# SHIP COLLISION ON OFFSHORE WIND TURBINES

by


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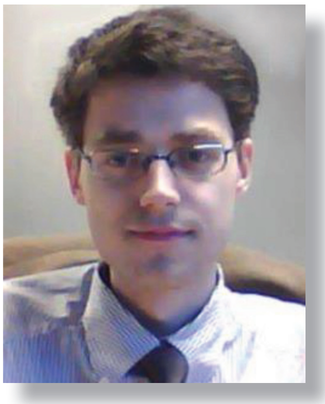
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## MOTS-CLES:

collision de navire, monopieu, fondation de type jacket, simulation numérique, approche analytique

## 1 INTRODUCTION

Every year, the worldwide electricity consumption tends to increase. The concern over global warming and environmental pollution has brought into attention the possibility of using alternative resources such as wind power.

Europe is the world leader in the offshore wind energy sector. From the installation of the first Offshore Wind Turbine (OWT) in Denmark in 1991 until now, the offshore wind energy sector has developed increasingly. In 2015 [1], 82 wind farms were fully grid connected in European waters with a total number of 3,072 offshore wind turbines and a combined capacity of 10,393.6 MW.

As the offshore wind energy sector is developing, offshore wind farms will cover large areas and will be located in deeper waters and also in the vicinity of traffic lanes. Therefore, ship collision represents a major concern.

During the lifetime of an offshore wind farm collision events may occur with Offshore Supply Vessels (OSV) during the inspection and maintenance process, but also with commercial and passenger ships coming from the traffic lanes. The main factors contributing to collision events are [2]:

- Human error: the direction of the ship is towards the wind farm and is maintained until the ship collides an OWT, without taking any measures to prevent the collision.
- Machinery breakdown.
    - Steering failure: in this case the rudder is blocked and the ship will navigate in circles with a radius which depends on the position of the rudder at the moment when it was blocked and on the underkeel clearance.
    - Failure of propulsion: when the propulsion system fails, the ship will start drifting. The drift direction is influenced by the current and wind direction. If a drifting ship moves toward a wind turbine a collision event may occur.
- Weather conditions: in case of fog or rough water, the visibility can be drastically reduced and a collision event may occur.

The consequences of collision events may include structural damage of the OWT or/and the striking ship, environmental damage and loss of human life.

Based on the principle of energy conservation the structural damage can be analysed. The formula for the total collision energy is:

$$E = \frac{1}{2} \cdot a \cdot m \cdot v_{ship}^2 \quad (1)$$

where $E$ is the total collision energy (J), $a$ is the added mass coefficient ($a$ = 1.1 for head-on collision and $a$ = 1.4 for sideway collision) [3],

$m$ is the ship displacement (kg) and $v_{ship}$ is the impact velocity (m/s).

Depending on the conditions which led to collision, but also on the occurred consequences, collision events can be divided in three categories [4]:

- Operational: impact occurred during normal operations such as loading and unloading
- Accidental: impact due to drifting of vessels up to the size of an OSV with a velocity of 2 m/s
- Catastrophic: major impacts with commercial and passenger ships coming from the traffic lanes

Some protective measures for OWT against ship collision can be taken by installing crashworthy shields or adaptive inflatable structures. Two studies are presented in [5] and [6] and the results obtained are promising.

For any new offshore wind farms, a collision risk analysis becomes mandatory in the pre-design stage of the project. In this phase, a large number of collision scenarios must be investigated in order to highlight the most unfavourable ones. Currently, this aspect is investigated by performing numerical simulations using finite elements method (FEM). This method gives accurate results, however is not suitable in the pre-design stage due to the long calculation time required. Therefore, an alternative and complementary method to rapidly assess the structural consequences of collision events is needed.

## 2 STRUCTURAL BEHAVIOUR

### 2.1 Effect of Ship Rigidity

When a collision event occurs, both the striking ship and the collided structure can be damaged. The deformation of the OWT and the ship can be estimated by using the curves from NORSOK N-004 [7] which are presented in Figure 1:

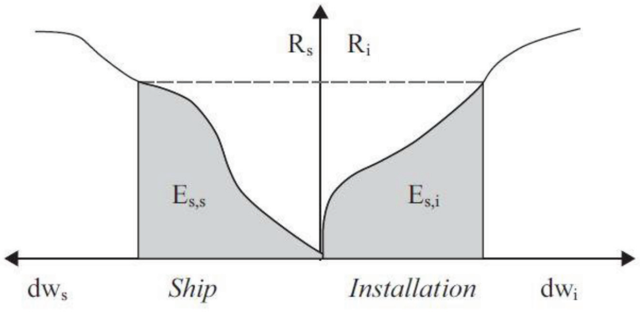

*Figure 1: Dissipation of strain energy in ship and platform [7]*

The areas under the load-deformation curves represent the energy dissipated through deformations occurred to the striking ship and the OWT.

Finite element simulation of ship collision on offshore jackets highlighted the effect of ship rigidity [8] and showed that energy absorption rate may vary significantly according to the type of colliding ship. For example, an OSV can dissipate around 80 % of the total energy whereas a bulk carrier is much more rigid and dissipates only around 20 % of the energy. The above mentioned values show that ship rigidity has to be considered when considering ship impact on offshore structures.

However, in order to highlight the behaviour and to make conservative assumption with regard to the OWT in case of collision events, numerical simulations have been performed for an OWT with monopile [9] and jacket [8] support systems collided by a rigid ship.

The results obtained for both kind of structures are discussed in the two next sections.

### 2.2 Monopile

In the study performed by A. Bela et al. [9], the behaviour of the OWT with a monopile support system when subjected to ship collision was investigated by means of nonlinear FEM simulations. The goal of the paper was to better understand the collision mechanism and the influence on the behaviour of the structure of a series of parameters such as impact velocity, nacelle mass, wind loads, soil stiffness, etc.

When the ship collides the OWT, only local deformations occur in the contact area during the first phase. The local deformations will increase up to a certain value when deformations will occur to the entire structure. Two deformation modes were highlighted: local crushing and global deformation.

The study showed that for the monopile, the most influential parameters are the impact velocity, wind loads and the soil stiffness.

A slight variation of the impact velocity value can lead from minor structural damage to collapse of the structure, as illustrated in Figure 2:

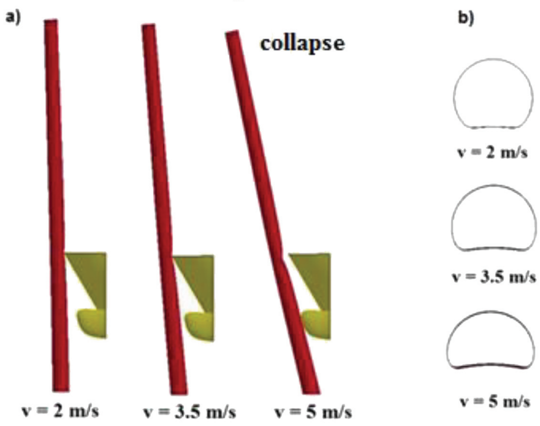

*Figure 2: Influence of the impact velocity (a – deformed shape of the structure; b – crushed area indentation) [9]*

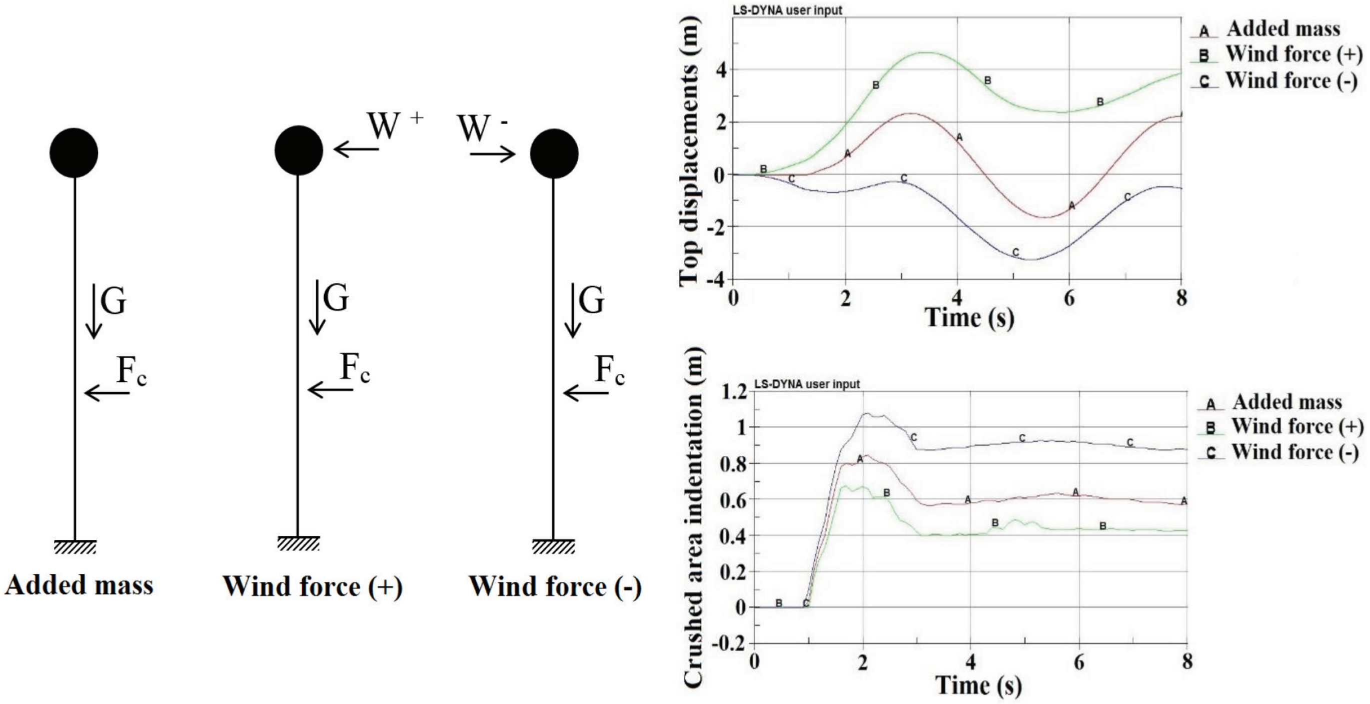

*Figure 3: Influence of the wind loads (a – case description; b – local indentation; c – top displacements) [9]*

The study of the influence of the wind loads on the behaviour of the structure showed that the wind direction with respect to the impact direction influences both the local indentation of the crushed area and the top displacements of the OWT (Figure 3).

Numerical simulations showed that monopile foundations are highly sensitive to soil stiffness. During collision, the base of the collided structure tends to rotate and the soil will undergo some deformations. Considering the structure as being clamped at the base leads to an overestimation of the internal energy.

### 2.3 Jackets

The jacket behaviour when submitted to ship collision was widely investigated by Le Sourne et al. [8]. The purpose of this paper was to identify the main determining parameters of the collision and the deformation modes.

Considering a rigid colliding ship and a given structure, the most influencing parameters are the impact point locations and the shape of the ship. Indeed, collision on a leg or on braces will give completely different results, as braces are much more flexible than legs. The shape of the colliding ship will affect the deformation pattern of the structure.

However, for the jacket foundation it was proved by Le Sourne et al. [8] that considering the soil stiffness instead of clamped boundaries at the bottom of each leg does not influence the behaviour of the structure. It can so be assumed that the jacket is fully clamped to the ground.

The effect of the tower and the weight of the OWT, (including nacelle, tower and jacket) does not affect the crushing behaviour of the jacket during the collision. The weight and the dynamic effect can therefore be neglected when developing the analytical method.

Numerical simulations allowed to identify the main deformation modes and are shown to be:

1. Deformation of the whole structure
2. Crushing of the impacted cylinder(s)
3. Punching of legs by compressed braces
4. Buckling of rear compressed legs

The repartition of energy dissipation may vary significantly according to the location of the impact point. For example, in case of an impact between two nodes of a leg, a large amount of energy will be dissipated by the second deformation mode. If the collision point is a node of a leg, the part of energy dissipated in the second mode will be decreased and distributed to the three other modes.

## 3 ANALYTICAL METHODS

### 3.1 Generals

The purpose of analytical methods is to evaluate the behaviour of a structure when submitted to load cases for which the analytical formulations are specifically developed. They account for nonlinear behaviour, geometrical as well as material, and can be used for any kind of structures. In order to be applied, this so-called super-element method requires to divide the structure into large structural units. Before being used in the case of ship-OWT collision, analytical formulations were developed for several cases, among which ship-ship collision [10; 11] or ship-lock gate collision [12].

The purpose of the here described research is to develop analytical formulations in the case of ship-OWT collision. As explained above, the structure is divided into large structural units: for the monopile is divided into three large elements corresponding to the monopile foundation, the transition piece and the tower; for the jacket, each cylinder is accounted for as an element.

For each of them, analytical developments are performed in order to compute the crushing resistance of the structure taking into account the influencing parameters described before.

In order to consider the plastic deformations, both local cross section and global deformation, we use the so-called upper-bound theorem that states that

$$F \cdot \dot{\delta} = \iiint_V \sigma_{ij} \cdot \dot{\epsilon}_{ij} \cdot dV = \dot{E}_{int} \tag{2}$$

where $\dot{\delta}$ is the striking ship surge velocity, $\sigma_{ij}$ is the stress tensor of the structure and $\dot{\epsilon}_{ij}$ is the strain rate tensor.

For each deformation mode, the deformation pattern has to be assumed. Then, solving the equation (2) provides the crushing force for a given indentation and further the internal energy can be derived.

This method is coupled with:

- Computation of the dynamics of the OWT, for the monopile
- Computation of the overall deformation, using similar approach as the finite element method, for the jacket

### 3.2 Application

In this section, we apply the methodology described here above to the case of an impact on a jacket. The considered jacket has a height of 56 metres and a width of 20 and 8 metres respectively at its bottom and at its top and its main other dimensions are given in Table 1.

| Structure | | Elements | |
|---|---|---|---|
| Height [m] | 56 | Leg diameter [m] | 1.3 |
| Bottom width [m] | 20 | Leg thick. [mm] | 50 |
| Top width [m] | 8 | Brace diam. [m] | 0.65 |
| $\sigma_0$ [MPa] | 255 | Brace thick. [mm] | 50 |

*Table 1: Jacket particulars*

The main ship data are in Table 2 and represented in Figure 4.

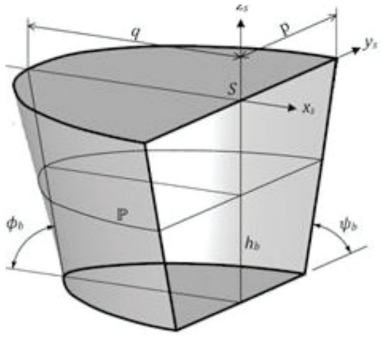

*Figure 4: Ship bow configuration*

| | | | | | |
|---|---|---|---|---|---|
| $p$ [m] | 5 | $\Phi_b$ [°] | 80 | $h_b$ [m] | 5 |
| $q$ [m] | 12 | $\Psi_b$ [°] | 78.7 | | |

*Table 2: Ship particulars*

The collision scenario corresponds to the one shown in Figure 5, which is an OSV weighting 6,000 tonnes (added mass included) with an initial speed of 5 m/s collinding the jacket on a leg between two nodes.

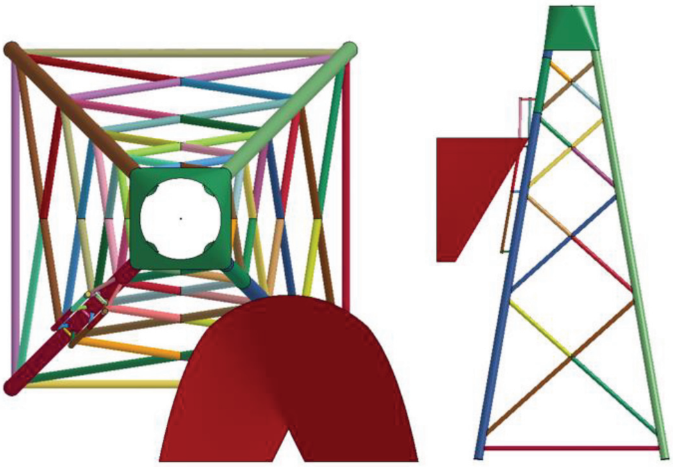

*Figure 5: Upper and side views of the collision scenarios [13]*

The results in term of crushing force and dissipated energy are given in Figures 6 and 7.

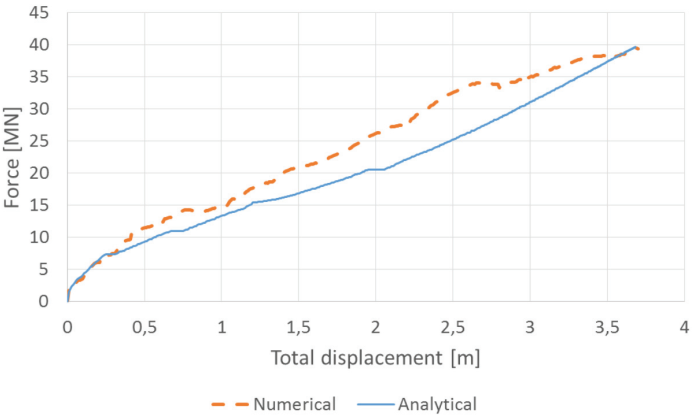

*Figure 6: Resultant force for the considered collision scenario [13]*

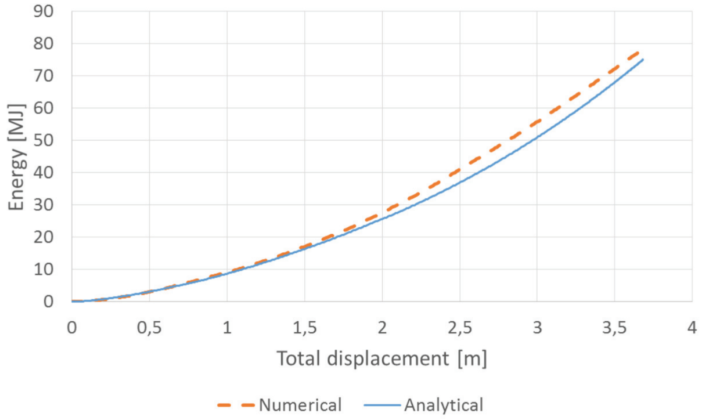

*Figure 7: Dissipated energy for the considered collision scenario [13]*

As can be seen, the results obtained with the analytical approach are very accurate, with a discrepency of 5 % at the end of the collision process.

## 4 CONCLUSIONS

The offshore wind energy sector is expanding and as a consequence, ship – OWT collision events may occur. The main factors which causes such events are the human failure, machinery breakdown and bad weather conditions. Therefore, collision risk analysis must be performed in the predesign stage of offshore wind farms.

Numerical simulations of collision events were performed for both monopiles and jackets to better understand their behaviour. For monopiles it was shown that the most influential parameters on the OWTs structural behaviour are the impact velocity, wind loads and the soil stiffness.

Simulations on jackets showed that considering gravity, inertia and soil stiffness does not bring to significant changes in terms of crushing force and energy. In opposite, the impact point and the shape of the colliding ship are the most determinant parameters for the crushing behaviour.

Finite elements simulations of collision events can provide accurate results. However, this method is time demanding and is not feasible for the investigation numerous collision scenarios in order to perform a collision risk analysis. Therefore, an analytical approach is more suitable due to the short calculation time required.

Following the analysis of the deformation modes, analytical developments were performed and validated for several structure dimensions and load cases. The results obtained by the analytical approach show good agreements with the numerical simulations.

Some analytical formulations have still to be developed in order to take into account all deformation modes and extensive validation process will have to be performed to fully validate the new approach.

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## SUMMARY

TIn a context of development of renewable energies, large offshore wind farms are being built close to traffic lanes and collision risk analysis on supporting structures is becoming a major concern. The aim of this paper is to present an overview on the ship – Offshore Wind Turbine (OWT) collision events. The behaviour of the OWTs structure with monopile and jacket foundations is investigated by means of numerical simulations. Furthermore, an analytical approach is presented for assessing the crashworthiness of the jacket foundation.

## RÉSUMÉ

Dans un contexte de développement des énergies renouvelables, d'importants champs d'éoliennes offshore sont implantés à proximité des couloirs de navigation et l'analyse des risques de collisions avec les structures d'appui devient une préoccupation importante. Cet article vise à présenter un aperçu des collisions entre les navires et les éoliennes offshore. Le comportement des éoliennes offshore fondées sur monopieu ou avec une fondation de type jacket est étudié au moyen de simulations numériques. Par ailleurs, cet article présente une approche analytique pour s'assurer de la résistance d'une fondation de type jacket en cas de collision.

## ZUSAMMENFASSUNG

Im Zuge der Entwicklung erneuerbarer Energien werden große Offshore-Windparks in der Nähe von Wasserstraßen gebaut und Risikoanalysen für die Kollision von Schiffen mit Gründungskonstruktionen werden zu einem wichtigen Anliegen. Ziel dieses Artikels ist es, einen Überblick über die Kollisionsereignisse von Schiff und Offshore-Windturbinen (OWT) zu geben. Das Verhalten der der OWT mit Monopile- oder Jacket-Gründungen wird mittels numerischer Simulationen untersucht. Außerdem wird eine analytische Vorgehensweise zur Einschätzung der Crashsicherheit der Jacket-Gründungen präsentiert.

## RESÚMEN

En un contexto de continuo desarrollo de las energías renovables, algunos parques eólicos marinos se están construyendo próximos a zonas o canales de navegación, donde los riesgos de colisión aumentan hasta convertirse en un elemento fundamental a gestionar dentro del proyecto. El objetivo de este artículo es presentar una visión de las situaciones en las que se puede producir una colisión entre un buque y los aerogeneradores eólicos. El comportamiento de la estructura eólica formada por un fuste cimentado mediante pilotes se representa a través de simulaciones numéricas. Adicionalmente, se presenta una aproximación analítica para evaluar la resistencia al impacto de la cimentación.