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Fractographic analysis of sandwich panels in a composite wind turbine blade using optical microscopy and X-ray computed tomography

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Abstract:

This study provides a new perspective on the failure of sandwich panels in a composite wind turbine blade. Fractographic characteristics of fracture regions are examined thoroughly using optical microscopy and X-ray computed tomography. The detailed fractographic analysis leads to the identification of the failure modes and failure sequence. This study addresses an important but rarely studied the failure process in the sandwich panels cored with grooved foams. The partially resin-filled grooves lead to large voids in the foams that cause crack migration of skin/core debonding from one side of sandwich panels to the other. In this study, the adverse effects of the partially resin-filled foams are addressed and the associated challenges in the blade design are highlighted. It is found that the fracture of skin laminates under biaxial compression is characterized by a shear-dominated failure mode in the form of kink bands in two directions. The whitening of skin laminates under tension is caused by micro-cracks in the matrix and the fiber/matrix interface. Moreover, fiber breakage also occurs in the whitening region although it is not visually apparent. These fractographic characteristics could help the identification of the root causes of blade failure if similar observations are found.

Keywords:

Matrix crack; kink band; debonding; river line; crack migration; X-ray computed tomography; DIC

1. Introduction

Maintaining the structural integrity of composite rotor blades is crucial for the continuous operation of the wind turbines. Sandwich structures are extensively used to construct aerodynamic shells and shear webs of rotor blades. Previous studies investigated fracture and failure of sandwich panels in the full-scale blade tests [1-5] and in fields [6]. These studies provided good understandings of failure mechanisms primarily from a structural perspective. As a blade failure involves many influential aspects, such as structures, materials, manufacturing, loads, controls, etc., studies from different perspectives could contribute to more understandings of the blade failure and help to improve a blade design.

It is known that sandwich panels may exhibit one or more failure modes, i.e., face fracture, core shear failure, face wrinkling, debonding, general buckling, shear crimping, face dimpling and local indentation [7]. For the sandwich panels used in composite wind turbine blades, skin laminate fracture, core shear failure and skin/core debonding are among the most reported failure modes as found in [1-6]. The formation of each failure mode is often due to progressive damages and may interact with other failure modes due to local details. This is particularly the case when the effects of core finishing options, such as grooves and perforations are taken into account. For example, the study [8] suggested a potential material reduction in the blade design taking advantage of the resin uptake in the core grooves based on the improved homogenized material properties. The studies [9-11] found the improvement of interfacial debonding toughness due to the perforated and grooved cores. The study [12] found that sandwich specimens with grooved cores showed increased local fracture resistance and temporary crack

arrest. On the other hand, the resin starved grooves resulted in low face/core toughness. The studies [13, 14] pointed out the adverse effects of core perforations that are only partially filled or resin-starving.

This study provides a new perspective on the failure of a sandwich panel using a fractographic approach. Fractography is commonly used in the failure analysis of materials and structures by studying the characteristics of fracture surfaces [15]. It provides evidence that helps to identify the failure mode, the process of failure and the cause of failure. Besides, the fractographic analysis could help to reveal new failure phenomena, which could facilitate the development of more accurate material damage models and more reliable structural analysis methods that capture the underlying mechanisms. Utilizing a sandwich construction of a composite blade segment tested to failure in a previous study [16], this work focuses on the fracture features of PVC foam cores and two skin laminates, establishing the relationship between macroscale structural failure and microscale material fracture characteristics. The effects of core finishing including both perforations and grooves on the fracture characteristics are examined. The challenges and implications for the blade design are addressed. The microscale fracture features of skin laminates are investigated and they are correlated to the macroscale structural failure of the specimen. X-ray computed tomography is used where the internal micro-cracks are of interest. The recorded fractographic characteristics may help to identify the root causes of the future failure of composite blades. As such, the contributions of this work are:

- This study provides a new understanding of the failure of a trailing edge sandwich panel from a fractographic perspective, which is of significance to the existing knowledge base.
- This study provides fractographic evidence to the adverse effect of partially resin-filled grooves and addresses the importance of foam core finishing which might compromise the structural integrity of composite rotor blades.
- The fractographic features recorded in this study could help to identify the failure process and the root causes of the future blade failure.

2. Test overview

A trailing edge segment of a composite blade was tested to failure quasi-statically under compression in a previous study [16] that focused on macroscale structural failure experimentally and numerically. The failure process was buckling-driven. It has been found that PVC foams failed before the ultimate load-carrying capacity, or the peak load, of the structure. The progressive failure in composite materials occurred in sandwich panels at the post-peak regime, leading to the final structural failure characteristics, which will be examined from a fractographic point of view in the current study.

The wet layup over-lamination was used to reinforce the boundaries so that the buckling and the subsequent failure occurred away from the boundaries. Figure 1 schematically shows the buckling region as well as the locations where composite failure was observed after the test. Figure 2 (a) shows the specimen after the test. The specimen failed mainly in two regions. The first region, denoted as I, is located at the trailing edge close to the bond line, see Figure 2(b) and (c). The second region is located in the middle of the sandwich panel and it is denoted as region II in Figure 2(b). Samples are cut from these two regions for further examinations.

Fig. 1 The test setup of the trailing edge subcomponent. Failure is expected to occur at the right side of the specimen due to its lower strength under the same load P . Overlamination is thus used to prevent failure of the specimen at the boundary. A slice of sandwich panel with composite failure is cut and used for fractographic analysis in this study.

Fig. 2 The photos of the test specimen and the failed regions. (a) The blade segment after the test, (b) A slice of the failed trailing edge sandwich panels, (c) The failed region close to the trailing edge bond line. Skin laminates failure in region II is investigated in Section 4 and 5 of this paper.

Fig. 3 The layup information of the failed sandwich panel in the region II

The layup of the failed sandwich panel is shown in Figure 3. In total, there are three and four layers of composite laminates in the outside and the inside skins of the sandwich panel, respectively. The thickness of PVC foam cores is 10 mm. Material properties of composite laminates and PVC foams are shown in Tables 1-3.

Table 1. Elastic properties of composite materials used in the sandwich panel [16]

	E_{11} GPa	E_{22} GPa	E_{33} GPa	ν_{12} -	ν_{13} -	ν_{23} -	G_{12} GPa	G_{13} GPa	G_{23} GPa
Biaxial laminate_type#1	11.58	11.58	11.58	0.48	0.10	0.10	10.66	10.66	5.77
Triaxial laminate_type#1	20.26	10.42	10.42	0.45	0.10	0.10	7.35	7.35	5.19
Triaxial laminate_type#2	16.70	8.59	8.59	0.45	0.10	0.10	6.61	6.61	4.28

The subscript 1, 2 and 3 denote longitudinal, transverse and through-thickness direction, respectively.

Table 2. Strength properties of composite materials used in the sandwich panel [16]

	$\sigma_{11}^{u,t}$ MPa	$\sigma_{11}^{u,c}$ MPa	$\sigma_{22}^{u,t}$ MPa	$\sigma_{22}^{u,c}$ MPa	$\sigma_{33}^{u,t}$ MPa	$\sigma_{33}^{u,c}$ MPa	σ_{12}^u MPa	σ_{13}^u MPa	σ_{23}^u MPa
Biaxial laminate_type#1	123.90	156.30	156.30	156.30	105.00	105.00	143.90	89.20	57.70
Triaxial laminate_type#1	472.06	324.16	127.12	127.12	105.00	105.00	99.25	89.20	57.70
Triaxial laminate_type#2	389.00	267.00	105.00	105.00	105.00	105.00	89.20	89.20	57.70

The superscripts t and c denote tension and compression, respectively.

Table 3. Material properties of PVC foam [16]

E MPa	ν -	σ_y MPa	ϵ_y %
48.5	0.4	1.4	2.89

σ_y, ϵ_y are the yielding stress and strain of PVC foam, respectively.

It should be noted that the material properties of the PVC foam shown in Table 3 are obtained from the bulk materials without finishing or resin uptake. During the manufacturing of sandwich structures, infusing with foam cores requires specific finishing options such as scoring, grooving, and/or perforating to achieve desired resin flow and saturation. Figure 4 shows the finishing of the PVC foam cores used in this study. Single-side grooves, sometimes referred to as slits, with a width of approximately 2 mm provide channels for the resin to flow in the longitudinal direction. Perforations, or holes, with a diameter of approximately 3 mm assist the resin to flow from one side of the sandwich panel to the other. The roles of these finishing in the fracture features are investigated in the following sections.

Fig. 4 The grooved and perforated PVC foam cores used in the sandwich panel

3. Failure of PVC foams

Fractographic features of PVC foams in the trailing edge region are shown in Figure 5. The fracture surface S and its matching surface show apparent delamination and skin/core debonding in this region, see Figure 5(a)-(c). The failure sequence of these two failure modes can be deduced from one of the most diagnostic fractographic morphologies, i.e., river lines, in the fractured foams on two fracture surfaces. The river lines are macroscopically visual in the foams although they are typically observed in the matrix of composite materials under Scanning Electron Microscope (SEM) examination as reported in [17]. The white arrows in the figures show the direction of the crack growth direction in which the river lines converge. Based on this observation, it is known that the skin/core debonding is due to the delamination of composite laminates in the trailing edge region.

Fig. 5 Fractographic features observed in the failed sandwich panel close to the trailing edge bond line. (a) The failed trailing edge region from a side view, (b) Delamination, river lines and skin/core debonding observed on the fracture surface S , (c) Failures observed in the matching surface, (d) The close-up of the fiber-tear failure due to the resin in foam perforations, (e) The close-up of the fiber-tear failure due to the resin in foam grooves.

The skin/core debonding occurs predominately in a thin layer of foams very near to the interface between skin laminates and foams. This failure mode is similar to the thin-layer cohesive failure of adhesively bonded joints for composites according to ASTM-D5573-99 (2012) [18]. It is worth noting that in addition to the thin-layer cohesive failure, the fracture surfaces exhibit the fiber-tear failure in the regions which resin is filled in the foam grooves and perforations, see Figure 5 (d) and (e). The skin laminates in these regions are visible on the fracture surfaces, which is unlike the rest of the fracture surfaces covered by a thin layer of foams. A microscopic close-up of a perforation shows cracks in the foam around resin as shown in Figure 6.

Fig. 6 Cracks around resin in a foam perforation

These observations show that the resin in the grooves and perforations affect the fracture characteristics of the skin/core debonding. A side view of the failed sandwich panel in Figure 7 shows that the skin/core debonding coexists with the foam cracks around the grooves partially filled with resin. The partially resin-filled grooves provide an easy channel, which requires the minimum fracture energy, for the crack to migrate from one side of the sandwich panel to the other. These partially resin-filled grooves are prevalent in the sandwich panel and can initiate cracks due to large voids as shown in Figure 8.

Fig. 7 A side view of the foam core failure in the failed sandwich panel

Fig. 8 The prevalent partially resin-filled grooves in sandwich panels with a crack initiated from a void in the foam

Noting that the favorable effects of the grooved and perforated cores found in [8-12] should be interpreted with caution. This is because, firstly these conclusions were based on an (implicit) assumption that the grooves and perforations in the core materials were completely filled with resin, which is not the case as observed in the sandwich panels cut from a commercial blade as shown in this study. Secondly, considering resin uptake in the

grooves and perforations leads to the increase of the homogenized core properties, this, however, does not mean that the fracture resistance or the strength of the sandwich structures would increase accordingly due to the intrinsic nature of material fracture and failure being local.

Moreover, the partially resin-filled grooves make the prediction of skin/core debonding a difficult task. The method based on the interface fracture toughness is only valid before the crack migration. Besides, a crack can initiate from a partially resin-filled groove and start a skin/core debonding process. Predicting this failure process is very challenging especially when large composite structures such as rotor blades are under concern. On the one hand, it is difficult to determine the extent and the distribution of discontinuity regarding resin filling in grooves and perforations; on the other hand, such local details within sandwich panels are impractical to model in a structural scale.

It is noted that the blade in this study was designed more than a decade ago and manufactured with different materials and processes than today. With the advances in manufacturing technologies, the resin infusion has been considerably improved. Nevertheless, potential issues still present regarding the discontinuities in the core materials during the blade manufacturing. As an example, Figure 9 shows prevailing gaps and perforations in the core materials in a more recent commercial blade.

Fig. 9 Natural lights illuminate the interior of a 47m commercial blade which is not painted from outside, enabling an aesthetic visualization of discontinuities filled (partially) with epoxy resin and adhesive paste. Gaps at intersections of core materials range from 4 to 8 mm in sandwich panels. The blade was manufactured in 2015 using vacuum-assisted resin infusion. The view points towards the blade tip.

4. Failure of skin laminates under compression

In addition to the foam core failure, the failure of skin laminates is also significant. Figure 10 shows the failed sandwich panel sampled from region II shown in Figure 2 (b). The surface with speckles is the front side. Due to panel buckling, the front side surface was under compression while the backside under tension. The specimens

exhibit skin laminate cracks in the front side that are indicated by the dashed green curves in Figure 10(a). The material separation is visually apparent at the cracking locations. The backside of the specimen exhibits whitening as shown in Figure 10(b) which will be discussed in the next section.

An optical microscopic observation on the cross-section of the front side of the fractured sandwich panels shows a typical compressive failure of composite laminates as shown in Figure 11. Skin laminates are found to have been subjected to crushing failure that exhibits a shear-dominated failure mode with kink bands through the thickness of the laminates. Delamination and foam cracking are also observed and they are regarded to be the consequence of the laminate compression failure. Noting that the compression failure occurs in the longitudinal direction. This indicates the presence of significant compressive stress in this direction during the failure.

Fig. 10 Skin laminate failures in the sandwich panel in region II as indicated in Fig. 2. (a) Skin laminate cracks on the front side (b) The whitening regions on the backside (c) A side view of foam core failure

Fig. 11 Longitudinal compression failure of skin laminates at the front side of the failed sandwich panel where kink bands, delamination, and the adjacent foam cracking occur driven by panel buckling

Fig. 12 Transverse compression failure of skin laminates at the front side of the failed sandwich panel where kink bands, delamination and foam cracking occur as observed from X-ray computed tomography

In order to examine some failure modes that might be hidden from the view, X-ray computed tomography is used and internal failures are shown in Figure 12. The cross-sectional views of the failed specimen show various failure modes, i.e., delamination in the skin laminates, skin/core debonding, foam cracks and kink bands in the laminates. Two observations are noted. The first observation is the change of crack path, or crack migration, in the foam due to the voids in a partially resin-filled groove as previously discussed. The second observation is the shear-dominated kink band failure and the laminate crushing failure. This observation provides evidence of compressive stress in the skin laminates along the transverse direction. Together with the compressive stress in the longitudinal direction discussed previously, the skin laminates on the front side of the failed sandwich panel is found to have been subjected to, and eventually failed due to, bi-axial compression. This finding is well supported by the strain measurements during the test as shown in Figure 13. Both longitudinal and transverse strains in the vicinity of the sample were larger than 2.0%, i.e., 20,000 $\mu\epsilon$, in compression, while their counterpart allowable compressive strains of the composite materials in the skin laminates are only 1.60% and 1.22% in compression, respectively.

It is noted that strain measurements from the DIC system were calibrated before the test following the standard procedure specified by the equipment producer. The calibration error is within 0.09 pixels. More details can be found in [16].

Fig. 13 Maximum strains of the blade segment measured by DIC in the test. (a) Longitudinal strain along the section where the failed sandwich panel is sampled, (b) Longitudinal strain contour measured by DIC when the specimen fails, (c) Transverse strain along the section where the failed sandwich panel is sampled, (d) Transverse strain contour measured by DIC when the specimen fails.

Based on the aforementioned observations, a probable failure sequence can be deduced. The skin laminates fail under bi-axial compression due to panel buckling although the specimen was subject to compression. The skin laminates' failure leads to cracking of the foam close to the skin/core interface and the subsequent debonding. The crack propagates in the interface and further kinks into the core where a void in a partially resin-filled groove

exists. One crack continues to propagate in the original interface and a new crack starts on the other side of the sandwich panel in the skin/core interface as found in the cross-section III in Figure 12.

5. Failure of skin laminates under tension

The whitening of the skin laminates on the backside of the failed sandwich panel as shown in Figure 10(b) is examined under an optical microscope. The whitening phenomenon is sometimes also referred to as stress whitening or crazing. Unlike the cracks on the front side, the whitening regions do not show visually apparent material separation on the specimen surface. As shown in Figure 14, the whitening region shows an inclination to the longitudinal direction with an angle of 22 to 24 degrees. Microcracks observed under the microscope align with fiber directions of ± 45 degrees in the skin laminates.

Fig. 14 Tensile failure of skin laminates at the backside of the failed sandwich panel where whitening regions occur

X-ray computed tomography is used to scan this whitening region. Figure 15 shows the scanning results of the skin laminates along its through-thickness direction. Matrix cracks are found on the surface of the laminates and they propagate into the fiber bundles within which fiber/matrix debonding occurs. The matrix cracks propagate further into either a void or another fiber bundle. Figure 16 shows an in-plane view of the whitening region. Both matrix cracks and fiber breakage are found although the fiber breakage is not visually apparent from an optical

microscope. Note that the crack paths of matrix cracking and fiber breakage are aligned, providing evidence of tension failure of the skin laminates in the whitening region.

Fig. 15 X-ray tomography of the whitening region along the through-thickness direction of the skin laminate

Fig. 16 X-ray tomography of the whitening region of the skin laminate with an in-plane view, providing evidence of tension failure of the skin laminates

6. Concluding remarks

This study provided a new perspective on the failure of sandwich panels in a composite wind turbine blade using a fractographic approach. The fracture regions were examined using an optical microscope and X-ray computed tomography. The deduced strain state of skin laminates at failure was confirmed by the digital image correlation measurement during the test.

An important failure process was addressed in this study regarding the sandwich panels with the grooved foam core materials. The partially resin-filled grooves lead to large voids in the foams that can not only initiate cracks but also change the crack path of skin/core debonding. This study provided fractographic evidence on the adverse effects of the partially resin-filled grooves and pointed out the associated challenges in the failure prediction of such sandwich panels. It is suggested that the favorable effects of resin uptake considering the property homogenization should be used with caution in the blade design unless the complete resin filling in the grooves can be ensured or reliable failure prediction models can be developed.

This study documented the fractographic characteristics of a glass-fiber epoxy skin laminate that failed under bi-axial compression due to panel buckling. The laminate is commonly used in the sandwich skins of composite rotor blades. The fracture of the laminates is characterized by a shear-dominated failure mode in the form of kink bands in two directions. Delamination, skin/core debonding and foam core cracking are also present as accompanying failure modes. An optical microscopic examination and X-ray computed tomography revealed the whitening of skin laminates under tension. Micro-cracks occur in the resin as well as in the fiber/matrix interface within fiber bundles. In addition, fiber breakage also occurs and follows the same path as matrix cracking although it is not visually apparent from a macroscopic point of view.

A few problems still need to be studied regarding blade sandwich structures. They include the damage tolerance of large-scale composite structures with unavoidable and sometimes even prevalent manufacturing-induced defects, the fatigue performance of material discontinuities and imperfection under high cycle loading, and the damage control by understanding and utilizing crack migration mechanisms.

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Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time due to technical or time limitations.

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Highlights:

- This study provides a new understanding of the failure of a sandwich panel from a fractographic perspective.
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The author has no conflict of interest in this study.

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