7]. Leading edge erosion and lightning strikes are the two most often observed damage mechanisms.

Several projects are underway at DTU Wind Energy, which seek to improve the blade protection, prevent the blade degradation and optimize the repair technologies. In this presentation, degradation mechanisms of wind turbine blades, repair of wind turbine blades, costs and technologies of repair are discussed.

2. Cost evaluation of repair technologies

The model for estimation of repair contribution to levelized cost of energy (LCOE) of wind energy has been presented in [1]:

$$LCOE = \frac{\sum (CAPEX_n + OPEX_n)/(1+r)^n}{\sum AEP_n/(1+r)^n} \tag{1}$$

where AEP – annual energy production, r – discount rate, n – year. OPEX is determined as:

$$OPEX = OPEX_{fixed} + OPEX_{variable} = OPEX_{fixed} + C_{PM} + C_{CM} \tag{2}$$

where $OPEX_{fixed}$ – fixed cost elements, not depending on failure and technologies, e.g. rental, administration, insurance, CCM – costs of random failures (unplanned maintenance), C_{PM} – cost related to regular, planned maintenance activities (inspection, monitoring, control). The annual costs of unscheduled maintenance/failures can be calculated as the cost of repair and downtimes, summarized over amount of repairs:

$$C_{CM} = \sum_{N_F} (c_D T_D + C_{rep1}) \tag{3}$$

where c_D – costs of downtime per hour, T_D – duration of downtime, N_F – amount of failures per year, C_{rep1} – costs of single repair. The single repair costs can be calculated:

$$C_{rep1} = C_{trans} + C_{equip} + C_{labor} \tag{4}$$

where C_{trans} – costs of transportation, C_{equip} – equipment and materials, C_{labor} – costs of field labor. $C_{labor}=Mt_{rep}c$, where M – size of team, c – hourly costs, t_{rep} – time of repair. Thus, the costs of annual unscheduled maintenance activities, repair of failures, can be estimated as:

$C_{CM}=\Sigma_{N\_F} (c_D T_D+C_{trans}+Mt_{rep}c+C_{equip})$ (5)

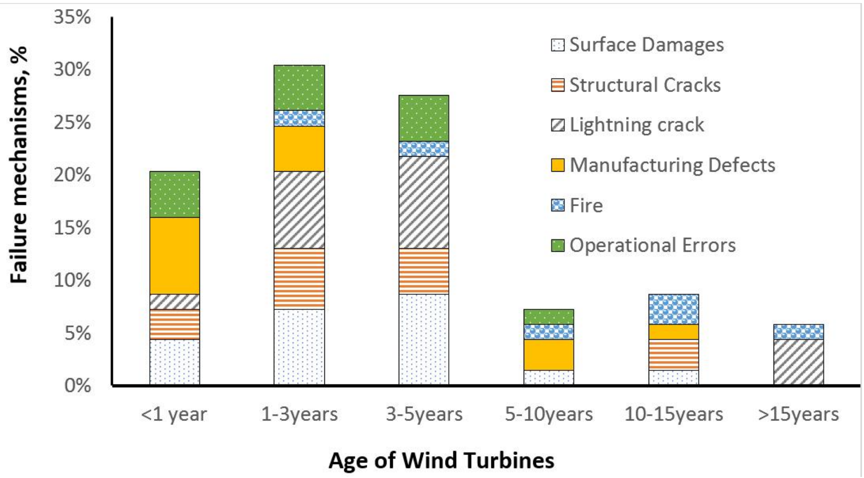


Figure 1. Results of survey of blade service companies: Frequency of wind turbine blade failure mechanisms depending on the age of wind turbines. Reprinted from [7].

The main parameters related to repair technology are: "input parameters" – duration of work t_w , size of team M, equipment and materials costs C_{equip} , and the "output parameter" – amount of repairs N_F (or inversely, average time between repairs, $1/N_F$). The onsite repair of wind turbine blades can last several hours, and is rather expensive. The formulas above allow the evaluation of saving potential of different technologies. One of the way to reduce the costs of the blade repair is to optimize the curing technology, for instance, by using ultraviolet (UV) curing or high temperature curing. For instance, by replacing the traditional heat curing by UV curing (i.e., 20 minutes instead of 4 hours), would allow to reduce the costs (C_{labor}) by ~ 9 to 10 times [1]. However, a formation of defects (void/trapped air, low cured regions) in cured adhesives is possible in this case, due to quick curing and inhomogeneous heat distribution in the adhesive layers. Thus, the challenge of repair of wind turbine blades lies in satisfying both the requirement of fast repair (to reduce the repair costs, by using quick bonding and curing technologies) and the requirement of high post-repair reliability.

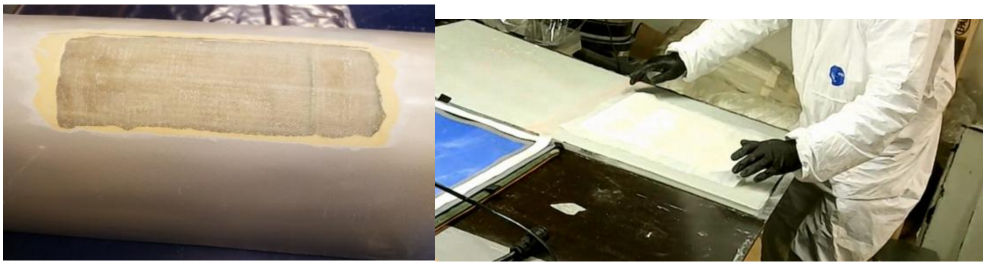


Figure 2. Repaired leading edge of the wind turbine blade (left, demonstration of composite repair by Danish Blade Service Aps, reprinted from [8])and test repair of composite plate (right)

3. Testing various repair technologies

In this study, the practical testing of several available repair technologies is carried out. Laminate plates were grinded to mimic the removal of a damage, and then repaired, using various repair technologies, available on market. The repair of blades was carried by an experienced repair technician with many years of practical repair experience of both offshore and onshore wind turbines. The repaired plates were tested in tension both under static and fatigue loading , and the structures of the repaired samples were investigated by computed X-ray tomography (CT scanning) .

The following technologies have been used: Hand layup lamination (traditional repair technology, with putting resin on the laminate and hand rolling afterwards) (HL); Vacuum repair with hand layup (V1): after the resin is put on the laminate and vacuum is applied, to get all the resin through the laminate and to get all the air out of the laminate; Vacuum repair with infusion (V2): dry laminate is put on the repair and vacuum is applied to pull the resin through the laminate with vacuum pressure Ultraviolet repair (UVh1): handheld, portable, continuous UV spectrum curing; ultraviolet repair (UV2): stationary device; high temperature thermal curing (HTC).

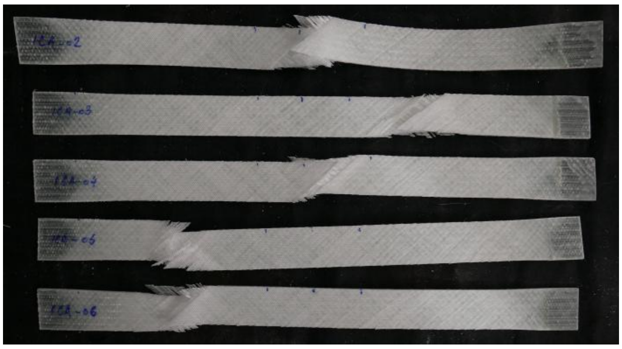


Figure 3. Tensile samples, after the failure [9].

All samples including the unrepaired reference plate was tested in uniaxial tension until failure. 3 samples were tested per each case. From each plate 4 samples where cut from the center on the scarf repair, with the dimensions 300×25mm. Due to the large elongation sample length had to be reduced to not cover the entire repair but only the center of patches. Samples where gripped using mechanical jaws and a test speed of 2 mm/min was applied.

Figure 3 shows the test samples. Figure 4 shows relative maximum failure stress for various repair cases, normalized by the failure stress of virgin (unrepaired) samples [9]. From the data on Figure 4, one can draw the following conclusions. Technologies with application of vacuum lead to stiffer repaired structures, which lead however to lower maximum stress. High temperature curing leads to softer structures, but with higher maximum stress. Ultraviolet curing technologies ensure average stiffness, and high strength.

The damaged samples were investigated by performing X-ray tomography at different locations in order to characterize the failure mechanisms. The air bubbles within the X-ray tomography reconstructions were segmented by setting a constant threshold. Figure 5 shows the distribution of voids in resin and voids in fiber bundles, for vacuum repair with hand layup (V1), hand layup lamination (HL) and ultraviolet repair, hand held (UVh1). Red areas show air bubbles within resin rich regions and turquoise areas show the air bubbles located within the fiber bundles. A volume of 1108 × 68 × 129 pixels with a pixel size of 9.64 micrometers were analyzed for all the samples. For vacuum repair with hand layup, many small air bubbles in the bundles and large air bubbles between bundles horizontally can be seen. For hand layup lamination (HL), less small air bubbles in the bundles, and a few large and more spherical air bubbles are seen. For handheld UV curing, both small and medium sized air bubbles in the bundles, and large and more spherical air bubbles between bundles are available. More details on this experimental program are given in [9]

The main conclusion of this section (and a more detailed study presented in [9]) is that different technologies of blade repair lead to different porosities in the adhesives and scarf. General observation is that all the technologies give relative good quality of repair with view on static strength. With view on fatigue strength, vacuum repair with hand layup (V1) shows the lowest performance, while handheld UV curing (UV1) shows the best lifetime. High temperature curing shows average level.

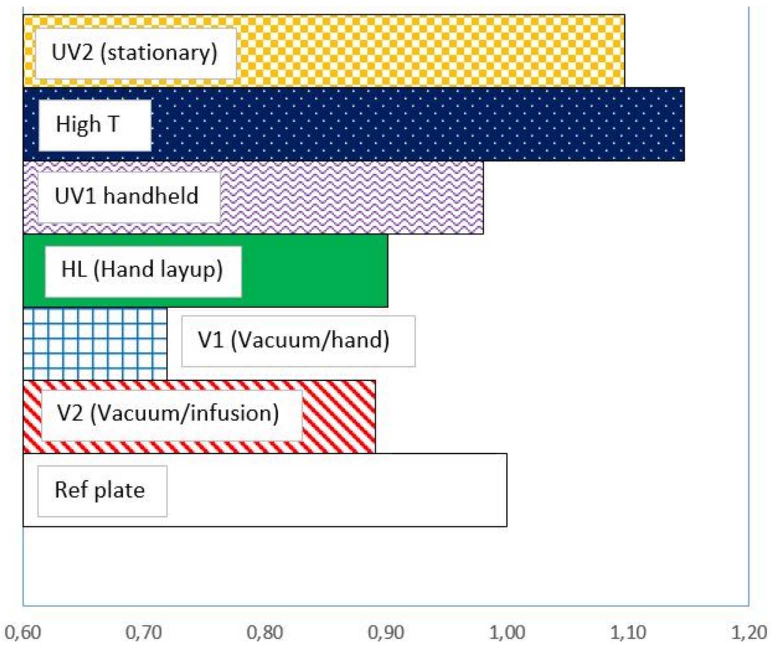


Figure 4. Comparison of different repair technologies. Relative maximum failure stress for various repair cases, normalized by the failure stress of virgin (unrepaired) samples (Reprinted from [9])

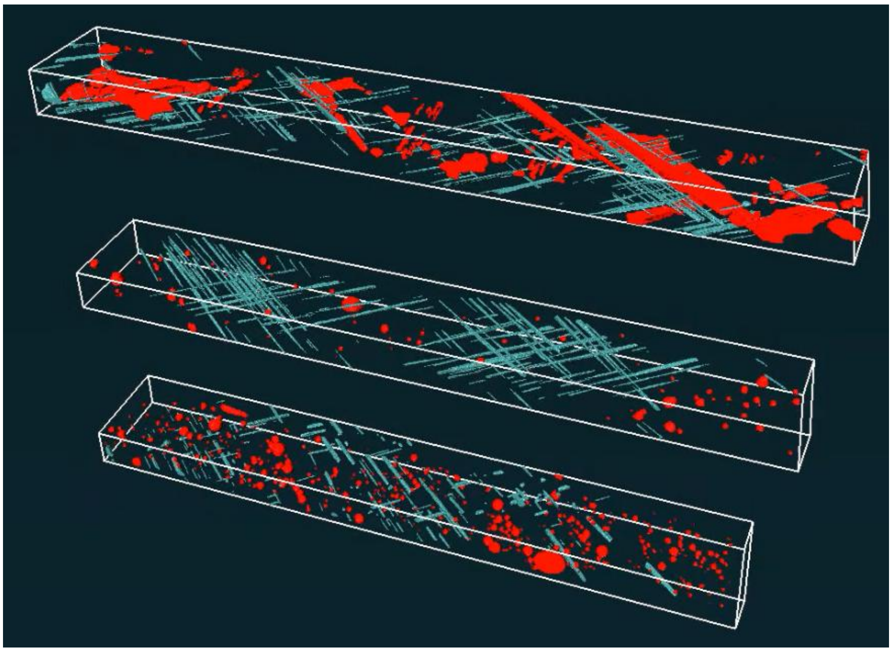


Figure 5. Segmented X-ray tomography reconstructions of 3 typical repaired structures. Voids in resin (red) versus voids near fibers (turquoise), for vacuum repair with hand layup (V1, upper), hand layup lamination (HL, medium), UV curing handheld (UV1, lower figure) (Reprinted from [9]).

4. Computational modelling of patch repair of wind turbine blades

Suboptimal, defected repair can lead to eccentric load path, bending in the patch and stresses in the adhesive and composite, early failure of wind turbine blades and necessity of early follow-up repair.
It is important to estimate the influence of various repair factors on the stress distribution, lifetime and reliability of post-repair structures and develop recommendations toward the optimal repair conditions.
In a number of works, analytical and computational modelling of the structural (patch) repair was carried out. The methods used include equilibrium analysis, beam theory, damage tolerance approach, fracture mechanics and finite element (FE) models.

In [8], computational model of repair of wind turbine blades has been developed. 3D finite element (FE) models of repaired blade structures are generated automatically in ABAQUS ® program, taking into account patch/adhesive/composite properties. The models allow carrying out computational studies of the effect of adhesive and coating properties, patch layout, repair geometry, parent and patch composite structures on the stress distribution in post-repair wind turbine blades.

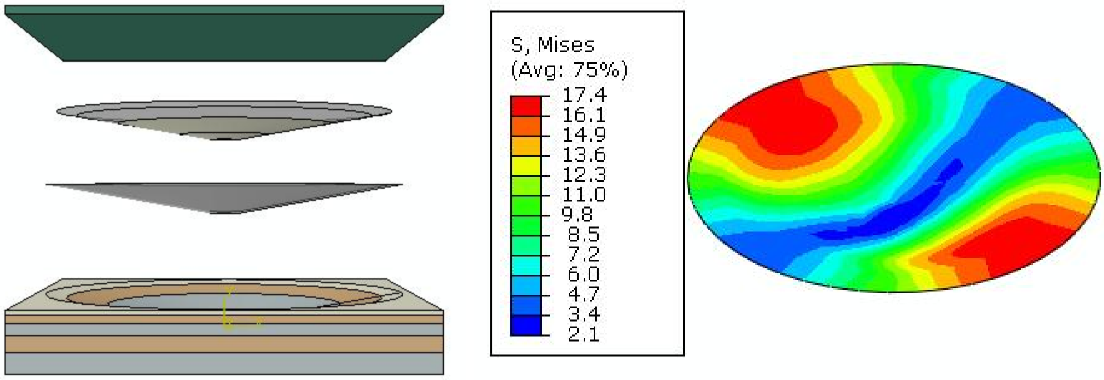
Figure 6 shows the von Mises stress in the adhesive layer at the scarf angle 10^{o}. It can be seen that the highest stressed region of the adhesive is in the upper part, adjacent to the coating.

One of the most typical defects in adhesives are voids, which create local stress concentration [1], [8], [11], [5]. Voids or micro voids in adhesives can form during curing by mechanical trapping of air, diffusion of dissolved water and gases in the resin, formation of volatiles and increase of resin stress due to the chemical shrinkage under constrained boundary conditions [10].

In order to analyze the effect of voids in the adhesive numerically, a submodelling approach was used. A number of spherical voids were generated in the submodel by creating spheres, copying, moving and Boolean cutting from the adhesive parts in the ABAQUS ® code.

Figure 7 shows a schema of placement of submodel representative volume element placed in the adhesive layer of the model. One can see that the voids create local stress concentration, increasing local stresses ~ 2 to3 times higher than in the material around. The increase of the void radius by 5 times (from 0.15mm and 0.75 mm) leads to the increase of the stresses near the voids ~12 to 23 MPa.

The main conclusion from this section is that the high local stresses in repaired structures are observed in the region near the blade surface, and can be drastically increased due to local porosity.



(a) (b)

Figure 6. Stress distribution in the adhesive layer (from [8])

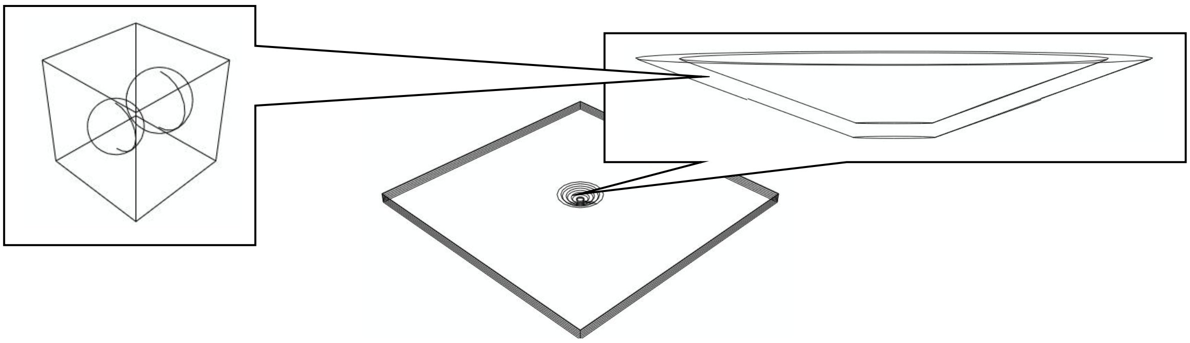


Figure 7. Schema: Voids in the adhesive between patch and the blade seen under microscope (Reprinted from [8])

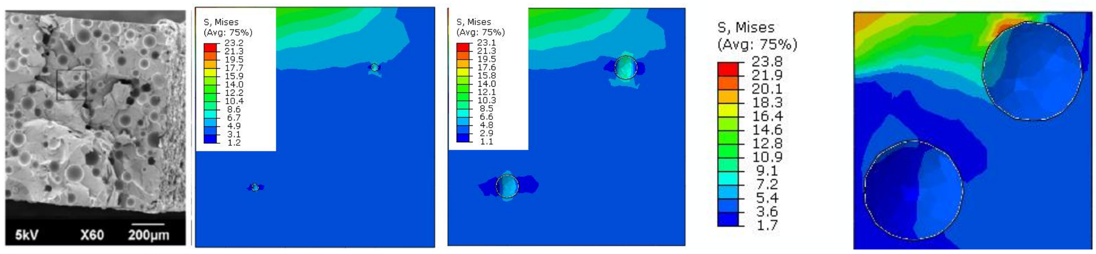


Figure 8. Stress concentration on voids in the adhesive layer: (a) voids in adhesive layer, reprinted from [8] with kind permission from Elsevier) and Mises stress distribution in the adhesive layer with small, medium and large voids, 0.05 mm, 0.15mm and 0.75 mm

5. Curing kinetics and void formation during repair

In the sections 3 and 4, it was observed experimentally and demonstrated numerically that voids/pores/defects in repaired wind turbine blades can drastically reduce the post-repair blade strength, just by increasing local stress concentration. In this section, the formation and growth of voids and development of residual stresses in wind turbine blades during the repair is analysed, using the approach from [10]. The entire curing regime has been divided into two parts based on the gel point of the resin used. _Autocatalytic cure kinetics model is developed and used to obtain the evolution of the degree of cure for a given temperature cycle [12]. This gives an evaluation of the rate of cure of the resin system and the total time taken up to gelation and complete cure. The cure data is then used in a modified WLF (Williams-Landel-Ferry)-type viscosity evolution model in order to obtain information regarding the viscosity of the system during the cure process. This is crucial in obtaining the gel point which is the stage at which the resin system stops flowing and beyond which residual stresses are set up significantly. A single-void growth model is then used to obtain the final void radius at the gel point. A combined model which includes both visco-mechanical and diffusion effects is used [13]. The voids do not grow significantly after the gel point as the system achieves a nearly solid state. This final void radius is then used to model a randomly distributed void system within a representative volume element (RVE). The RVE is incorporated into a scarf model from [8]. The scarf model, along with the submodel containing the voids, is then subject to the thermal cycle as per the cure parameters used. The average and maximum residual stresses in the submodel at the end of the cure process are noted. This gives a relationship between the cure parameters, void data and the residual stresses developed in the adhesive patch.

The steps involving analytical modelling are performed using MATLAB. The numerical analysis of the scarf model with the submodel is done using Abaqus.

Figure 9 shows a schema of the heating blanket during thermal curing of scarf/blade. Figure 10 shows schematically single and two ramp temperature cycle in curing [10].

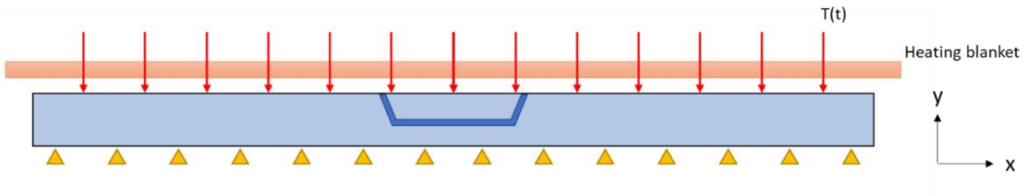


Figure 9. A schematic of the loads applied on the scarf model. Reprinted from [10]

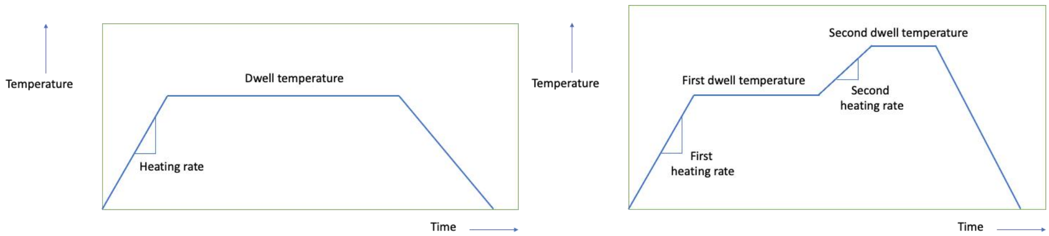


Figure 10. Single (left) and two ramp temperature (right) cycle in curing. Reprinted from [10]

It was observed in the simulations that the temperature cycle affects both the time taken for complete cure and the residual stresses developed in the adhesive. Single-ramp and two-ramp temperature cycles are studied. Increasing either of the ramp temperatures is found to decrease the time taken to cure significantly. However, having a higher dwell temperature after the first ramp results in a larger final void size. The residual stresses due to temperature changes in the cure cycle and chemical shrinkage are obtained using a numerical analysis of the scarf repair patch. The model in this section can be used as a basis for the optimization of the blade repair technology [10]. An expanded version of this model, including the UV curing, is under development now-

6. Conclusions

An overview of the investigations of repair technologies of wind turbine blades given. A model for estimation of repair contribution to costs of wind energy is presented. It is demonstrated that the costs of blade repair can be reduced by using quicker curing technologies (for instance, ultraviolet/UV curing), and on the other side, by preventing the repair defects and ensuring better repair quality. The role and formation of defects in repaired structures is analyzed. It is demonstrated that voids in repaired blades drastically increase the local stress concentration, thus, reducing the post-repair blade lifetime. Various technologies of repair of composite blades are tested and compared. While UV curing shows average results with view on porosity and strength of repaired blades, vacuum assisted hand layup can lead to rather high porosity in repaired blades. Computational model of the formation of defects in the blade during curing (voids, residual stresses) is developed. Summarizing, this paper presents an overview of the comprehensive quantitative approach to the evaluation and estimation of wind turbine blade repair technologies, including the cost estimation, evaluation of main cost factors, analysis of defects formed in blades during repair, and their influence on the post-repair blade strength, and evaluation of different available curing technologies.

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