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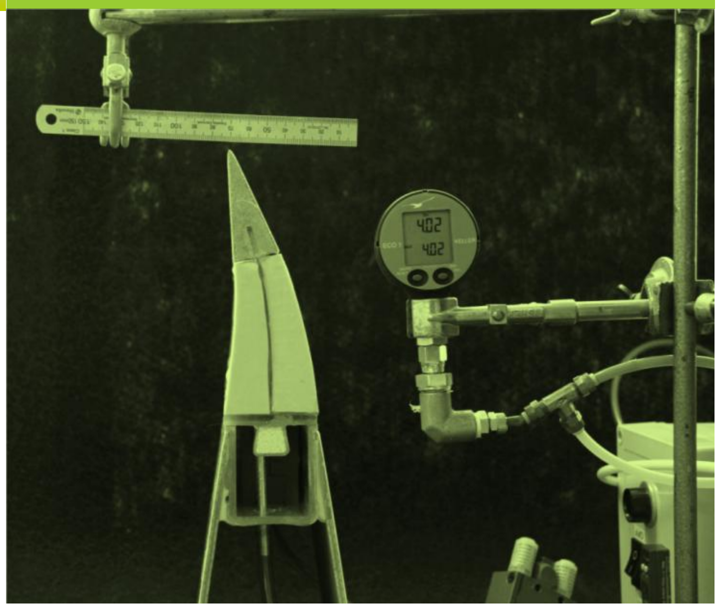
Design, manufacturing and testing of Controllable Rubber Trailing Edge Flaps

Department of Wind Energy
E Report 2015



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DTU Vindenergi-E-0076(EN)

January 2015

DTU Vindenergi
Institut for Vindenergi

Authors: Tom L. Andersen, Helge A. Madsen, Thanasis K. Barlas, Ulrich Mortensen, Peter B. Andersen
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This report covers experimental work at DTU Wind Energy including design, manufacture and test of different configurations of flaps with voids in chord- or spanwise direction. Development of rubber flaps has involved further design improvements. Non-metallic spring elements and solutions for sealing of continuous extruded rubber profiles have been investigated.

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Preface

This report serves as a summary of the work conducted in relation to the design and development of Controllable Rubber Trailing Edge Flap (CRTEF) prototypes performed in the INDUFLAP project.

Roskilde, January 2015

Tom L. Andersen
Senior development engineer

Content

Summary

The overall goal for the INDUFLAP project was realization of a test facility for development and test of Controllable Rubber Trailing Edge Flaps (CRTEF) for wind turbines. A CRTEF can be described as a flexible trailing edge blade part that can be moved independent of the wind turbine blade movement and thereby the aerodynamic profile changed. Movement of the flap is controlled by pressurization of one of two rows of voids in the flap profile. The pressure will expand the voids and thereby move the rubber profile. This report covers experimental work at DTU Wind Energy including design, manufacture and test of different configurations of flaps with voids in chord- or spanwise direction. Development of rubber flaps has involved further design improvements. Non-metallic spring elements and solutions for sealing of continuous extruded rubber profiles have been investigated.

1. Introduction

This report summarizes work conducted in relation to the design and development of Controllable Rubber Trailing Edge Flap (CRTEF) prototypes in the INDUFLAP project period from 2011-2014 and is mainly based on previous published work [1, 2] and updates.
The project was funded by the Danish Energy Agency through the EUDP 2011 programme. The industrial project partners in the project were Rehau (DE), Hydratech Industries (DK) and Dansk Gummi Industri (DK).

The overall goal for the INDUFLAP project was realization of a test facility for development and test of Controllable Rubber Trailing Edge Flaps for wind turbines. Several numerical studies [3] in the past 10 years have shown big potentials for load reduction on MW turbines using distributed control for alleviation of the fluctuating loads along the blade span. However, the requirements by the wind turbine industry of robust actuator solutions where the strongest specifications mean no metal and electrical parts in the blades have so far limited the use of the smart blade technology on wind turbines.

The initial investigations back in 2006 of finding a suitable, robust flap actuation concept led to the design of the CRTEF. A design concept that fulfills the requirements of: 1) no mechanical parts; 2) no metal parts and 3) no electronics in the blade. The CRTEF is a trailing edge flap manufactured in an elastic material such as e.g. rubber or a polymer material and with suitable reinforced voids that can be pressurized with a medium such as air or a liquid and, thus giving the desired deflection of the flap. If the lower row of voids is pressurized the flap will deflect upwards as shown in the left illustration of Figure 1 and likewise a downward deflection is obtained by pressurizing the upper row of voids.

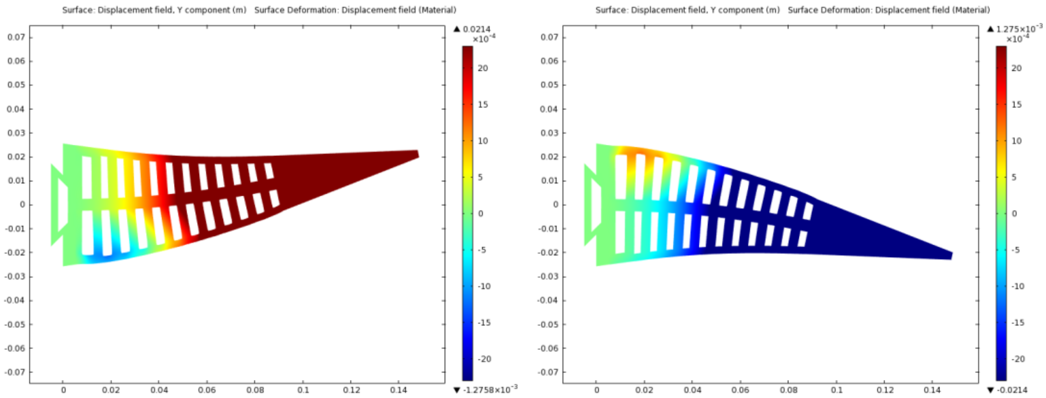

Figure 1: To the left, the lower row of voids is pressurized giving an upward deflection. To the right, the upper row of voids is pressurized giving a downward deflection.

Two basically different concepts have been investigated: 1) flaps with voids in the chordwise direction as shown in the left part of Figure 2, and 2) flap designs with voids in the spanwise direction as shown to the right in Figure 2. The flap designs with the chordwise voids were used in the first part of the development work from 2006 to 2010 and a solution with spanwise voids initiated at the beginning of the INDUFLAP project in 2011.

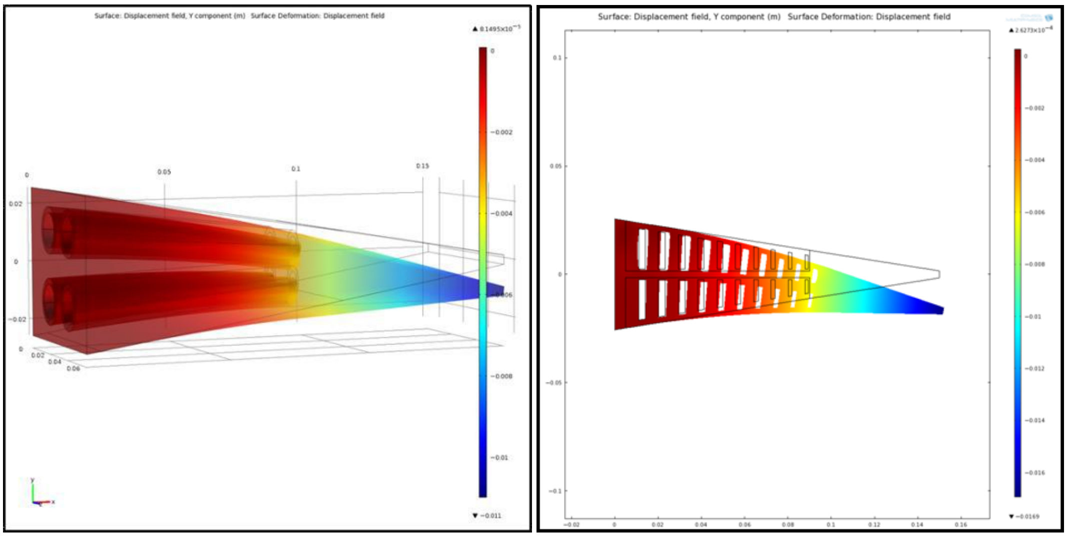

Figure 2: To the left, modelling of chordwise voids formed as individual cones in the rubber part and to the right, cross section of a CRTEF showing the spanwise voids with different size.

The flap concepts also represent two different process technologies. Flaps with Chordwise voids are best suited for a batch production of individual flaps where the shape of the rubber profile can change over the span, whereas flaps with spanwise voids ideally are manufactured by a continuous extrusion process, having a fixed geometry.

The realized test facility, illustrated in Figure 3, was designed with a 2m long wind turbine blade section placed at the end of a 10m long boom. The selected NACA0015 airfoil is symmetrical and was built with a total 1m chord length, of which the CRTEF at the trailing edge is 15cm long. More information on the test rig can be found in the project report [4]

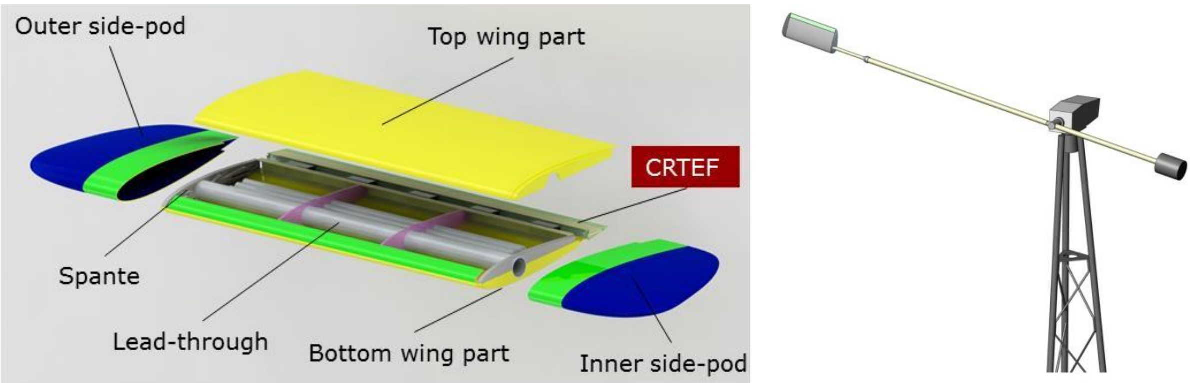

Figure 3: To the right, the rotating rig with the blade section at the end of the boom and a counterweight at the other end. To the left, a sketch shows the basic design of the NACA0015 airfoil with mounted CRTEF and side-pods in both ends.

2. Flaps with chordwise voids

Focus for the new flap prototypes with chordwise voids were two folded: 1) introduction of a stiff tip part to obtain improved deflection when the CRTEF is in operation, as the wind load could deflect a more ductile material and 2) replacement of all metal parts to obtain an operational safe mode for lightning. Some changes are illustrated in Figure 4, where a new and previous version of a CRTEF is shown. To the right is a new CRTEF with a white stiff polyethylene (PE) polymer tip part. The aluminium metal base was partly replaced and polymer inserts with thread for mounting of the CRTEF can be observed as the black spots between the voids. The green rubber material is in both cases Silastic J from Dow Chemicals. The prototypes were manufactured in the same mold having a chordwise length of 15cm and a spanwise length of 30cm with 14 voids on each side.

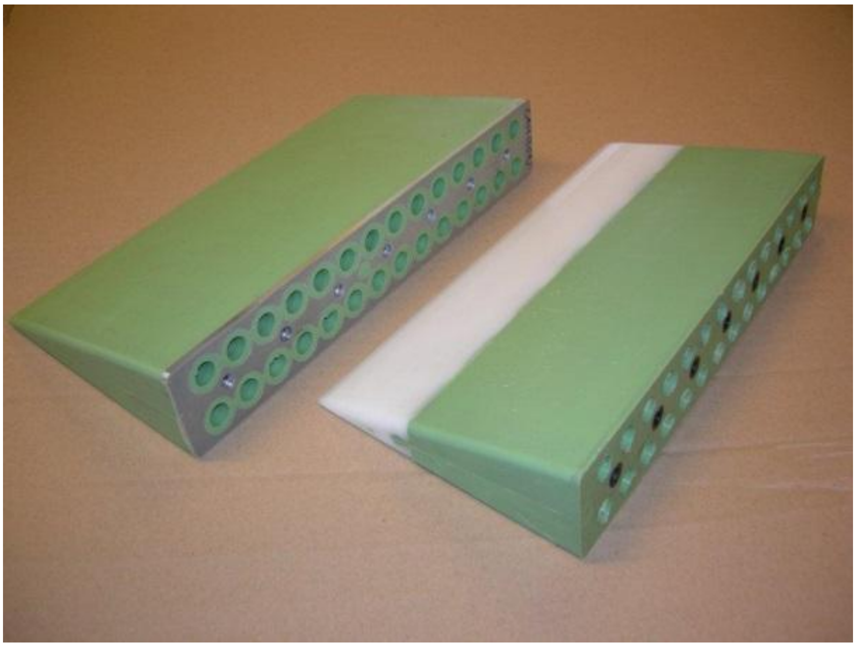

Figure 4: Comparison of previous (top left) and new design (bottom right).

Stiff top part

A stiff top part made of PE was placed in the mold and connected with seven steel rods in the center to the base, as seen in Figure 5. Each of the concave voids were reinforced with a concave spring allowing axial movement whereas the radial expansion is suppressed when the cavity in the rubber part is pressurized. All metal parts; springs, base and rods, were cleaned in acetone and treated with a metal primer to improve the bonding to the silicone rubber. Initial problems with debonding between springs and rubber were observed where the springs touched the inner side of the cavity due to metal/metal contact during the casting. To prevent failure the individual springs were coated with the rubber material prior to the casting and a thin rubber layer on the surface of the springs was achieved, and the metal/metal contact avoided. Preparation of the mold with pre-coated springs can be seen in Figure 5, photo to right.

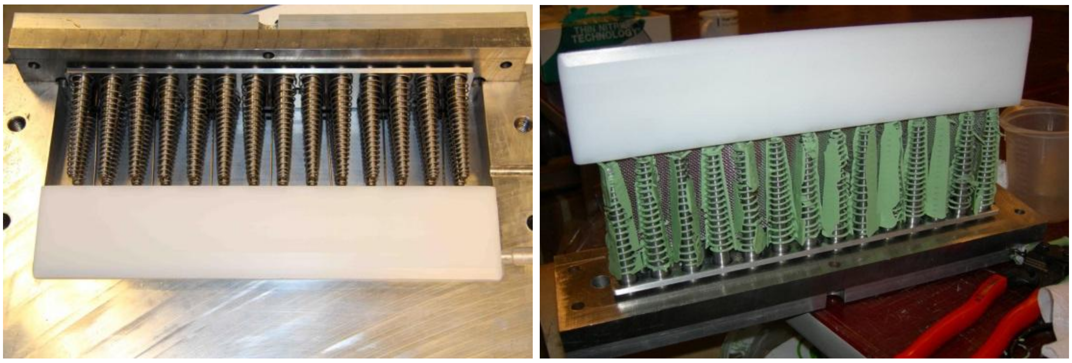

Figure 5: Preparation of the mold and inserts prior to casting.

Vacuum casting of rubber material

Air inclusions in casted rubber parts were observed in most of the initial casted specimens and a vacuum casting method therefore developed. The entire mold was placed sideward in a vacuum chamber where it was possible to connect a tube to a hole in the bottom of the mold. The other end of the tube was outside the vacuum chamber feeded with the liquid rubber material from a bucket. By evacuation of the chamber the rubber material was sucked into the mold cavity. Vacuum was applied until the rubber could be observed in the outlet reservoir at the top of the mold. The developed vacuum casting technique is shown in Figure 6.

Figure 6: Vacuum casting of CRTEF part. To the left, the green rubber material is visual in the tube connection and in the outlet reservoir at the top of the mold inside the vacuum chamber. To the right is shown the cured specimen before trimming of excess material.

Non-metallic springs

For replacement of the metal springs as void reinforcement concave filament wound springs were investigated. Most of the investigated springs were based on a fine (200tex) flax fiber yarn, since good bond to the rubber was achieved. First step in the concept is casting of a rubber inner liner. The reinforcement is then wound on top of the liner and the spring element realized by a second rubber casting, whereby the fiber reinforcement is fixated. This concept is illustrated in Figure 7 and a cross section of a spring element is shown in Figure 8.

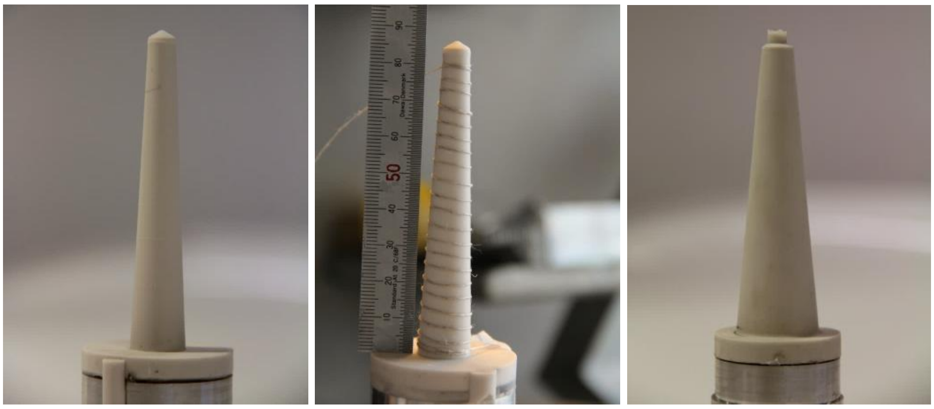

Figure 7: Concept for manufacture of non-metallic springs. Step1: Casting of inner liner, step 2: Winding of non-metallic spring element and step 3: Fixation of reinforcement by second casting.

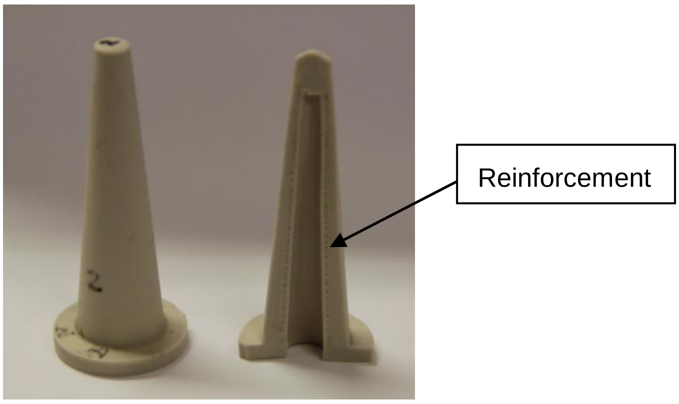

Figure 8: Cross section of spring element. Notice the dots from the reinforcement equally distributed along the cavity.

The spring characteristic depends on the winding pattern. Different configurations were investigated in order to find the best suited, using the pattern from the steel reinforced rubber as reference. Three of the used winding patterns are shown in Figure 9.

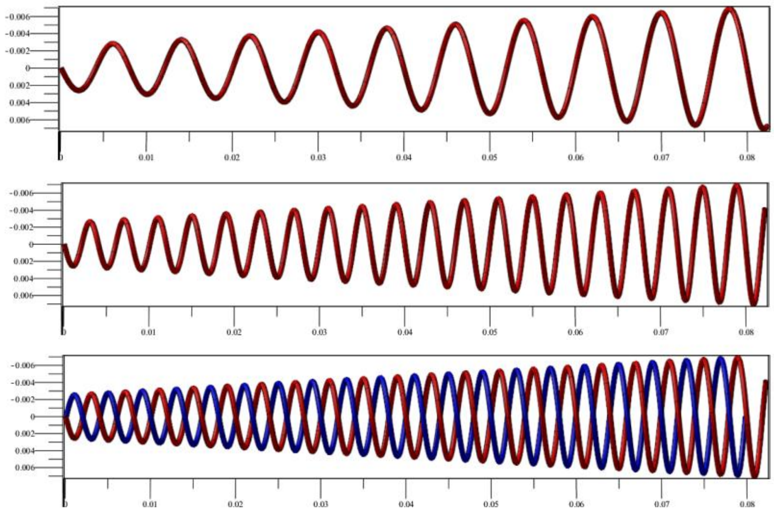

Figure 9: Different winding patterns. Top and middle shows one set of 10 and 20 windings respectively, and bottom 20+20 windings, going both forwards and backwards during the winding.

A higher number of windings results in a steeper fiber angle, as can be seen in Figure 9, where a low horizontal fiber angle of the reinforcement will restrict the elongation more than a steeper vertical fiber angel. This expected effect was demonstrated using a test rig, shown in Figure 10, for determination and comparison of the spring's characteristic by measurement of void pressure and corresponding elongation of the rubber part. Pictures from a test series is also shown in Figure 10 and plots of selected spring elements are shown in Figure 11.

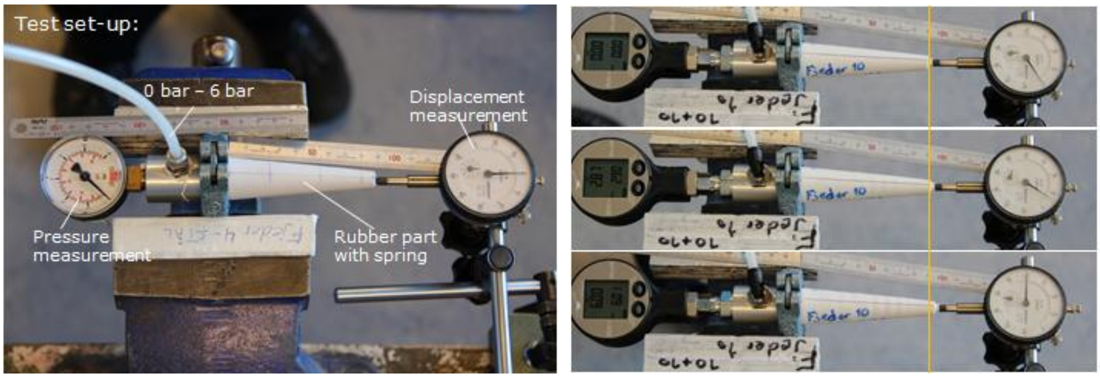

Figure 10: Test rig for investigation of spring elements. Pictures from a test series at three pressure levels: 0bar, 3bar and 6bar. The yellow line marks the tip position at 0bar.

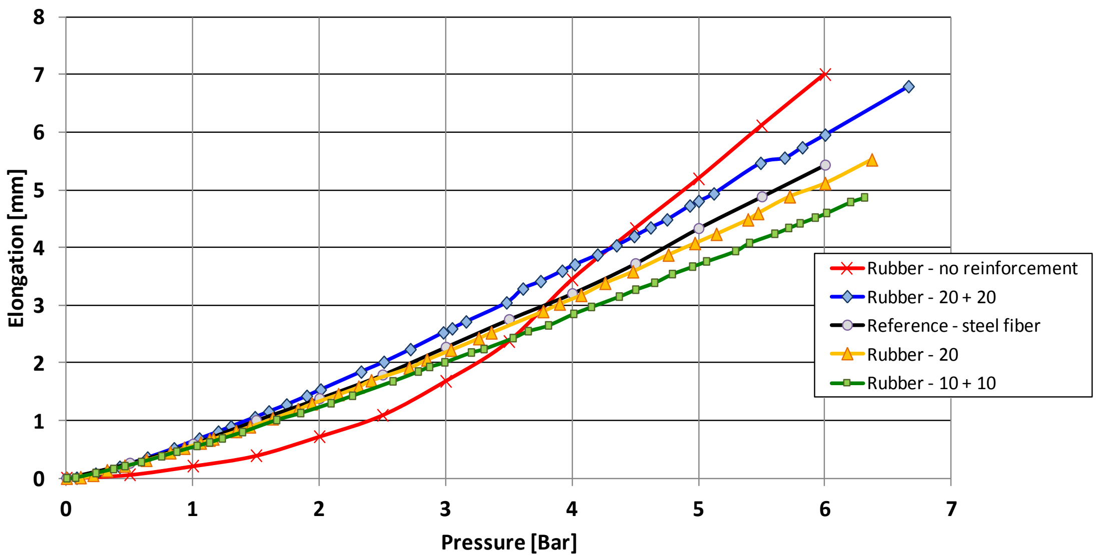

Figure 11: Plot of selected spring characteristics - linear elongation as function of void pressure

The non-linear elongation of the rubber element with no reinforcement, the red graph in Figure 11, shows a parabolic behaviour whereas all the reinforced rubber elements have a more linear behaviour. The best fit to the steel fiber rubber element (black graph) was obtained with Rubber 20, having 20 windings (yellow graph). Twist of spring elements based on only one set of winding, e.g. rubber 20, was observed, besides the linear elongation, during test. This effect could be eliminated by winding both forwards and backwards, e.g. 10 + 10 or 20 + 20. The Rubber 20 + 20 configuration was the most preferable spring element as it have the highest linear elongation for a given pressure in the range from 0bar to 6bar.

Fatigue test of a Rubber 20 + 20 spring elements was performed with a 2Hz frequency, see Figure 12. After approximately 2 hours test the spring element in the root section failed outside the reinforcement area. The fatigue test was repeated with another specimen and the same result. It was therefore concluded that fatigue test of the individual spring elements, in the given configuration, was not possible.

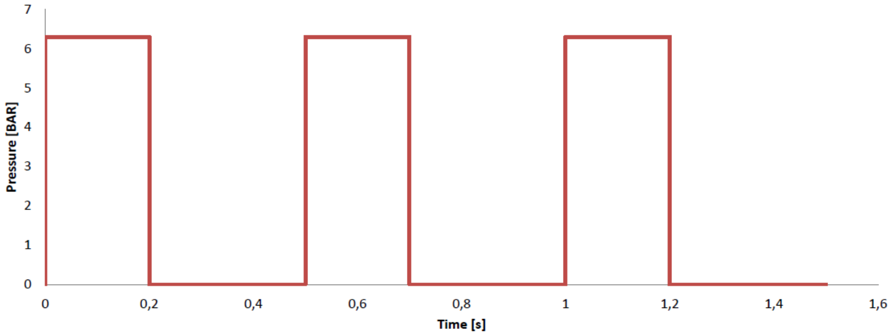

Figure 12: Pressure pulse signal for cyclic loading of spring elements

Manufactured flaps with spanwise voids

Two of the manufactured flaps are shown in Figure 13. The specimen based on Silastic J silicone rubber from Dow Chemicals failed due to debonding between the rubber material and primer treated metal parts. Another prototype specimen was manufactured using Elastosil M4670 A/B (beige) from Wacker Chemie AG. This two-component silicone rubber material has a Shore A hardness of 55 (ISO 868), vulcanize at room temperature (addition-curing) and are further characteristic by being pourable at room temperature (7000 mPa s, ISO 3219) [5]. The pressurized specimen failed due to leaks in the sealing between the rubber part and the base manifold with pressure supply.

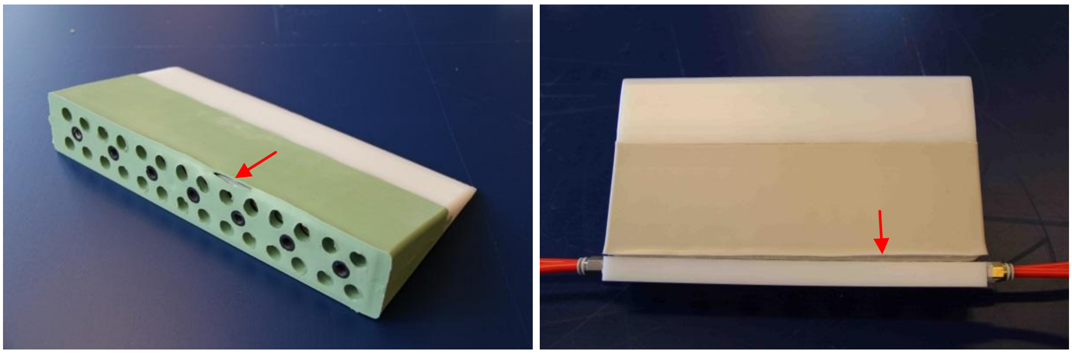

Figure 13: To the left, CRTEF specimen based on Silastic J and to the right, CRTEF specimen based on Elastosil M4670. Red arrows indicate where pressurized specimens failed.

Conclusions for CRTEFs with chordwise channels

- Good results were obtained mounting a stiff tip part on the CRTEF.
- Non-metallic spring elements have been manufactured with wanted pressure-deflection characteristics by use of a 20 + 20 winding pattern and a 200tex flax fiber yarn.
- Preparation of mold, fabrication of reinforcements, vacuum casting of rubber and demolding was all together evaluated to be too time consuming and risky and thereby too difficult to commercialize. Work on CRTEFs with chordwise voids was stopped and focus addressed to solutions with spanwise voids.

3. Flaps with spanwise voids

The basic concept for flaps with spanwise voids can be divided in to a passive part and two symmetric active parts. The elements are glued together for realization of the flap. One of the advantages of this concept is the possibility of processing the active and passive parts in a continuous extrusion process. The challenging part of the concept is the end sealing of the continuous hollow polymer profiles and pressurization of all channels in the rubber part. The main components are shown in Figure 14 also showing a demonstrator from project partner Rehau.

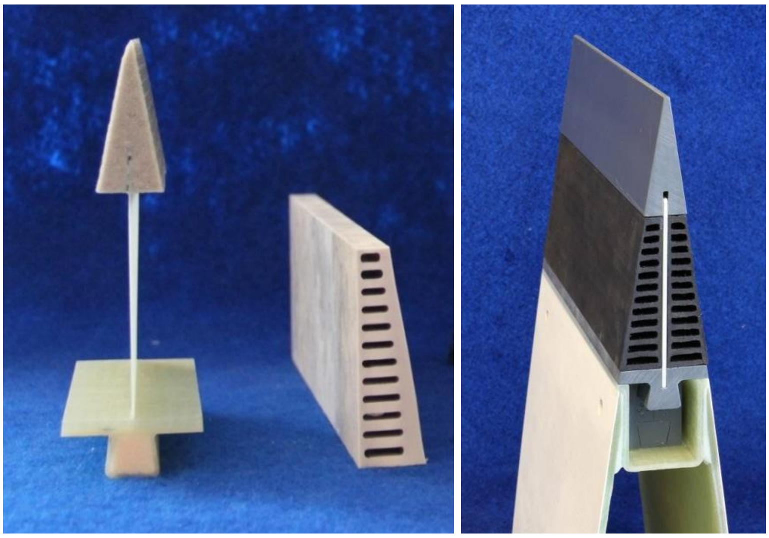

Figure 14: The passive part with tip and base for mounting on the blade and an open active rubber part. Rubber parts were sealed in the ends before gluing two the passive part. On right photo the solution from project partner Rehau, where the passive part is divided in to three sub-components.

Flap design and manufacturing at Rehau

The detailed design of the flaps was mainly done by the use of the COMSOL software [6] simulating the complex stress distribution in the flaps with voids [1]. High stress concentration at the rear flap region was seen for the initial flap design near the sharp edges in cavities and non-optimal wall height between cavity and outer flap surface, Figure 15 [1].

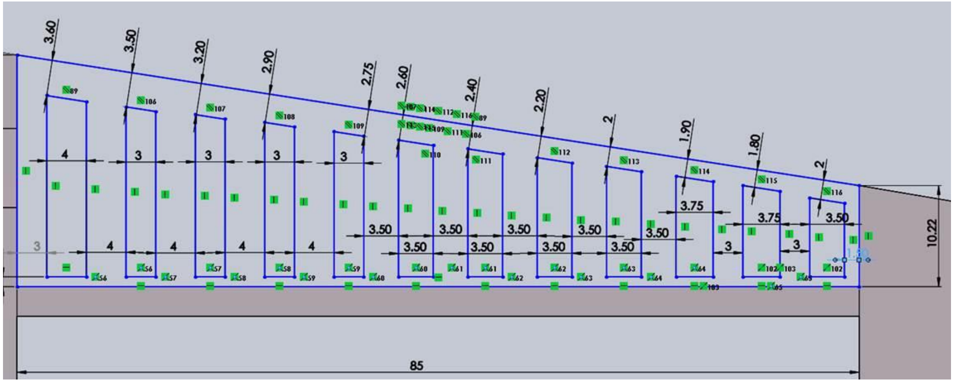

Figure 15: The figure illustrates the initial spanwise cavity flap design, all dimensions are in mm.

Geometry of the voids and the wall thickness were optimized to achieve a lower and more uniform stress level. New design with rounded edges of voids is shown in Figure 16 [1]. The result of the improved design is seen from Figure 17, where von Mises stresses in the surface are plotted for the two designs [1].

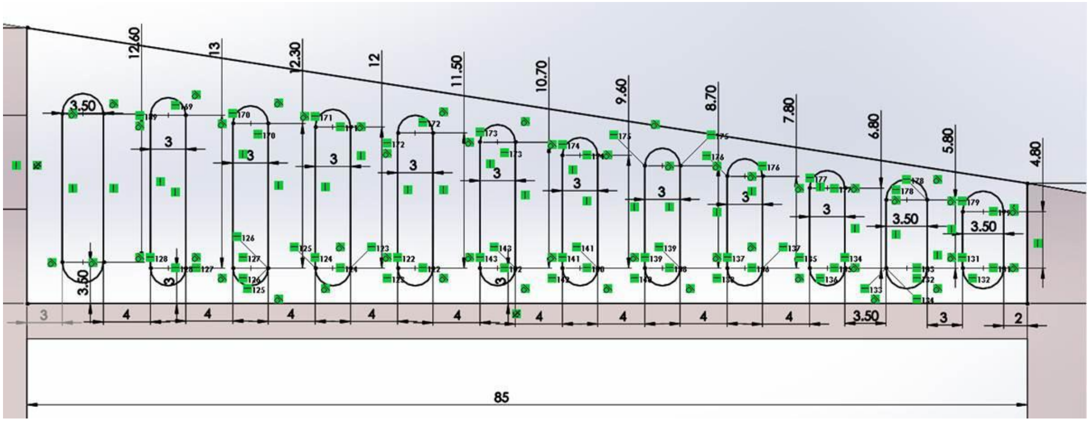

Figure 16: New design with rounded edges of voids

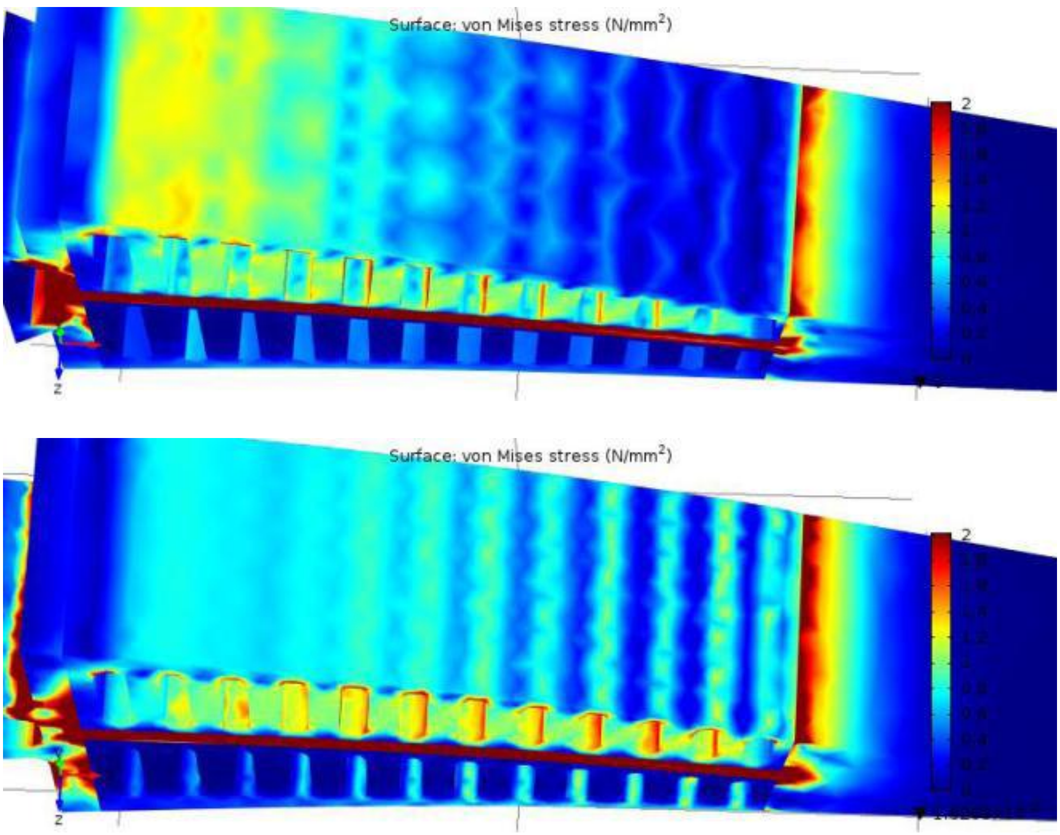

Figure 17 Computed stress contour levels on the flap with initial void geometry on top and improved design below. The latter design was optimized with respect to achieve a more uniform stress level on the surface.

Manufacture of prototypes with spanwise voids

A first trial was performed by modification of an old mold to ensure that rods in the casted rubber material could be removed and voids realized. Based on the successfully test, shown in Figure 18,a simple prototype mold was designed, Figure 19.

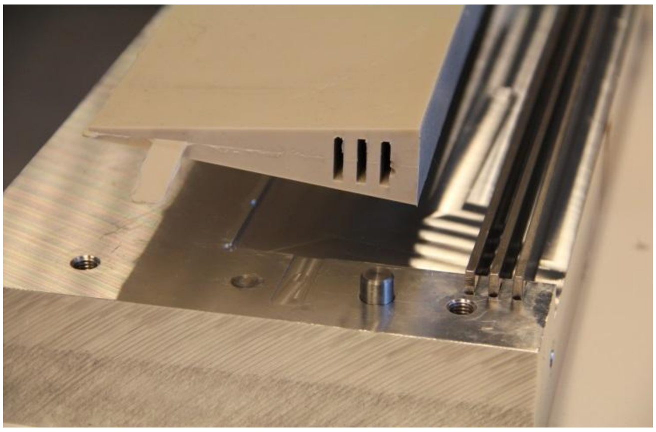

Figure 18 Initial trials with modified old mold to investigate the possibility of removing the rods forming the voids then the rubber was cured. The test was successfully.

Figure 19 Mold for casting of active rubber flap parts with spanwise voids. Inlet holes for voids were casted in both ends, see yellow arrows. Manual removal of air bubbles in the resin before a top plate close the mold. The rods forming the voids are sticking out of the end flange of the mold, red arrow, making it possible to grab and remove them from the cured specimen.

A transparent rubber material, Elastosil M4641 A/B, Shore A hardness 43, from Wacker Chemie AG was selected for process development to ease the detection of any air enclosure in the casted parts, and also crack initiations and leaks during the following test.

The mixed two component rubber material was easy to pour into the open mold and air bubbles were removed manually before the mold was closed by a top plate. The specimen cured at room temperature overnight. A casted specimen having 12 voids is shown in Figure 20.

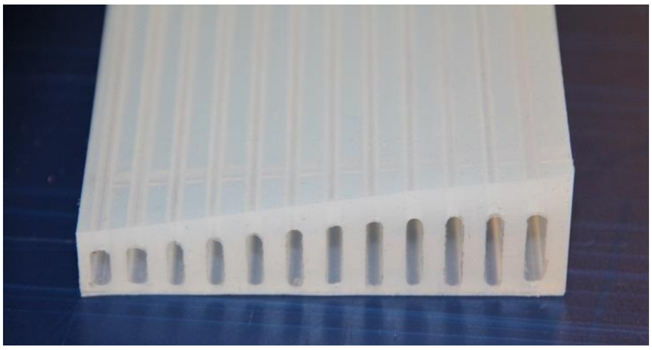

Figure 20 Casted prototype of active rubber part for flaps with 12 spanwise voids.

A suggestion for an end flange sealing of the voids was sketched having a design with additional bonding area inside the individual voids to ensure a tight sealing, Figure 21.

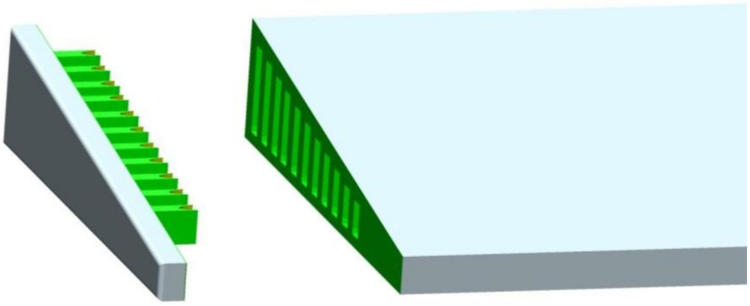

Figure 21 Sketch of suggestion for end flange with increased bonding area inside the individual voids to ensure a tight sealing.

The flange sealing was realized in a simple manner by casting directly on the manufactured flap using the mold without rods and a tight end flange. Flap mold was placed vertically and a small (transparent) top plate was used to trap a small tuned amount of liquid rubber in the bottom. The casted rubber flap was placed in the mold allowing some rubber to flow partially into the voids and at the same time building the flange. Casting of the flange concept is shown in Figure 22 and the cured result is shown in Figure 23.

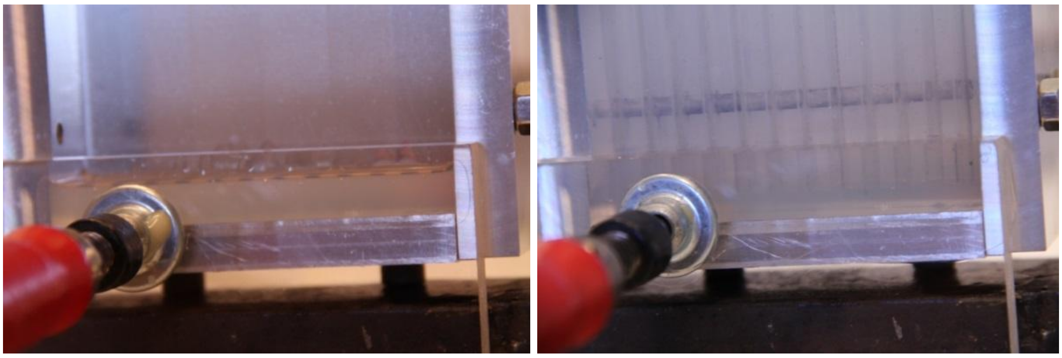

Figure 22 A tuned amount of liquid rubber is poured in the bottom of the vertical flap mold, left photo, and the casted rubber flap subsequently placed, right photo, allowing for directly casting of end flange and voids support.

Figure 23 End sealed rubber flap. The casted flange and support inside the individual voids can be seen together with one of the inlet holes connecting the voids.

For bonding of the rubber parts was first Elastosil E43 and later Elastosil E47 - ”excellent adhesion to silicones - acetic acid-curing system” also from Wacker Chemie AG selected based on recommendations from the supplier. The adhesive is a one component system, which cures at room temperature under the influence of atmospheric moisture.

Test of manufactured flaps with spanwise voids

Test of manufactured rubber flaps was done in a simplified setup where the passive part was replaced by polymer blocks of PolyVinyl Chloride (PVC) connected with a 0.8mm thin glass fiber laminate glued into a slit in each PVC block. The glass fiber laminate was manufactured with a ±45° fiber orientation. The tip was made of cardboard and cut to mimic the real dimensions of a flap having a chord length of 150mm. Vertical deflection of flap was measured as function of applied pressure. Test results are shown in Figure 24 and Figure 25

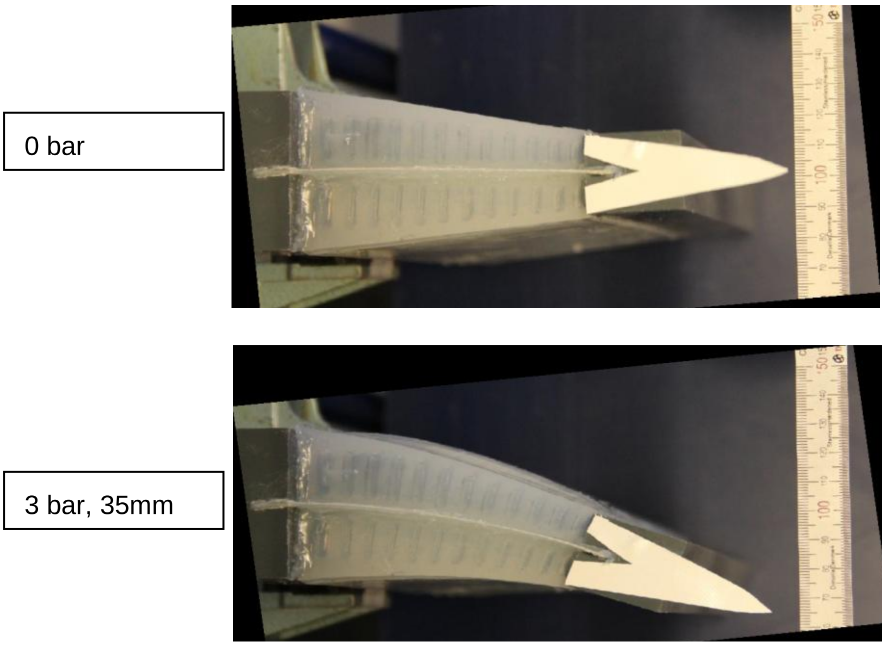

Figure 24 Test of Wacker Elastosil M4641 A/B, Hardness 43. ±35mm vertical deflection at ±3bar.

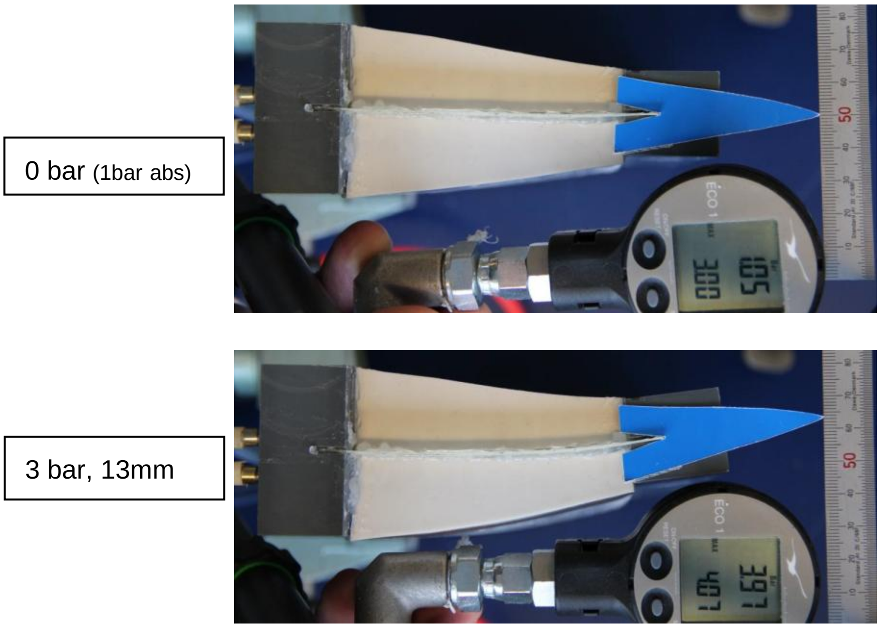

Figure 25 Test of Wacker Elastosil M4670 A/B, Hardness 55. ±14mm vertical deflection at ±3bar.

Fatigue test performed with the two prototype specimens revealed that bondlines between stationary and flexible part is a challenge. Elastosil E43 and E47 adhesives are both characterized as non-slump and behave as a paste who maintains the structure. It is therefore also very difficult to obtain a thin, well defined and uniform bondline between the passive part and the soft active parts. The fatigue test also indicated that the casted end flange sealing work well.

Improvements of the passive part were included in a final prototype specimen. Tip and base was manufactured as stiff lightweight sandwich elements with a foam core and glass fiber skin layers. Blade flange and connection between tip and base was also manufactured as glass fiber composite components. The flange has a thickness of 5mm and the connection has a thickness of 0.75mm. The manufactured passive part is shown in Figure 26, left photo, and the right photo shows how flaps easily could be mounted to a blade section by use of a Π-profile. The Π-profile has well defined dimensions and makes it possible both to fit the height and angle of the blade profile where the flap is mounted.

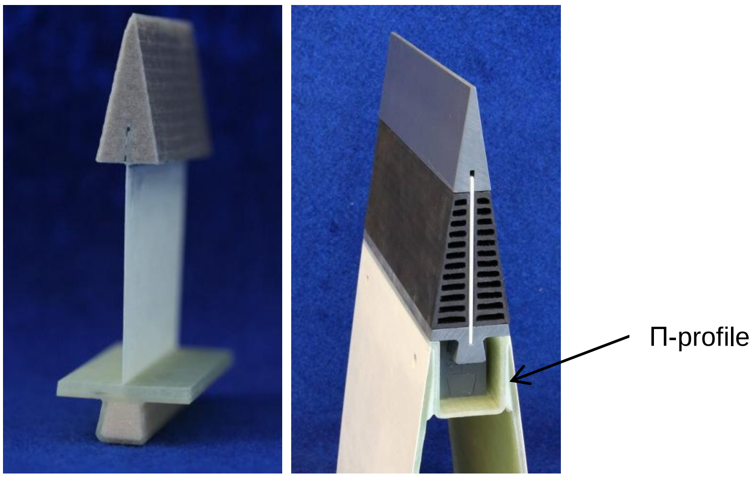

Figure 26 Left: Manufactured passive part. Right: Π-profile for easy mounting of flaps.

Test of the demonstrator blade section is shown in Figure 27. Pressure of 1bar, 2bar and 3 bar resulted in 7mm, 14mm and 21mm tip deflection, respectively

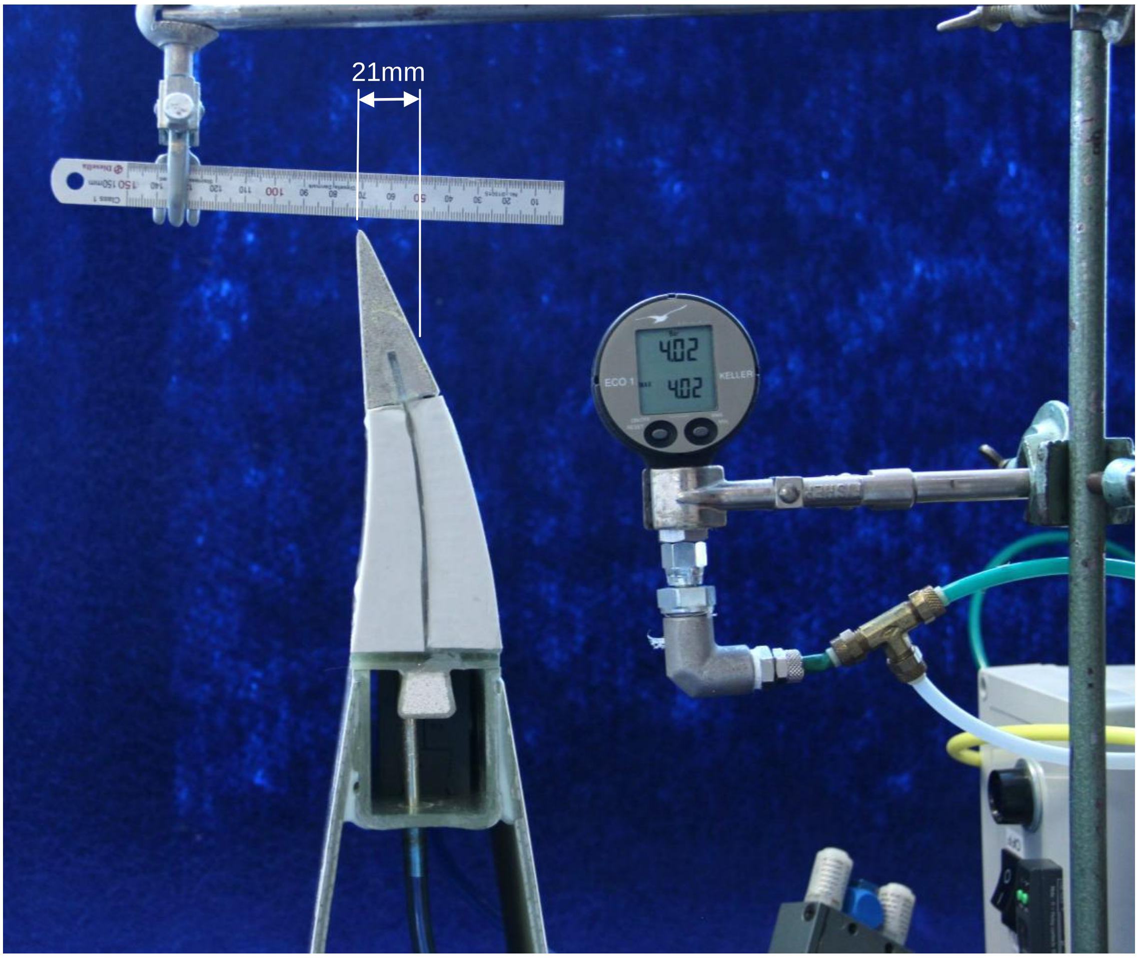

Figure 27 Test setup for measurement of tip deflection for Wacker Elastosil M4670 rubber profiles mounted on modified passive part and fixated on a 30cm wide blade section for demonstration. Voids pressure of 1bar, 2bar and 3 bar resulted in 7mm, 14mm and 21mm deflection, respectively.

4. Conclusions

Deflection of flaps with chordwise voids was measured to ±12mm for ±6bar in previous work [1]. Flaps with spanwise voids work very well and the measured deflection is higher than flaps with chordwise voids for the same pressure.

The apparently best suited prototype solution is based on Wacker Elastosil M4670, Shore A hardness 55 and have a linear deflection characteristic in the pressure range from 1 to 3 bar of 7mm/bar, corresponding to ±21mm for ±3bar.

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DTU Wind Energy is a department of the Technical University of Denmark with a unique integration of research, education, innovation and public/private sector consulting in the field of wind energy. Our activities develop new opportunities and technology for the global and Danish exploitation of wind energy. Research focuses on key technical-scientific fields, which are central for the development, innovation and use of wind energy and provides the basis for advanced education at the education.

We have more than 240 staff members of which approximately 60 are PhD students. Research is conducted within nine research programmes organized into three main topics: Wind energy systems, Wind turbine technology and Basics for wind energy.

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