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DESIGN AND MANUFACTURING OF A MORPHING FLAP FOR WIND TURBINE BLADES

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Summary. *This document describes the current status of the flap prototype development in the INDUFLAP project funded by the EUDP programme from the Danish Ministry of Energy.*

1 INTRODUCTION

Wind turbine blades are constantly exposed to unsteady loads due to turbulence and gusts in the incoming flow and this increase significantly the cost. Therefore, researchers and industry are aimed at finding technical solutions that can alleviate the loads on the turbines. The specific solution that has been under development at Risø since 2006 is a flexible trailing edge of rubber or plastic. Movement of the trailing edge is achieved by elastic deformations caused by cavities that can be pressurized with air or hydraulics. It is these controlled movements that counteract the forces from wind gusts.

The current paper describes the current status of the flap cavity designs and results of some of the prototype test results.

2 DESIGN

The basic design of the flap is made of a flexible material, like rubber or plastic with suitable reinforced voids that can be pressurized with a medium such as air or a liquid and in this way give the desired deflection of the flap.

A number of prototypes with a chord of 150 mm, based on the NACA0015 airfoil shape, have been manufactured and tested showing a maximum deflection of ± 12 mm for a pressure of ± 6 bar. Six of these prototypes were glued together and mounted on a 1.9 m long airfoil section model with a chord of 1 m. In the wind tunnel measurements the total change in lift coefficient ΔCL was around ±0.2 for maximum flap deflection [1]. Despite the success of the wind tunnel campaign further development was deemed necessary to ensure a more robust flap design.

Two overall cavity design concepts have been considered. The first overall concept supplies air or hydraulics from a manifold attached to the rear of the flap, see figure 1, intended for mould manufacturing. The second flap concept supplies air from the sides of the flap in cavities following the spanwise blade direction and intended for extrusion. According to industrial partners the second concept should be used to keep cost of the flap production low from a manufacturing perspective.

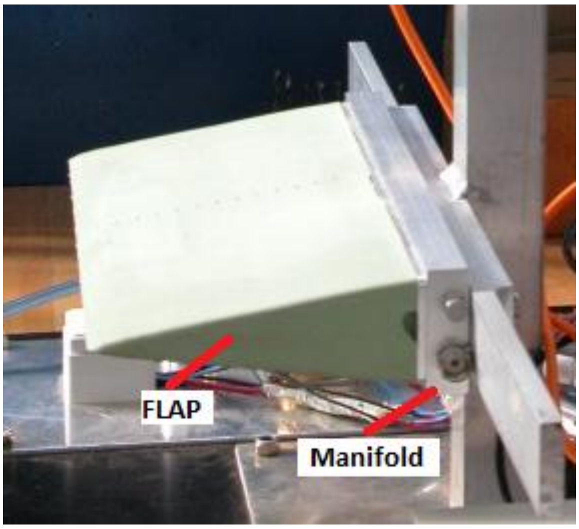

Figure 1: Manifold attached to the rear of the flap.

For all cavity designs it was important to keep the stress concentration low without losing maximum flap deflection. The COMSOL® [2] software package has been used for the Finite Element (FE) modeling of cavity configurations, exploring various void arrangements, and internal reinforcement structure concepts. The object functions for the flap cavity designs are;

1. stress level within material tolerance
2. maximize flap tip deflection
3. cavity wall tolerances vs. production cost

A number of thermoplastic rubber materials were considered for use in Mooney-Rivlin computations Santoprene 101-73 thermoplastic vulcanizate from ExxonMobil Chemical and examples of flap prototypes with Wacker 4670 silicon rubber will be shown in result chapter. Due to the highly nonlinear nature of the computations it should be mentioned that the maximum stress' for the rubber flap part at 15% material elongation was set to 8N/mm^2 or 8MPa [3]. The steady state flap deflection angle, β, is defined by

$$\tan\beta = \frac{h}{s} \ , \tag{1}$$

where the chordwise flap length, s, is 150mm and the tip deflection from un-deformed to steady state tip deflection is h. Attempts were made to keep 8 degree deflection, which correspond to change in the airfoil lift coefficient ΔCL ≈ -0.2. Finally geometry steps in cavity wall dimensions should not be smaller than 0.1mm, due to higher cost at finer tolerances. The stresses, von Mises, in the original flap design [4] have been organized in three categories "outer rubber stress", "inner rubber stress" and "reinforcement stress", see figure 2. As no standards exists in IEC61400-1 for extreme rubber trailing edge loads, stress computations are provided with DLC 1.1 partial safety factor 1.35 for normal operation. High stress concentration at the rear flap region was seen for the original flap design near the sharp edges in cavities and non-optimal wall height between cavity and outer flap surface.

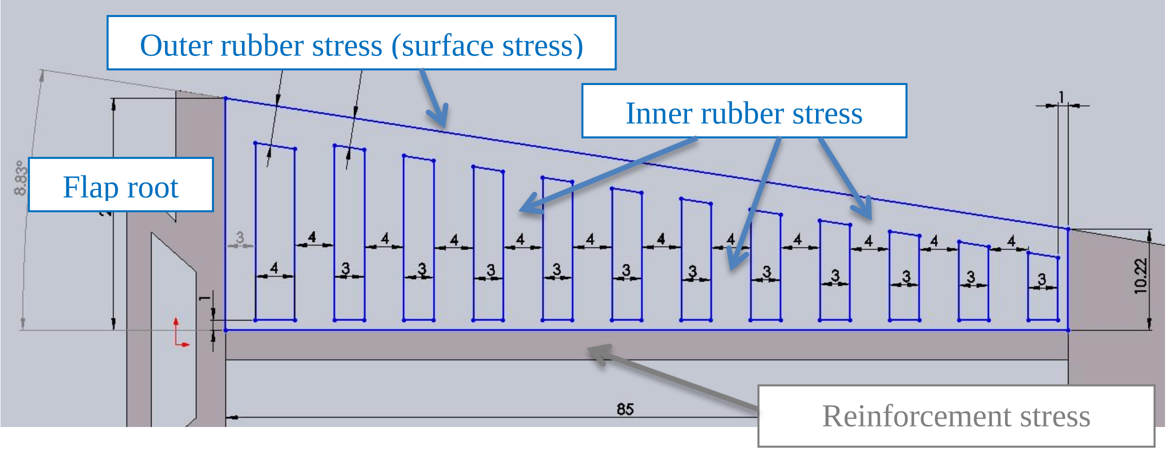

Figure 2: Different zones of interest for extreme stress computations. The figure illustrates the original spanwise cavity flap design, all dimensions are in mm.

The need to focus on lowering the maximum outer surface stress levels near the flap root has been seen in early prototype tests where faults in the connection between rubber flap and manifold for pressure levels above 7 bars was seen, see "zone of detachment" in figure 3.

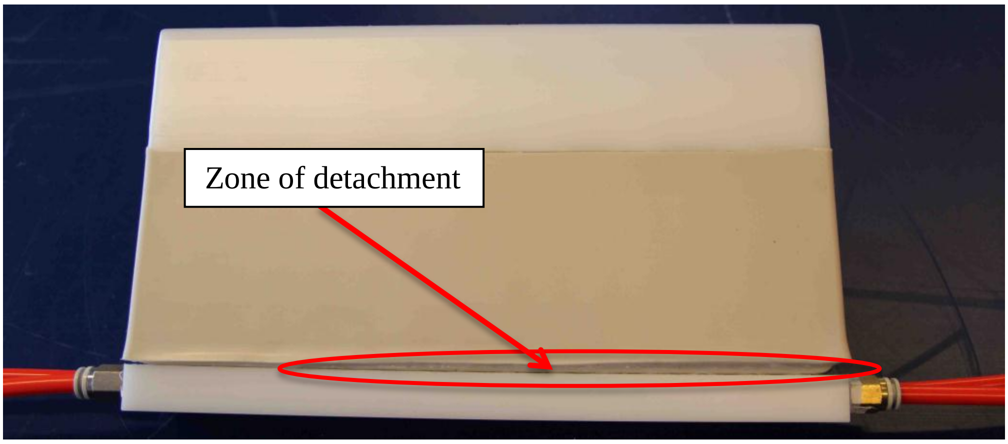

Figure 3: Zone of detachment in thermoplastic rubber material and manifold.

Hence a new cavity design was undertaken aiming at lowering steady state stress levels, preferably keeping the same flap deflection and not doing smaller increments in wall thickness' than 0.1mm. The results of the new designs are presented in the next chapter along with recent pictures of the new prototypes utilizing cavities in span wise direction.

3 RESULTS

The starting point for the new design was the original span wise flap cavity design. Improving the rubber/thermo plastic part had focus, whereas the reinforcement element remained unchanged. A limit to the outer flap surface curvature gradient was introduced on experimental basis but it quickly became obvious it was better to check the designs manually afterwards for aerodynamic performance through outer surface smoothness. Aerodynamic feedback to the flap was modeled through a constant pressure of one percent of atmospheric pressure for the NACA0015 airfoil near the trailing edge, see figure 4.

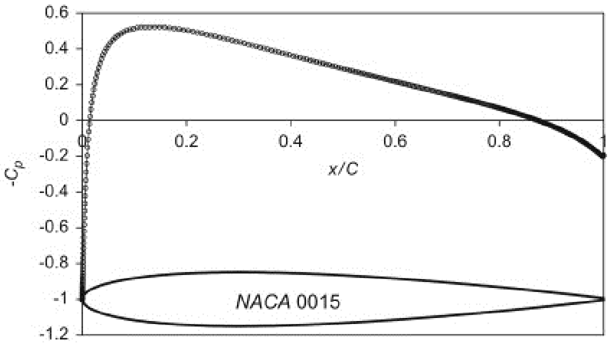

Figure 4: pressure coefficient around a NACA0015 airfoil for some positive incidence angle

Free tetrahedral elements was used in COMSOL, the number of elements used was investigated by sweeping from a few hundred to several hundred thousand. The best ration in terms of computational time to accuracy was around 25 thousands, see figure 5. Symmetric boundary condition is applied to all faces in span wise direction and the rear part of the flap is constrained in movement.

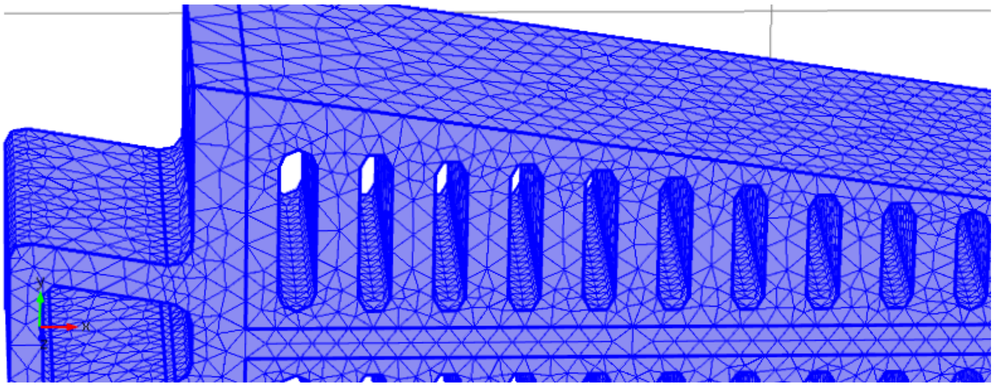

Figure 5: The typical mesh used for the steady state flap prototype computation.

In the following table 1 comparison results between the original design with square cavities, *"old square"*, and two new designs *"square"* and *"rounded"* is outlined for maximum stress level and maximum flap deflection.

		Flap deflection		Rubber			Reinforcement	
				outer	**Inner**	***w/ part.***	**inner**	***w/ part.***
Cavity	**pressure**	**angle**	**displa.**	**Stress**	**Stress**	***safty fac.***	**stress**	***saf. fac.***
design	bar	deg	mm	N/mm^2	N/mm^2	*N/mm^2*	N/mm^2	*N/mm^2*
Rounded	4	4.2	11.0		1.7	*2.3 (3.48)*	8	*11*
old square	6	6.6	17.4	3.2	4.1	*5.5 (1.45)*	12	*16*
Square	6	6.8	17.8	2.5	4.0	*5.4 (1.48)*	12	*16*
Rounded	6	6.5	17.1	2.4	2.6	*3.5 (2.29)*	12	*16*
old square	8	8.3	21.9		6.1	*8.2 (0.97)*	14	*19*
Square	8	8.9	23.5		6.0	*8.1 (0.99)*	14	*19*
Rounded	8	9.1	23.9		4.1	*5.5 (1.45)*	14	*19*

Table 1 maximum stress and flap deflection for three different designs and different cavity pressures. The "Square" cavity design is shown in Figure 6 and the "Rounded" cavity design is shown in Figure 7. Inner stresses in the "rubber part" with 1.35 partial safty factor and parenteses values indicate safty margin to 8MPa or 8M/mm^2 limit. Outer surface stress for 6 bars is also shown in Figure 8 and 9 comparing the original and the new spanwise cavity designs. An illustration of the difference between "inner" and "outer" rubber stress and reinforcement stress is shown in Figure 2.

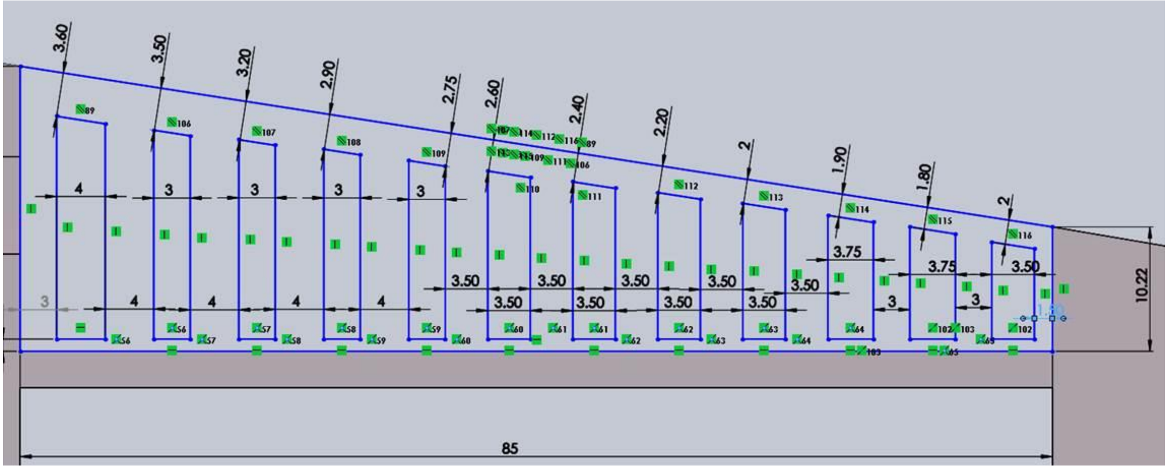

Figure 6: Cavity design involving sharp edges

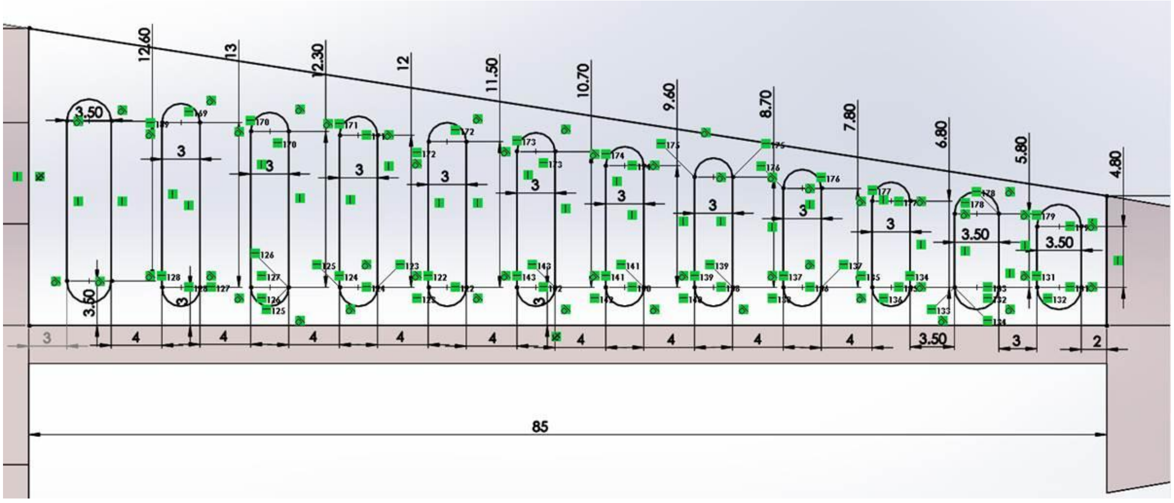

Figure 7: Cavity design involving rounded edges

One of the design inputs from the industrial partner in the INDUFLAP consortium was the cavity wall dimensions should not be designed in steps less than 0.1mm, see figure 7, simply because these tolerances would increase the production cost too much.

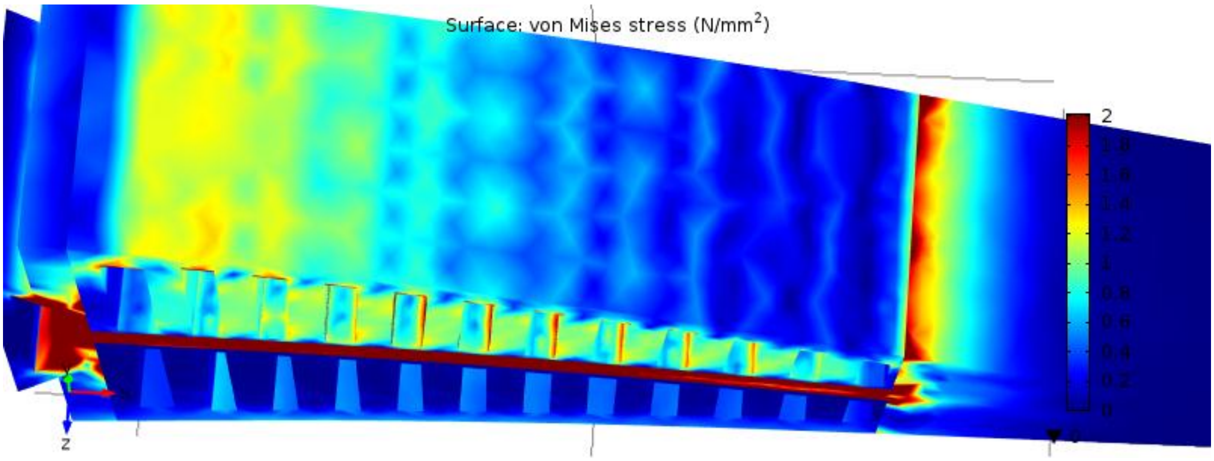

Figure 8: Outer surface stress levels for original spanwise cavity flap design

Less stresses at the rear part of the flap

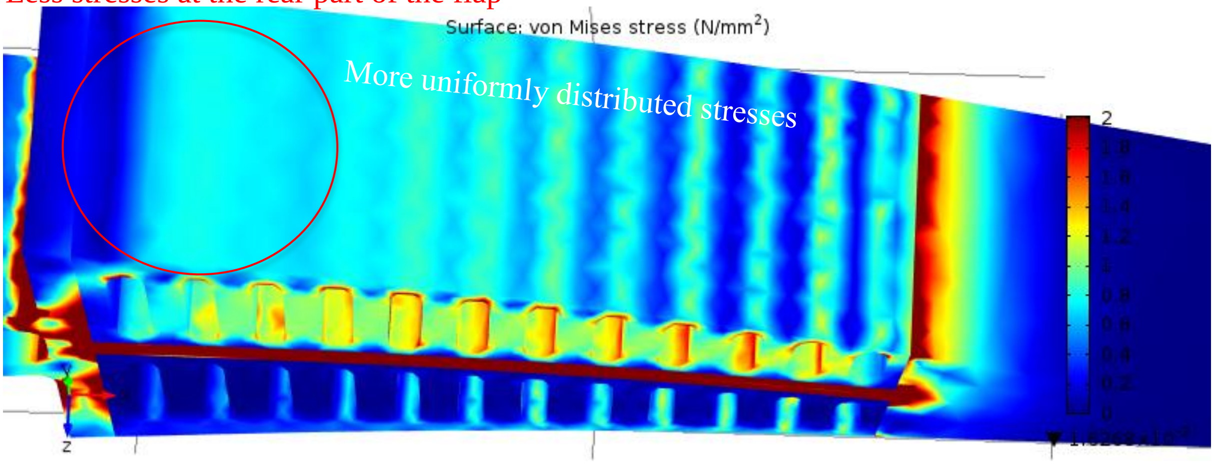

Figure 9: Outer surface stress levels for new spanwise cavity flap design

Finally figure 10 is added to illustrate the production process for a simple case with square three cavities.

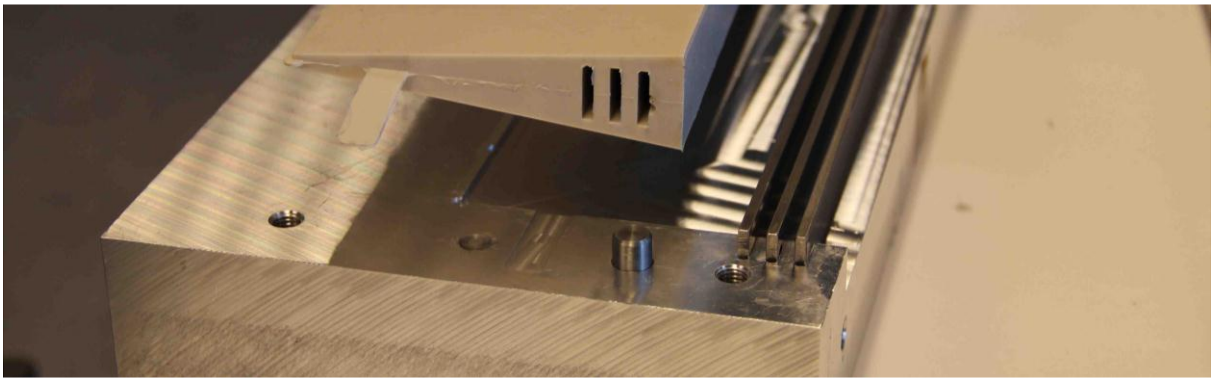

Figure 10: Example of three square cavities produced at DTU Wind Energy Department.

4 CONCLUSIONS

It has been proposed to use the thermoplastic rubber material Santoprene 101-73 for the trailing edge flap. For 15% material elongation the critical stress level is 8MPa. To ensure greater safety margin to 8MPa a new spanwise cavity design for the trailing edge flap is proposed. The new design lowers the critical stresses from 8.2MPa to 5.5MPa for 8bar cavity overpressure and 5.5MPa to 3.5MPa for 6bar cavity overpressure including partial safety factors.

Compared to the original design the flap deflection angles remain almost the same. This is important as the flap deflection angle is a direct measure of the performance and usefulness of the flap.

According to finite element simulation the recommendation is to use round edges instead of sharp edges as it lowers the maximum stresses in the rubber part of the trailing edge flap significantly.

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