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Publication date:
2017

Document Version
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STRUCTURAL DESIGN OPTIMIZATION OF A MORPHING TRAILING EDGE FLAP FOR WIND TURBINE BLADES

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Key words: Morphing, flap, optimization, wind turbine

Abstract. A flap actuation system, the Controllable Rubber Trailing Edge Flap (CRTEF), for distributed load control on a wind turbine blade had been developed in the period from 2006 to 2013 at DTU (http://www.induflap.dk/). The purpose of the presented work is to optimize the structural design of the flexible part of the CRTEF based on a realistic blade section geometry in order to meet the required objectives and constraints. The objectives include the deflection requirements and the energy efficiency, while the constraints include the bending stiffness of the structure, the local shape deformations, critical material strength, and manufacturing limitations. A model with arches forming concave on the flap surface and enclosing the voids to be pressurized results in the bending movement of the flap when pressure is applied on the voids to straighten the arches. The model is designed using SolidWorks for the parameterization of the design and ANSYS Workbench for the static structural Finite Element Analysis (FEA) simulations. The built-in parametric optimizer of ANSYS Workbench, Direct Optimization of Design Exploration is used to optimize the design with the parameters of the geometry. The surface pressure loads during operation of the turbine with the flap installed are evaluated with XFOIL and included in the simulations. The model is developed first by qualitative analyses to obtain a reasonable preliminary design, and then by parametric optimization to have the final design. The parameterization of the design is improved on the way of optimizations, in order to expand the design space to solve the problem of stress concentration, so that it covers the design with an acceptable material safety factor. With the consideration of surface pressure loads during operation of the turbine, the optimum design fulfils the requirements for flap angle of 15deg and -15deg with the actuation pressure of 0.428 MPa and 0.386 MPa, and the material safety factor margins, respectively. The design also meets the objective for energy efficiency by the lower actuation pressure than in earlier designs and by the small volume of the voids. Besides, the constraint of the bending stiffness is fulfilled with the deflection of less than the flap angle of ±5deg when the turbine is operating without the actuation pressure, and the constraints of the local shape deformations and manufacturing limitations are also fulfilled.

1   INTRODUCTION

The size of wind turbines has increased steadily in the past decade. With a bigger rotor, the loads carried by all the components of a wind turbine have become an issue and consequently cost. Since the lower cost of energy per kWh is desired, reducing the loads on the blades is certainly one of the main focus of the research on wind turbines. One of the possible ways to reduce the loads without increasing the cost too much is to build blades with distributed local control surfaces and this concept is usually called 'smart rotor control'. Flaps, as one kind of the trailing edge aerodynamic devices, can serve as the control surface to reduce the loads on the blades [1]. A controllable flap can be actuated by different mechanisms. However, the strongest specifications for a robust control mechanism required by the wind turbine industry indicate no mechanical, metal and electrical parts in the blades. Therefore, the Controllable Rubber Trailing Edge Flap (CRTEF) has been designed, manufactured, and tested at Risø DTU in order to meet the requirements and realize the application in the industry of wind turbines [2, 3]. The CRTEF controls the flap by applying fluid or air pressure on the voids (chambers) in the rubber flap, and the geometry change of the voids results in the effect of the flap. Therefore, the geometry and distribution of the voids play important roles in the effect and efficiency of the flap mechanism. The presented work is focused on the optimization of the geometry and the distribution of the voids so that the desired flap angle can be met under several constraints, with the main design innovation being the use of only two actuation voids [4].

A conceptual prototype of the CRTEF has built and tested in the INDUFLAP project (Figure 1), the design of the geometry has to be further optimized. Instead of basing on a symmetrical airfoil, the present work is aimed at designing for the DTU 10MW reference turbine [5], and therefore FFA-W3-241 is the airfoil evaluated. Due to the feature of the extrusion process which is expected to be used in manufacturing, the project is focused on analyzing the 2D geometry of the flap with a span-wise constant cross section. The size of the chord to be analyzed is defined by the chord length of the DTU 10MW reference turbine at 80% rotor radius from the rotor center, which is the span-wise location that gives the optimum reduction in the blade root moment fatigue load. The ratio of the chord to be replaced with the rubber flap is determined to be 10% so that the flap is able to change the lift sufficiently to attenuate a big portion of the expected load fluctuation with insignificant drag penalty. There is a lot of literature covering different concepts of actuators for morphing or flap control. The biggest common challenge of the material and the structure in this application is the conflict between the requirement for low bending stiffness of the flap which leads to low actuation force and the requirement for high bending stiffness of the flap which is relevant to resisting the surface pressure loads during operation. The conflict is resolved by trying to balance the two requirements.
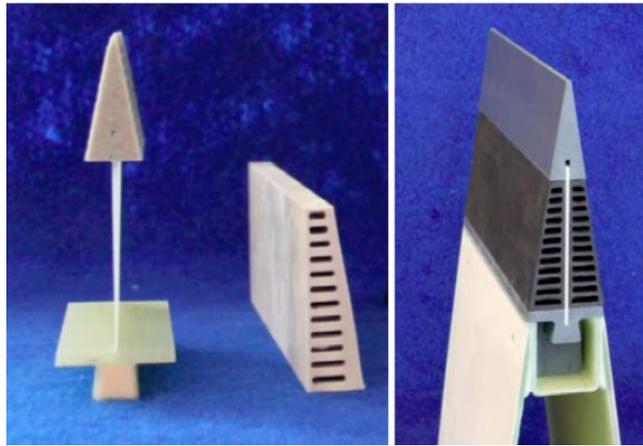
Figure 1: CRTEF design developed in the INDUFLAP project.

The presented work is structured as follows: In section 2, the objectives and constraints of the project are illustrated, followed by the methods, models and software used in the project. The load cases are determined and estimated in section 3. In section 4, the development of the preliminary design and its optimization is presented, and the design is then evaluated in section 5. Based on the evaluated results, the achievements and the disadvantages are concluded in section 6, followed by recommendations for future work.

2 OPTIMIZATION PROBLEM AND NUMERICAL TOOLS

Initially, the objectives of the design optimization include:
1. maximizing the effect of the flap angle
2. Maximizing the energy efficiency of the flap control system by minimizing the actuation pressure and the volume of the voids
3. maximizing the bending stiffness of the structure

The constraints include:
1. local shape deformations
2. the strength of the material
3. the manufacturing limitations

Although the overall objectives and the constraints are provided, the different objectives are actually contradicting. As a result, based on the priority and the extents to which the objectives are desired, some of the objectives and the constraints are quantified. The ideal goal of the flap angle is determined to be ±15deg, and ±10deg in a limited operation scenario. In order to evaluate the effect of flap angle more directly in the analyses, the equivalent tip deflection in the vertical direction of the flap angle is used as the measurement of the flap angle. In order to have a safe design which does not deflect too much when the actuator is not working, a flap angle within ±5deg during normal operation of the wind turbine without void pressure is set as the objective. The material used in the design is determined to be the thermoplastic Santoprene 101-73, due to the resistance of the material to the environment conditions which include UV radiation, fatigue, and lightening, and the fact that the material

is elastic with high strength and suitable for extrusion process. For strength analysis, the tensile stress at break $\sigma_U = 8.8$ MPa is used when evaluating the equivalent von Mises stress in the simulations. Due to the manufacturing efficiency in terms of time and cost, the flap is determined to be manufactured by extrusion which indicates a constant cross section, and this process limits the minimum wall or void thickness of the flap geometry to be 2 mm and the tolerance being no less than 0.1 mm.

In the work, several analysis tools were used. XFOIL [6] was used to estimate the static pressure on the surface of the flap, so that the loads during operation of the turbine can also be considered in the design process. SolidWorks [7] was used to design the geometry of the flap with the the built-in feature of parametric design. Static Structural analysis system in ANSYS 16.0 workbench [8] was then used to perform the simulations using the finite element method. With the results of the simulations, the performance of the designs was qualitatively analyzed, in order to have a better preliminary design. Finally, the Direct Optimization system, a built-in Design Exploration system in ANSYS 16.0, was used in combination with the parametric design in SolidWorks to conduct parametric optimizations.

The airfoil profile of FFA-W3-241 with 79 coordinate points and a unit chord was used in the analysis. After the profile was loaded, the desired flap angle was then added by modifying the geometry of the airfoil. The hinge point of the flap was added at 10% chord from the trailing edge and 50% thickness at the position. With the airfoil with desired flap, the viscous analysis with Reynold's number, Re = 5e6, was performed. The Reynold's number was calculated based on a kinematic viscosity of 1.456e−5 m2/s and a flow velocity of V = 72.6 m/s based on the 80% blade span section on the reference wind turbine at rated power operation. The pressure coefficient, Cp, distributed on the surface of the airfoil was calculated with the input angle of attack (AOA) in the analysis. The pressure coefficients were then used to calculate the static pressure loads on the surface of the flap.

SolidWorks is a 3-dimension (3D) computer-aided design (CAD) software. However, in the project, since the flap was determined to be designed with a constant cross section along the span due to the limitations of manufacturing, a 2-dimension (2D) analysis with the plane strain behavior should be as valid as a 3D analysis, and a 2D analysis is computationally cheaper. Therefore, the work is based on 2D analyses and the designed component in SolidWorks will be a 2D surface. SolidWorks was chosen as the CAD software to be used because of its friendly user interface, handy sketch tools, and most importantly, its feature of parametric design which can easily be coupled with the parametric analysis in ANSYS 16.0.

The finite element analysis (FEA) software to be used is ANSYS 16.0, which is powerful in parametric analysis. Static Structural analysis system in ANSYS 16.0 workbench is the system used. The non-linearity of the material is implemented with Mooney-Rivlin model with the coefficients provided by the material test data, and the material is assumed to be incompressible. The Mooney-Rivlin model with two parameters is used with different sets of parameters for different strain ranges, varying from 10-50%, depending on the simulated load case. The mesh settings of the simulations have been changed for different designs. The general idea is to have finer mesh at the edges with high curvature and large deformation, and coarser mesh for the rest of the model. Although a finer mesh gives more accurate solutions especially for stress values, it is more computationally expensive. Therefore, during the design process, the model is meshed fine enough to have valid results with acceptable computational cost. In order to make sure the mesh is fine enough, convergence tests are

carried out from time to time and most importantly, for the optimum model. The element types used in the simulations are 8-node quadrilateral (Quad8) and 6-node triangle (Tri6). The meshing tool first generate the mesh with all triangles and then converts most of the triangles to quadrilaterals, creating a quadrilateral dominant mesh. Due to the non-linear behavior of the design, large deflection calculations are enabled in Ansys, which includes stiffness changed resulting from changes in element shape and orientation due to large deflection, large rotation, and large strain. In terms of boundary conditions, the edge on the leading edge side of the flap is set to be fixed to simulate the connection to the main part of the blade, and the pressure is applied on the edge of the void, as well as a tip force at the trailing edge, equivalent to the aerodynamic pressure on the flap surface (Figure 2).
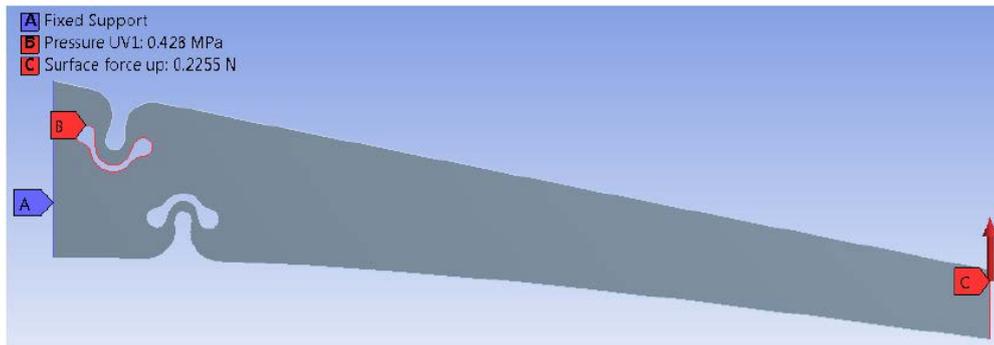

**Figure 2:** Boundary conditions on the flap geometry.

In order to perform parametric optimization, the built-in optimizer in ANSYS 16.0 is chosen, which is coupled with SolidWorks to change the parameters of the geometry and perform simulations automatically. In order to get the global optimum instead of local optimum, the direct optimization method 'Multiple-Objective Genetic Algorithm (MOGA)' is utilized. In the MOGA method, crossover and mutation are performed to generate a new population in every iteration, making it a more refined method than Screening. With the global optimum from MOGA as the starting point, the gradient-based approach 'Nonlinear Programming by Quadratic Lagrangian (NLPQL)', which is based on quasi-Newton methods is used to find the even more refined local optimum.

3 LOAD CASES

During the normal operation of the wind turbine installed with the flap, two load scenarios should be considered:
1. When the flap is not actuated, i.e. no void pressure.
2. When the flap is actuated with the desired effects.

Four load cases were designed using XFOIL and the equivalent tip forces were estimated for these two load scenarios. The equivalent tip force was obtained by applying the tip force which could result in approximately the same tip deflection (Figure 3).
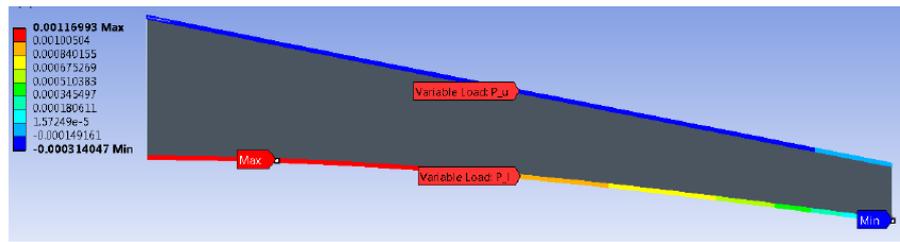
(a) When the surface pressure loads [MPa] of the case of stiffness up check were applied on the surface of the complete flap without voids, a tip deflection of flap was 5.79 mm.
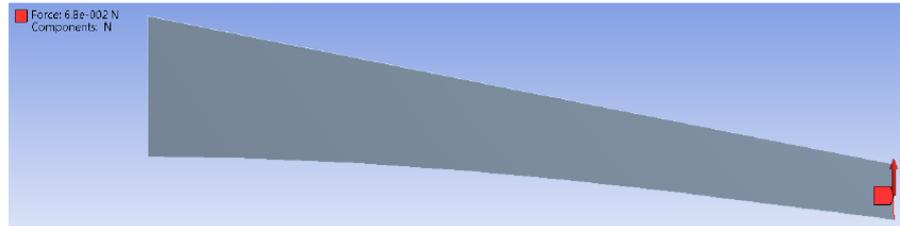
(b) A tip force of 0.068 N/mm causing a tip deflection of 5.87 mm was considered as the equivalent tip force in this case.

Figure 3: Surface pressure and equivalent tip force calculations.

In the first scenario, the flap is still carrying the surface loads during operation, and the stiffness of the flap without void pressure should be designed based on this scenario. In order to cover the operational range of the turbine, the two most extreme cases of the scenario should be considered.

1. The stiffness up load case: In this load case, the flap is deflected to -5deg under the maximum surface pressure load which corresponds to the AOA with the maximum Cl.
2. The stiffness down load case. In this load case, the flap is deflected to 5deg under the maximum surface pressure load which corresponds to the AOA with the minimum Cl.

The values of the AOA for these two load cases were then found with XFOIL to be 16deg for the first case and -20.4deg for the second case. These two cases were then defined as the first and second design load cases. In the second scenario, the desired flap angles are ±15deg. When the flap is actuated to such effects, it should reach the desired flap angles while carrying the surface loads. Therefore, two more extreme load cases were then defined.

1. The upper void effect load case: In this load case, the flap angle is actuated to 15deg, and the actuated structure is carrying the surface pressure load which corresponds to the AOA with the maximum Cl.
2. The lower void effect load case: In this load case, the flap angle is actuated to -15deg, and the actuated structure is carrying the surface pressure load which corresponds to the AOA with the minimum Cl within the operational range (AOA within ±15deg).

The values of the AOA for these two load cases were then found with XFOIL to be 14.9deg for the first case and -15deg for the second case.

For these four design load cases, the Cp values distributed on the airfoil were then output from XFOIL.

The pressure values to be applied on the surface of the flap were then calculated using the equations:

$$C_p = \frac{p - p_\infty}{q_\infty} \qquad \textbf{(Equation 1)}$$

6

$$q_\infty = \frac{1}{2}\rho_\infty V_\infty^2 \quad \textbf{(Equation 2)}$$

where $V_\infty = 73$ m/s is the freestream velocity approximated from the freestream velocity, $\rho_\infty = 1.225$ kg/m^3 is the freestream air density; q_∞ is the freestream dynamic pressure and can be calculated to be 3.267e3 Pa, p_∞ is the freestream static pressure; and p is the static pressure at the point where Cp is evaluated. The summary of load cases and equivalent tip force estimation are shown in Table 1.

Table 1: Summary of load cases and equivalent tip force estimation.

	Name	Stiffness		Upper void effect		Lower void effect	
		up	down				
	Flap Actuated	No	No	No	Yes	No	Yes
	Flap Angle [°]	-5	5	0	15	0	-15
Load Case	AOA [°]	16.0	-20.4	16	14.9	-20.4	-15.0
	Notes	Used	Ignored	Start	End	Start	End
	Tip Deflection at Flap Angle [mm]	26.03	-26.21	0	-79.64	0	79.26
	Tip Deflection with all loads [mm]	25.99	-26.07	-0.30	-80.08	0.47	79.29
Estimation	Counteracting Tip Force [N/mm]	-0.088	0.02	-0.108	-0.205	0.045	0.115
	Safety Factor	1.1	1.1	1.1	1.1	1.1	1.1
	Equivalent Tip Force [N/mm]	0.0968	-0.022	0.1188	0.2255	-0.0495	-0.1265

4   DEVELOPMENT OF THE DESIGN

Based on literature and previous work, an arch model with arches forming concave on the flap surface and enclosing the voids to be pressurized is expected to result in the bending movement of the flap when pressure is applied on the voids to straighten the arches. First, a qualitative investigation was performed with sweeping the main design parameters in order to have a preliminary design for the shape and location of the voids. The design is parameterized and the upper void of the design is analyzed qualitatively in order to have the preliminary design. With this preliminary design, the stiffness and the material safety factor of the upper void are parametrically optimized. Then, the design space is expanded with more parameters to deal with the problem of stress concentration. After the parametric optimizations within the expanded design space covering the design with acceptable safety factor, the lower void is then parametrically optimized followed by the determination of the locations of the voids. Another iteration of the estimation of the surface loads is then carried out, followed by the iterated optimization of the lower void. This gives the optimum design of the project. The geometry of the preliminary design is shown in Figure 4.
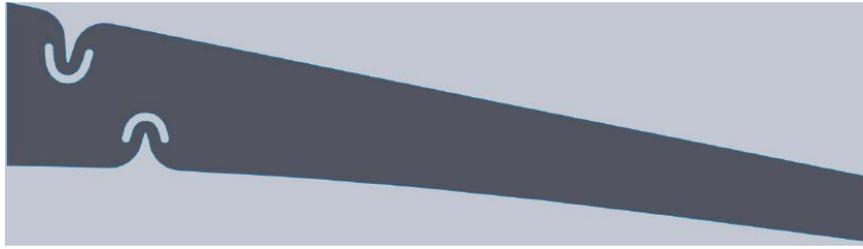
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Figure 4: Geometry of the preliminary design.

The arch geometry of the voids is then parametrized using 10 geometrical variables, as shown in Figure 5 and Table 2.
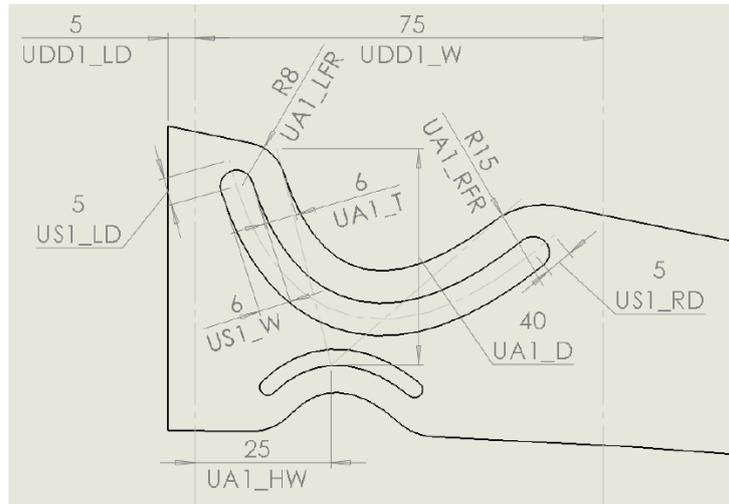

Figure 5: Parameterization of the design.

Table 2: Design parameters for the preliminary design.

Code	Value [mm]	Definition
UDD1_LD	5	Distance between the left end and the design domain
UDD1_W	35	Width of the design domain
UA1_D	30	Depth (of the control point) of the arch
UA1_T	4	Thickness of the arch
US1_W	3	Width of the slot
US1_LD/ US1_RD	10	Distance between the left/right end of the centerline and the center of the left/right cap of the slot
UA1_LFR/ UA1_RFR	11	Radius of the fillet of the left/right corner

In order to solve the stress concentration issues found in the preliminary design, the parts with stress concentration were trimmed with higher curvature. First, the diameter of the half-circle caps at the slot ends was increased. Second, the upper side of the arch was trimmed with a spline with lower curvature. Besides, the spline which constructs the arch was made perpendicular to the surface in order to have a symmetric stress distribution (Figure 6).
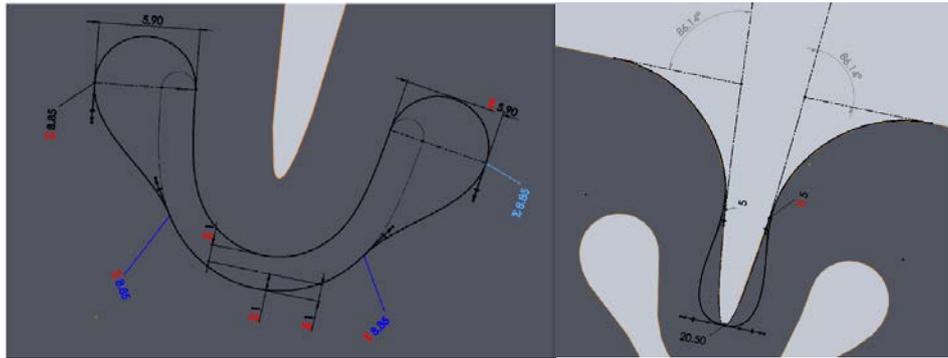
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Figure 6: Parametrization of detailed design of slot ends.

The purpose of the optimization was to increase the safety factor to an acceptable value. In order to have a global optimum, a global optimization was first carried out, followed by the local optimization to refine the optimum. With the design with an acceptable safety factor, the optimizations for the lower void pressure were then performed, and finally the position of the voids. The optimization methods, objectives, constraints, input variables and results for the upper void can be found in Table 3.

Expanded Design Space Global Optimization for Safety Factor						Expanded Design Space Local Optimization for Safety Factor						
Method	MOGA					Method	NLPQL					
Objectives	Maximize Safety Factor					Objectives	Maximize Safety Factor					
Constraints	Effect Tip Deflection ≤ -80 mm Arch location ≤ 62 mm Stiffness Tip Deflection ≤ 20 mm					Constraints	Effect Tip Deflection ≤ -80 mm Arch location ≤ 62 mm Stiffness Tip Deflection ≤ 20 mm					
Converged	Yes					Converged	No, but validated					
		Units	Optimum	Lower bound	Upper bound			Units	Start	Optimum	Lower bound	Upper bound
Input Variables	UDD1_W	mm	35.58	34.00	37.00	Input Variables	UDD1_W	mm	35.58	35.11	34.00	37.00
	UA1_T	mm	5.35	5.00	7.00		UA1_T	mm	5.35	5.00	5.00	7.00
	US1_LD	mm	13.23	10.00	15.00		US1_LD	mm	13.23	14.21	10.00	15.00
	UA1_D	mm	35.07	30.00	36.00		UA1_D	mm	35.07	35.15	30.00	36.00
	UA1_LFR	mm	9.75	8.00	12.00		UA1_LFR	mm	9.75	9.20	8.00	12.00
	UA1_UF_W	mm	26.30	15.00	30.00		UA1_UF_W	mm	26.30	27.61	15.00	30.00
	US1_End_Dia	mm	5.09	5.00	8.00		US1_End_Dia	mm	5.30	6.06	5.00	8.00
	US1_End_TF	mm	0.830	0.800	1.20		US1_End_TF	mm	0.830	0.825	0.80	1.20
	Void Pressure	MPa	0.475	0.400	0.500		Void Pressure	MPa	0.451	0.463	0.400	0.500
Results	Stiffness Tip Deflection	mm	19.93	-	-	Results	Stiffness Tip Deflection	mm	20.00	20.00	-	-
	Effect Tip Deflection	mm	-90.30	-	-		Effect Tip Deflection	mm	-80.44	-80.03	-	-
	Arch Location	mm	61.20	-	-		Arch Location	mm	60.64	60.64	-	-
	Safety Factor	-	0.92	-	-		Safety Factor	-	1.12	1.31	-	-
	Minimum SF Location	-	Slot	-	-		Minimum SF Location	-	Slot	Slot	-	-

Table 3: Global and local optimization parameters and results.

The optimum design gives a minimum safety factor of 1.31, effect tip deflection of -80.06 mm, stiffness tip deflection of 20 mm and arch location of 60.64 mm. The lower void optimization gives similar results with an arch location of 19.77mm. The convex shape and the non-linearity of the design point were both considered to be acceptable.

4   EVALUATION OF THE DESIGN

The details of the final optimum design which fulfills the objectives of the project of having a flap effect of ±15deg with voids of small volume and achieving the stiffness requirement were examined. The mesh of the final design, consisting of 5000 elements is shown in Figure 7.
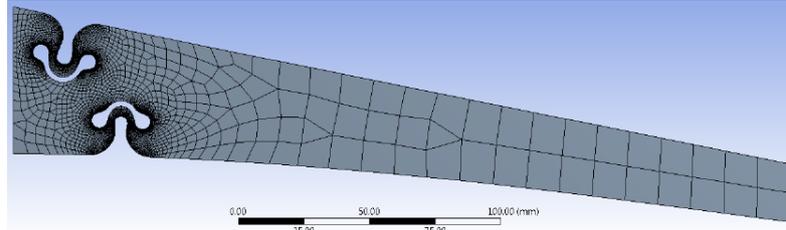

Figure 7: Mesh of the final design.

The deformed shape with the upper void activation, as well as the equivalent stress distribution is shown in Figure 8, showing an acceptable convex shape and stress distribution.
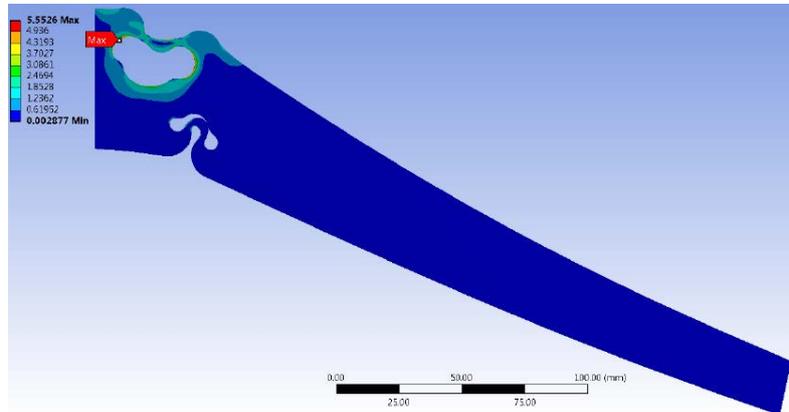

Figure 8: Deformed shape and equivalent stress of final design.

5   CONCLUSIONS

The flap design has been developed by using the qualitative analysis and parametric optimization, with the strategy of utilizing the allowable stiffness of the structure, while the desired deflection is fulfilled, to optimize for the material safety factor and the energy efficiency. The optimum design point fulfills the main objective of the project, which is having ±15deg flap angle under surface loads during operation of the turbine. It also meets the bending stiffness constraint of deflecting within ±5deg during operation of the turbine without actuation pressure, the local deformation constraint of having acceptable deformed shape locally and the material strength constraints by having a minimum safety factor, while respecting all manufacturing constraints. Further work includes developing the design solution for having a smooth aerodynamic surface on the deformed arch shape, and aerodynamically testing the developed design in the wind tunnel and rotating rig.

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