X-ray laminographic inspection of sandwich shell segments for wind turbine rotor blades

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Abstract

3D structural investigations are described by X-ray laminography studies of sandwich shell segments, made of a PVC foam core, covered by non-crimp fabric glass fibre composite lay-ups processed by vacuum assisted resin infusion of epoxy. The specific scope of this study is to image transversal flaws within the foam core (joints) and of single ply overlaps. Test flaws were purposely implemented in order to simulate typical failure under cyclic load. In a dedicated test rig for shell structures, the flaw evolution/propagation is monitored by thermography and optical 3D inspection of deformation. Due to the unfavourable preconditions for classical computed tomography as of large aspect ratio, the samples were investigated by coplanar translational laminography. Its limited range of observation angles of ± 45°, results in anisotropic artefacts about the normal to the sample surface, but the typical flaws are well visualized in the as-prepared state, in a state of early damage, and in the repaired state.

1. Introduction

Statistically, every 7 years a wind power plant is out of order due to a technical defect at the rotor blade. In particular off-shore turbines are exposed to extreme thermo-mechanical and climatic loads. They are usually made of fibre reinforced plastics (FRP). Typically, the size of rotor blades is about 60 m in length and about 6 m in depth. The maximum roll width of technical textiles, which are used as fibre reinforcement, is about 2.5 m (100 inch). The foam core is produced as 1 × 2 m² plates. Consequently, in manufacturing of rotor blades certain types of joints in the reinforcement and foam panels are unavoidable. Depending on the respective procedure, those imperfections are the preferred seeds for later damages in long term usage. The most frequent damages during operation of wind turbines are cracks in the blade shell. They occur long before the designed service life time of 20 years is reached. About 80 % of those damages are due to imperfections during the manufacturing procedure. Once they occur, they progress due to cyclic load and environmental conditions (such as harsh weather or salinity of air and spray water). In the worst case, within a few years blade shell cracks can grow to lengths, which necessitate a shut-down of the wind turbine with expensive repair measures.

As a matter of principle, rotor blade damages can be repaired. However, repair/maintenance concepts for off-shore applications are not well established. In the
literature, studies about structural endurance of repaired shell segments are missing, in particular, the fatigue behavior of repaired larger sandwich shells compared to virgin components. Mandell et al. (1) investigated the fatigue behavior of ply drops under laboratory conditions at ambient temperature.

At the state of the art repairs of rotor blades are performed by scarfing the damaged area/volume and replacing the foam core and the textile fabric followed by polyester or epoxy resin impregnation.

In a recent research initiative at BAM, a dedicated test rig to simulate operation loads at curved specimens was developed. Fatigue tests in the range of in-service load levels aim at monitoring the evolution (and progress) of damages in shell segments. Therefore, a combined condition monitoring using thermography and optical 3D deformation analysis is applied. In order to determine the impact of repair on the sustainability (i.e., the structural durability) of the wing and to compare different repair procedures repairs need investigation by means of nondestructive techniques.

The 3D visualization of the transversal flaws within the foam core and the ply overlaps of the sandwich shell segments is accomplished by X-ray laminography. Although the method goes back to medical diagnostics in the early 1930s (2), it has not been applied extensively, mainly due to inherent image reconstruction artefacts. Different from computed tomography (CT), the absorptive sample intensity projections are not acquired over a full circle angular range giving rise to strong streaky image artefacts of details. These origin from missing information under inaccessible rotation angles in analogy to a special case of limited view CT. Laminography is an imaging technique well suited for flat samples when the projection angles near the surface direction are not usable due to the sample size or the limited transmission at these angles. There are two general topological principles: rotation laminography using a relative sample rotation axis (inclined) between source and detector, and translation (or linear) laminography, replacing rotation by displacement. Some renaming to “Computed Laminography” occurred later than the first computer uses.

In a contemporary comparison of two common approaches, the classical Filtered Back Projection FBP reveals better density representation but the Algebraic Reconstruction Technique ART is in favour for higher spatial resolution (3). Comparing CT and laminography with respect to artefacts, the latter has proven to be favourable in certain cases (4). The presented investigations are performed by coplanar translational laminography due to reconstruction advantages.

2. Experimental

2.1 Shell segment specimens

The presented investigations are performed on separately manufactured sandwich shell structures, which represent a blade shell section of real rotor blades. The specimens are made of double layers of +/-45° glass fibre reinforced plastics (GFRP) skin layers on both sides. A PVC foam core of 10 mm thickness in combination with a curvature ratio of 1:10 enables the buckling stability to reach the compression loading to the design load level with an appropriate safety factor as it is common for real rotor blades. 1 mm channels facilitate bending of the stiff foam plates in the curved segments. They are manually prepared with several purposely introduced imperfections, which are typical
for the manufacturing process. The specimens are subject to fatigue and static load testing in order to investigate the impact of imperfections on the service life. Different types of imperfections were purposely introduced into the specimens. The investigated specimens contained foams joints, i.e., gaps between foam panels of some millimeters.

Table 1: Manufacturing details of the specimens

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>810 × 510 × 12.5 mm³</th>
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<tbody>
<tr>
<td>Curvature ratio</td>
<td>1:10</td>
</tr>
<tr>
<td>Radius</td>
<td>650 mm</td>
</tr>
<tr>
<td>Structure</td>
<td>Sandwich shell specimen</td>
</tr>
<tr>
<td>Skin layers</td>
<td>+/- 45° Non-crimped glass fibre fabric</td>
</tr>
<tr>
<td>Core</td>
<td>PVC foam</td>
</tr>
<tr>
<td>Resin</td>
<td>Epoxy</td>
</tr>
<tr>
<td>Process</td>
<td>Vacuum assisted Resin Infusion (VARI)</td>
</tr>
<tr>
<td>Imperfections</td>
<td>Foam joints</td>
</tr>
</tbody>
</table>

Specimens in three different stages were investigated by laminographic imaging:
- segments in the as-prepared state with a 7 mm foam joint,
- in a state of early damage after 64000 load cycles at a strain level of about +/− 3 ‰, and
- in the repaired state, where a 150 mm patch is prepared from the exterior side.

Figure 1. The specimens in different states of damage. Left: coated exterior side of the as-prepared specimen with the foam joint indicated, center: uncoated interior side with a clearly visible 45° crack, right: exterior side of the repaired specimen.

2.2 Laminographic set-up

In order to reveal the internal 3D structure an X-ray tomographic approach is needed. However, the large aspect ratio of the shell segments (thickness:width ~ 1:40, cf. table 1) makes classical (rotational) tomography a disadvantageous technique for this specific task. Provided that a full rotation is possible for geometrical reasons, there would be a large angular sector of nearly zero transmission due to increasing thickness at the selected X-ray energy spectrum (5). If alternatively for improvement, the tube voltage would be raised significantly, the contrast would drop in similar manner. Therefore, the samples were investigated by coplanar translational laminography. As sketched in Fig. 2, this technique is based on an X-ray tube movement parallel to the
horizontal pixel lines of the digital detector array (DDA). Projection images are collected at each source position, \(x_s\). For experimental details see Table 2. The large cone beam ensures that these images correspond to different projection angles. Stacking the intensity profiles of fixed pixel lines yields the so-called linograms (Fig. 3).

Table 2: Experimental details of the laminographic set-up

<table>
<thead>
<tr>
<th>X-ray tube</th>
<th>COMET AG, MXR-160/HP-FB</th>
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<tbody>
<tr>
<td>Voltage</td>
<td>30 kV</td>
</tr>
<tr>
<td>Current</td>
<td>16 mA</td>
</tr>
<tr>
<td>Filter</td>
<td>0.8 mm Be</td>
</tr>
<tr>
<td>Detector (DDA)</td>
<td>Dexela (CsI scintillation screen)</td>
</tr>
<tr>
<td>Frame rate</td>
<td>30 fps (5 exposures averaged)</td>
</tr>
<tr>
<td>Pixel size</td>
<td>75 µm</td>
</tr>
<tr>
<td>Pixels</td>
<td>1536 × 1944 (actually used: 884 × 1346)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source-detector distance (SDD)</td>
</tr>
<tr>
<td>Mean object-detector distance (ODD)</td>
</tr>
<tr>
<td>Source manipulation</td>
</tr>
</tbody>
</table>

Instead of sinusoidal trajectories (as known from tomography) one obtains trajectories along inclined straight lines. The slope of the individual trajectories corresponds to the position of the respective mass element relative to the source-detector distance (SDD). Actually, laminographic data could be converted to sinograms by introducing an arbitrary rotation axis.

![Figure 2. Principle and view of the laminographic set-up (left), sketch of the actual geometry.](image)

The linograms are subject to filtering, where the length of the filter kernel was adapted empirically with respect to minimal missing wedge artefacts. The final reconstructions we performed by integration of numerically sheared filtered linograms (Fig. 3) on standard PCs by a dedicated C program “lami1” and “tomoplan WPU”.

In the present study, the laminographic observation angle was ± 45°, resulting in strong anisotropic reconstruction artefacts elongated parallel to the mean irradiation direction.
(i.e., perpendicular to the source translation). This type of artefacts is known as “missing wedge”, which is most prominent in electron tomography (3).

Figure 3. Schematics of processing laminographic data: stack of single projection (left), two linograms are exemplary extracted from single lines in foam core and in the foam joint (center), linograms are numerically sheared to obtain the reconstruction by integration (right).

3. Results

The reconstruction of the as-prepared sample reveals the sample’s inner details with the expected missing wedge artefacts in z-direction. Figure 4 displays a transversal (x-z) section of intensity to indicate the sample details with estimated measures: the total thickness of 13 mm, the thickness of the foam core of 10 mm, the separation of the GFRP plies of about 0.7 mm, a resin filled channel of 1 mm width and the foam pores of about 0.7 mm diameter. Due to the missing high frequency information it is delicate to determine the thickness measures precisely. This refers to the total thickness as well as to the GFRP/ foam boundary. Actually, the position of fibre plies is best visualized by the gaps between the rovings (bright features).

Figure 4. A transversal section of the as-prepared sample indicating in detail the components of the shell segment. The inset (lower right) is a frontal section of the foam core.

Figure 5 displays some reconstructed details obtained from the as-prepared sample. Undesired air bubbles are observed inside resin filled joint (Fig. 5D). They are concentrated at the interior side (Fig. 5A). The mean bubble diameter is about 1 mm, the maximum diameter observed is 3.7 mm. The specimen thickness decreases by about 1
mm in the joint region (Fig. 5C). The fibre rovings show a z-modulation of 5 mm period along y (Fig. 5E) due to the presence of binding yarns running in x-direction. Despite the insufficient depth resolution additional image processing is successful in separating the single plies indirectly by means of the roving gaps (Fig. 5F). The distance of the two plies is 0.7 mm.

Figure 5. Transversal (A, B) and frontal (D, E) sections of the as-prepared sample: in the foam joint (A), in the foam core (B), in the half-thickness position (D), and in the exterior GFRP face sheet (E). (C) visualizes the smaller total thickness in the foam joint region (red dots) in comparison to the foam core region (green dots) by superposition of gaps in the face sheets. (F) indicates the separability of the two GFRP plies at the exterior face by superposition of gap lines taken from z positions separated by 0.7 mm.

Apart from elongating objects along z, the missing wedge produces several other artefacts. (i) The foam joint has the same resin filling as the channels running in y-direction. In the raw projections (Fig. 3), joint and channels show similar attenuation. However, in the reconstruction, the channels are contrasted very well, while the joint shows nearly no contrast (Fig. 5D) due to the missing high frequency information along x. (ii) The pores inside the foam exhibit a high contrast along x and no contrast along z. (Fig. 5B). (iii) Artificial black/white contrasts are observed at air bubbles in the joint (Fig. 5D) and this is very pronounced at the roving gaps (Fig. 5A, B, E).

Details of the damaged sample are shown in Fig. 6. Whereas the 45° oriented crack damage is clearly visible photo- optically at the surface. It might be interesting how deep it penetrates the shell structure. It is indeed hardly detectable with X-rays as there is no extra contrast along a line. But at both adjacent local levels a buckling of the fibre composite layers is detected by means of a small curvature and reverse maximum contrast in different depth positions (Δz ~ 0.5 mm). This is shown in Figs. 6 B and C and improved by their colour coded difference (Fig. 6D). Thus the optical 1D flaw at the surface is recognised by a 2D indication caused by a shift in the local ply level.

While in the damaged region, the foam micro structure exhibits no peculiarities as a result of cyclic load, the foam joint is macroscopically deformed from a linear to a curved shape (Fig. 6E). The bright-dark modulations in are due to the superimposed fibre fabric structure.
Figure 6. Photograph of sample after cyclic loading with surface crack in 45° fibre direction (A). Indirect allocation of the damage by frontal sections at different z positions (B) and (C), and their colour coded difference (D). A frontal section at half-thickness position reveals the foam joint distortion (E).

Figure 7A displays the photo-optical image of the repaired sample’s interior side and the marked area of about a quarter of the repair patch relating to the laminographic image details of Fig. 7 C to E. Its borders are clearly visible. The repair PVC foam has a smaller pore size of about 380 µm. A 1 mm gap between the two foams is visible along x- and y-direction (Fig. 7 B and D).

Figure 7. Photograph of repaired sample’s interior side (A) and frontal sections covering about a quarter of the repair patch. The foam pore size of the repair is significantly smaller than the original one. The patch channels are not filled with resin (B). The repair patch’s fibre reinforcement is located beneath the original face sheet at the interior side (C). Averaging frontal sections at exterior side reveals (directional) matching of GFRP layers (D). Averaging frontal sections at interior side reveals the mismatch of fibres of the repair patch and the original ones (E).
The channels of the patch are not filled with resin. Their black artificial borders are again due to the missing wedge artefacts. The textile fabric repair layer is located beneath the original face sheet at the interior side (C). Averaging the frontal sections at the exterior side reveals (directional) matching of the GFRP layers (D). In contrast, at the interior (concave) side the fibre directions exhibit a mismatch and disorder (due to cutting, Fig. 7E).

4. Conclusions

Laminographic imaging of structural details within rotor blade shell segments for wind turbines by X-rays has proved to be very suitable for observing the issues of interest. Such details comprise the GFRP face sheets, the PVC foam core as well as flaws and repaired test structures.

In the present case, the limited spatial resolution due to missing wedge artefacts about 10 pixel corresponds to 700 µm in depth direction. Thus, contrast information along this direction is reduced but sufficient for visualising the boundaries air/GFRP and GFRP/foam, and the separation of single plies. In contrast, the lateral resolution of about 100 µm is above expectations.

Acknowledgements

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References

1. JF Mandell, D Sambrowski, „Composite Material Fatigue Database; Test Methods, Materials and Analysis”, Report Montana State University, 1997.