THE ANCHORING OF A RETROFIT REINFORCEMENT CONCEPT IN THE TRAILING EDGE OF WIND TURBINE BLADES

P. Bortolotti1*, K.N. Anyfantis1, C. Berggreen1, M. Lagerbon2, R. Sajous2
1Department of Mechanical Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark
2Bladena ApS, Ringsted, Denmark
*Corresponding author (pibo@dtu.dk)

Abstract
Large cracks have been recently detected along the trailing edge of operational wind turbine blades and retrofit solutions need to be implemented. A retrofit reinforcement concept for sandwich panels has been developed that consists of two plugs connected with tie-strings to reduce the out-of-plane displacements of the sandwich shell panels close to the trailing edge. In this study, focus is given to the anchoring of the strings to the sandwich panels. The anchoring is performed through conical plugs inserted into holes in the sandwich panels on the pressure and suction sides of the blade and connected through a string. Numerical simulations have been performed followed by an experimental validation of the anchoring concept. An optimized shape of the plug is finally discussed in order to achieve a uniform pressure distribution of the plug.

1 Introduction
Recently, large cracks have been discovered in the trailing edge of commercial wind turbine blades as a result of in-service loads. Such damages have been detected during early normal service operation and the crack size jeopardizes the integrity and performance of the entire wind turbine [1]. A retrofit solution must be developed to avoid growth of the existing cracks and structural failure of blades that are already in operation.
This challenge is being tackled by the Danish company Bladena, which has defined a set of guidelines and constraints together with wind turbine manufacturers and wind farm operators for the development phases towards an effective retrofit solution:
- The solution with the shortest down-time of the wind turbine shall be implemented.
Therefore, retrofit of the turbine blades must be carried out on site and at hub height.
- The retrofit must be kept simple yet effective, with as few components being installed as possible.
- No changes in the outer shape of the blade are allowed.
- Non-metallic parts must be used.
- Moving parts shall be avoided.
- Materials must be UV, saltwater and heat resistant.

A retrofit concept has emerged following these tight constraints and has been patented by Bladena [2]. It consists of conical plugs inserted in the sandwich panels connected by tie-strings, which reduce the out-of-plane displacements of the shell panels close to the trailing edge. This concept is schematically illustrated in Fig. 1.
The idea is then for a retrofit crew rappelling down from the wind turbine hub, installing plugs and strings between the suction and pressure side in different locations along the TE of the blades. The retrofit crew will drill holes on each side of the blade and insert a polymer string anchored by plastic insert plugs. The string will be pre-tensioned by the crew operators. The hole in the face sheets will then be covered with wear resistant glue and finally coated to protect the blade from water, solar radiation and heat. Once the strings are installed, the retrofit will not be visible on the outside of the blade.
However, many knowledge gaps are present for the retrofit concept, such as the anchoring of the strings in the sandwich shells. To this end, a cooperative framework has been formed involving Bladena and the Lightweight Structures Group at the Technical University of Denmark (DTU – Department of Mechanical Engineering). The goal of the project is to develop a strong and fatigue resistant anchoring
solution. To achieve this goal, a combined experimental and numerical study has been conducted. This work presents a stress analysis of the anchoring of the tie-strings to the shell of wind turbine blades. Firstly, the geometry and the materials of the cones and of the sandwich panels are discussed. Then, the results from preliminary numerical simulations are presented, followed by an experimental validation of the finite element model. Lastly, a discussion on potential improvements of the anchoring concept is presented, together with recommendations for future work.

2 Preliminary design and materials testing

The strings need to be strongly attached to the blades, preserving the overall strength of the shell panels and avoiding debonding between the core and the inner and outer face sheet layers, Fig. 1. The initial design of the plugs had a conical shape. This was decided in order to distribute the loads as uniformly as possible in the foam core of the shell panels. Due to the small thickness of the face sheets compared to the foam core, the cones were designed to fit entirely in the core. Polyoxymethylene (POM) was found to be a suitable material for the plugs. The cone internal structure, shown in Fig. 2, was specifically designed so as to allow tightening of the string without any metallic or moveable part.

The area where the fittings are to be installed is a foam cored sandwich shell, consisting of two face sheets of tri-axial E-glass (0°/±45° orientation) in an epoxy matrix over a structural foam core, see Fig. 3. The thickness of the core of the shell panels ranges between 20 and 50 mm along the trailing edge. The cone has a number of geometric constraints: a minimum diameter of 10 mm, in order for the worker to easily introduce the string into the blade, and a maximum length of 20 mm, to fit the entire cone inside the core at minimum shell thickness. Also, a diameter of the hole in the panels of the blade shell of 45 mm was identified as the maximum allowable.

Square specimens from the sandwich shells were cut from the TE region of a 34 meter long commercial blade. Material properties for POM and the face sheets were obtained from the blade manufacturer’s material datasheets. The core was made from polyvinyl chloride foam (PVC) with density of 80 kg/m³. Based on preliminary experimental observations and numerical simulations, the strength of the anchoring depends on the crushing strength of the foam core. Hence, the compressive strength for the failure analysis was required as input. It was therefore decided to test foam in compression to carefully evaluate its compressive mechanical behavior. Core parallelepipeds were cut from the sandwich panels with nominal dimensions 15x15x30 mm and loaded in the panel thickness direction.

Surface strains were monitored using an optical non-contact 2D Digital Image Correlation (DIC) technology. The ARAMIS 4M system, from GOM GmbH, was used for measurements and post-processing. A random grey-scale paint pattern was sprayed onto the foam surface. One camera was placed perpendicular to the face of the sample with a sampling rate of 1 Hz monitoring the surface deformations. The DIC measurement produces a full field strain distribution, which is necessary to well characterize the complex crushing behavior of foams [3,4].

A typical experimental stress-strain curve of the PVC foam under compression is shown in Fig. 4. Foam crushing has been extensively studied [3-7] and the results obtained here compare well with those obtained in these studies. The mechanical properties of the materials examined are listed in Table 1.

3 Numerical simulations

3.1 FE modeling

A computational model of the retrofit concept was developed in the commercial finite element software ANSYS. A 2D axisymmetric model was built with contact elements at the interface between insert and foam. Contact elements were necessary to model the sliding between cone and foam core throughout the entire loading history. Geometrical and material non-linear behaviors were accommodated. Models of a circular panel with diameter of 360 mm, core thickness of 20 mm and upper and lower face
sheets thicknesses of 4 and 2 mm respectively were built. Two plug geometries were modeled with two different heights. Both cones had an upper diameter of 45 mm and a lower diameter of 10 mm. Two cone angles $\theta$ were examined: 35° and 45°. The boundary conditions are schematically depicted in Fig. 5. The edges of the panel were assumed to be fully clamped with symmetry conditions applied to the nodes at the center line, while a vertical displacement $u$ was applied on the center line of the cone to simulate the string tension. The model was meshed with quadrilateral elements obtained through controlled line divisions, as shown in Fig. 6.

While the face sheets and POM materials were assumed to be linear elastic, the PVC foam was assumed to behave in an elastic perfectly plastic manner with Young’s modulus of 80 MPa and a yield stress of 1.38 MPa. This idealized model is shown with a dashed line in Fig. 4. The yield stress from the ideal elastic-plastic model in Fig. 3 was set equal to the same work $W$ of deformation per unit volume measured in experiments.

$$W = \int \sigma \cdot d\varepsilon$$ (1)

It is known that foams may be heterogeneous and present anisotropic behavior due to density variations and directionality of the cells during the manufacturing process [3,4]. However, for simplicity, isotropic behavior was assumed in this initial study.

### 3.2 FE results

The initial simulations were performed with a vertical displacement $u$ equal to 2 mm. The two cones perfectly fitting inside the hole in the unloaded configuration of the panel were analyzed. However, due to the bending of the panel and the stiffness mismatch, the contact pressure distribution along the interface became non uniform. This can be clearly seen in Fig. 7, where the von Mises stress is shown in the PVC foam at 45° cone angle. The cone experienced an almost pure vertical translation, which caused panel bending and consequently a rotation of the foam surface. This generated a high stress concentration in the foam at the contact point with the upper edge of the cone.

### 4 Experimental tests

#### 4.1 Test setup

In order to experimentally validate the numerical model, the strains in the PVC foam core close to the cone upper edge were to be monitored. This was made possible by cutting a sandwich panel in two equal halves along the centerline. A half cone could then be mounted on the piston of a 100 kN MTS 810 universal testing machine equipped with a 10 kN load cell and displaced vertically downwards into the semi-conical hole in the panel. The test setup is shown in Figs. 8 and 9.

Due to the asymmetry of the test setup, the displacements of both the half panel and half cone had to be constrained in the plane of the panel. This issue was solved by clamping the half panel to a steel frame and by using a special device to limit the in-plane displacement of the cone. This device, shown in Fig. 9 and marked “piston rail”, consists of a hollow cylinder that can be aligned with the piston and anchored to the frame of the machine. The piston can then slide inside the cylinder and can withstand lateral loads without off-axis displacements.

The displacements and the surface strains were monitored using the ARAMIS 4M system. 2 synchronized cameras were used to obtain a 3D displacement field at the specimen surface.

Two cone angles were tested, with 3 repetitions per angle, for a total of 6 half panels tested. The half panels were rectangular with side lengths of 360x180 mm and core thickness of 20 mm. The thicknesses of the upper and lower face sheets were 4 and 2 mm respectively.

A displacement rate of 1 mm/min was imposed to the cone, while a sampling rate of 1 Hz was used for the two DIC cameras. Tests were stopped at a vertical displacement of 10 mm.

#### 4.2 Test results

During the vertical translation of the cone, the panel was subjected to bi-axial bending. This implied that the PVC foam contact surfaces underwent a rotation. However, due to the stiffness mismatch between foam and POM, the much stiffer cone did not conform to the foam deformation and this caused high stress concentrations and localized plastic deformation of the PVC foam.
Shear strain results from DIC measurements are shown in Figs. 10 and 11 for a vertical displacement of 1.5 mm at a compressive load of approximately 500 N. The shear strains are shown in both the half cone and half panel.

As expected, the cone is under small strains due to the high stiffness of POM. For the PVC foam, however, substantial strain concentrations are developed close to the upper edge of the cone.

In addition, it is also clear that both the elastic and plastic deformations of PVC foam are strongly localized in the vicinity of the upper edge of the cone. Therefore, no good distribution of the strains inside the core of the panels was achieved. This followed the foam behavior detected by Rizov et al. [5].

All six tests produced similar results, i.e. stress concentrations in the foam with localized plastic deformation. No significant differences were found between the two cone angles.

5 Optimized fittings

The cones caused plastic deformations in the PVC foams even at small loads due to a non-uniform pressure distribution along the POM-PVC foam interface, see Fig. 12. As the anchoring system needs to be designed for fatigue loads, the configuration is required to minimize local plastic deformation of the PVC foam.

An optimized design has therefore been investigated considering different shapes for the fittings. The goal of the new cone shape is to conform to the hole in the panel in the loaded configuration. A curved surface of the fitting proved to be promising during numerical simulations.

Several shapes have been modeled with different angles and different curvatures. Fig. 13 shows the contact pressure distribution for the original design at 45° and for a curved cone at a vertical displacement of the cone center line of 2 mm.

6 Conclusions

This study investigates a retrofit reinforcement concept for the trailing edge of wind turbine rotor blades. The concept consists of two plugs connected by tie-strings that reduce the opening displacement of the sandwich panels.

The strings are anchored in the blade sandwich shells using cones, which distribute the loads into the core of the sandwich panels. Numerical models have been developed and experiments were performed. It has been shown that the cone shapes lead to high stress concentrations and plastic deformation of the foam in the vicinity of the upper edge of the cone-foam interface.

A cone with curved side could achieve a better contact pressure distribution along the interface in the loaded state and reduce the local stress concentrations.

Work is presently ongoing to refine modeling of PVC foams and to improve the accuracy of the numerical model.

Acknowledgments

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References

**Tables and Figures**

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Table 1. Material properties of constituent materials.

Fig. 1. Installation of “strings” in the TE part of a blade [2].

Fig. 2. Internal structure of a string-cone anchoring plug.

Fig. 3. Anchoring coupons for the retrofit concept.

Fig. 4. Compressive stress-strain curve of PVC foam.

Fig. 5. Schematic drawing for the 2D axisymmetric model and boundary conditions.
Fig. 6. Meshing of the cone-panel interface.

Fig. 7. von Mises stress distribution in the PVC foam for the 45° cone.

Fig. 8. Schematic of the test setup for panel testing.

Fig. 9. Test setup for panel testing.
Fig. 10. $\varepsilon_{xy}$ for the 45° cone.

Fig. 11. $\varepsilon_{xy}$ for the 35° cone.
Fig. 12. Plastic shear strain distribution in the PVC foam for the 45° cone at vertical displacement $u$ of 1.16, 1.51, 1.86 and 2 mm.

Fig. 13. Pressure profile along the contact line for 45° flat and edge-curved cone shapes.