ReliaBlade Project: A Material’s Perspective towards the Digitalization of Wind Turbine Rotor Blades

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Abstract. In many industries, digitalization is expected to have a significant economic potential. The digitalization of wind turbine rotor blades including their materials could contribute to accelerate the development of novel and tailored materials, to improve the blades’ reliability, and to make wind energy more cost efficient. However, the digitalization of the blades through their entire life cycle is challenging e.g. due to the dependence of the material properties on the manufacturing process parameters, the complex structural health monitoring and the challenging modelling of blade response under complex loading. In the presented work based on the results of the ReliaBlade project, a theoretical approach is attempted towards describing the blade in-situ structural performance, based on the material properties, the blade manufacturing processes and loading history. In the first phase of the ReliaBlade project, an experimental blade for full-scale testing with three pre-defined internal damage modes is designed. Based on these damage modes the digitalization approach towards increasing the blade structural reliability is exemplarily shown.

1. Introduction

A huge technical and economic potential is foreseen from the digitalization of many structural components (see e.g. [1], [2]). This is also valid for wind turbines. Nevertheless, the specific economic potential from digitalization of wind turbine blades is not explored in the literature.

The objectives of digitalization are typically to contribute to an improvement of the design, manufacturing and operation. There is a strong dependence of the manufacturing process parameters on the material properties. This together with the quality of structural health monitoring systems and data availability, the development of reliable digital blade twins is very challenging and requires collaborative work between different fields of expertise (see e.g. [3]).

The work started in the framework of the ReliaBlade project [4] is aiming at contributing to the formulation of a wind turbine blade digital twin concept. Thus, it is attempted to describe the structural blade performance based on the material properties, the blade manufacturing processes and loading history. Furthermore, application of non-destructive inspections (NDI) and structural health monitoring (SHM) methods are investigated, as these technologies could enhance modeling of the blades at defined times through the lifetime [3]. Within the project, major wind turbine manufacturers (including blade design and manufacturing), relevant industry partners and OEMs contribute with their specific know-
how. Figure 1 gives an overview of the ReliaBlade project activities during the different life phases of a blade. Blades of 12.6 and 30 m will be investigated through the design, the manufacturing and the operation phase (represented by full-scale blade testing). Beside innovative technologies, artificial intelligence will support the design, the manufacturing data and the test measurements by optimizing the processes and the data evaluation.

Advanced physically based material models will be one major objective within the ReliaBlade project to support the digitalization approaches and the development of digital blade twins. These are aiming to enhance the understanding of the mechanical material behavior on one hand, thus reducing the property uncertainties, resulting in increased structural reliability as introduced by Toft et al. [5]. On the other hand, they reduce the number of variables and the calculation effort in the digitalization procedures.

Figure 2 illustrates schematically the implemented digital material twin concept. In contrast to traditional design philosophy the material properties shall not be described as a set of properties, but as a function of the manufacturing parameters and the operational conditions. This is essential for composite materials, as the in-situ material properties are a function of the manufacturing and operational/environmental variables, see e.g. [7].

For the manufacturing of wind turbine blades a so-called vacuum bag infusion process is common. In this process dry fibres and core materials are infiltrated with a resin under a vacuum bag and the resin bonds the materials and hardens due to a chemical reaction (so-called curing). Therefore, the infusion and curing processes are of high relevance for the material properties and the physical based modelling.

In the following, an introduction to the process related behaviour of epoxy (EP) systems is given. Based on this description, a typical blade manufacturing process is presented. In a third step the relevance of such measurement based digital material twins will be exemplary investigated for inter-fibre failure in shell laminates.
2. Introduction to process related behaviour of epoxy systems

Although it is not represented in the traditional stress calculation procedures in the wind industry, it is known that the local resulting stress state and the strength in epoxy based composites or adhesive bond lines are influenced by the manufacturing process ([23], [25]). In this work only process induced effect will be considered. It might be needed, that other effects such as moisture content and/or uptake are taken into account. Although in the stress/strength analysis of rotor blades the thermal and chemical shrinkage effects are covered through safety factors (e.g. according to DNV-GL [6]), it might be that they are not covered sufficiently, e.g. [7] and [10].

Figure 3 gives a schematic and idealized illustration of the thermal and chemical shrinkage during the curing of an EP system by plotting the density over the temperature. Density changes due to a degassing of a solvent or similar are not considered for EP systems as they cure by a polycondensation. An uncured system is heated up from room to curing temperature (A-B). The material expands with the coefficient of thermal expansion of the uncured system and therefore the density reduces. At the curing temperature the chemical shrinkage takes place (B-C). The description between A and C is a simplification as the cross linking starts already at room temperature and the cross linking rate increases with temperature. Therefore a density increase will start already with the temperature increase during ramp up. After point C the thermal shrinkage will take place. As EP systems show two different coefficients of thermal expansion (above and below T_g) this is a bi-linear function. In practice the given description of the curing process is a strong simplification as the described processes will overlap.

This schematic description in Figure 3 does not represent the behavior in an industrial curing process. In Figure 4 the density is plotted together with a possible curing temperature profile over time. The process consists of a ramp up, a holding and a cool down phase. The material will start to expand due to the increasing temperature and at the same time will start to develop cross links. With increasing temperature the cross linking speed will increase. For this reason the start of the holding phase is described by A-B*. During the holding phase the cross linking will develop further and reach, with a small safety margin, the required value before the cool down phase. In an ideal process the level of cure will reach the desired level (B*-C*). In the cool down phase the bi-linear thermal shrinkage will take
place (C*-D* and D*-E). The stages A and E have to be interpreted in the same way as A and E in Figure 3.

![Figure 3: Schematic illustration of thermal and chemical shrinkage during curing of EP system according to Holst [8].](image)

![Figure 4: Interpretation of thermal and chemical shrinkage (expressed as density) of EP system for a typical curing.](image)

From an engineering perspective the chemical and thermal shrinkage effects must be mathematically described from the gelation point, which can be interpreted as the degree of cure at which a polymer network is developed that can transfer mechanical loads (e.g. shear loads). Furthermore shrinkage effects, such as moisture absorption should be modelled if required.

The chemical shrinkage for epoxy systems will lead to a volume change, of which one part will occur in the liquid phase and the second part in the solid phase (see Figure 5). Typical values for the chemical shrinkage are 6 % in volume, of which approx. 30 % is happening in the solid phase (see e.g. Khoun et al. [9], Holst et al. [28] and Nielsen [10]).

![Figure 5: Schematic illustration of curing degree dependency of the elastic modulus and the volume shrinkage for isothermal conditions (see e.g. Khoun et al. [9] and Nielsen [10]).](image)

The thermal shrinkage can be calculated with the coefficients of thermal expansion. As described earlier one value below and above the $T_g$ is required for epoxy systems.

To calculate the resulting stresses from the shrinkage effects in a structural application the “effective modulus” at the strain development must be described. A schematic illustration of the modulus over temperature is given in Figure 6 together with the coefficient of thermal expansion.

An examination on the development of residual stresses in epoxy based systems can be performed for a “1-D” simplification of a sandwich panel exposed to a temperature change. Such a situation can be found in bond lines (e.g. trailing or spar cap to web bond line) as well as between two glass fibres and the surrounding resin (strong idealization).
Figure 6: Schematic illustration of temperature dependency of the elastic modulus and the coefficient of thermal expansion (see also Khoun et al. [9] and Nielsen [10]).

Figure 7: Schematic illustration for the development of thermal residual stresses in a bonded structure. Figure 8: Schematic illustration of resulting residual stresses in epoxy adhesive bond line.

Figure 7 illustrates the potential free thermal shrinkage of adherents and adhesive as well as the total shrinkage and the resulting residual stresses in a bonded configuration. In the left side of the figure the two adherents and the adhesive are shown. The dotted lines indicate the length of these at the bonding temperature $T_1$. The solid line shows the dimensional changes of these bond line elements after a temperature drop to $T_0$ assuming a free deformation of the parts without any bonding between the adherents and the adhesive. In the right part of the figure the same temperature change is assumed after a bonding of the parts at $T_1$ (due to the bonding, the length of all parts will be identical at all temperatures). Due to the different coefficients of thermal expansion residual stresses have to develop. Based on material data, the thermal induced residual stresses can be calculated (see e.g. [10]). Such a model does not consider potential relaxation effects that might reduce the resulting residual stresses. As relaxation effects are more pronounced at high temperatures and epoxy systems consist of a solid cross
linked polymer network relaxation effects are often considered to be small below the glass transition temperature (T_g).

3. Blade Manufacturing Process

Details on the manufacturing process of modern WTB are typically not public available. However, a general description of the manufacturing process can be given and such a process is also followed within the ReliaBlade processes. Most WTB are manufactured by vacuum infusion process. Manufacturers typically produce two blade shells which are bonded with at least one additional web to form the WTB. A schematic overview on the manufacturing process of WTBs is shown in Figure 9.

The lay-up in the mold is in most cases a manual process. However, often pre-manufactured spar caps and root inserts are put into the mold with dry materials (the thickness of single glass or carbon fibre plies usually between 0.5 and 2 mm). While the shells are typically made from relative thin biax (up to 2 mm) laminates with a PVC, PET or Balsa core (between 10 mm and 50 mm thick), the spar caps, the transition area and the root section are made from thick laminates. The maximum thickness of spar caps typically varies between 40 and 80 mm and the thickness in the transition area and the root depends on the design and the root connection and is around 30 to 150 mm (with the root having the higher values). Due to the thickness of the composite materials and the typical curing temperatures of 80 °C, exothermal peaks of approx. 120 to 130 °C are observed.

In the bonding process an adhesive is typically applied to the bonding areas of the blade shell with a mixing and dosing machine. After the adhesive application the molds are closed with a hinge system. The adhesive is cured in the mold by the mold heating system (again approx. 80 °C) and exothermal peaks above 100 °C have to be expected.

![Figure 9: Typical wind turbine blade manufacturing process.](image)

In the manufacturing of the ReliaBlade test blade, the temperatures will be monitored at critical locations with integrated sensing elements like thermocouples. Relevant WTB areas are observed non-invasively by picking up heat signatures with thermal imaging methods. While single temperature measurements are state of the art for process control in industry, instrumentation with both temperature sensors and thermography cameras is atypical. The resin gelation and the development of the curing degree will also be monitored with an advanced network of sensors.

In addition to this, a few local measurements of the fibre orientation will be conducted with a laser scanning system. The major focus is on the continuous improved documentation method of the manufacturing process for each blade which means a proper description of potential imperfections.

An example of thermal imaging is shown in Figure 10. Local effect, e.g. from hose shading or the crimped vacuum foil need to be excluded from the image. This indicates the effort to integrate such methods in an automated monitoring process and digital twins.
4. Shell laminates and inter-fibre failure as an example for digitalization of material performance

Since wind turbine rotor blades are designed/qualified against first ply failure, i.e. the development of matrix inter-fibre fracture, it is of vital importance to estimate accurately the polymer properties and the stresses that they are bearing. The resin can be seen as an adhesive, which bonds the fibres together. Again residual stresses can develop in the resin and thus the mechanical performance including the inter-fibre fracture resistance, is strongly dependent on the manufacturing process and the applied curing cycle ([12], [13]). According to [12] and [13] the evolution of the curing degree is a function of the applied curing temperature profile, therefore it is a prerequisite for the estimation of the matrix mechanical performance. A number of models published in literature could enhance the estimation of the conversion degree of polymers ([14], [15]).

The evolution of the curing degree is directly impacting the stiffness and the strength of the polymers which can also be influenced from the operational temperature ([7], [13], [18]), see Figure 11 and Figure 12. These are the basic building block input parameters for the estimation of the in-situ laminate stiffnesses, residual stresses and strengths. The observed stiffness peak at curing degrees below one is surprising, however is also described by other authors, see e.g. [7], [17].

On the laminate level, the composite properties are depending on parameters with an uncertainty mirroring the manufacturing process. The fibre orientation and the resulting stiffness and strength ([19], [21]), the roving pattern geometry in the laminate cross section (quadratic, hexagonal, etc.), see e.g.
[22], [23] and the Fibre Volume Fraction (FVF) [24] are typical examples. Physically based micromechanical formulations [25] and the application of the classical lamination theory [26] can describe the variability of the aforementioned parameters and thus reduce modelling uncertainty, while increasing the overall reliability [5] at the same time.

Depending on the specific blade manufacturing outcome, each separate digital twin e.g. trailing edge shell or spar cap laminate, can be updated accordingly. For example in the case of varying laminate thickness resulting from the infusion, the corresponding model FVF will have to be adjusted in order to mirror the actual properties. Therefore, the in-situ material properties can be optimally estimated.

For the typical case of infused laminates with Vacuum Assisted Resin Infusion Moulding (VARIM) with an FVF range of 50-60% [24], the model results concerning the in-plane stiffness variation of a unidirectional (UD) glass-epoxy laminate are illustrated in Figure 13, while being compared with experiments [26].

![Figure 13: Typical variation of in-plane laminate properties with FVF.](image)

For the ply stress analysis, 3-dimensional (3D) orthotropic stress components are implemented, considering also the residual stresses that are developed in the matrix [25]. Moreover, relaxation effects of the residual stresses during the curing process are taken into account, as described in ([8], [12]). Continuum mechanics is used for the prediction of the static limit stress state, i.e. the prediction of the inter-fibre fracture initiation. A strain energy equivalent stress criteria was applied to describe the behaviour of the isotropic matrix, resulting in an equivalent stress of the 3D matrix element within a lamina [29]. Assuming that the inter-fibre fracture is initiating in the matrix, for a given stress tensor, it can be estimated in terms of the stress effort $e_M$ as defined from Puck [30]. When the ratio of the equivalent stress to the static tensile strength becomes unity, then the crack initiation occurs. The static strength is derived by means of standard material tests.

The same principle of the equivalent matrix stress is also employed for the alternating load calculations of matrix dominated laminates. The stress limit levels are derived with a fitting procedure of uniaxial fatigue experimental data of pure resin material [31]. The applied model results from the convolution of Stüssi [34] and Goodman formulations [35]. To describe the S/N performance with an S-shape formulation, as suggested by Stüssi [36] was used. The Goodman formulation is used to correlate the alternating stress and the allowable cycle number depending on the applied R ratio. Moreover, the implementation of a Weibull distribution for the fatigue strength is enhancing the description of the reliability level.

A validation example for the fatigue inter-fibre fracture model of a UD laminate loaded transverse to the fibres (UD90) is presented in Figure 14. The prediction is correlated to the experimental crack initiation which is detected during a fatigue test. A typical matrix crack is illustrated in Figure 15.
Figure 14: Inter-fibre fracture initiation. Comparison of model with fatigue experimental data of a UD90 laminate.

Figure 15: Typical inter-fibre fracture.

This work on the inter-fibre failure damages shows the connection between manufacturing process data and the material modelling results in a more realistic representation of the material performance. The application of such concepts is practically only possible by the use of digitalization, due to the bandwidth of parameter variations in real structures and the resulting amount of data.

It is important to have a look at the measurement technologies needed. Measurement technologies for the temperature distribution in the blade during manufacturing are available. As the blade molds are not closed, mold based sensors and thermography are suitable methods. To determine the local fibre volume content, which would most likely only be conducted locally, ultrasonic inspections or laser / optical based geometry measurements might be applied. With regard to the fibre orientation, existing methods have to be developed further or new technologies need to be applied to cover most of the blade fibre material. However, also statistical methods and simulation procedures might be applied to a larger degree as today.

From a material modelling point of view many details need to be investigated and validated. The variety of materials is large and the loading scenarios manifold. Also the effect of defects should be understood better.

5. Conclusions
In this paper, a future approach for the design and operation of wind turbine blades has been outlined. This approach is based on a physical based material modelling and measurements in the manufacturing and the operation life phase of the blade. The measurement data from the manufacturing can be used to model the local material properties in the blade. Together with measurements from the operational blade phase, the local material strength can be compared to the local blade loading and thus the material usage, the material reserve factor or the remaining life can be calculated more realistically.

With the inter-fibre failure an example was shown and the potential and relevance of material models that consider the manufacturing process parameters was shown. As the material model is connected with measurement data for a specific blade (location) such a concept is interpreted by the authors as a step in the direction of digitalization of wind turbine blades from a material perspective.

Nevertheless, only small and exemplary steps towards a digitalization for structural wind turbine blade applications were presented. Open topics for the inter-fibre failure damage mode remain and other damage modes need also to be evaluated. In addition to that, for the application of such methods, further work is required e.g. the damage models and the in line measurement methods need to be validated, the
uncertainties quantified and the certification methods need to be adapted. Also the role of sensor systems in the operation phase for a continuous model updating should be analysed.

Besides the physical based modelling of damage modes, the validation of such models is in focus of the second half of the ReliaBlade project. In a first step, blades up to 30m length will be manufactured under lab conditions and many process parameters will be measured during the process. These data will enable to update the numerical blade models and better predict the blade structural performance. In full scale blade tests, the structural performance of the blades for different damage modes will be determined and compared with the numerical models of the structure. In addition to that the blade will be instrumented with structural health monitoring sensors and the sensor readings will be used to update the digital blade twin.

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