FATIGUE LOADING OF SANDWICH SHELL TEST SPECIMENS WITH SIMULATED PRODUCTION IMPERFECTIONS AND IN-SITU NDT

V. Trappe^{*}, D. Nielow,

Bundesanstalt für Materialforschung und -prüfung, Unter den Eichen 87, 12205 Berlin, Department 5 Materials Engineering, *volker.trappe@bam.de

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Abstract

A shell test bench was developed at BAM 5.3 which allows for static and fatigue testing of curved fiber-reinforced plastic (FRP) structures, during which in-situ the damage state can be non-destructively inspected by thermography and strain-field measurement techniques. Sandwich shell specimens with typical wind turbine blade manufacturing defects were designed and tested. The tested imperfections show a fairly significant reduction (up to 90%) of the shell test specimens ' lifetime, depending on the type of imperfection. Using the in-situ NDT methods incorporated in the shell test bench, the location and cycle time of the initial defects and the damage evolution was investigated.

1 Introduction



Figure 1: Structural design of rotor blades (left) and design of representative sandwich shell specimen (right).

Wind turbine rotor blades often fail significantly before their projected 20-year lifespan. This is because of imperfections (i.e. cracks) caused by operational fatigue which are present in the shell of the blades. 70%-80% of these defects originate during the manufacturing process. Environmental conditions, especially for offshore turbines, then further damage the blades, leading to crack propagation throughout the body. The cost-intensive outcomes of "on the ropes" repairs are one of the inhibitors of wind turbine operation. In Germany, statistics show



that each wind power plant must be taken out of service for 3.5 days every 6 years due to a defect on the rotor blades [1]. This adds up to costs of approximately \notin 20,000 to \notin 40,000 due to of loss of earnings and the repairing charges.

Wind turbine rotor blades are produced using fiber reinforced plastics (FRP). Except the root section and the spar caps, the majority of the blade is a sandwich shell structure. Rotor blades typically have a length of 40m - 70m and a width of 3m - 6m (see Figure 1). The typical width of technical textiles used for fiber reinforcement is a maximum of 2.5m. Foam plates used in the structure core have dimensions of approximately 1.2m x 2.5m. Hence, ply overlaps and gaps between the foam plates are sometimes inevitably brought in to the structure during production. Additionally, the number of outer layers covering the length of the blade decrease toward the blade tip according to the bending moment, and thus lead to ply drops. Ultimately, these imperfections are unavoidable and design rules must be incorporated to make their impact on the in-service strength as low as possible. This task was subsequently addressed in the course of this project.

In this project, funded by the German Ministry of Economics (BMWi), a sandwich shell specimen was developed with structural mechanical properties and designed to be representative of the sandwich shell structure of large rotor blades. The textiles, PVC-foam, and matrix material utilized were coordinated with industry partners, and are commonly found in present-day blade production. The inner stress state and the safety factors against buckling (global-, shear-buckling, and wrinkling) are adjusted to also be quite similar to the real applications. A catalog of typical imperfections was evaluated with industry partners, and embedded in the representative shell specimens to investigate their impact on the fatigue life. Additionally, a test bench was developed for static and cyclic loading in tension and compression. Alongside the mechanical loading, NDT-techniques incorporated into the test bench enable the in-situ monitoring of the initial crack location and the damage progression during the specimen lifespan.

2 Experimental set up, shell test bench, in-situ NDT, and shell specimens



Figure 2: Shell test bench with infrared thermography camera (red) and field strain measurement system



A shell test bench developed at the BAM 5.3 allows for static and fatigue testing of curved fiber-reinforced plastic (FRP) structures. The experimental set up was integrated into a 500kN MTS 810 axial test machine (see Figure 2) to simulate typical operational loads. The load is transferred by each of the seven grips at the top and bottom of the specimen, and a hollow piston cylinder applies a maximum clamping force of 125kN on each grip. Finally, a maximum load per unit length of 1kN/mm can be applied to the shell specimen. This unique, intentional construction of the test bench allows for a guaranteed homogeneous load transfer to the test specimens (see Figure 3 - tensile load 50kN, tensile strain $\varepsilon_y = 0.31 + 0.02$ %). A combined GOM ARAMIS 5M field strain and Infratec IR8300 thermography camera system is used to non-destructively detect defects as well as their evolution. With these systems, the development of defects can be followed in-situ during the fatigue testing.



Figure 3: Field strain measurement on a defect-free shell specimen. Tensile load 50kN, strain ϵ_y = 0.31 +/- 0.02%

ply (Seemann Composites Resin Infusion Molding Process), which is one of the most common resin infusion techniques (see Figure 4, A-D). First, the tailored dry glass fiber textile and the foam plate are positioned in the mold (Fig.4, A). The 10mm thick PVC-foam has lengthwise slits, allowing for easier laying into the curved mold and acting as channels for resin flow during. Next, the preform is covered with a vacuum foil and sealed to the mold (Fig.4, B). The preform is subsequently evacuated, and the resin infusion begins. The specimen is then tempered after production for 15 hours at 80°C. Finally, holes for clamping were drilled in the specimen (Fig.4, C) and the edges were tailored to allow for comfortable fit into the shell test bench (Fig.4, D).



Figure 4: SCRIMP production process of the sandwich shell specimens.

The outer layers each consist of two biaxial $+/-45^{\circ}$ non-crimp fabrics of $810g/m^2$ weight with an effective total thickness of 1.3mm. The10mm thick AIREX C70.55 PVC-foam core had a density of $60kg/m^2$, and the epoxy matrix system used was RIM R135/ RIM H137. In the clamping section, the foam core was replaced by 0°-glass-fiber non-crimp fabric to enhance the compressive strength, and a scarf joint was performed for a smooth load transfer from complete laminate to the sandwich portion (see Figure 1, right). The following typical imperfections were incorporated into the above-described fabrication of the defect-free specimen (see Figure 5):



- Foam gap, with an epoxy filled gap of 3mm, 5mm, 7mm
- Single-ply overlap
- Double-ply overlap

The defect-free shell specimens fail from compressive loading at 149kN due to core shear buckling, and from tensile loading at 150kN due to the tensile strength of the outer layers.



Figure 5: Typical manufacturing of imperfections often seen in blade production. Ply overlap (left), and foam gap (middle und right).

3 Fatigue loading, effect of imperfections, and in-situ NDT

The typical flatwise loading of wind turbine blades in operation has a strain range of 0.2% - 0.5% for normal operation to the 50-year gust load [2]. The edgewise loading stresses on the material are five times less. The blade shell is loaded in tension on the pressure side, and on the suction side it is loaded in compression. Therefore, a cyclic loading with a strain amplitude between 0.2% and 0.3% with a load ratio of R = -1 was chosen to be representative. This strain range complies with a load range of +/-35kN to +/-49kN on the sandwich shell specimens. Cyclic loaded +/-45°-laminates show a significant mechanical hysteresis due to the viscoelastic properties in the undamaged and increasing plasticity in the damaged state [3]. On the first order, the dissipated energy in each cycle is proportional to the square of the load amplitude. The maximum test frequency is thus limited, and was chosen to be 3 Hz for the +/-35kN and 1,5Hz for the +/-49kN load level. This results in a 5°C to 15°C mean increase in surface temperature at room temperature, depending on the damage state. At defect locations, the maximum temperature can reach over 70°C. The typical eigenfrequency of original blades is 0.1Hz to 0.2Hz.



Figure 6.: Test specimen SI_2. Tensile strain 2 ‰. After 8.2 million load cycles. Photo of rear side of specimen with inter-fiber failure cracks (left). The contrast is (middle). With frame rate 8 Hz, in-situ fatigue test (right).



The self-heating of the shell specimens is used for the passive thermography. Figure 6 shows a shell specimen without artificial imperfection after 8.2 million load cycles at +/-35kN. Microcracks are clearly visible on the rear side of the specimen (Figure 6, left). Depending on the frame rate, the thermal contrast maps only the surface cracks (8Hz, right) or additionally the foam core (80Hz, middle). Furthermore, it is advantageous to stop the test, let the specimen cool down, and then restart the cyclic loading and take the thermogram in the warm-up phase. This procedure was automated by means of the test bench computer control.



Figure 7: Test specimen SI_4. Tensile strain 0.3%. Strain field measurement (ARAMIS) and passive thermography showing damage evolution.

The front side of the specimen was coated with a white color and black speckles for the strain field measurement. This coating is transparent for the thermal contrast. Figure 7 compares the tensile strain field and the thermogram for different damage states. The specimen did not have any incorporated imperfection, and was subjected to cyclic loaded with a load amplitude of +/-49kN. Both techniques image the developing micro-cracking in the middle of the specimen until a cleavage fracture occurs. The temperature range of all thermograms was adjusted to be equal. Thus, the severe damaged region emerges in the thermal contrast, and the outer region becomes less visible. The damage was found to begin in the middle of the specimen, and was not affected from the free edge or clamping region. This result was the first proof of concept concerning the design of the specimens and the test bench.

The shell specimens with typical imperfections were investigated in the second stage (see Figure 8). Again, all specimens began to fail in the middle region, regardless of the imperfection type. The foam gap and ply overlay can be imaged clearly with passive thermography (see Figure 8, top). However, the strain field measurement is not as sensitive. The increased local stiffness causes a decrease in local strain. The foam gaps are hardly visible in the tensile strain image. On the contrary, the ply overlaps are clearly imaged, but the contrast has a lower quality compared to the thermography. In the damaged state, both techniques indicate the location of the initial defect and the progression until the final failure. The initial damage always begins at the imperfection. In the case of the ply overlays, the position of the initial failure is at the edge of the ending ply. Again, the temperature range was equally adjusted for all experiments. Thus, the contrast in the thermograms emphasizes the position of the cleavage fracture.



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Figure 8: Strain field and thermogram in undamaged (top) and damaged state (bottom) for specimens without (left) and with different imperfections.

4 Discussion

Passive thermography is a suitable technique for the in-situ monitoring of fatigue phenomena in FRP specimens [4,5]. In addition to strain field measurement, the thermography was used for the first time as structural health monitoring of fatigue-loaded shell structures. In expansion to these methods, the active thermography, air coupled ultrasound, and X-ray-laminography NDT techniques were investigated for reference [6]. Air coupled ultrasound and X-raylaminography are applied in transmission. The quality of resolution of these techniques is much better. However, the specimen must be demounted from the test bench, i.e. cannot be executed in-situ. Finally, the passive and active thermography seems to be the most efficient and practical methodology package to track the damage state of sandwich shell structures because this is applicable from only one side of the specimen. With the active thermography and infrared heater and/or login techniques, the thermal contrast can be adjusted to the depth of the sandwich structure. The operator can visualize the cracks in the skin layer or in the foam core in different images.

Finally, all specimens fail across the entire width. Thus, without the in-situ technique it is impossible to track the origin of the cleavage fracture. All tests run fully automated, overnight when necessary. The colored front side is designed to be similar to original blades. This means that the active thermography can be applied to real blades for quality control or inspections, and has already been done [7,8].



Comparing the impact of the investigated imperfections led to a number of conclusions about the effects of various defects. A short ply overlap has the most significant reduction of the lifetime of the sandwich shell specimens, followed by foam gaps with a width of over 5 mm. The double ply overlap works like a stringer and increases the lifespan. Numerical analysis is currently still being processed to extrapolate the effect onto real rotor blade dimensions.

5 Conclusion

In the presented project, a test bench and sandwich shell specimens were developed at BAM 5.3 to investigate the impact of imperfections during fatigue loading of wind turbine rotor blades at an intermediate scale. With the specific design of the test bench and the specimens, the source of the cleavage fracture was found to be in the middle region of the test shell. The origin and progression of the damages can be followed automatically with the in-situ NDT techniques of passive thermography and strain field measurement. Finally, an efficient method was designed and built to investigate the fatigue behavior of curved shell structures.

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References

- [1] Windenergiereport Deutschland 2008, Seite 39. <u>http://windmonitor.iee.fraunhofer.de/opencms/export/sites/windmonitor/img/Windenergie_Report_2008.pdf</u>
- [2] Grasse, F., Trappe, V., Thöns, S., Said, S.: "Structural health monitoring of wind turbine blades by strain measurement and vibration analysis", EURODYN 2011 - 8th International conference on structural dynamics (Proceedings) (2011) MS25 Tue, 3490-3497; Hrsg.: Katholieke Universiteit Leuven ISBN 978-90-760-1931-4
- [3] Trappe, V., Harbich, K.-W., Ernst, H.: "Intralaminar fatigue behaviour of carbon fibre reinforced plastics"; *Int. Journal of Fatigue* 28 (2006), pp. 1187-1196
- [4] Schmidt F, Rheinfurth M, Horst P, Busse G.: "Multiaxial fatigue behaviour of GFRP with evenly distributed or accumulated voids monitored by various NDT methodologies". Int J Fatigue 43, 207–216 (2012)
- [5] Harizi W, Chaki S, Bourse G, Ourak M.: "Mechanical damage assessment of Glass Fiber-Reinforced Polymer composites using passive infrared thermography". Compos Part B Eng. 59, 74–79 (2014)
- [6] Trappe, V., Nielow, D., Hickmann, S., Kupsch, A., Gaal, M., Redmer, B., Krankenhagen, R.: "Sandwich-Schalenstrukturen in situ charakterisiert mit Thermographie und Felddehnungsmessungen", Proceeding DGZfP-Jahrestagung, Di.1.B.3, Leipzig, Germany 2018, ISBN 978-3-940283-92-4
- [7] Worzewski, T., Krankenhagen, R., Doroshtnasir, M., Röllig, M., Mairhofer, C., Steinfurth, H.: "Thermographic inspection of wind turbine rotor blade segment utilizing natural conditions as excitation source, Part I: Solar excitation for detecting deep structures in GFRP". Journal of Infrared Physics and Technology 76 (2016) 756-766
- [8] Worzewski, T., Krankenhagen, R., Doroshtnasir, M.: "Thermographic inspection of wind turbine rotor blade segment utilizing natural conditions as excitation source, Part II: The effect of climatic conditions on thermographic inspections – A long term outdoor experiment". Journal of Infrared Physics and Technology 76 (2016) 767-776

