DESIGN METHODS TO ASSESS THE RESISTANCE OF OFFSHORE WIND TURBINE STRUCTURES IMPACTED BY A SHIP

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Abstract

The dynamic modes of jacket, monopile and Floating offshore wind turbines (FOWT) after a collision event are presented. The authors have developed simplified analytical formulations based on plastic limit analysis to assess the resistance of an offshore wind turbine jacket impacted by a ship. For the case of collisions with monopile foundations and FOWT, the crushing behaviour and structure dynamics are studied by means of finite elements simulations. Numerical results for both monopile and floating structures will serve for further developments of simplified analytical tools, similar to that used for jacket structures.

INTRODUCTION

Offshore structures require a regular maintenance with the use of Offshore Supply Vessels (OSV), this and the construction of wind farms closer to the traffic lanes increases the risk of collision. Some of the consequences of such accidents are the loss of human lives upon the collapse of wind turbine on the ship and ecological damage. Risk collision analysis is therefore mandatory for the design of a wind farm. The work presented in this paper focuses on the crashworthiness of jacket structures, monopile foundations and floating offshore wind turbines (FOWT), thus comprising a wide wind energy market from shallow to deep waters, as presented in Figure 1.

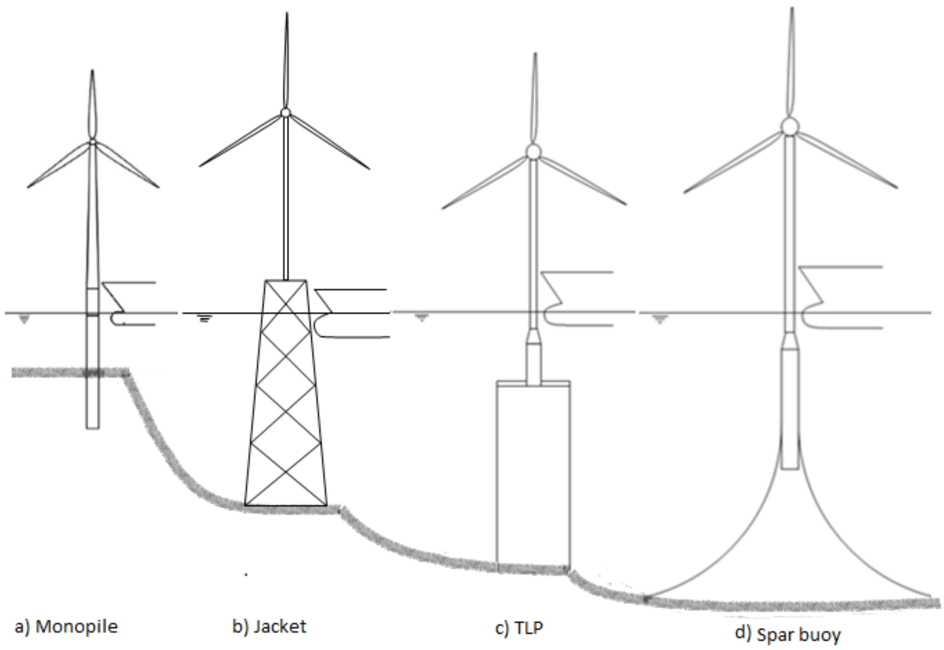


Figure 1. Different configurations studied

Numerical analysis of ship collision with monopile foundations is presented by Bela et al. in [7]. This study intends to understand the crushing behaviour and the nacelle dynamics of a monopile offshore wind turbine (MOWT) when impacted by a ship. The influence of various parameters (ship impact velocity and location, wind direction, soil stiffness and deformability of the striking ship) was also investigated. The analysis was carried out by means of nonlinear numerical simulations of ship-MOWT collisions.

Currently, similar analyses are carried out simulating ship-FOWT collisions. For this type of structure it is important to study the mooring system response to high loads and displacements, as well as fluid structure interaction for the submerged platform and the influence of wind loads on the tower (and turbine). Different type of FOWT are evaluated: i.e. floating spar buoy with catenary mooring and tensioned leg platform (TLP).

For jacket structures, a new simplified tool was developed based on the work developed by Paik et al. [1] and Soreide et al. [2] for analysing the local crushing of impacted structural elements (stiffened panels and tubular offshore structures). Plastic limit analysis is used to assess the local crushing resistance of the members of a wind turbine jacket for different deformation modes (i.e. leg punching and leg foot buckling). Some of the results are presented by Buldgen et al. [3] and Le Sourne et al. in [4] and [5] and Pire et al. [6].

STRUCTURAL BEHAVIOUR

To guarantee the safety and operational durability of OWT, it is necessary to perform a collision risk analysis, due to the increase of probability of occurrence of such event. In this matter, research has been carried out in order to characterize the collision and eventual failure of structures (and vessel). The purpose of such studies is to reduce the risk of collision, mitigate the environmental damage and prevent the loss of lives.

As the experimental (or accidental) results of this type of accidents are not available, nonlinear numerical simulations are sufficient to understand the behaviour of each type of structure. Le Sourne et al. [4] mention some of the models developed in this area.

For fixed structures, such as monopiles and jackets, the energy dissipation manner is very different comparing to the floating structures. Fixed structures present, among others, global deflection, local denting, elastic and plastic beam bending modes. Furthermore floating structures present a high rigid-body dynamic response, the energy dissipation being more influenced by the fluid structure interaction and response of mooring system. The next sections describe the response of each structure, as observed with nonlinear numerical simulations.

Monopile Foundation

Bela et al. [7] investigated numerically the behaviour of a MOWT under a collision impact, using the explicit time integration solver LS-DYNA. In their study the influence of different parameters on the behaviour of the structure was considered. It was outlined that the most relevant parameters were the impact velocity, wind direction and soil stiffness. For this analysis, the ship was considered as a rigid body.

The tower of the OWT was modelled with a non-uniform mesh using Belytchko-Tsai shell elements. For simplification, the rotor and nacelle were replaced by a lumped mass at the top of the tower. Moreover, the striking ship was not modelled entirely, but only the ship bow hull was considered using rigid shell elements. The rest of the ship was described as a rigid part.

As the structure is considered clamped at the base, the free end (corresponding to the top lumped mass) has a dynamic response to the collision force. Therefore, when studying the influence of each parameter, the dynamics of the tower plays an important role for the results. Moreover, as the electrical equipment can be damaged by high acceleration, this aspect was investigated for each parameter as well.

First the influence of the impact velocity was investigated, varying from 1 m/s to 5 m/s. In this case the wind loads were not taken into account. A 5000 tons ship (with 250 tons added mass) was used. It was observed that after the collision, not all the kinetic energy was absorbed by the tower as strain energy, but some remaining energy allows the ship to move backwards after impact.

Also, for small impact velocities (1-2 m/s), the tower top movement is opposite to the collision direction, due to both plastic deformations in the contact area and nacelle inertia. Only minor structural damage was observed for this range of impact velocity. However, for higher velocities (3-4 m/s), the tower top displacement is in the same direction as the collision, due to deformations of the monopile occurring near the mudline. Furthermore, at a 5 m/s impact velocity, a plastic hinge leads to the collapse of the structure and larger deformations near the mudline appear, as shown in figure 2.

As a conclusion, regarding the velocity influence on the crashworthiness of MOWT, three types of deformations are considered: small or quasi-elastic (1-2 m/s), critical or elastoplastic (3-4 m/s) and collapse (5 m/s). In the first case, no repairs of the OWT are required, for the second one, heavy repairs must be conducted. For the third case, the entire structure should be replaced. The top acceleration on the other hand is 2.6 m/s2 for small velocities, 4 m/s^2 for critical velocities and exceeds 20 m/s^2 during the collapse mode at high velocities.

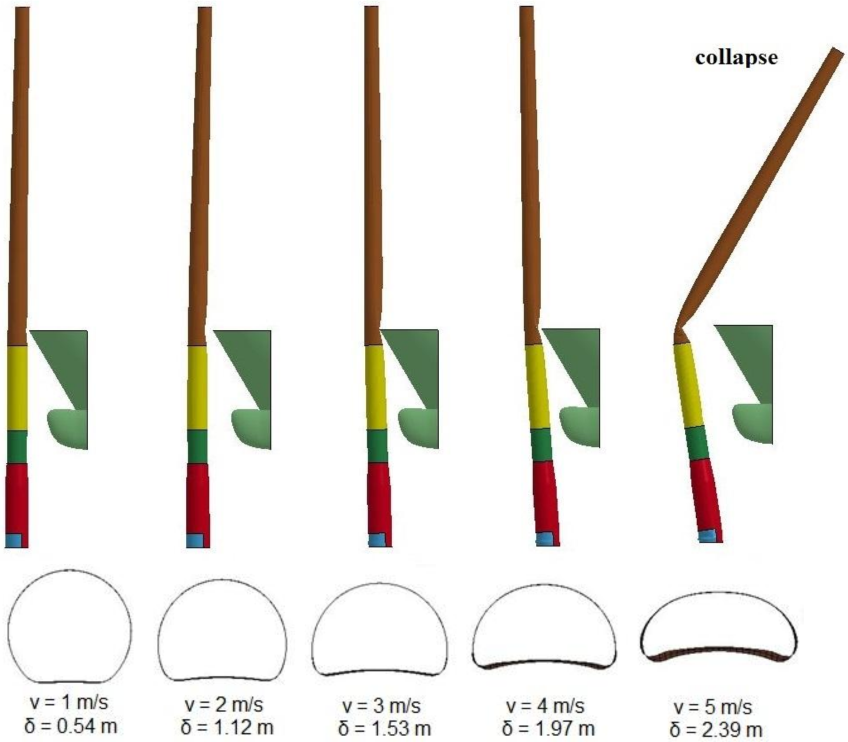


Figure 2. Deformed shape of the OWT. Bottom: shape at impact area [7]

As mentioned, the influence of the wind loads is also investigated. For an operating wind turbine the main loads acting on the structure are induced by the wind. For this analysis, field measurements of forces and moment (performed by STX France) were used. Three cases were analysed: wind force in the same direction of collision (0°), perpendicular (90°) and opposite direction (180°).

As a main finding, it appears that the perpendicular force does not influence in great manner the results. On the contrary, the wind direction opposite to the collision direction amplifies the indentation of crushed area. The collapse of structure would occur at 5 m/s for 0° and 90° wind, but when the wind direction is 180°, collapse occurs at an impact velocity of 3 m/s. These loads have an influence on the tower top displacement as well. In this case, the highest top acceleration was found at wind direction equal to the collision (0°).

Finally, the soil stiffness is considered in order to take into account the flexibility of the soil. The soil stiffness was modelled using rotational and translational spring elements. The values of soil stiffness were provided after measurements at 40 m depth by STX France. As a result it was found that less plastic deformation leads to more elastic energy remaining in the system, increasing the oscillations of the monopile. Also, the indentation of the crushed area was smaller. Additionally, because the soil acts as a spring, multiple contacts occur between the ship and the monopile. Here the maximum accelerations of the top are reached when considering soil flexibility and wind blowing in the same direction as the ship.

Jacket Structure

The behaviour of an offshore wind turbine jacket collided by a ship was also investigated by Le Sourne et al. [4] using the finite elements software LS-DYNA. Several collision scenarios parameters were studied, such as the impact point, the effects of gravity and inertia, the influence of the tower and the nacelle and the soil-stiffness interaction. In order to focus only on the jacket behaviour, the colliding vessel is considered as rigid.

Concerning the impact location on the jacket, it was observed that the impact on a leg is more harmful to the structure than to a brace joint. In that case, the impacted leg dissipates about 60% of total internal energy (causing its total rupture), while plastic deformations are also observed on rear legs that may be punched by the compressed connected braces, representing 15% of the total dissipated energy. In addition, some plastic hinges are found near the mudline as well. The deformation and the plastic strain corresponding to this scenario are illustrated in figure 3, where the red parts correspond to a strain larger than 1%.

In case of a large energy scenario, the collision could cause the rupture of the leg and hence the loss of stability of the whole structure. In case of a collision on a brace joint, the distribution of energy dissipation is obviously different. For a given penetration, the crushing force is lower, as a leg is stiffer than a brace. In case of a brace rupture, the leg is usually only few deformed and the structure remains stable even if weakened.

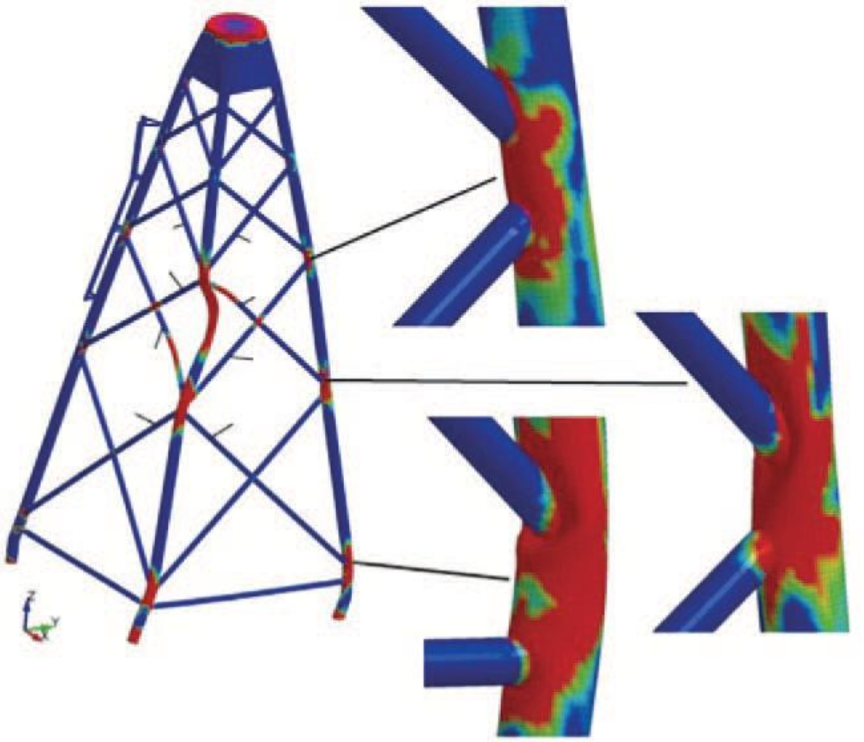


Figure 3. Effective strain-Punching on rear leg [4]

The effect of gravity on the maximum ship penetration in the jacket during a collision was also studied. Both results, with or without considering gravity were similar, whatever the collision scenario studied, which shows that gravity can be neglected when the structure is designed against ship collision. Similarly, finite elements simulations were performed on the same jacket with and without the tower and its nacelle. The results show that up to the maximum penetration, there is not a high influence of the dynamics coming from the tower.

Those previous analyses were performed taking the soil stiffness as infinite, i.e. the legs are perfectly clamped at seabed level. Using the model of the jacket with the wind turbine, the flexibility of soil was considered, as for the monopile, by modelling it with spring elements at four legs extremities. The value of the spring's stiffness was computed from in-situ measurements results and adapted to correspond to an equivalent stiffness at mudline. It was observed that, with the stiffness values used and contrary to the monopile, the jacket legs behaviour does not change in great manner near the mudline and the maximum penetration variation is very small.

Floating Offshore Wind Turbines

The authors are currently studying the behaviour of a FOWT after a ship impact. The first question that arises regarding this is about the initial dynamic response of the structure and the subsequent response of the mooring system. In addition to the damage on the structure and the dynamics of the nacelle that are covered for monopiles or jackets, the potential rupture of the mooring system and the platform capsizing have to be covered for FOWT.

Since there are several types of floating structures and mooring system used in the construction of FOWT, a TLP platform and a spar buoy with catenary mooring were selected as the initial models for the study, as presented in figure 1. These FOWT were selected because of simplicity in the modelling and also because they are widely studied in the literature.

Some of the most important physical aspects of the floating turbines are presented by Jonkman [8]. This author has done several studies on FOWT dynamics, using the comprehensive aeroelastic simulator FAST (Fatigue, Aerodynamics, Structures, and Turbulence) developed at the National Renewable Energy Laboratory (NREL).

Floating structures in general involve several modes in the physical behaviour. The system has a response due to diverse sources such as wind and waves, gravity loads, current, buoyancy and control of the turbine, as shown in figure 4 (left). These effects would also have an impact in the case of a ship collision. This can lead to several degrees of freedom (DOF) of the structure, simplified in figure 4 (right) replacing the turbine by a generator disk.

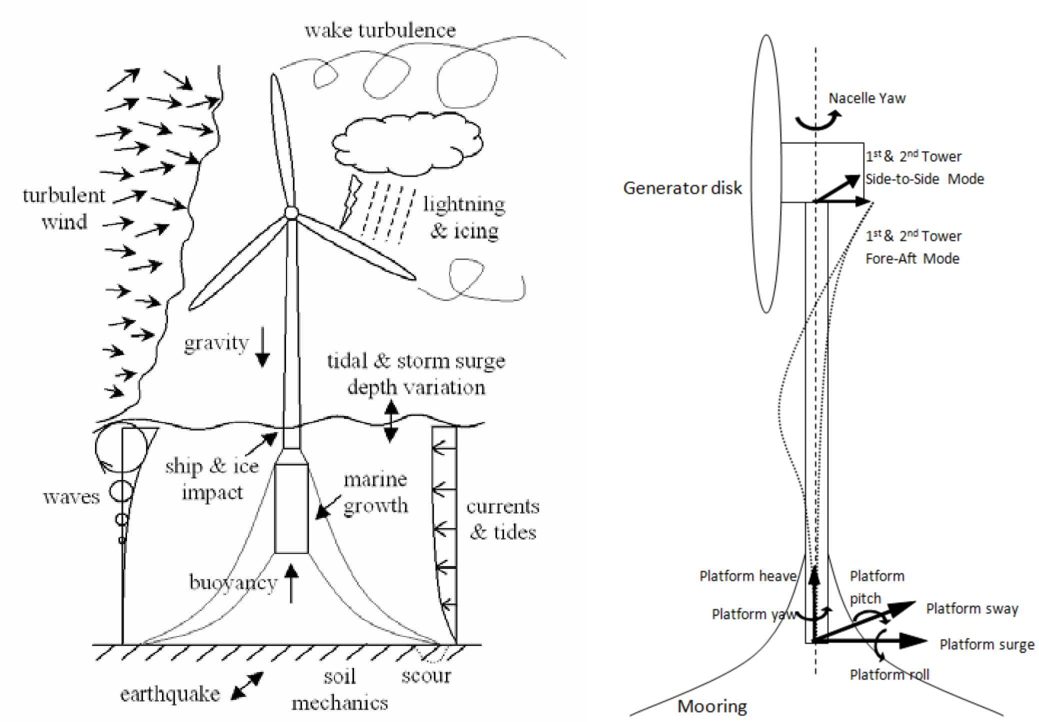


Figure 4. Offshore Turbine Loading Sources (left)[9] and Platform DOF (right)

Some authors have presented deep studies on the dynamics of FOWT. Jeon et al. [10], for instance, analysed the dynamic response of a spar-type floating structure moored with 3 catenary cables to irregular wave excitation. It is shown that the mooring system present the best response to minimize surge and pitch if connected to the centre of buoyancy (or slightly above). Then Ma et al. [11] studied the hydrodynamic characteristics of a spar-buoy and the dynamic response of the tower, as well as the response of motions and mooring system to different sea states and wind conditions. From their results, a coupling between surge and pitch of the platform was found. Moreover, the yaw motion is excited by the gyroscopic effects from the rotating turbine combined with pitch motion. Furthermore, it was demonstrated that the response from the mooring system is also affected in high manner by the wind. If one line is aligned opposite to the incoming waves and wind, and a large force (such as a collision force) acts in the same direction, there is a risk of failure of the line for being slack after a large drift.

Second-order hydrodynamics, as explained by Bayati et al. [12], can induce loads proportional to the square of the wave amplitude with frequencies equal to the sum and difference of pairs of incident wave frequencies. They have studied these effects on a semisubmersible FOWT, having into account that despite the second-order hydrodynamic loads normally are small in magnitude; the resonant effect can be significant. And this is especially dangerous for a TLP configuration; in which the natural frequencies in pitch, roll and heave are higher. Roald et al [13] have shown that when comparing a spar-buoy with a TLP, the second-order effects on a TLP are higher, leading to a higher motion response, which could also be dangerous in the case of a collision.

As initial step of the present research, it is important to calculate the mass and damping matrixes of each OWT model. This is done using the software from Bureau Veritas *HydroStar* or the open source from NREL *FAST-V8.* After these values are obtained, an MCOL file can be created in order to introduce the seakeeping response of the structure to the LS-DYNA simulation [14]. The latter is then programmed as for the MOWT and jacket structures collision simulations, presented before.

It is important as well to define the mooring system modelling to use in the FEM simulation, since this could be decisive for a realistic result. For instance, Hall et al. [15] demonstrated that the quasi-static mooring models are well-suited for spar-buoys (in normal operation), but not for TLP, and certainly not in extreme conditions as the case of a collision.

The main parameters to study in the simulations are ship impact velocity, - location, - direction, mooring system rupture limit (with soil stiffness effect), and wind influence (which could lead to gyroscopic effects and dynamic response of the tower, affecting yaw, pitch and roll).

Results from this study will serve to develop an analytical method, similar to that used for jacket structures, in order to avoid heavy computational demanding finite element simulations.

ANALYTICAL DEVELOPMENTS

Up to now, the presented results were obtained with finite elements simulations. This method provides very accurate results but is time-demanding. For a complete collision risk analysis, thousands of scenarios have to be investigated by varying several parameters, including amongst others the shape, the mass and the initial velocity of the ship, the collision point and the trajectory of the ship. The use of numerical method is therefore not suitable for a pre-design stage.

New simplified analytical methods, based on the so-called upper-bound theorem, are being developed by the authors in order to compute the crashworthiness of offshore wind turbine structures collided by a ship in a faster way. The method, widely explained by Jones [16] in case of impacts, simply expresses that the external power is equal to the internal power during the whole collision process (see eq. 1).

$$F \cdot \dot{\delta} = \iiint_V \sigma_{ij} \cdot \dot{\epsilon}_{ij} \cdot dV = \dot{E}_{int} \qquad (1)$$

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

In order to compute the internal power, a kinematically admissible displacement field has to be assumed. This assumption can be based on the analytical results or thanks to real tests in a laboratory

In this paper, the focus is on the presentation of the method in case of a ship collision with an offshore wind turbine jacket. Le Sourne et al. [4] identified four deformation modes, namely the overall motion of the structure (figure 5 (a)), the local crushing of the impacted cylinder(figure 5 (b)), the punching of leg by compressed braces (figure 5 (c)), and the deformation at the base of the structure (figure 5 (d)), and analytical formulations were developed for each of them.

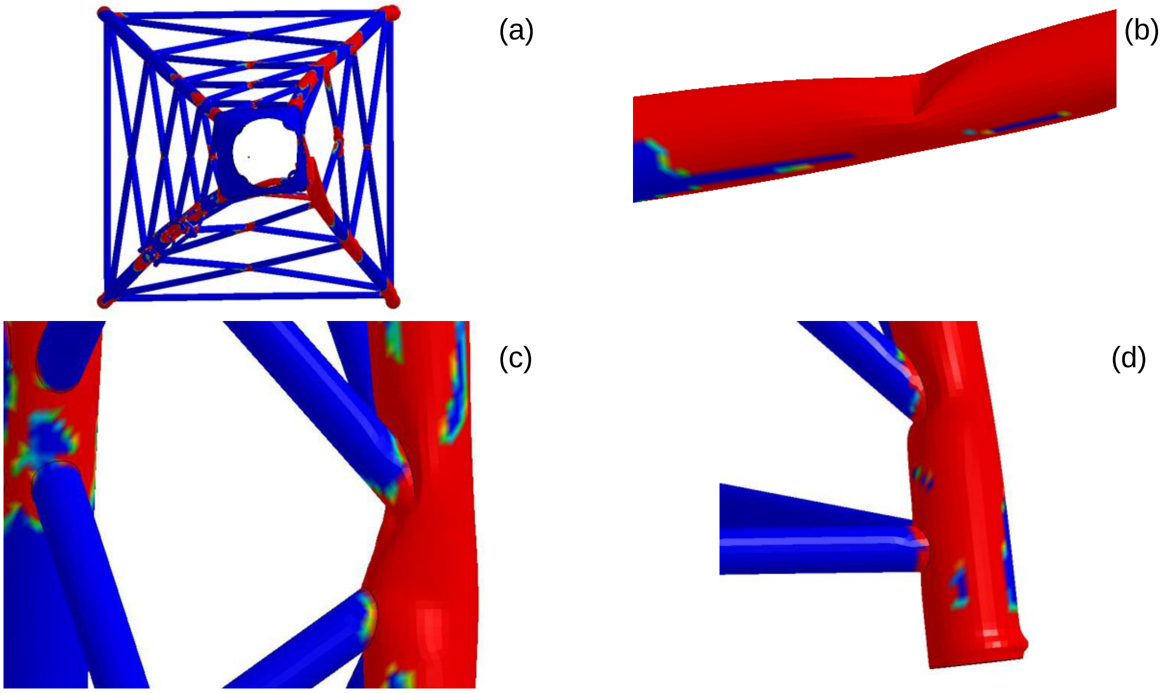
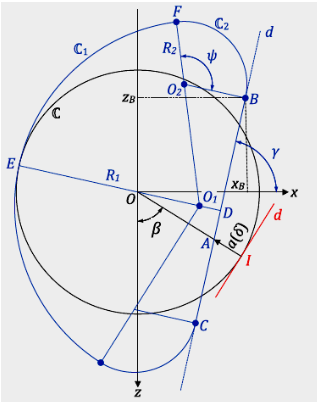


Figure 5. Deformation modes of the jacket structure [17]
a) Overall motion of structure; b) Local crushing of impacted cylinder
c) Punching of leg compressed by braces; d) Deformation of base of the structure

First, the overall motion of the whole structure was computed with an algorithm similar to a finite elements method. Each cylinder was considered as a single beam element with 6 DOF at each extremity. Then, the local crushing of the impacted cylinders was studied by Buldgen et al. [3]. The assumptions done are presented in figure 6. The application of eq. 1 provides the resistant force and allows computing the dissipated energy. Similarly, Hsieh [18] extended the analytical developments to the punching of leg by compressed braces mode. Finally, the deformation at the base of the jacket was studied by Pire et al. [6].

All the analytical formulations were validated with numerical results performed by the finite elements software LS-DYNA. For all of them, discrepancies lower than 15% were observed, which shows the accuracy of the method.



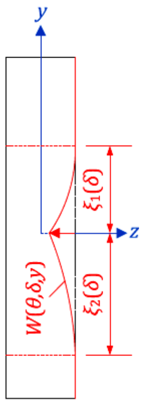


Figure 6. Assumptions for analysis of punched leg [3]

An algorithm, described by Le Sourne et al. [5], combines the analytical formulations for all the deformation modes described above. The crushing process is divided in several time steps, and the resistant force is computed for the four modes at each of them. The total resistant force is then considered as the lowest one. Here again, validation was achieved by considering a collision with a non-bulbous 6000 tons OSV with an initial velocity of 5 m/s. The discrepancy in terms of dissipated energy is low, whatever the collision scenario considered.

CONCLUSION

A description of the dynamic modes of a jacket and a monopile foundation after a collision event is presented. The dynamic behaviour of FOWT is also summarized, in order to account it for collision analysis. A simplified analytical formulation based on plastic limit analysis has been developed to assess the resistance of an offshore wind turbine jacket impacted by a ship. Such methodologies are useful for the early design stages of OWT, in which computational simulations are time consuming. For the case of collisions with monopile foundations and FOWT, the crushing behaviour and structure dynamics are currently studied by means of finite elements simulations. Specifically for FOWT, special attention is necessary for the mooring system behaviour and tower dynamics. Developing a complete analytical tool for risk analysis is the purpose of studying a wide range of types of OWT under collision forces.

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