Influence of cracks on the buckling of wind turbine towers

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Abstract. The collapse of a wind turbine can be caused by the buckling of the tower when it is subjected to a critical load. This load is related, for instance, to a strong storm or a blade impact on the tower. Buckling occurs when the elastic limit is reached in part of the tower. Plasticity leads to bending with large rotations and large displacements. Structures are designed to avoid this phenomenon. However, a wind turbine is subjected during its entire service life to operation loads which cause fatigue of the structure. This results in the initiation of cracks and their propagation in the tower. These cracks can reduce the tower strength and it is, thus, interesting to study how the presence of such damage can affect the resistance of a wind turbine tower to the buckling. The influence of different parameters, such as position and length of the crack, is analyzed. Finally, the critical buckling load is related to wind site condition by considering an aero-elastic modeling of the wind turbine.

1. Introduction
When a wind turbine (WT) collapses, observations on the ground show that the tower bends around a hinge point associated with a buckling phenomenon. Figure 1 shows a tower fallen in Germany in 2017. One can clearly see the the pivot point at the lower part of the tower.

Figure 1. Wind turbine collapse in Germany on 2017.

This phenomenon is linked to an instability in the tower response. Indeed the geometry of a WT tower is that of a thin cylindrical hull which may be affected by this kind of instability. Buckling occurs when the elastic limit of the material is reached in part of the tower, involving...
plasticity [2, 3]. It leads to bending with large rotations and displacements. In the design phase, extreme events [1] (strong storm, rotor overspeed, blade impact, etc.) and the related critical loads are taken into account in order to avoid collapse. However, the design phase is concerned by a set of uncertainties. The tower of WT is made from slender, tubular, tapered steel sections. Such sections are manufactured and jointed into “cans” using conventional “can-welding” methods. Several cans are then welded circumferentially into larger sections, and flanges are attached to each end. This process is a source of uncertainties for the fatigue design. This design ensures that the nucleation of any cracks does not occur during the first 20 years. However, several defects may be generated during the manufacturing process, especially during the welding. These defects accelerate the crack nucleation. Crack propagation is then possible under the cyclic load due to wind-structure interactions\(^1\). In order to avoid tower collapse, it is necessary to analyse the residual strength of the WT tower when a crack has reached a given size. Even if one considers that no defects derive from the manufacturing process, the fatigue design is ensured for the first 20 years of operations. After that period, if an extension of the operation of the wind farm is considered, one should assess the residual strength and the stability of the towers. Some non-destructive tests are necessary in order to detect defects in the structure. The question then becomes whether the presence of a defect in the tower, such as a fatigue-induced crack, can affect the buckling resistance of the tower. The buckling of WT towers has already been simulated by Kaoshan et al. \([4]\) showing that the plasticity in the model is necessary to properly estimate the critical buckling load. They also show that, a misalignment between the wind direction and the WT rotor axis leads to higher loads than aligned winds. Guo et al. \([5]\) and Dimo et al. \([6]\) have also analyzed the buckling of towers. They take into account bending loads but they do not address the issue of the presence of a crack.

In this work a numerical model is set up to reproduce the buckling of a WT tower and calculate the critical load associated with collapse. Simulations are performed with an elasto-plastic constitutive law with linear hardening, large deformations and rotations and control of the loading by elastic prediction. Afterwards, a crack traversing the tower plate thickness is introduced into the initial mesh to compare the behavior of a healthy tower and a damaged tower. It is represented as a surface of discontinuity in the mesh. Frictionless contact is taken into account in order to treat the crack in compression zone of the tower. The influence of different parameters such as length and position of crack is analyses. A relationship between the critical buckling load and wind site conditions is established by considering an aero-elastic model of the same WT. This leads to some conclusions about critical conditions for the WT operation.

2. Wind turbine model

As test case, the NREL 5MW \([7]\) is considered. It is representative of an offshore WT. However, in this work it has been considered bottom-fixed as an onshore WT. To simplify the geometry, the tower is considered to be a truncated cone. The thickness varies linearly from the base to the top. The Rotor Nacelle Assembly (RNA) is considered as a simple mass point in order to simplify the model. This geometry does not take into account the effects related to welds and thickness steps between two parts of the tower. This is a limit of the model since joints, welds and thickness discontinuities can be seen as defects affecting the buckling, reducing the real critical load. Hence, the critical load given by this work is over estimated by the model simplifications. However, it is still useful to understand the influence of the crack and to have the order of magnitude of the critical load. The geometric and material specification of the

\(^1\) the rotor of WT generates loads that are cyclic for several reasons: (i) the passage of a blade in front of the tower generates a sudden perturbation of the flow around the blade (3P frequency). Then, the turbulence of the inflow wind has a spectral multi-frequency content. Also a misalignment of the inflow wind with the rotor axis may generates a cyclic load.
model of the tower are reported in Table 1. Those are the properties of a steel S355 with a density slightly higher than the original document in order to take into account the weight of neglected elements, as bolts. In [7], elastic limit is not provided, it is chosen according to the knowledge of the material. A plasticity behavior is chosen with linear isotropic hardening with an elastic threshold.

Table 1. Model parameters.

| Parameter                                      | Value                      |
|------------------------------------------------|----------------------------|
| Size of tower                                  | 87.6 m                     |
| Diameter: from base to top (linear variation)  | 6 – 3.87 m                 |
| Thickness: from base to top (linear variation) | 19 – 27 mm                 |
| Young’s modulus                               | 210 GPa                    |
| Poisson’s modulus                             | 0.3                        |
| Elastic limit                                  | 355 MPa                    |
| Hardening tangent modulus                      | 8.4 GPa                    |
| Density                                        | 8500 kg/m                  |
| Nacelle mass (in COG)                          | 297 tons                   |
| Nacelle COG coordinates from tower axis        | −0.579, 0.0, 87.6 m        |

Figure 2. The scheme of the model.

The thrust force of the RNA is modeled by a transverse force applied to the top of the tower. Figure 2 depicts the scheme of the model. The distributed drag pressure over the tower is neglected in order to simplify the analysis and the conclusions in terms of critical loads. However, it is to be noted that this drag pressure is an important contribution for high wind speed\(^2\). The self-weight of the tower is considered as a distributed load and the weight of the RNA is applied to the top of the tower.

3. Buckling of tower without crack

For the numerical model, the environment chosen is the EDF R&D Finite Element Modeling (FEM) open-source code: *Code_Aster*. First, a study for the mesh of the model is performed. The choice is for 3D elements hexahedrons with 20 nodes to better represent the gradients in the thickness. Sub integrated elements are considered in order to avoid numerical locking related to the non compressible behavior of the plasticity. A refinement in the direction of the tower axis is

\(^2\) Typically, for over-rated wind speeds, this contribution is not negligible with respect to the RNA thrust.
considered where the buckling occurs since the gradients are stronger when instability is attained. The maximum edge length of an element in this zone is 10 cm. Since the problem is symmetric, only half of the tower is meshed with normal displacement blocked for degrees of freedom in the symmetry plane. The analysis is of pushover type: the tower undergoes a constant vertical loading and a variable $F_{RNA}$ up to the post-buckling regime. In order to properly reproduce the phenomenon, two main ingredients are mandatory: (i) large deformations and rotations, (ii) plasticity. However, a numerical strategy is necessary for the solver to converge. In fact, buckling is an instability of the structure. At the instability point (critical point), the problem to solve is singular. Hence, infinite solutions are possible. For the numerical solver this is a problem for the convergence. In order for Newton’s algorithm to converge, it is necessary to decompose the problem in several stages of loading, as a quasi-static process. At each step, the transverse force applied to the tower increases. This makes the resolution of a strongly nonlinear problem become the resolution of series of problems with weak nonlinearity. However, Newton’s algorithm is unable to find a solution if the response of the tower isn’t monotonic in loading and displacement. The buckling of the tower causes a loss of rigidity which leads to a snapback, that is to say a non-monotonic response of the loading-displacement function. It is therefore necessary to complete Newton’s algorithm with a ”piloting” method. This technique enables the algorithm to converge. It is, thus, possible to observe the post-critical behavior of the buckling tower. A piloting method consists in setting up an inverse problem. In this problem, the amplitude of a part of the external forces is incremented under a given condition $\Delta \tau$. In this case, this part of the forces is the RNA thrust, $F_{RNA}$. The rest of the external forces, $W_{RNA}$, remains constant. This amplitude, $\eta$, is a new variable of the problem:

$$F = F^{inpo} + \eta F^{pilo} = W_{RNA} + \eta F_{RNA}. \quad (1)$$

In Code_Aster, different type of piloting methods are implemented. For behavior laws that involve an evolving threshold, the most adapted is the one called ”by elastic prediction”. This method imposes that at each time step of the quasi static scheme there is at least one integration point deviating from the threshold function of the elastic domain by a given quantity $\Delta \tau$. For the plasticity with linear isotropic hardening, the threshold function at time step $n$ is:

$$f(\sigma_n, p_n) = \sigma_n^{eq} - R(p_n) \leq 0. \quad (2)$$

This is a function of the cumulative plastic strain $p_n$ and stress tensor $\sigma_n$ at step $n$. $R(p_n)$ is the current elastic threshold for a simple tensile test and $\sigma_n^{eq}$ is the equivalent stress level as defined by a criterion, such as Von Mises in the present case. To write the piloting condition at time step $n+1$, one writes for the elastic prediction:

$$\max f^{elas}(\sigma_n) = \Delta \tau. \quad (3)$$

By coupling equation 1 with this latter, the solver is able to solve equation 1 for eta. The solver follows a direction ensuring the increase of the cumulative plastic strain at each time step. For further details, the reader is referred to [8].

Figures 3 shows the force-displacement evolution at the tower top. For each of those regimes, the related displacement of the tower is reported in figure 4. The displacement is magnified ×1.5. The colors highlights the cumulative plastic strain.

Different regimes can be recognised:

- regime A: elastic-plastic behavior. The hardening of the structure is not really evident. The behaviour of the structure is quasi-fragile although the constitutive material law is of the considered steel is soft. This is a geometric effect.

- regime B: critical point. In the zone of maximum cumulative plastic strain (25m from the bottom), a pattern of wavelets appears. Those are the buckling modes. They increase the cumulative plastic strain in that zone. This is the point of instability of the WT tower. For industrial purposes, the check of this point is sufficient to assess the tower strength. The measure of this strength is the load associated to the critical point.
regime C: Snap-back. The tower shows a large loss of stiffness. The solver needs to decrease massively the force in order to find a unique solution and follow the large rotation of the tower. The tower skin warps.

regime D: Post buckling regime. The decrease of stiffness continues. The tower shows an increasing displacement at the tower top while the load is almost constant. The structure is collapsing and the local warping progresses. Geometric effects give a residual strength to the structure during the falling.

Figure 3. External force versus displacement at tower top.

Figure 4. Displacement of the tower (magnified ×1.5). Zoom zone focus around 25 meters and the colors are related to the cumulative plastic strain.

Figure 5. Example of wind turbine tower failing by buckling.

The shape of the tower in the buckling zone is typical of the post-mortem observation on buckled WT. In [9], the example of WT tower failing by buckling is given. It is reported in figure 5. The alternative pattern of the distortion is inclined at 45 degrees. The inclination of this pattern is led by the direction of the maximum shear stress. In fact, shear initiates the slip planes related to the dislocations. Those are at the origin of the plasticity.

4. Influence of a crack on the critical buckling load

The influence of the presence of a crack in the model is analyzed. A parametric study is performed considering a set of cracks varying in size and position. For the sake of simplicity,
all cracks are considered traversing the thickness. A crack is introduced into the mesh thanks to Z-cracks software. Details about the algorithms implemented in Z-cracks can be found in [10]. The crack is considered as a surface, boundary of the discrete domain. It is located in the plane of symmetry defined by the force vector at tower top and the tower longitudinal axis. The problem is still symmetric and, hence, only half of the tower is considered. Figure 6 shows the mesh of the tower with and without the crack. Let note the refinement around the crack. Figure 7 shows a zoom of the mesh describing the crack. On the right a cut of the mesh highlights the crack front.

![Figure 6](image1.png)

**Figure 6.** The tower mesh. Without crack on the left, with a crack on the right.

![Figure 7](image2.png)

**Figure 7.** Zoom around the mesh of the crack. On the right, it is possible to remark the front of the crack. It is to be noted that, for the some buckling simulations this level of refinement for the crack front is not necessary.

Figure 8 shows how the presence of a crack at 24 meters localizes the stress in the zone around the crack. Figure 9 compares the cumulative plastic strain for the tower with and without the crack at 24 meters for the same load. The cumulative plastic strain is increased by the presence of the crack. It reaches a maximum at 24 meters instead of 25 meters for a tower without cracks.

Crack influence is analyzed for a crack located in the tension (upwind) and in the compression zone (downwind) of the tower. For this latter, a contact condition is added to the finite element model. Friction is not considered in the contact. This is a conservative assumption because friction would dissipate some of the energy. For the numerical solver, the contact is a penalization condition \( \epsilon^n \) to the normal penetration \( g^n \) of the two sides of the crack. The normal force, \( F \), given by the contact is then:

\[
\begin{align*}
F &= 0 \quad \text{if } g^n \leq 0 \\
F &= \epsilon^n \quad \text{if } g^n > 0
\end{align*}
\]  

(2)

Figure 10 shows how a crack located in the compression zone of the tower has much more influence than a crack located in the tensile zone. For this latter the influence is really weak. The explanation of this result can be deduced looking at figure 11. In this figure, the influence of a crack on the critical buckling load is investigated moving the crack at different elevations in the tower. The crack has a remarkable influence when the crack is in the zone of the maximum stress and maximum plastic strain. Comparing this image with figure 9, one could notice that this is the zone where the wavelets of the buckling modes appear and the cumulative plastic strain is maximum. Finally, it can be concluded that the influence of the crack on buckling takes place when the crack interacts with the buckling modes.
Figure 8. Stress distribution in the tower when the wavelets appears. On left without the crack, on the right with a crack at 24 meters. The maximum stress elevation is led by the crack position.

Figure 9. The cumulative plastic strain. Comparison between a tower without crack and one with a crack at 24 meters. The presence of the crack amplifies the plastic strain.

Figure 10. Influence of a crack on the critical buckling load when located in the tearing side (upwind) compared with the one in the compression side (downwind).

Figure 11. Influence of a crack on the critical buckling load for different elevations in the tower.

5. Correlation with environmental conditions: the aero-elastic model

For the same WT, an aero-elastic model is considered. The goal is to evaluate the load flowing from RNA to the tower top. This enables one to correlate the analysis described in the previous sections to environmental conditions on wind farms. The aerodynamic loads are evaluated by discretizing each blade in many sections. For each section of a blade one knows the angle of attack of the section, $\alpha$, with respect the wind vector. Pitch and twist of each section are taken
into account as the angles between the chord of the section and the plane of the rotor disk. Once the angle $\alpha$ is known, the lift and drag forces are evaluated by considering the airfoils polar curves of each section of each blade. For the considered WT, the polar curves are given in [7]. Those forces are integrated and projected on the rotor disk, giving the thrust force and a lateral force on the tower. Let note that the process is simplified by the assumption that the rotor is in the blocked position. For rotating rotors, a more complex method is necessary to obtain the right wind speed magnitude and direction with respect to each section of the blade. The wind energy industry traditionally considers the Blade Element Momentum Theory (BEMT) to estimate the aerodynamic forces on the blades. At EDF R&D, this is done by an in-house full aero-hydro-servo-elastic solver, DIEGO. In DIEGO, the fluid-structure interaction is ensured at each time step by projecting the aerodynamic loads on a structural model at the scale of the entire WT. In DIEGO, as the standard nowadays, the BEMT is corrected to take into account the unsteady flow effects (Pitt and Peters model adapted to the acceleration potential method) and a stall delay model (Beddoes-Leishman model) to take into account 3D effects on the blades. The effect of the structural dynamics on the aerodynamics is also taken into account (strong coupling). The dynamics of the structures is solved by a Newmark’s time integration scheme. This ensures dynamic effects related to the RNA and tower masses are taken into account. Blades and tower are modeled as beams finite elements.

A picture of the NREL 5MW WT model in DIEGO is given in figure 12 and 13. Figure 12 shows the structural finite element mesh made of beam elements. Figure 13 presents the aerodynamic sections composing the blade superposed to the structural finite element mesh. For this analysis, the WT is considered not operating and blocked facing the wind. This is the case when storms strike a wind farm with winds stronger than about 25 m/s.

The following scenario is investigated: the wind is initially considered flowing at 30 m/s. The wind is constant, turbulence is not considered. The pitch of the blades is set to 90 degrees. It means that the leading edge of the blade is upwind to minimize drag and lift. This is ensured by the fact that the angle of attack of the blade elements is close to $\alpha_{0,\text{lift}}$, the alpha which minimizes the lift force of the airfoil. 100 seconds after the beginning of the simulation, the wind suddenly changes direction (in 1.0 seconds) and increases the magnitude up to 80 m/s.

Different misalignments are considered. For each of them, the internal forces of the structural model are considered at tower top. The internal forces incorporate the dynamic effects of the structures. In fact, the acceleration produced by the gust makes the RNA mass produce a big...

Figure 12. Aero-elastic model of the NREL 5MW in DIEGO. The structural mesh made by beam elements.

Figure 13. Aero-elastic model of the NREL 5MW in DIEGO. The aero-dynamic mesh is made by discrete elements. Each of them is related to an airfoil with its polar curves.
inertial force on the tower. Figure 14 shows the lateral wind acting on the WT. The bending of the blades can be appreciate (there is not magnification in this figure). Figure 15 reports the norm of the transverse components of the internal forces at tower top. This force increases when the wind shows a misalignment with respect to the rotor axis. In fact, the angle of attack of each blade section moves from the \( \alpha_0, \text{lift} \). Hence, lift and drag increase. In the same figure, the critical buckling load of this tower is reported. The critical buckling load affected by a crack is also presented. Without lack of generality, this is considered to be 8% less than the normal critical buckling load. For the considered gust, when the misalignment reaches 30 degrees, the presence of a crack leads to the buckling. When the misalignment reaches 50 degrees, even a healthy tower buckles.

It is interesting to remark that, the norm\(^4\) recommends to verify the tower strength for the 1–year storm with 20 degrees of misalignment and for the 50–years storm with 8 degrees of misalignment. It can be deduced that: during a strong storm, the design of the tower does not ensure the tower strength, whenever the RNA of the WT is misaligned with respect the wind direction more than 20 degrees.

Normally the RNA is aligned in the wind. However, in some zone where the storms are related to typhoons, the wind can have a rotating behavior. Equivalently, if a problem in the yaw actuator system occurs, the RNA is not able to align with the wind.

6. Conclusions
In this document, the collapse of a WT has been analyzed reproducing the buckling of the tower. This has been produced by a pushover scheme. In order to explain the methodology, the NREL 5MW has been considered. This WT has been modeled in Code\_Aster by considering an elasto-plastic material behavior with linear isotropic hardening and large deformations and rotations. The WT has been charged with a transverse force at tower top. The weight of the structure and the RNA have also been taken into account. The convergence of the numerical scheme has been obtained by a quasi-static process. For each time step a Newton’s linearization technique has

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\(^4\) IEC 61400-1 (2005), Wind Turbines design requirements.
been considered. The increment of the load for each new time step was the result of an inverse problem (the piloting process). The buckling zone is the one of maximum stress and maximum cumulative plastic strain. When the critical force is attained, the buckling modes appear in the deformation as local wavelets. The snapback has been reproduced and the post-buckling regime also. In this regime, the typical pattern of the warped cylinder has been reproduced.

In the second part of the article, the influence of the presence of a transversing crack on the critical buckling load is analyzed. It has been found that the crack is more affecting when it is on the compressive side of the tower (downwind) than the tensile side (upwind). The crack, when located in the buckling zone, tends to localize the plastic strain and, hence, the buckling phenomenon. A reduction of the critical load in the order of 8% has been observed when the size of the crack reaches 30 – 40 cm. For the considered WT, an aero-elastic model has been built using DIEGO. This aero-elastic model has shown that when the misalignment between the rotor axis and the wind direction reaches 50 degrees, a strong gust can lead to the tower collapse. If the tower presents a crack in the zone of maximum stress, 30 degrees are already critical. Those results are not in line with the recommendations of the norm for which 20 degrees is the maximum misalignment to be verified in case of the 1--year storm.

The considered model implies a list of hypotheses and limitations:

- The distributed drag pressure acting on the tower is not considered. This makes the critical force estimated at tower top higher than a model considering this pressure.
- The model does not consider thickness discontinuities in the tower, welds and bolted connections. This makes the critical force at tower top higher than a model considering those material and geometrical details.
- The considered environmental scenario is hypothesized. 80 m/s is a strong gust and the sudden change in magnitude and direction for the wind is an improbable scenario. The choice of this scenario is led by a pedagogic purpose in order to highlight that a lateral gust drastically increases the load of the tower. Even if this scenario is unlikely, some unexpected situations (e.g. yam system fail) can increase the misalignment between rotor axis and wind direction over the value prescribed by norms. It leads to reduce the margin considered by the wind turbine tower designer and, eventually, to tower collapse.

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