# Fibreglass wind turbine blades: Damage tolerant design and verification

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**A. Sellitto, A. Russo, A. Riccio, and M. Damiano**

# Fibreglass Wind Turbine Blades: Damage Tolerant Design and Verification

A. Sellitto[1,a)], A. Russo[1,b)], A. Riccio[1,c)], and M. Damiano[2,d)]

[1]*Università degli Studi della Campania "Luigi Vanvitelli", Department of Engineering, Via Roma 29, Aversa (CE) 81031, Italy*
[2]*Cartflow S.r.l., Via Centauro, 1 - 81030 Castel Volturno, Caserta, Italy.*

[a)]Corresponding author: andrea.sellitto@unicampania.it
[b)]angela.russo@unicampania.it
[c)]aniello.riccio@unicampania.it
[d)]michele.damiano@cartflow.com

**Abstract.** This paper presents the damage tolerant design and verification of a composite materials wind turbine blade expected to be manufactured with the manufacturing process named OneShot Blade® technology. This technology allows the production of wind turbine blades without adhesives and/or bonding processes, leading to a significant reduction in labour hours, costs and materials. Here, the OneShot Blade® oriented design of a 10-meter long fibreglass blade is introduced. Two different configurations (conventional and lightened) have been investigated highlighting their damage tolerant characteristics. Structural performances have been evaluated to verify that the structure complies with the IEC 61400-2 and Germanischer-Lloyd (GL) regulations by considering several loading conditions. Finally, comparisons against a similar wind turbine blade, manufactured by means of a standard process, has been presented, to highlight the advantages of the proposed technology.

## INTRODUCTION

In the last few decades, the progressive reduction of energy resources and the increase in pollutant emissions have led to a significant increase in the development of renewable energy systems technologies, such as wind power systems. The mutual interaction between the forces due to the external environment and the wind turbine components, produces not only the desired energy but also critical stresses in constituent materials. Hence, the design of the wind turbine system becomes extremely important in tailoring its strength and durability, taking into account the desired production costs which must be commensurate with the value of the produced energy. Indeed, one of the hot topics in wind energy research is the development of new design and manufacturing methodologies, able to fully exploit the potential of advanced composite materials by introducing light-weight structural concepts associated to the reduction of the production times and costs. Different methodologies and approaches for the design of wind turbine systems can be found in literature [1-5]. All the structural wind turbine blades solutions proposed in the literature are characterized by the presence of bonded components and/or shear webs, needed to guarantee the shear strength of the blade. However, bonded components and shear webs, generally, increase the weight of the wind turbine blade and complicate the manufacturing process with a consequent increase in production time and costs. Very few examples of one-piece blades can be found in literature [6], generally, providing no clear information about the adopted structural design solutions and providing no quantification of the advantages with respect to standard manufacturing technologies. In this paper, a new methodology for wind turbine blade production, named One Shot Blade® able to avoid the use of any bonding process, has been taken into account to design a "one piece" 10 meters long fibreglass blade. The design is performed by considering that the blade can be produced as a "one-piece structure" by means of a single infusion process. Structural analyses, according to the IEC 61400-2 [7] and Germanischer-Lloyd (GL) [8] regulations, have been performed to validate the proposed innovative

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methodology under several dimensioning loading conditions. Once defined a suitable configuration for the turbine blade, an evolved lightened configuration has been obtained by redesigning the blade according to a damage tolerant approach. Both the configurations have been analysed and compared to assess the mass saving, the damage tolerant characteristics and the structural performances.

## THEORETICAL BACKGROUND

In the frame of the structural design of the wind turbine blades, components' structural integrity, such as rotor blade, rotor hub, nacelle, tower, and connections, is of primary concern. The collapse of such components is verified by means of tests and/or calculations, and the load-carrying capability is determined according to specific safety levels. The structural analyses are based on ISO 2394 (General principles on reliability for structures [9]) or equivalent regulations.

To verify the compliance of the structure to the requirements, the maximum allowable stress $\sigma_d$ is evaluated as a function of the characteristic material strength (in general, the yield strength) $f_k$ and of the partial safety factor for material $\gamma_m$, as expressed in Equation (1).

$$\sigma_d = \frac{f_k}{\gamma_m} \tag{1}$$

The partial safety factor for material strength for the short-term verification, $\gamma_m$, is calculated by multiplying the partial safety factor $\gamma_{m0}$ = 1.35 by reduction factors $C_{ix}$, as described by Equation (2).

$$\gamma_m = \gamma_{m0} \cdot \prod_i C_{ix} \tag{2}$$

The following reduction factors should be considered:

- $C_{1a}$ = 1.35 influence of material degradation;
- $C_{2a}$ = 1.1 influence of temperature;
- $C_{3a}$ = 1.1 influence of manufacturing process (laminates manufactured by means of prepregs, filament winding, pultrusion or resin infusion);
- $C_{4a}$ = 1.0/1.1 respectively for post-cured laminate and non-post-cured laminate.

In the framework of the wind turbine blades structural integrity verifications, damages which interfere with the safe operations of the blade are not allowed, such as substantial loss of stiffness, plastic deformation, buckling and/or cracking. One of the most important requirements is related to the minimum clearance between the tower and the other components of the wind turbine system. The maximum predicted tip deflection must not exceed the 30% of the blade length for the turning rotor and the 5% for the still rotor, and the most severe bending moments distribution must be considered for the tip deflection determination. A number of loading points is used to distribute the loads along the blade length. The location of the loading points and the magnitude of the applied loads must be chosen appropriately to reproduce the expected blade root bending moments.

## THE ONESHOT BLADE® MANUFACTURING PROCESS

The OneShot Blade® Technology is an innovative manufacturing process which allows the production of wind turbine blades as "one-piece blades", by avoiding any bonding procedure. The structure is manufactured throughout a single infusion process, leading to a relevant time-saving, if compared to the classical production time, and a significant reduction in materials needed for the blade manufacturing. The costs reduction, the ease of production, the short Bill Of Materials (BOM) and the resultant high-strength structures are the main added values of the proposed OneShot Blade® technology. Each glass or carbon layer is housed into the mould, according to the stacking sequence, both on suction and pressure sides; then, the inner mould is placed, and the cure process begins. The single-body structure, resulting from this process, guarantees the absence of misalignments between the upper and lower blade surfaces. Figure 1 shows a blade cross-section manufactured with OneShot Blade® technology compared against a conventional blade.


**FIGURE 1.** Wind turbine blade cross-section.

Several structural designs comply with this technology, thus demonstrating the OneShot Blade® as a flexible manufacturing process. Indeed, both polyester and epoxy resins can be used for the manufacturing, also pre-form parts and/or carbon fibres pultruded spar caps can be introduced. As in all the manufacturing processes, defects and pre-damages can occur during OneShot Blade® production, such as fibres wrinkling, resin voids and inter-ply sliding. On the contrary, problems related to the debonding at trailing and leading edges and/or adhesives and shear webs damages have been avoided due to the absence of any bonding process.

# ONESHOT BLADE® DESIGN

## Conceptual Design and FE Modelling

The wind turbine blade geometry has been modelled in a CAD software starting from eleven aerodynamic profiles, representing different blade cross-sections. The first circular section corresponds to the blade junction on the hub. Each profile has been positioned along the pitch axis and rotated by a certain angle, as shown in Figure 2. The upper and lower blade surfaces have been defined by connecting the profiles (Figure 3).

**FIGURE 2.** Aerodynamic profiles representing the cross-sections of the blade.

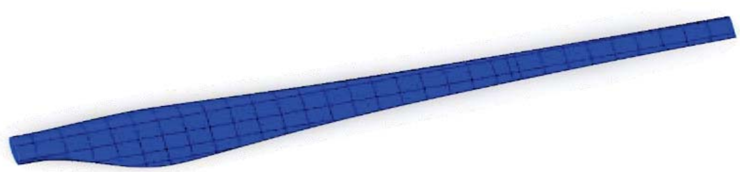


**FIGURE 3.** Geometry of the blade.

Three materials have been used for the blade design and modelling:

- Uniaxial fiberglass UD1000 (1000 kg/m$^2$);
- Quadriaxial fiberglass QD1200 (1200 kg/m$^2$);
- PVC foam.

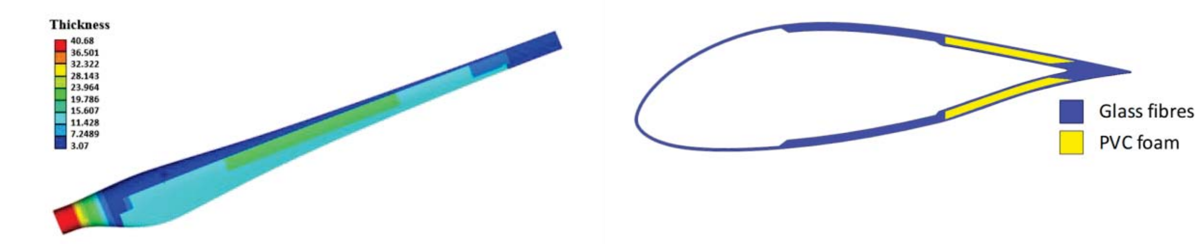
The composite materials properties, listed in Table 1, have been determined by taking into account the dry fibres data sheets, provided by the manufacturer.

TABLE 1. Materials properties.

| Properties | Units | Uniaxial fiberglass UD100 | Quadriaxial fiberglass UD100 |
|---|---|---|---|
| $E_1$ | [MPa] | 37001.46 | 16411.2 |
| $E_2$ | [MPa] | 11614.77 | 16411.2 |
| $G_{12}$ | [MPa] | 4529.87 | 7453.46 |
| $v_{12}$ | [-] | 0.28 | 0.28 |

The procedure used to define the composite layup provides adequate flexural strength and buckling resistance of the blade. First, the skin structure has been built, by stacking two unidirectional and two quadriaxial fibreglass sheets. Then, a certain number of layers have been added, section-by-section, starting from the blade root, allowing the blade-hub coupling. In the spar-cap regions (suction and pressure sides) unidirectional fibreglass sheets have been progressively added in order to reduce the blade deflection and the strains, to assure that the safety factors, prescribed by the regulations, are satisfied.

Finally, in order to limit the blade weight and increase the buckling resistance, PVC foam core has been inserted between the spar caps and the trailing edge, both in pressure and suction sides. Figure 4 shows the thickness distribution on the blade and the cross-section.




(a) (b)

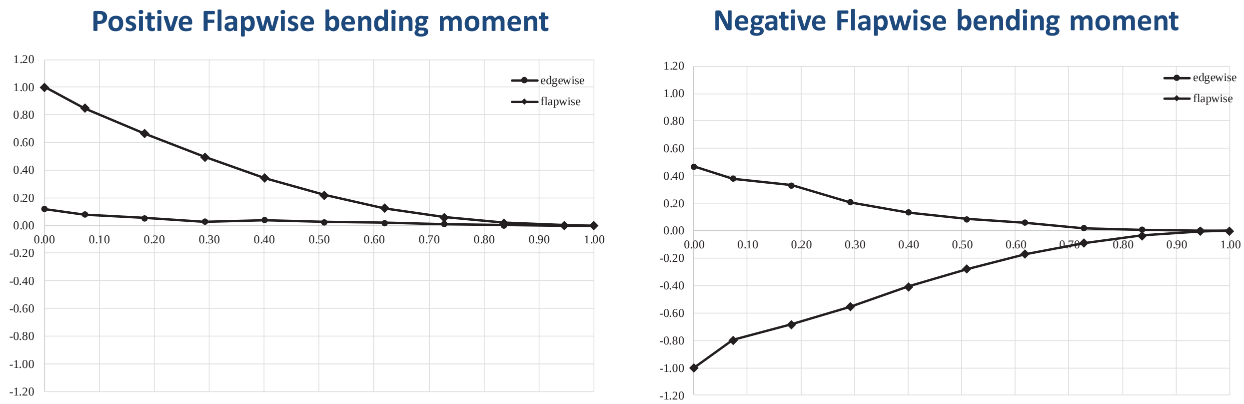
**FIGURE 4.** (a) Thickness distribution (mm); (b) Blade cross-section.

When setting up the Finite Element (FE) model, a preliminary mesh sensitivity analysis has been carried out in order to try to reduce the computational cost, without compromising the solutions accuracy; 30 mm elements size, corresponding to 35072 nodes, has been chosen for the analyses.

## Analyses and Results

Numerical analyses have been performed to assess the safety of the wind turbine blade. Indeed, no mechanical interference between the blade and the tower can occur. The maximum tip deflection, multiplied by the appropriate safety factor, should not exceed the clearance between the blade and the tower. The tip deflection analyses have been performed taking as an input two critical bending moments distributions:

- Positive Flapwise bending moment (Figure 5a);
- Negative Flapwise bending moment (Figure 5b).

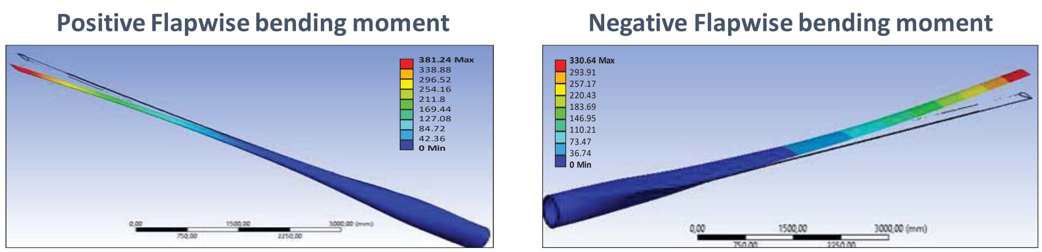



(a) (b)

**FIGURE 5.** Flapwise bending moment: (a) positive; (b) negative**.**

In Figures 5, the non-dimensional loads distribution (the ratio between the load and the maximum load) as a function of the non-dimensional blade length, are presented. Each point of the graphs is obtained by considering a specific severe condition for the structural integrity of the blade. According to Figure 5, the flapwise load cannot be separated from the edgewise load. Each of the flapwise moments will carry an edgewise moment component, which depends on the severe conditions considered for the definition of that load.

Figure 6 reports the total deformation due to both the flapwise bending moments.




(a) (b)

**FIGURE 6:** Total deformation: (a) positive flapwise; (b) negative flapwise.

It has been found that the maximum deflection for the positive and negative flapwise bending moments are respectively 381.24 and 330.64 mm. These deflections are slightly above 4% and 3% of the blade length. After, the tensile strain values due to negative and positive flapwise bending moments have been predicted, which are, respectively, 1858 με and 2131 με. Such values, compared against the material limit values and multiplied by the degradation factors provide by the regulations, provide the global minimum safety margins respectively of 69% and 63%, where the safety margin has been calculated as in Equation (3):

$$MS = \left(1 - \frac{\varepsilon}{\varepsilon_{amm}}\right) \cdot 100 \qquad (3)$$

Subsequently, linear buckling analyses have been performed, for each loading conditions. Figure 7 represents the total deformation with the displacements contour plots of the buckling Mode I. As expected, the wind turbine blade buckling loads ($F_{crit}$) result 2.4 (positive flapwise bending moment), 2.98 (negative flapwise bending moment) times bigger than the blade service loads ($F_{DLC}$).

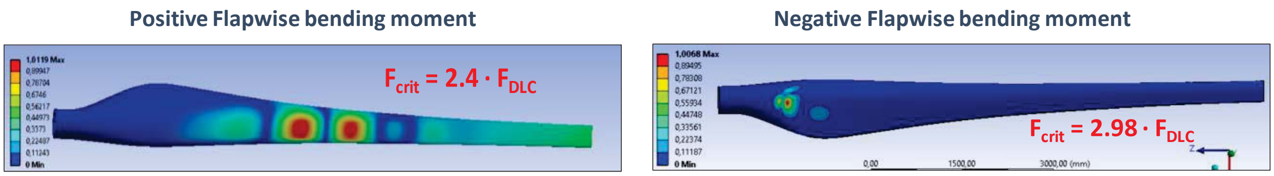



**FIGURE 7.** First mode of buckling due to positive and negative flapwise bending moment.

The provided numerical analyses have proved the robustness of the OneShot Blade® manufacturing technology oriented design. The blade design complies with the International Standard for the small wind blades. Additionally, a reduction of about 10% of the blade weight respect to conventional wind turbine blade has been obtained, as shown in Figure 8, highlighting the added value of the proposed technology.

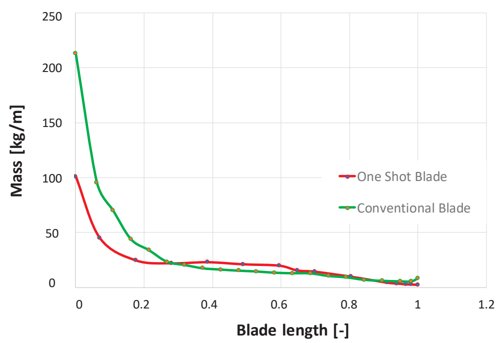



**FIGURE 8.** Mass Vs. Blade dimensionless length: comparison between Conventional Blade configuration and One Shot Blade® configuration.

## ONESHOT BLADE® DAMAGE TOLERANCE RE-DESIGN

The conventional OneShot Blade®, designed according to the IEC 61400-2 and Germanischer-Lloyd (GL) regulations, has been demonstrated to be extremely over-dimensioned. To accomplish a weight reduction, while preserving the strength, durability and stiffness requirements, an attempt to re-design the blade according to a damage tolerant design approach has been adopted. Such approach includes non-linear structural FE analyses to investigate the effects of buckling on the structural deformations. Actually, with the aim to lighten the structure, a certain number of layers has been removed, section-by section, starting from the blade root with respect to the previous model. Figure 9 shows a comparison, in terms of thickness distribution, between the two blades configurations.

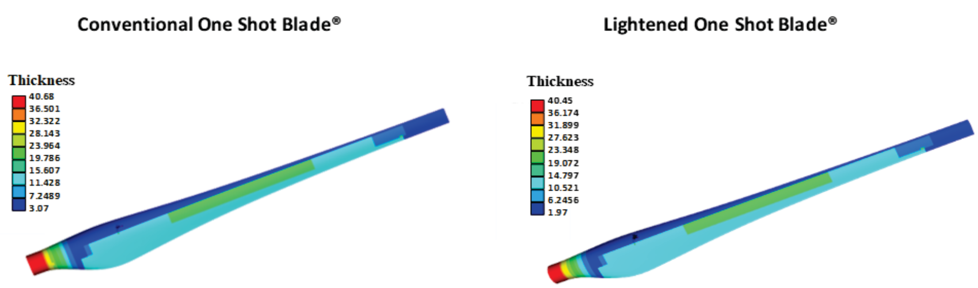



**FIGURE 9.** Thicknesses comparison: one shot base and lightened configurations.

The tip deflection analyses have been performed considering the most severe loading condition, such as the negative flapwise banding moment. The maximum deflection for the conventional and lightened OneShot Blade® configurations are 381.24 mm and 458.38 mm, respectively. Therefore, even if there is an increase in deflection from 3.8% to 4.6% of the blade length, the maximum deflection remains below the minimum safety threshold, imposed by the regulations. Moreover, the tensile strain value has been predicted, which provide a global minimum safety margin respectively of 63%, compared with the 69% of the conventional OneShot Blade® configuration.

Once the regulation requirements have been verified, linear and nonlinear buckling analyses have been carried out on the lightened OneShot Blade® in order to investigate the damage behaviour under service loads. A peak load three times higher than the operating load has been considered to check the damage tolerance of the blade. The curves normalized load (load/operational load ratio) as a function of the normalized displacement (displacement/blade length ratio), obtained for the negative flapwise bending moment, are compared in Figure 10. From the nonlinear trend, the stiffness reduction due to the buckling phenomenon can be appreciated.

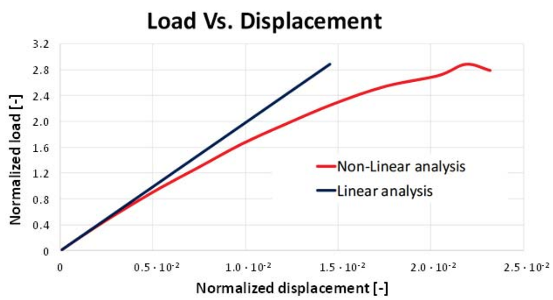



**FIGURE 10.** Load Vs Displacement.

In addition, Conventional One Shot Blade® and lightened One Shot Blade® have been compared in terms of intra-laminar damage, according to Hashin's criteria [10-12]. These comparisons, at the maximum applied load, have been reported in Figure 11, where red areas are representative of completely damaged locations.

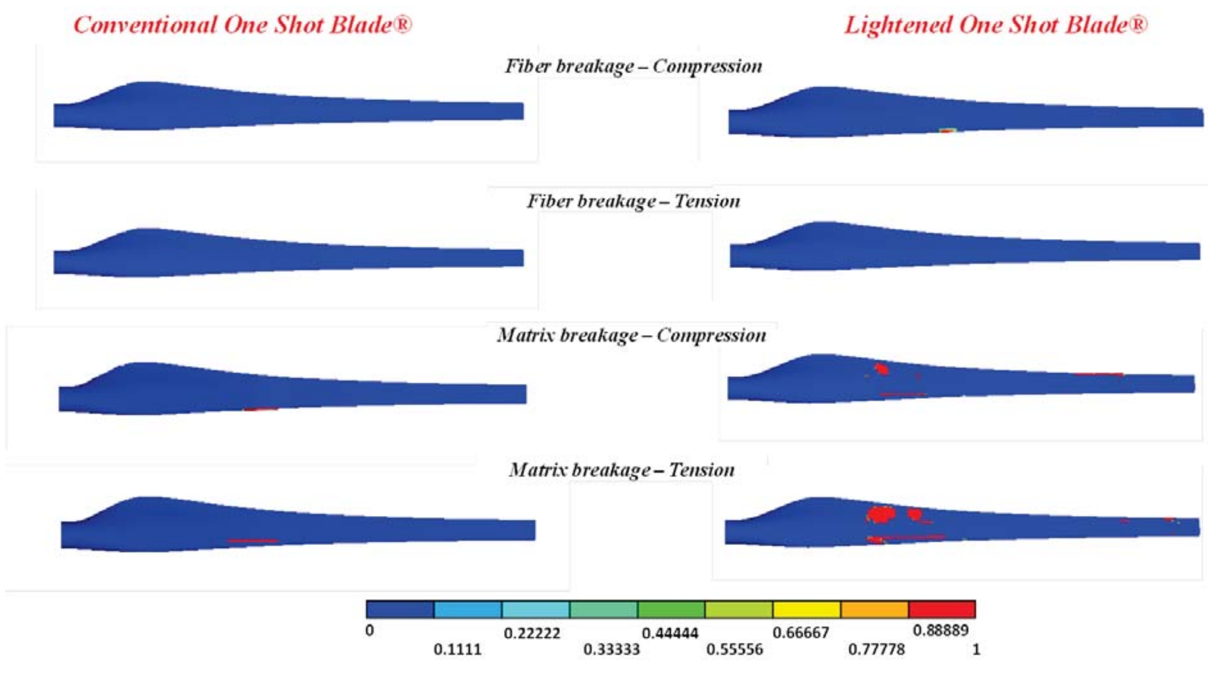



**FIGURE 11.** Intra-laminar damages comparison.

Although in the Lightened One Shot Blade® configuration the intra-laminar damage occurs earlier than in the conventional configuration, this configuration is still safe at the maximum service load condition. However, as shown in Figure 12, the lightened configuration allows a clear reduction in terms of weight (11% compared to conventional one shot blade configuration).

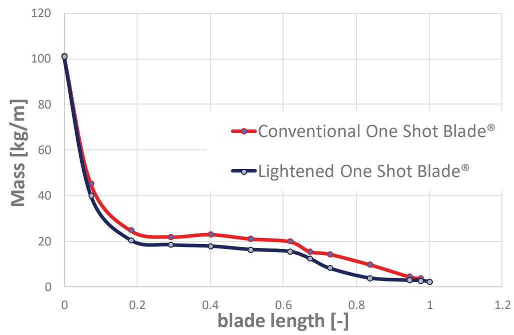



**FIGURE 12.** Mass Vs. Blade dimensionless length: comparison between Lightened One Shot Blade® configuration and conventional One Shot Blade® configuration.

## CONCLUSIONS

This paper presents the damage tolerant design and verification of a composite wind turbine blade expected to be manufactured with the manufacturing process named OneShot Blade® technology able to reduce production time and costs, A ten-meters long fiberglass wind turbine blade, without adhesives and shear webs, according to the OneShot Blade® technology process, has been, first, designed. Critical deflection analyses have been carried out in order to assure that no interference between the blade and the tower could affect the safety of the wind turbine blade. International standard for small wind turbines design (IEC 61400-2) and Germanischer-Lloyd (GL) regulations have been checked by means of the numerical analyses. Two loading conditions have been analysed: positive and negative flapwise bending moments. The maximum deflection found is up to 4% of the blade length, which falls within the safety margins for the small wind turbine blades. Tensile strain values, evaluated for all the considered loading conditions, have shown global minimum safety margins of 63% and 69%, demonstrating that the wind turbine blade has been over-dimensioned. Hence a lightened configuration has been designed by adopting a damage tolerant design approach. Indeed, this last configuration has been found capable to comply with the regulation requirements, with a relevant reduction of weight, even if the presence of a more extended damage area beyond the service load can be appreciated. Linear and non-linear buckling analyses and intra-laminar failure analyses have been performed, confirming that both the OneShot Blade® technology-based configurations complies with the International standard for small wind turbines design regulations. Finally, comparison against a standard wind turbine blade design has demonstrated that a reduction from 10% to 20% in weight can be achieved by using the newly developed OneShot Blade® manufacturing-based design.

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