Progressive structural scaling of a 20 MW two-bladed offshore wind turbine rotor blade examined by finite element analyses

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Abstract. Two-bladed turbines offer a promising opportunity for rotor cost savings, especially considering the ongoing growth trend in rotor size. An increased chord and airfoil thickness of a two-bladed turbine’s blade results in potential structural improvements caused by a rapidly growing second moment of area. Compared to a three-bladed turbine’s blade, the blade structure would theoretically require less material, while withstanding 50% higher flapwise loads. An analytical method of progressive structural scaling for three-dimensional rotor blade structures, based on equal material stresses, is introduced to calculate the modified structural thickness properties of the two-bladed turbine’s blade. It simplifies the airfoil-shaped structure to a thin-walled rectangle, utilizes a fixed initial flapwise load factor, and scales the edgewise loads proportionally to the required blade mass. To evaluate the validity of this analytical approach, a progressively scaled and an iterated 20 MW two-bladed turbine’s blade are examined with finite element analyses for static loads. The outcomes are then compared to corresponding analyses of a three-bladed turbine’s reference blade. Overall, the static stress comparisons at different blade positions show good agreement with the analytical results. Nevertheless, the buckling analyses performed reveal stability issues, which subsequently will lead to a readjustment of the blade mass.

1. Introduction

Today’s on- and offshore wind energy market is dominated by three-bladed turbines. However, the growth trend of modern wind turbines in terms of rated power and rotor diameter will present new and unprecedented challenges for the wind energy industry concerning, inter alia, required material properties and structural design solutions of the rotor blades [1, 2].

Two-bladed turbines could be a promising solution to postpone these upcoming challenges, due to – theoretical – structural blade improvements of mass and stiffness. From a structural point of view, increasing the chord lengths and blade thicknesses, when redesigning a three-bladed turbine into a two-bladed one, leads to a rapidly growing second moment of area. When utilizing an analytical stress-based blade scaling, this would result in a lighter rotor and thus fewer costs, and stiffer blades, while withstanding 50% higher flapwise and edgewise loads as proposed by [3].

Going even one step further, the over-proportionally lower blade self-weight and consequently reduced gravitational force would cause lower dynamic edgewise loads, in theory. Under the premise of 50% higher flapwise loads, but weight driven edgewise loads, the benefits of larger chord lengths result in an even higher mass reduction than identified by [3]. These analytical
scaling relations can be re-formulated as a new method named “progressive structural scaling” and will be introduced in the following Section 2. It enables a greatly simplified insight into structural blade redesign from a three-bladed reference turbine into a two-bladed one, to point out the effect of different (structural) influences in a clear and transparent manner. Thus, an optimization of the structural properties, such as [4, 5], has been avoided.

Interestingly, the analytical approach of [3] and the “progressive structural scaling” reveals the highest mass reduction effect for a redesign approach with unchanged rotation speed and \( \sim 50\% \) longer chord lengths, as performed by [3, 6, 7, 8]. Rotating faster, which was considered by [9, 10, 11, 12, 13], results in a reduction of the rotor solidity and thus in smaller chord lengths, which lower the structural advantages described above. Note, that a faster rotation offers other cost benefits, e.g. in the drive train, depending greatly on the chosen turbine concept [14].

To clarify if the structural advantages of the new analytical method are also given for complex material stress issues, examinations with finite element analyses (FEA) of three-dimensional rotor blades are mandatory. Therefore, corresponding analyses are performed first for a three-bladed reference, and second for a redesigned two-bladed turbine (see Section 3). In this context, it is essential to consider also the tip deflection and buckling issues, even though the analytical method of progressive structural scaling does not take these characteristics into account (see Section 2). For the sake of simplicity, the absolute rotor blade length stays unaltered, which yields a \( \sim 4\% \) lower absolute turbine power curve [8]. As a reference, the rotor blade from the INNWIND 20 MW reference wind turbine [15, 16, 17] is used. With the results of the FEAs (see Section 4), the present study answers the question, whether the significant mass reduction resulting from the progressive analytical blade scaling is reasonable and if the derived blade design can ensure the same structural strength. Furthermore, the comparisons give some insights into the blade deflections and buckling issues.

2. The method of progressive structural scaling

The starting point of the progressive structural scaling is the simplification of the three-dimensional load-carrying airfoil-shaped structure to a thin-walled rectangle. Thus, the complex geometry can be reduced to only four parameters, namely the height \( h \), the width \( b \), and the respective wall thicknesses \( t_1 \) and \( t_2 \). These relations are an extension of the considerations of [3], who assumed a constant wall thickness \( t \) for the whole rectangular profile. The height \( h \) and width \( b \) are directly related by the aspect ratio \( f_R \) of the respective airfoil. The geometry is shown in Figure 1:

![Figure 1. Simplified thin-wall rectangular-shaped cross-section.](image-url)
airfoil thicknesses are (re-)scaled proportionally along the blade (index "i" for the position of the respective cross-section). The corresponding scaling factor is called the chord factor $f_{c,i}$:

$$f_{c,i} = \frac{c_{2B,i}}{c_{3B,i}} = \frac{b_{2B,i}}{b_{3B,i}} = \frac{h_{2B,i}}{h_{3B,i}} = \text{const.} \quad (1)$$

As the airfoils, the tip speed, the direction of the lift vector, and the relative wind speed remain unaltered, the increase of the aerodynamic force can be assumed to be proportional to the increase in chord lengths. Therefore an additional static flapwise loading of $\sim 50\%$ per blade is presumed, based on [3, 8, 9], which is a reasonable choice as long as the turbine concept (upwind, variable-speed, fixed-hub) does not change during the redesign. A first examination of whether this approximation also applies for dynamic simulations of DLC 1.2 has been reported in [18] and shows promising agreement. The flapwise load factor $f_{L,flap}$ is assumed to be constant over the whole blade length:

$$f_{L,flap} = \frac{L_{flap,2B}}{L_{flap,3B}} \approx 1.5 \quad (2)$$

$L_{flap}$ represents the summarized flapwise blade root bending moment. In the following, all indices named "3B" and "2B" will be neglected and all indices named "2B" will be marked with an apostrophe, for the sake of simplicity. In addition, the equations will be described for one cross-section only, whereas the dependencies are valid for all cross-sections, which have to be utilized for a complete blade scaling. To simplify the following calculations further, some dependencies and factors are defined, namely a factor $f_t$ for the thickness ratio of the three-bladed turbine and a factor $f_t'$ for the thickness ratio of the two-bladed turbine. Due to the proportional scaling, the theoretical aspect ratio $f_R$ between the rectangular cross-section’s height and width is equal for both turbines:

$$f_{t,3B} = \frac{t_{2,3B}}{t_{1,3B}} = \frac{t_2}{t_1} = f_t; \quad f_{t,2B} = \frac{t_{2,2B}}{t_{1,2B}} = \frac{t_2'}{t_1'} = f_t'; \quad f_R = \frac{b_{3B}}{b_{2B}} = \frac{b_3}{b_2} = \frac{b}{b'} \quad (3)$$

The objective of the progressive structural scaling method is to achieve equal material stresses of both structures (see above “stress-based” blade scaling). Therefore, the flapwise load factor $f_{L,flap}$ should be in equilibrium with the corresponding section modulus $W_y$. When neglecting terms of a higher order according to [19], the section moduli $W$ in both directions result for the specified geometry (see Figure 1) in:

$$W_x = \frac{I_x}{0.5 \cdot b} \approx bht_2 + \frac{1}{3} b^2 t_1; \quad W_y = \frac{I_y}{0.5 \cdot h} \approx bht_1 + \frac{1}{3} h^2 t_2 \quad (4)$$

It may be mentioned here that the analytical method could be applied analogously for an equal structural blade stiffness, utilizing the second moment of area $I$, if the tip-tower-clearance is the dimensioning design driver. While that approach would offer an even higher reduction of material and thus additionally less gravitational loading, the chosen stress-based method with the section modulus $W$ is more conservative and thus preferred. Nevertheless, the result is a two-bladed turbine’s blade with an over-proportional stiffness even for $50\%$ higher loads and equal material stresses. The same relations from Equation (4) are valid and will again be marked with an apostrophe. Consequently, the following relationship can be formulated:

$$f_{L,flap} = \frac{W_y'}{W_y} = f_c^2 \cdot \frac{f_R + \frac{1}{3} f_t'}{f_R + \frac{1}{3} f_t} \cdot \frac{t_1'}{t_1} \quad (5)$$

After rearranging this equation, the thickness ratio between the two-bladed turbine’s blade and the three-bladed turbine’s blade can be written as:

$$\frac{t_1'}{t_1} = \frac{f_{L,flap}}{f_c^2} \cdot \frac{f_R + \frac{1}{3} f_t}{f_R + \frac{1}{3} f_t'} \quad (6)$$
By analogy to Equation (5) the edgewise load factor \( f_{L,\text{edge}} \) should also be in equilibrium with the corresponding section modulus \( W_x \):

\[
f_{L,\text{edge}} = \frac{W'_x}{W_x} = f_c^2 \cdot \frac{f'_t + \frac{1}{3}f_R}{f_t + \frac{1}{3}f_R} \cdot \frac{t'_1}{t_1} \tag{7}
\]

While the flapwise load factor \( f_{L,\text{flap}} \) is defined for a specific value (see Equation (2)), the edgewise loads have to be approximated directly from the change in blade mass \( m \), since it is assumed that these loads are almost completely driven by gravitational forces [20]. To achieve this connection, the mass is approximated by the corresponding cross-section area \( A \), assuming that the relative density stays unchanged:

\[
f_{L,\text{edge}} = \frac{m'}{m} = \frac{A'}{A} = f_c \cdot \frac{f'_t + f_R}{f_t + f_R} \cdot \frac{t'_1}{t_1} \tag{8}
\]

Thus, the combination of Equations (7) and (8) results in:

\[
f'_t = \frac{f_t f_R (1 - \frac{1}{3}f_c) + \frac{1}{3}f_R^2 (1 - f_c)}{f_t (f_c - 1) + f_R (f_c - \frac{1}{3})} \tag{9}
\]

At this point only the chord factor \( f_c \) and the flapwise load factor \( f_{L,\text{flap}} \) are known. To eliminate even more unknowns, factors for the bending stiffness \( f_{BS} \) and for the shear stiffness \( f_{SS} \) are introduced:

\[
f_{BS} = \frac{EI_x}{EI_y} = f_c^2 \cdot \frac{f_l + \frac{1}{3}f_R}{1 + \frac{1}{3}f_R} \tag{10}
\]

\[
f_{SS} = \frac{GA_x^e}{GA_y} = \frac{f_l}{f_R} \tag{11}
\]

The bending stiffnesses in both directions are given by the corresponding second moments of area \( I \) and the elasticity moduli \( E \). The shear stiffnesses along both directions are approximated by a homogeneous shear modulus \( G \) for both orientations and the effective shear areas \( A^e \), which consists of the strips orientated in the direction of the indices \( x \) or \( y \) of the rectangular geometry (see Figure 1) [19]. Note, that this method might not be the most precise and might need to be revised in the future. The bending stiffnesses and the shear stiffnesses in both directions are known from the three-bladed reference blade. As a consequence, the combination of Equations (10) and (11) results in the aspect ratio factor \( f_R \) and the thickness ratio \( f_t \):

\[
f_R = \sqrt{\frac{f_{BS} \cdot \frac{3 + f_{SS}}{3 f_{SS} + 1}}{f_{BS} \cdot \frac{3 + f_{SS}}{3 f_{SS} + 1}} \cdot f_{SS}} \tag{12}
\]

\[
f_t = \sqrt{\frac{f_{BS} \cdot \frac{3 + f_{SS}}{3 f_{SS} + 1}}{f_{BS} \cdot \frac{3 + f_{SS}}{3 f_{SS} + 1}} \cdot f_{SS}} \tag{13}
\]

Now, the first thickness ratio \( t'_1 / t_1 \) can be calculated according to Equation (6). The second thickness ratio \( t'_2 / t_2 \) can be determined using the following relation:

\[
\frac{t'_2}{t_2} = \frac{f'_t}{f_t} \cdot \frac{t'_1}{t_1} \tag{14}
\]

The thickness ratios from Equations (6) and (14) are used later on when designing the FEA model of the two-bladed turbine’s blade. They can be utilized to scale the thickness properties of the corresponding two-bladed turbine’s airfoil parts (see Figure 2) based on the three-bladed
reference. Keep in mind the omitted index “i” for different positions of the respective cross-section along the blade span. The procedure used is explained in Section 3. Finally, the expected mass $m$ per position $i$ can be calculated according to:

$$f_m = \frac{m'}{m} = \frac{f_{L}}{f_{c}^{2}} = f_{R} + \frac{1}{3} f_{t}, f'_{t} + f_{R}$$

(15)

The numerical stress results for the two-bladed turbine’s blade, designed using the method of progressive structural scaling introduced here, are presented in Section 4, together with the corresponding results for the blade from the three-bladed INNWIND 20 MW reference turbine. Firstly, however, the methodology for the examination of the method with finite element analyses based on three-dimensional structures will be described.

3. Methodology for material stress examination by finite element analyses

To quantify the validity, for achieving structural strength equality, of the newly introduced method of progressive structural scaling, three different blades are compared:

(i) The three-bladed INNWIND 20 MW reference turbine’s blade,
(ii) a two-bladed turbine’s progressively scaled blade, and
(iii) a two-bladed turbine’s blade with approximately equal stresses as (i) by thickness iteration.

The examination begins with the generation of a finite element model of the blade from the three-bladed INNWIND 20 MW reference turbine (i). The model, which is based on publicly available data [15, 16, 17], will then be used to perform structural strength analyses. The results, in turn, represent the reference values for the upcoming analyses of two-bladed turbines.

Following this, the finite element model of the progressively scaled blade (ii) is generated in three steps:

(1) *Aerodynamic redesign*: Convert the three-bladed INNWIND 20 MW reference turbine into a two-bladed one with an equal tip speed by increasing the chord lengths by 50 %, utilizing the same airfoil shapes and positions, and layer thicknesses [8].

(2) *Analytical structural scaling*: Adapt the material thicknesses of the spar caps, the shell structures and the leading and trailing edge reinforcements (see Figure 2), utilizing the same material properties of the reference blade (i), since the focus of all considerations is to point out the different (structural) influences as transparently as possible (see Section 1). The material layers are scaled proportionally according to the newly introduced method.
of progressive structural scaling by the use of the thickness ratios from Equations (6) and (14). Useful relations have to be applied to transfer the thickness changes from the rectangle to the airfoil geometry only based on the two given thickness ratios: The spar caps, which are loaded by the flapwise forces (and fit well to the orientation of the horizontal strips from the rectangle), are scaled according to $t_1'/t_1$ by the use of Equation (6). The leading and trailing edge reinforcements, which support the edgewise loads (and fit well to the orientation of the vertical strips from the rectangle), are scaled by $t_2'/t_2$ regarding Equation (14). Furthermore, the shell structures are scaled by $(t_1'/t_1 + t_2'/t_2)/2$, since their orientation and loading is a mixture of the two previously described ones. This procedure of adapting the material thicknesses is subject to some degree of uncertainty, since it is based on a simplified rectangular geometry. Here, more precise relations might be found later on, based on the numerical results.

(3) Supplementary structural scaling: To possess unchanged shear stress in the web panels, the cross-section area of the shear webs should, in theory, be adapted proportionally to the variation in shear force. Therefore, this area is increased in proportion to the flapwise loads, by 50%. In this case, the flapwise loads and the airfoil chords and thicknesses are scaled with the same value (see Equations (1) and (2)), and thus result in an unaltered web panel thicknesses.

Next, the finite element model of the third blade (iii) is generated by an iterative adaptation of the wall thickness. The respective differences in stresses between the progressively scaled blade (ii) and the three-bladed INNWIND 20 MW reference turbine’s blade (i) are compared at continuous positions along the blade span for each structural component (spar caps, shells, reinforcements and shear webs). The relative stress differences are then multiplied by the initially used scaling factors of the progressively scaled blade (ii) at every position. In sum, two iteration loops were necessary, to achieve almost the same stresses as those of the three-bladed reference (i).

Table 1 summarizes the different scaling approaches for the structural blade properties. It is important to keep in mind, that the flapwise load is 50% higher for the two-bladed turbine’s blades during all analyses and that the chord lengths and airfoil thicknesses are increased by $f_c = 1.5$ according to [3, 6, 7, 8].

Table 1. Scaling factors to derive the structural properties of the real airfoil geometry based on the simplified rectangular geometry (see Figure 1).

| blade name               | spar caps | shell structure | reinforcements | shear webs |
|--------------------------|-----------|-----------------|----------------|------------|
| (i) 3B reference blade   | 1         | 1               | 1              | 1          |
| (ii) 2B progressively scaled blade | $t_1'/t_1$ | $(t_1'/t_1 + t_2'/t_2)/2$ | $t_2'/t_2$ | 1          |
| (iii) 2B blade appr. equal stresses | iterated | iterated | iterated | iterated |

To simplify the process of creating three-dimensional finite element models for the three-bladed turbine’s reference blade (i) and the redesigned two-bladed turbine’s blades (ii) and (iii), the tool NuMAD (Numerical Manufacturing And Design) from Sandia National Laboratories has been used. This open-source tool allows the management of all blade information including the airfoils, the materials, the layer thicknesses of the composites, and the material placements [21]. After implementing all necessary data, NuMAD creates a transfer file, which can be imported by ANSYS® Mechanical APDL (Ansys Parametric Design Language). The FE models have been built with quadratic shell-elements (SHELL 281).

To represent a reasonable load situation for the three-bladed turbine’s reference blade (i), loads based on aeroelastic simulations of the DLC 1.2 [22] in the software “Bladed” from...
DNV GL® are adopted. For the calculations, an aeroelastic model of the INNWIND 20 MW reference turbine [15, 16] and a controller derived from [23] are used. To ensure the precision of the aeroelastic model, the calculated flapwise blade root bending moments using six seeds for wind bins of 2 m/s from cut-in to cut-out wind speed, are compared with good agreement to publicly available loads from the INNWIND report [15]. Finally, the maximum loads of the DLC 1.2 are selected and used for the simulations. Note, that in general, the maximum loads of DLC 1.2 are not the turbine’s overall extreme loads. However, the loads from DLC 1.2 have been chosen for traceability.

According to the method of progressive structural scaling (see Section 2), the two-bladed turbine’s blade structures are only valid for ∼50% higher flapwise loads and weight dependent edgewise loads. This approximation has been observed also in dynamic simulations of DLC 1.2 [18]. Nevertheless, the emphasis of this work is on investigating the progressive scaling method. The loads of the two-bladed turbine’s blades (ii) and (iii) are thus simply upscaled and not calculated with aeroelastic load simulations.

In the next step, the calculated loads for all the blades being considered are applied to eight predefined stations along the blade span. They have been chosen in a way to represent the real load distribution as well as possible. In detail, the loads are applied to the spar panels on both the suction and pressure side, using rigid body elements (RBE3) to prevent singularities. In general, RBE3 elements could be used for a consistent application of forces and masses. They distribute the loads – here single forces in the flapwise direction – from a reference point to a set of selected nodes on the spar caps [24]. The edgewise loads depend, in accordance with the theory, on the blade’s self-weight, induced by the gravity. For this reason, the FE models will also be simulated using gravity, with blades in horizontal positions and leading edge upward. The analyses performed contain linear calculations for material strength, deflection, and buckling, based on the applied loads. The corresponding results are presented in Section 4. Bear in mind that this simplified approach is a starting point to investigate the structural influences of redesigning a three-bladed turbine into a two-bladed one. An all-embracing blade design and analysis of the structure is much more complex and might be part of later studies on that topic.

To examine the analytically calculated mass reduction, the stresses of the three-bladed turbine’s reference blade (i) are compared to the two different two-bladed turbine blade designs (ii) and (iii). In this process, all different blade parts along the blade, in detail the spar caps, the shell structures, the shear webs, and the leading and trailing edge reinforcements (see Figure 2), have been evaluated. The stresses were examined at the same relative positions on all the blades under consideration. The maximum nodal stresses at the selected positions were compared. They were chosen in such a way that modeling uncertainties do not effect the results. Therefore, the examination positions are located neither, e.g., at the load application nor at the locations of material changes.

4. Results
The newly presented analytical method of progressive structural scaling predicts a mass of the two-bladed turbine’s blade (ii) of 90.9 t. Comparing this blade mass to that of the available three-bladed 20 MW INNWIND turbine’s data of 117.6 t per blade reveals a mass reduction of 22.8% per blade and 48.6% for the complete rotor. Note, that a two-bladed turbine with an equal absolute power curve needs a ∼2% larger rotor to counterbalance aerodynamic losses, which again increases the necessary blade material by ∼8% [8]. Increasing the rated tip speed results in fewer mass savings, according to the analytical scaling method.

In the next step, these analytical results can now be compared with the outcomes of the FEAs. Figure 3 shows the static stress comparison results of the numerical simulations. As examples, four different blade parts are shown, namely the spar caps at both the suction and the pressure side, as well as the front shell at the suction side and the front shear web (see Figure 2).
Figure 3. Maximum principal stresses along blade span at different positions: (a) spar cap at suction side, (b) front shell at suction side, (c) spar cap at pressure side, and (d) front shear web.

The red lines (see Figure 3) represent the stress distribution at the different blade positions for the reference blade of the three-bladed turbine (i). They are the baselines for comparisons of the different structural scaling approaches of the two-bladed turbine’s blade (see Table 1). The overall weight calculated from the FE model is 106.8 t, which is 11 t lighter compared to the available INNWIND data (117.8 t), which is reasonable due to missing non-structural masses like e.g. additional resin, adhesive, and coating. Assuming that the non-structural masses are scaled linearly to the blade geometry, a blade that was scaled according to the newly introduced method of progressive structural scaling should result in a mass of approximately 82.4 t.

The black lines (see Figure 3) depict the progressively scaled two-bladed turbine’s blade (ii). Such a design (see Table 1) results in an overall weight of 104.8 t, which is \(\sim 27.2\%\) higher than expected (82.4 t), but still results in rotor mass savings of \(\sim 33\%\). A possible explanation is the lack of precision due to the simplifications of converting the rectangular structure into the complex airfoil shape, as explained in Section 3. However, the main objective of the method of progressive structural scaling is to achieve equal material stresses of the compared structures. In this context, the spar caps at both, suction and pressure side, are mostly under-loaded. The average deviation to the reference blade (see Figure 3, red lines) is at both sides
approximately 10%. Also, the shell structure is continuously under-loaded over the whole blade length, e.g. at the front shell at the suction side by \(~17\%\) on average. In contrast, the shear web structures are continuously over-loaded along the blade length. The front shear web shown here possesses on average approximately 35\% increased stresses (see Figure 3 (d)), where the stress peaks occur due to the load application. The corresponding RBE3 elements are located at the spar caps exactly at these blade positions. Overall, this first scaling approach presents, for the purpose of this study, a good agreement with the three-bladed turbine’s reference blade (i) (see Figure 3, red lines).

Finally, the third blade, which has approximately equal stresses (iii), is illustrated by the green lines (see Figure 3). The design results in an overall weight of 104.8 t, which is again almost equal to the weight of the reference blade (see Figure 3, red lines) and leads again to rotor mass savings of \(~33\%\). This outcome agrees with the results found by [3]. The stress distribution of the spar caps on both the suction and the pressure side, is nearly the same, with an average deviation of \(~2\%\) for both sides. Also, the stresses at the shell structure match that of the reference blade (i) (see Figure 3 (b)) even better. They are still mostly under-loaded by, e.g. \(~6\%\) on average in case of the front shell shown. Furthermore, the stresses at the webs are slightly increased by \(~8\%\) on average (see Figure 3 (d)). Note, that this is the result of only two iteration loops. More iteration loops would fit the reference stresses even better.

To take the study further, the maximum tip deflections and the results of the buckling analyses of the different scaling approaches (see Table 1) are compared to the three-bladed turbine’s reference blade (i). In fact, both two-bladed turbines (ii) and (iii) have less maximum tip deflections. These outcomes are caused by the over-proportionally higher blade stiffnesses of the two-bladed turbine’s blades (ii) and (iii), due to the rapidly growing second moment of area when increasing chord lengths and blade thicknesses. This effect might benefit the flutter behavior of the blades, since generally flutter speeds are increased together with the blade stiffness [25]. Table 2 sum up the deflections.

Table 2. Maximum tip deflections and results of the buckling analyses with 50\% higher flapwise loads for both two-bladed turbines (ii) and (iii) compared to the three-bladed reference (i).

| blade name               | blade weight | max. tip deflection | buckling load factor | buckling position              |
|-------------------------|--------------|---------------------|----------------------|--------------------------------|
| (i) 3B reference blade  | 106.8 t      | 17.21 m             | 1.16                 | 23.1% (spar cap suct. side)    |
| (ii) 2B progressively scaled blade | 104.8 t | 10.07 m | 0.34 | 20.7% (reinforce. lead. edge) |
| (iii) 2B blade appr. equal stresses | 104.8 t | 11.23 m | 0.23 | 22.5% (rear shell suct. side) |

To ensure a comparable blade stability for the scaled blades, the two-bladed turbine’s blades should possess an equal or even higher buckling resistance compared to the three-bladed turbine’s reference blade. The results of the examination are also summarized in Table 2. The critical load factors of the first buckling mode shapes, as well as the corresponding buckling positions (blade lengths) and blade parts, are shown. Interestingly, both considered two-bladed designs, show severe buckling characteristics, compared to the three-bladed reference (i), due to the thinner wall thicknesses (see Table 1). The different buckling positions are in good agreement with the change in the wall thicknesses. The critical load factor is the lowest for the iterated blade with approximately equal stresses (iii), whose first buckling shape is shown in Figure 4 (b) compared to the three-bladed turbine’s reference buckling shape (see Figure 4 (a)). As a consequence, the structural properties of the two-bladed turbine’s blade and thus the corresponding blade mass need to be readjusted to ensure buckling stability. This does not automatically mean that the overall blade weight will increase significantly. However, a corresponding buckling optimization of the blade structures is out of scope for the present work.
Figure 4. Results of the buckling analyses of (a) the three-bladed turbine’s reference blade (i), and (b) the two-bladed turbine’s blade with approximately equal stresses (iii).

5. Conclusions and outlook

The introduced analytical method of progressive structural scaling predicts a significant mass reduction when redesigning the structural properties of a three-bladed turbine’s blade into a two-bladed one. For the redesigned blade of the INNWIND 20 MW reference turbine, which was considered in this work, the analytically calculated mass saving is 22.8% per blade. The corresponding examinations utilizing finite element analyses result in approximately an equal blade weight for the two-bladed turbine’s blade compared to the three-bladed reference, which accounts for an overall rotor mass reduction of 33%. At the same time, there is good agreement when comparing the stresses to the reference blade. The few differences occur due to some limitations of the analytical method, which approximates the continuous changing airfoil shape with a constant thin-walled rectangular cross-section shape. For that reason, the blade was improved afterwards to almost equal stresses, iteratively. It was shown that such a blade is able to withstand ~50% higher flapwise loads retaining equal material stresses, while it will not become heavier compared to the reference. Comparing the blade stiffnesses, both two-bladed turbines revealed a reduction of the blade deflection by ~40%, while being exposed to these increased (flapwise) loadings. In addition, buckling issues were examined. The buckling analyses performed reveal stability problems. Therefore a readjustment of the structural properties is necessary. In the course of this, one possibility is to adapt the layer structure by e.g. thicker core material, or to equip the blade structure with additional stiffeners, e.g. ribs or another shear web. Whether the overall blade mass after a readjustment is still below that of the three-bladed turbine’s reference blade or not, cannot currently be answered and has to be addressed in further investigations. On the other hand, maintaining the same chord length and increasing the tip speed ratio when redesigning a three-bladed turbine into a two-bladed one while retaining the same turbine concept (upwind, variable-speed, fixed hub), directly leads to a higher blade weight [8, 9]. In contrast, a change in turbine concept (e.g. downwind) could still lead to mass savings for faster rotating two-bladed turbines [11, 12]. In summary, increasing the chord lengths theoretically leads to a lighter blade, but due to buckling issues, additional mass needs to be added subsequently. Thus, a challenging task for future research on this topic would be to find a good compromise between saving rotor mass and preventing buckling. If this is achieved, two-bladed turbines could be a solution to enable even larger rotors, which are increasingly limited by blade stiffness and gravitational issues.
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