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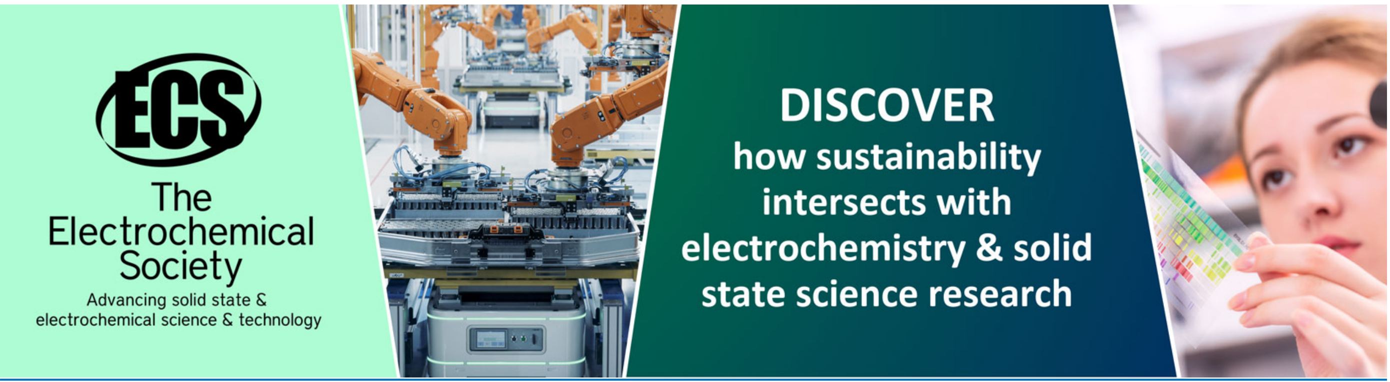

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Structural design of a multi-megawatt wind turbine blade with ONE SHOT BLADE® Technology

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Abstract. This paper presents the ONE SHOT BLADE® technology introduced in the wind turbine blade manufacturing process in order to reduce the time, and hence the costs required to build the blade. A comparison with respect to the standard process is also highlighted. The aim of this study is to optimize the structural configuration of a 50m length blade, built with this innovative manufacturing technique, providing a feasible design according to the international standard requirements.

1. Introduction

A major challenge in the wind power industry is to reduce the time and cost required to manufacture the rotor blades. Modern wind turbine rotor blades must provide multi-megawatt output and ensure 20 years of service in all operating conditions. A key point to obtain an overall cost reduction is not only to improve the manufacturing process, but also to optimize the structural design for the manufacturing process [1]. This paper presents a feasible design according to an innovative manufacturing technology targeting high cost-effectiveness.

A brief description of the standard blade manufacturing process is required to understand the main differences versus the proposed technology. The standard manufacturing task list reported in Table 1 (see Ref. [2]). Figure 1 shows that many items are required in the typical blade workflow; each item requires many labor hours, tools, and equipment.

Table 1. Manufacturing task list.

Task number	Description
1	Material Kitting
2	High Pressure Skin
3	Low Pressure Skin
4	Leading Edge Shear Web
5	Trailing Edge Shear Web
6	Assembly preparation
7	Bonding
8	Root Attachment System
9	Finishing
10	Inspection
11	Testing
12	Shipping

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In Figure 1, one can also see the complexity of a typical wind turbine blade, which includes several structural parts. In this scenario, the tasks related to the blade assembly and bonding phases involve bonding (gluing) of the two shells with structural adhesive (epoxy, polyurethane, etc.) at the leading and trailing edges, and also the bonding of the box girder (also called main spar [3]) between the two shells. These bonds are very important to obtain a high-quality and safe product.

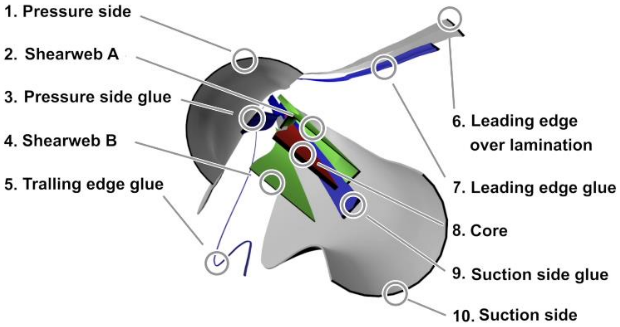

Figure 1. Anatomy of a bonded blade structure.

2. Introduction to ONE SHOT BLADE® Technology

In this paper, the ONE SHOT BLADE® Technology is introduced as a manufacturing process which allows production of a wind turbine blade without any bonding processes. The blade is produced through a single infusion, leading to substantial time savings compared to the typical production cycle time. The associated reduction in labor hours and material savings is the key to understand the value in switching from a standard technology to One-Shot.

The guidelines followed in developing this technology are simple: cost reduction, shorter bill of materials (BOM), ease of manufacturing, and high strength. The higher strength is guaranteed by the absence of bonding processes; indeed, the resulting blade is a one-piece structure, either with one or more or without a shear web (spar). The ease in manufacturing lies is provided by eliminating the bonding processes and by using a single infusion of the whole structure to obtain the final product. Saving labor hours for each blade, reducing waste materials, and avoiding the use of any glue are the keys to reduce the overall production cost. In One-Shot blade process each glass or carbon fabric layer is laid into the mold and once the stacking sequence of the shell (e.g. suction side) is completed the inner mold is placed and fabric layers are wrapped around it to complete stacking sequence on the other shell (e.g. pressure side).

Although the concept of a one-piece blade has been presented in the past, e.g. IntegralBlade® (that uses a flexible inner part that is taken out of the finished wind blade), it is difficult to find details on these technologies in the scientific literature. Indeed, there is a lack of knowledge about structural designs with similar technology and how the structural design is strongly influenced by manufacturing aims. The results that we have obtained come out from our real-world experience and at the same time show that the technology that we have developed is scalable to longer blades.

Several structural layouts can comply with this technology, even if there are some restrictions from topological point of view. The restrictions on structural layout mostly depend on blade shape and length, e.g. airfoil thickness. In the following, the consequences of these constraints will be outlined. Furthermore, the one-shot technology is fully compatible with both polyester and epoxy resins, and the introduction of precast parts and/or carbon fiber pultruded spar caps is also acceptable. All these features make the ONE SHOT BLADE® Technology really flexible.

One of the main advantages of producing with this technology is the high precision (repeatability) of blade weight. This benefit is related to the manufacturing process itself that works with a constant volume, i.e. the difference between external and internal rigid molds. Furthermore, since the blade is produced as a one-piece structure, as a single body, there is no possibility to have a misalignment flaw

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between the two sides of the blade. This technology suffers of same manufacturing defects that could occur during standard process such as laminate placement and fiber waves with same occurrences because these tasks are in common with standard manufacturing process. These and other manufacturing defects can lead to failure mechanisms such as fiber failure, interface cracking and matrix cracking responsible of onset of micro-buckling, transverse cracking and delaminations [4]. These defects can propagate under normal operative loads and lead to structural collapse. So, in order to reduce the weight of structures introducing a damage tolerant design approach these defects are the most critical points to take in account for further developments, e.g. adopting both linear and non-linear numerical procedure [5] for a structural optimization.

The blades produced with One-Shot Technology will not be exposed to some common failure mechanisms. The most common failure and damage modes are well documented in literature [5]. Without structural adhesive, the failures related to debonding at trailing and leading edges as well as to adhesive joint failure (due to fatigue failure or lightning strikes) are impossible. These failure mechanisms can even lead to catastrophic failure of the entire wind turbine, which poses a safety risk and brings a premature end of operating life.

3. Structural solutions for ONE SHOT BLADE®

The structural layout proposed by this technology is strictly connected to the process itself: each fiber-glass layer wraps around one or more internal rigid molds and no adhesive joints are present. In this way, the shear web(s) can be located at specific position(s) of the blade, in both the spanwise and chordwise direction. For larger blades in particular, the shear webs are useful to reduce the effective width of relatively flat areas (panels) on the blade surface so as to increase the critical compressive (buckling) load. Another design solution is to increase the thickness of the panel areas to and thereby increase the panel bending stiffness [7]. Both solutions can be utilized in the ONE SHOT BLADE®, but they must be adapted and optimized to each blade size and geometry. The key is to ensure production feasibility (manufacturability) from the beginning of the structural design.

So, several solutions are possible for each blade length, e.g. a monolithic configuration (without using any core or sandwich material) has proven to be suitable for shorter blades (up to 200kW wind turbine). Figure 2 shows, for example, a comparison between the cross-section of a 100kW wind turbine blade with conventional structural layout (left) and with the ONE SHOT BLADE® technology (right).

The mechanical property distributions over the blade span (Figure 3) show the differences between the two structural configurations. The ONE SHOT BLADE® is generally stiffer in both flapwise and edgewise directions because of the specific material placement required to obtain sufficient stability (buckling) capacity. Indeed, the spar caps are wider to take advantage of larger distance from neutral bending axis. These is necessary to increase the panel stiffness and replace the optimal shear web position.

The different mass and stiffness distributions also change the dynamic behavior with respect to a conventional structural configuration, so the natural frequencies need to be investigated for different operational speeds.

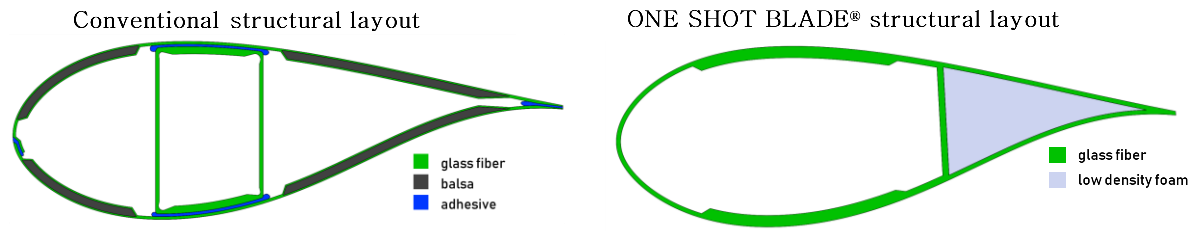

Figure 2. Structural layouts comparison (maximum chord of 100kW wind turbine blade).

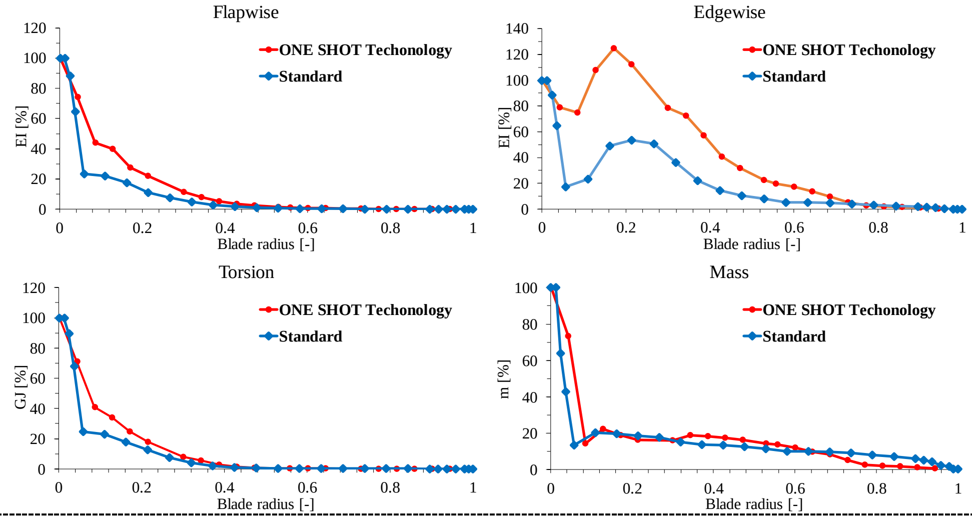

Figure 3. Distribution of mechanical properties over blade span.

One drawback of the presented technology is the satisfaction of the buckling criterion because of the non-conventional positioning of shear web(s) and the resulting large panel which must withstand compressive loads. Indeed, as described in [8], in adopting a hollow structure on a 3.6 MW wind turbine blade, the buckling criterion was the only structural criterion unfulfilled.

In order to withstand to stability requirements, as stated in [9], specific structural solutions need to be taken in account by using available structural design tools [10] and innovative engineering solutions. Typically, as the blade length increases, core material and reinforced core material need to be introduced in the structural configuration to increase the flexural stiffness of the blade. In our case, in order to limit the blade weight, the classical reinforced core has been replaced with a structural element formed by wrapping a number of layers around a brick of low-density core. This solution is able to provide the necessary stiffness without increasing the total blade mass, and it has been introduced in the lamination plan of the ONE SHOT BLADE®. Its manufacturing parameters, i.e. the number and orientation of layers wrapped around the single brick and its geometrical dimensions, can be optimized along the blade span. A representative cross-section of a multi-megawatt blade adopting this sub-structure is shown in Figure 4. For example, at 25% of a 50m blade span, each reinforced core element is a block of 70x20mm wrapped by two bi-axial layers.

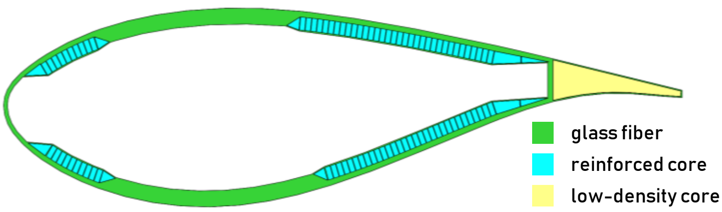

Figure 4. Cross section at 25% of 50m blade with ONE SHOT BLADE® Technology.

If required (e.g. for larger blades), the positioning of a shear web in the middle portion of the cross-section is also compatible with One Shot Technology. The central shear web defines a different topology: two closed cells called “O-boxes” (in Figure 5 there is an O-box at the leading edge and one at the trailing edge), which are obtained by wrapping the glass fabric around rigid internal molds.

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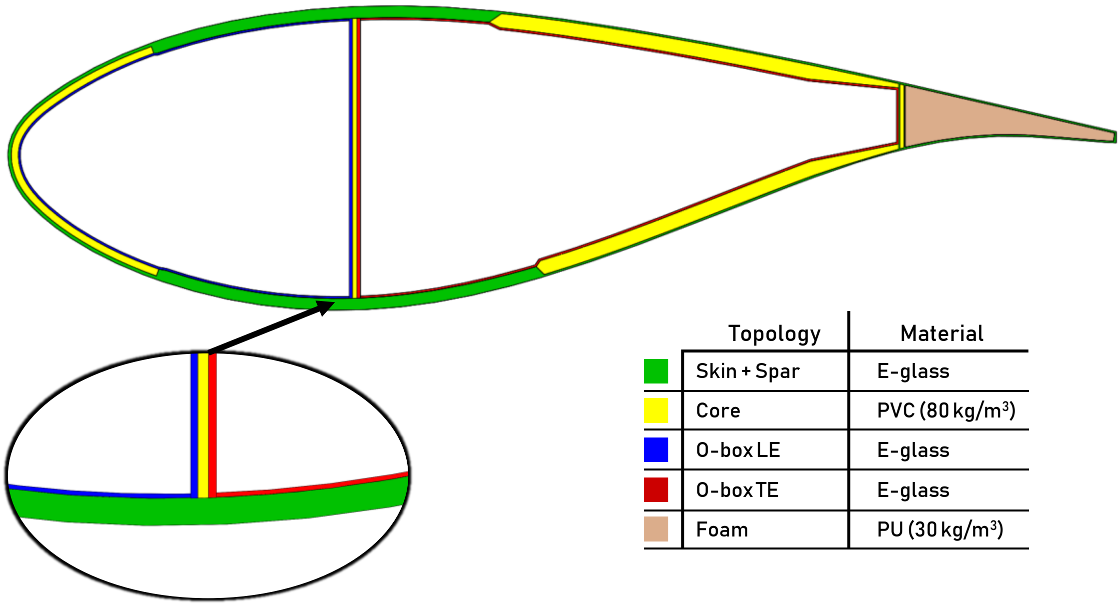

Figure 5. Structural topology of a ONE SHOT BLADE® with central shear web (spar).

4. Results

In this section the main results of performed structural analyses are shown. Two topological configurations have been analysed and compared to the reference structure (SL-0 in the following) under the same flapwise bending moment of 10100kNm. The reference solution SL-0 refers to a design of an existing wind blade produced with standard technology. So, the materials used in the lamination schedule of SL-0 differ from the design solutions proposed within this work. The reference blade structure is useful to highlight the differences between the two design approaches and the interchangeability of the solutions obtained with presented technology in terms of structural behaviour. Additionally, a major challenge with One-Shot technology is to develop a design that is compatible with manufacturing process.

The structural layout SL-1 has been designed with a single shear web positioned from 4.2% to 57.6% of blade length in the trailing edge area (as shown in Figure 4) is more suitable from manufacturing point of view. The structural layout SL-2 with an additional central shear web from 21% to 100% of blade length is shown in Figure 6 and has been designed to be built with ONE SHOT BLADE® technology.

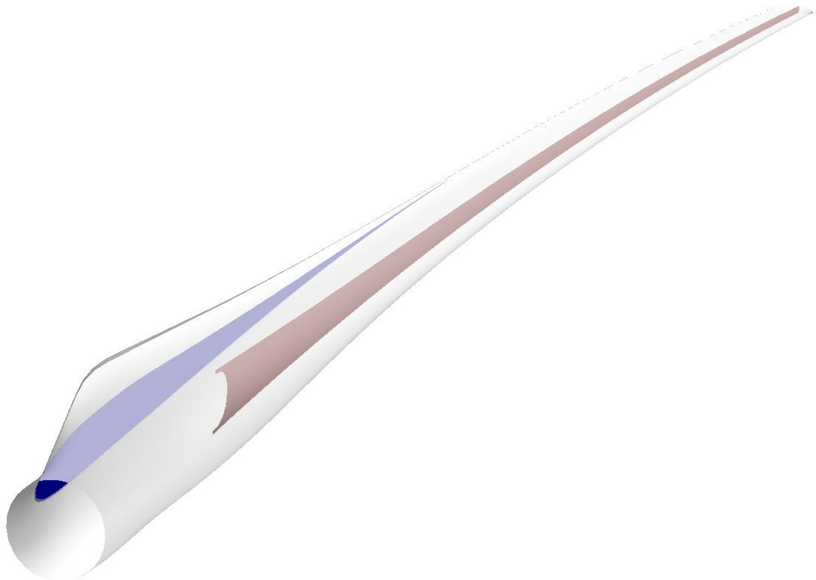

Figure 6. 50m ONE SHOT BLADE® configuration with two shear web.

Table 2 summarizes the main results from structural analyses in terms of buckling loads, tip displacement, principal strains, natural frequencies and mass for both layouts. Table 2 shows also that SL-1 is stiffer than SL-2 due to material added to withstand buckling requirements according to IEC 61400-1 [9].

Table 2. Summary of structural analyses results.

Structural layout	Weigth [kg]	Weigth difference from reference [%]	max tip displacement [mm]	Max Principal Strain [με]	Min Principal Strain [με]	Buckling Load [kNm]	I flap frequency (ref. 0.648 HZ) [Hz]	I edge frequency (ref. 1.226 Hz) [Hz]
SL-1	13563.25	+16.92%	7155	3412	-3532	20863.31	0.785	1.326
SL-2	12213.71	+5.29%	8658	3813	-3716	21546.81	0.723	1.288

Furthermore, the solution SL-1 shown a mass increment of 16.8% that could be not suitable from commercial point of view and implies to re-evaluate loads on whole turbine system (drive, tower, etc.). In Figure 7 has been shown the distributions of mass and stiffness in flap and edge directions compared to reference 50 m blade designed with a conventional layout for standard production technology (see Figure 2).

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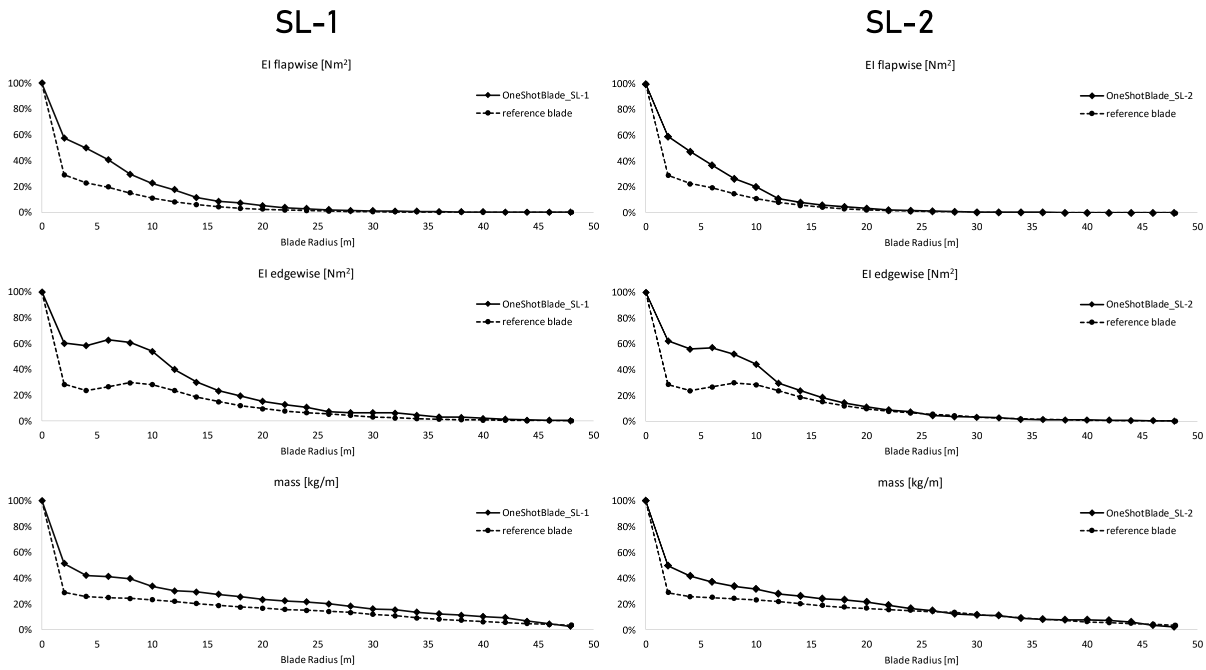

Figure 7. Structural properties and mass distribution.

5. Conclusions

In this study ONE SHOT BLADE® technology has been presented as a manufacturing process able to produce a wind turbine blade as one-piece structure trough a single infusion. The main concept behind this innovative technology is to reduce and simplify each step of the whole production process, allowing significant reduction in manufacturing costs. The developed technology is aimed to reduce both direct and indirect costs. Regarding direct costs, the savings are related to a dramatic simplification in the manufacturing task list and hence labor time [2], as well as a reduction of items (raw materials) in the bill of materials. The presented technology directly affects cost of energy (CoE) concerning both reduction of cost of turbine (CoT) and cost of maintenance (CoM). An accurate evaluation of CoT and CoM reduction should be performed modifying the cost models available in literature to compare standard technologies with ONE SHOT. Furthermore, from a structural point of view, the principal benefit of using the presented technology is the absence of any kind of adhesive to produce a blade. This in turn improves reliability and reduces maintenance costs also.

The structural configurations suitable for use with ONE SHOT BLADE® technology have been described and associated to different blade sizes. It has been shown that a structural layout composed by a single shear web near trailing edge area is suitable for small blades (less than 200kW wind turbine). For larger blade the weight increment becomes substantial, so several structural solutions have been proposed and analyzed.

A 50m blade of a commercial 2.5 MW wind turbine has been used as case study. Starting from aerodynamic surface and worst bending moment condition a multi megawatt ONE SHOT BLADE® has been designed to withstand to IEC 61400-1 requirements. An assessment of blade deflection, principal strains, and buckling stability at the maximum flapwise bending moment has also been presented. The structural layouts investigated have been compared to the reference blade in terms of mechanical properties and natural frequencies. Results compared to a blade constructed using standard manufacturing processes have shown that differences in mass and stiffness distributions affect dynamic behaviour of blade. Future researches should aim for comparing fatigue response under cyclic loads of bonded structure against one-piece structure. The evaluation should be performed in terms of both

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damage tolerant and damage resistant design approach, highlighting and quantifying manufacturing and maintenance cost differences between the two technologies.

A complete assessment of whole turbine needs to evaluate aero-structural behavior under operative load conditions to allow complete switch to ONE SHOT BLADE® technology considering an existing turbine design, while it is different to start a new project from scratch. Finally, the technology presented in this work has proven to be really cost-effectiveness due to a reduction in manufacturing costs.

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