Developments in the Collision and Grounding of Ships and Offshore Structures – Guedes Soares (Ed.)

Numerical crashworthiness analysis of a spar floating offshore wind turbine impacted by a ship

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ABSTRACT: With the new developments of floating offshore wind turbines (FOWT), wind farms are located in deeper water, meaning they are closer to traffic cargo and passenger lanes, increasing probability of collision. This paper aims to analyze the crashworthiness of a spar FOWT by performing non-linear finite element simulations, which in the future will serve to validate a simplified analytical method for performing the same analysis in a faster and reliable way. The influence of parameters like nacelle mass, hydrodynamic forces, gravity, ballast mass and mooring line tension is analyzed. First simulations are run assuming a rigid striking ship in order to understand the crashworthiness of FOWT only. Then, the ship is modelledas deformable and the effect of bow deformability is investigated. Regarding internal mechanics, the main deformation modes are identified and deformation energies, structure indentations andresistant forces are post-processed. As external mechanics is concerned, rigid-bodies motions during and after the collision are analyzed for different collision scenarios.

1 INTRODUCTION

1.1 *FOWT collision risk*

With the purpose of using more renewable energies for the decarbonisation of EU, some European countries are beginning to implement floating wind farms. In the North Sea (25 km offshore Peterhead, Scotland), the Hywind floating Wind Park is already in operation by Statoil (Fig. 1).

Although clearly advantageous regarding the energy sector, new wind farms will be often located closer to traffic lanes, meaning that ship collision probability also increases.

Figure 1. Location of Hywind Scotland Pilot Park.

The ship collision with Offshore Wind Turbines – OWT has been studied for the past 20 years, because a clear risk is identified. Christensen et al. (2001) presented a model for calculating the collision frequencies for the wind farms. The most important issues identified in such collisions are *ship traffic*, *navigation routes*, *geometry of wind farm* and *bathymetry* in the wind farm area.

A more advanced risk analysis is presented by Dai et al. (2012). They have observed that the more damaging situations for the OWT is the head-on collision, in which the OWT absorbs a great amount of the ship kinetic energy.

The present paper focuses on the crashworthiness of OWT design through numerical simulations of some collision scenarios, more precisely a spar buoy type of floating offshore wind turbine -FOWT, which due to the novelty of this technology, has not been widely studied. The purpose of the overall research project will be to develop a tool based on analytical formulations that would be able to assess the consequences of such a collision in a shorter time.

1.2 *OWT collision analysis*

In general, collisions against offshore structures have been studied since the installation of the first oil platforms. In the NORSOK N-004 (2004) standard, a ship collision event is characterized by the kinetic energy, governed by the ship mass, water added mass andimpact velocity. Figure 2 presents the load-deformation

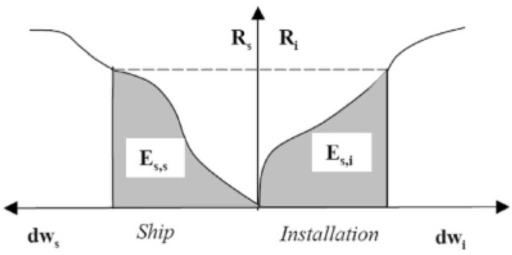


Figure 2. Dissipation of strain energy for the striking ship and the collided structure. NORSOK N-004 (2004).

relationship for both the collided structure and the striking ship.

Biehl & Lehmann (2006) used finite element – FE simulations for analyzing different types of fixed OWT (tripod, monopile and jacket) collided by different ships. In their findings, the very critical scenario is a collision of any ship with a tripod, which could cause irreversible damage to the ship's hull. In the monopile and jacket scenarios, the structural foundations absorb most of the energy, endangering this way the wind turbines.

More recently, Bela et al. (2017) analyzed several collision scenarios in which a monopile OWT is involved. A sensitivity analysis was performed for a series of parameters: impact velocity, wind loads, soil stiffness and ship deformability. They found that the most influencing parameter for this type of collision is the striking ship initial kinetic energy. In some situations, an impact by an offshore supply vessel (OSV) can lead to the collapse of the overall OWT.

Jacket structures have been also studied. Le Sourne et al. (2015) performed several nonlinear FE analyses to investigate the resulting deformation modes and the distribution of dissipated energy in the crushing behavior of a jacket impacted by a ship. However, as the floating structures are concerned, the studies remain very limited to the present. Few researches have been performed for TLP oil platforms, but due the novelty of FOWT systems, studies on such collisions are rare. Moan et al. (1993) have investigated the damage probability of concrete TLP platforms due to ship collisions and dropped objects. Further research on floating platforms has been focused on the load analysis (wind and waves) using tools such as aero-hydro-servo-elastic simulation, as presented by Jonkman & Buhl (2007).

The collision analysis for FOWT is therefore important in the nowadays industry, especially because these systems are starting to enter into the market of wind energy.

1.3 *Analytical method for OWT crashworthiness*

Finite elements method – FEM is widely used nowadays to simulate marine structure response to ship collision. Such approach provides accurate results but is often time-demanding. Moreover, setting realistic models requires some expertise since the crushing behavior, the action of mooring lines and hydrodynamic forces have to be considered.

A faster and reliable simplified method is thus required in order to study the sensitivity of the FOWT response when collided by a ship. This is the final purpose of this research, to develop a semi analytical tool to understand the crashworthiness of FOWT, moreover to study different parameters like the striking ship kinetic energy, impact location and direction, etc.

Indeed, Buldgen et al. (2014) developed formulations to assess the impacted cylinder resistance (being the cylinder a part of a jacket structure) by considering its local crushing and global bending modes. Le Sourne et al. (2016) used Buldgen's work to derive analytical expressions that give the resistant force opposed by a leg that is punched by one or two braces, as well as the energy dissipated through this deformation mode. Finally, above development were re-used and completed by Pire et al. (2018) who developed simplified formulas for assessing the energy dissipated at the base of compressed jacket legs that may buckle near the foundation level.

Regarding floating structures, deJonge & Laukeland (2013) presented a study of collisions between a tanker and a spar platform, where a closed form solution for the energy that has to be dissipated for a head-on collision is derived.

The present research study is focused on a collision analysis program, specific for the spar buoy FOWT, based on plastic limit analysis coupled with a large rotational structure movement analysis tool (Le Sourne, 2007), considering both striking ship and FOWT external dynamics. The development of such tool aims to facilitate ship-FOWT collision simulations at early design stage and identify dangerous scenarios for both the ship and the FOWT structure.

The method is still under development; therefore the results presented in this paper focus on the first step towards the main objective, which consists in performing nonlinear FE simulations using *Ls-Dyna/MCOL* software. Numerical analyses are run for different collision scenarios, where the main deformation modes that govern the response of theFOWT are studied for each part of the collision phases as follows:

- Plastic indentation near the initial collided area of the tower;
- Beam-like response of the overall floating structure;
- FOWT surge displacement, leading to quasi-linear tension in mooring lines;
- FOWT turning moment, with a plastic hinge developing in the ballast level, due the strong hydrodynamic restoring forces.

2 FINITE ELEMENT ANALYSIS

2.1 *Problem description*

A simplified model for the collision between the FOWT spar buoy and OSV bow is considered as reference study case, represented on Figure 3. The

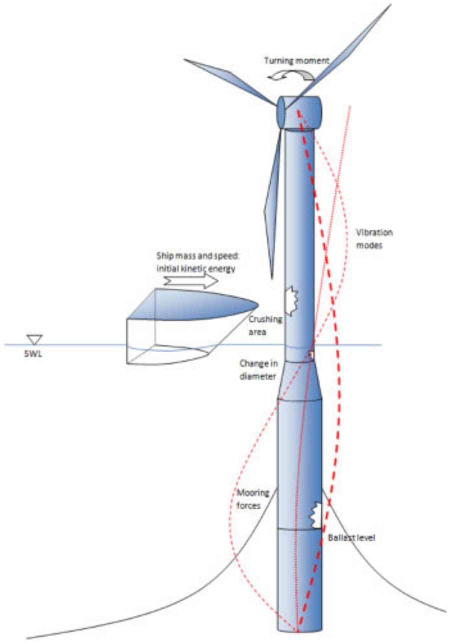


Figure 3. FOWT collision description.

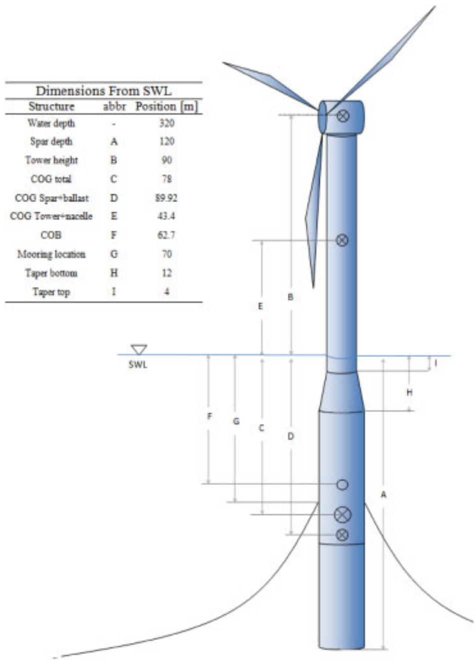


Figure 4. OC3-Hywind main dimensions.

wind turbine is not explicitly modeled but represented by a lumped mass located at the tower upper extremity.

When the collision occurs, local crushing appears near the impact point and part of the initial kinetic energy is transformed into elastic-plastic deformation energy. Several elastic vibration modes are immediately excited and, at the same time, plastichinges can appear in some zones, due to a change in diameter (from the tower-floater transition) or the presence of ballast material, which can produce some additional localized deformation.

Since the FOWT is moored, some lines get taut (depending on the collision direction), causing new forces appearing in the system. These forces might not lead to rupture of the mooring cables, but in some cases rupture of the fairleads which work as a mechanical fuse (rupture limit below cable rupture limit). This situation would induce high moments and forces in the system, but for now this is not considered.

The presence of the wind turbine at the tower top might lead to a big turning moment (upon a total collapse of the structure), which may endanger the ship. These forces can be influenced by the turbine status (idle or rotating) and wind direction, however in this paper we only focus on the turbine as a lumped mass on top of the tower.

In Figure 4 the main dimensions of the OC3-Hywind FOWT are presented. These data are extracted from an NREL report, Jonkman et al. (2009).

2.2 *Striking ship description*

The ship bow is idealized as a paraboladescribed by its two radii (p, q) and its center S (Fig. 5, left). The stem and side angles are denoted by ϕ_b and ψ_b respectively while the height of the stem is denoted h_b. Table 1 lists the data required tofully describe the striking ship geometry.

Figure 5 (right) shows the model used in the FE simulations.

Table 1. Input data for the striking ship.

Description	Notation	Unit	Value
Elliptic radius 1	p	m	6
Elliptic radius 2	q	m	8
Total height 2	h_b	m	7
Stem angle	Φ_b	deg	78
Side angle	Ψ_b	deg	74

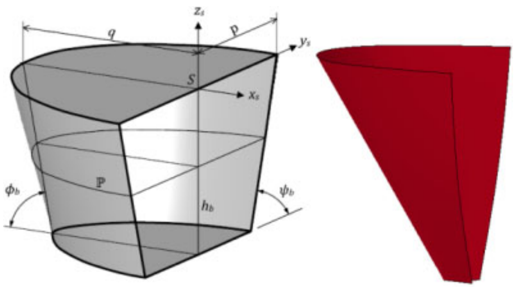


Figure 5. Ship dimensions and finite element model used.

Figure 6. Example of ships considered in the collision scenario.

The striking ship is considered as rigid in the first part of the analysis; therefore, there is no need to describe the internal stiffening system.

The model used is the same for all the simulations, only the mass inertia matrix is changed for accounting the difference DWT.

2.3 *Initial kinetic energy*

Two main collision scenarios are considered, defined by the type of ship used for the FE simulations. An OSV (Fig. 6, left) which can vary from 15 to 25 m length, having a total DWT of 6000 tons (lower than the FOWT displacement, around 8000 tons); and a container ship, like the Suezmax of 285 m in Figure 6, right with a total DWT of 200 000 tons (much higher than the FOWT displacement). A frontal collision is considered, in which the consequences of a collision can be dramatic for both the ship and the FOWT.

In normal operation, these ships are navigating at an average speed of 10–20 knots (5–10 m/s), depending on the size of the ship. However, in the case of a collision with a FOWT, the situation could happen at a lower speed, because the navigation rules would require the ship to travel at a lower limit in the vicinity of such structures. However, it is worth noting that a collision at a high speed already took place in Corsica in 2018, due to a series of human errors, as reported by Safety4sea. 2019.

In a collision event, it is normally assumed that there is an approach maneuver. As a matter of fact, in the crashworthiness of fixed offshore structures (as jacket and monopile wind turbines), the recommended velocity ranges between 0.15 to 2 m/s. Accounting for this, the total kinetic energy E_1 of the vessel is given by:

$$E_1 = \frac{M_1 u_1^2}{2} \tag{1}$$

where M_1 includes both the ship mass and the water added mass in surge direction and u_1 is the initial velocity. For both structures (ship and FOWT), a seakeeping code (*HydroStar*) is used to obtain the water added mass matrix.

Each vessel is studied for two collision speeds. The initial kinetic energy E_1 for each case is given in Table 2. This energy has to be partially absorbed by the deformation of the tower and the dynamic response (including vibrations), as the striking ship

Table 2. Initial internal energy for each striking ship velocities.

Ship	DWT [kt]	u_1 [m/s]	E_1 [MJ]
OSV	6	2	12
		5	75
Container ship	200	0.866	75
		2	400

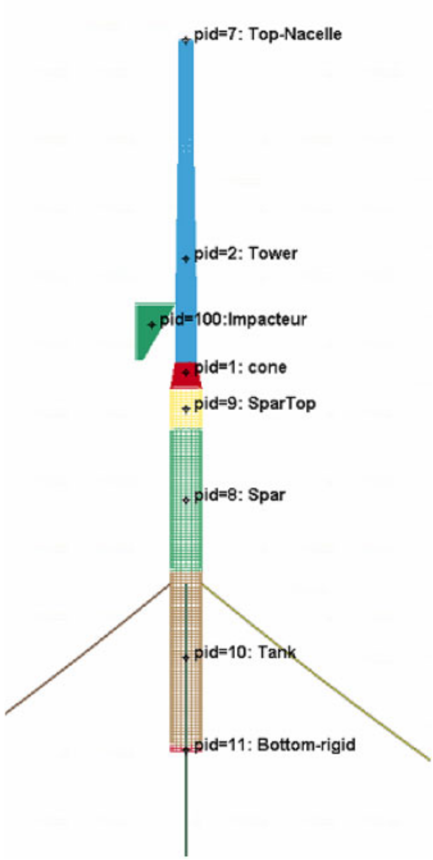


Figure 7. Finite element model of the FOWT.

is considered perfectly rigid. Then part of the energy is also conserved by the ship only as kinetic energy.

2.4 *Numerical model*

In the finite element model presented in Figure 7, each color represents a different part of the FOWT, providing the thickness and diameter as it is shown in Table 3, with the purpose that the simulation is as close to reality as possible.

The mooring data used in the simulations are given in Table 4.

Four catenary lines are modeled as cable beam elements. It is assumed that the mooring lines are simply supported at the anchor and fairlead, giving the

Table 3. Structural data of FOWT.

Part	Thickness [mm]	Radius [m]	Mass [t]
Cone	27	3.25	41
Tower	23	3.25	252
Nacelle	22	2.123	353
Spar	27	4.7	73
Spar top	27	4.7	290
Tank	27	4.7	7010
Bottom	27	4.7	32
Total mass			8301

Table 4. Structural data of mooring system.

Property	Value	Unit
Number of mooring lines	4	
Diameter	100	mm
Horizontal distance to anchor	853.87	m
Submerged weight	683.26	N/m
Axial stiffness	384.243	MN
Cross section	78.5	mm^2
Density	77.7	kg/m
Young modulus	489.233	GPa

cable beam elements only rotational freedom but zero displacement at extremity.

Other external loads due to blades rotation and wind are not included in these simulations, but in future studies it could be interesting to investigate the influence of such forces, as done by Bela et al. (2017) for monopoles.

3 SIMULATIONS CONSIDERING A RIGID SHIP

3.1 *Collision description*

The resulting deformation modes have to be clearly identified.To simulate the worst condition scenario, the ship is assumed to impact the FOWT in the direction of the mooring lines, in which only one line may get taut.

Part of the initial kinetic energy of the ship should be transferred to different mechanisms, such as plastic deformation of the FOWT, elastic bending response, restoring mooring system force and hydrodynamic effects. Based on this study, the dynamics of the FOWT can be split into two parts:

- **External dynamics**: hydrodynamic loads, seakeeping response (calculated with the tool *MCOL*, Ferry, M. 2002)
- **Internal dynamics:** resistance force of FOWT and moorings, tower plastic deformation, elastic vibration (calculated with *LS-Dyna*)

A calibration test is run using an OSV at a collision speed of 5 m/s, which could be considered as a dangerous condition (because this speed is higher than in a

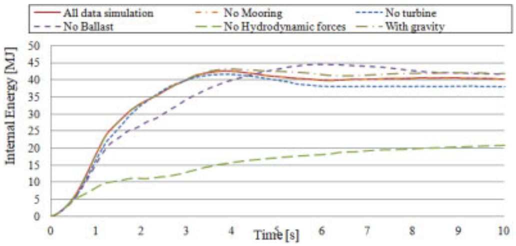


Figure 8. Comparison: FOWT internal energy time history.

maneuver operation). Figure 7 summarizes the results in terms of collision force and energy distribution.

A first impact during the first eight seconds transfers most of the initial kinetic energy from the ship to the FOWT. The maximum collision force is reached at 1 second, when local crushing is maximum and the FOWT starts to surge. However, a second impact appears after 12 seconds, transferring the remaining kinetic energy from the ship. This second impact increases the internal energy of the FOWT due to an additional plastic deformation.

Due to the dynamic nature of the problem, the simulation needs to last longer than a traditional ship collision scenario. For the calibration tests, 30 seconds have been selected in order to see possible effects of multiple contacts and capsizing condition.

For the subsequent scenarios, 10 seconds will be sufficient to understand the behavior after a first impact, and serve as an initial approach for the analytical developments. The dynamics for subsequent contacts will be studied in detail in the future in order to understand deeply the post collision behavior.

3.2 *Sensitivity analysis*

The same collision configuration is used to determine the influence of some parameters like:

- Gravity acceleration.
- Presence of turbine lumped mass.
- Mooring system.
- Presence of ballast.
- Hydrodynamic forces.

Part of the ship initial kinetic energy is transferred to the FOWTas deformation energy (Fig. 8); it is interesting to study the sensitivity of the response to each parameter. The base simulation is run considering all parameters (except gravity), and from now, it is called *all data simulation*.

Figure 9 shows the *all data simulation* plastic effective strain distribution which adds up to the internal energy, after 10 seconds in the different zones: local crushing, ballast tank (elephant foot) and tower top folding.

Figure 10 (sixth tower) shows that not taking into account the **hydrodynamic forces** (i.e. running *LS-Dyna* alone without *MCOL* module), results in a simulation very far from what is expected (due mainly

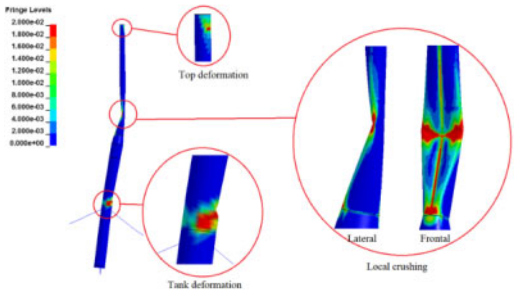


Figure 9. All data simulation: FOWT deformation after 10 seconds (Effective Plastic Strain).

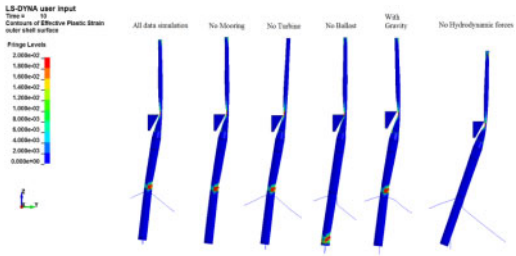


Figure 10. Comparison: FOWT deformation after 10 seconds (Effective Plastic Strain).

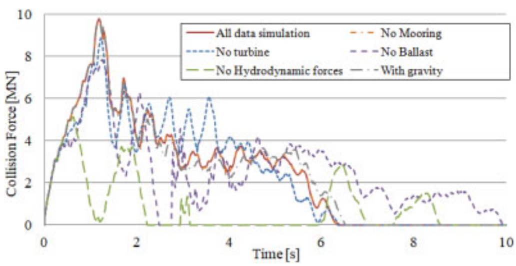


Figure 11. Comparison: Collision force time history.

to the lack of hydrostatic restoring forces). Here, the FOWT starts a big rotation (pitch) and the rotor-nacelle arrangement is in danger to fall apart. Moreover, the deformation energy is only half the one related to *all data simulation* model, as plastic deformation in the tank never appears (Fig. 8).

Concerning the impact without **mooring lines** (Fig. 10 second tower), the difference is negligible regarding the internal energy and crushing force (Fig. 8 and Fig. 11), however mooring lines affect clearly the external dynamics of the floater. When the mooring lines are completely ignored, the FOWT adrift far from the initial position, therefore this parameter needs to be considered in further simulations (and should be studied in more detail).

Neglecting the **turbine mass** (Fig. 10 third tower), an alteration of internal energy of about 7% is obtained (Fig. 8).

However, the collision force is similar (Fig. 11). This parameter affects the overall mass of the FOWT, which clearly changes the dynamic behavior and elastic vibrating response (due the induced moment of the mass at the top of the tower).

It is important to mention that no rotation of blades is taken into account, although the authors are aware that the force applied by the wind and turbine gyroscopic effect may have some influence on the FOWT response. This study is mostly focused in the general structural behavior and the turbine is only modelled as a lumped mass located on the top of the tower. For future studies, it is recommended to go in a more detailed analysis.

Not including the **ballast** (Fig. 10 forth tower), influences the internal energy only of 4% (Fig. 8), but then the collision force varies greatly (Fig. 11), especially because the duration of contact is longer. The difference is also important in the deformation of the entire structure. Since the simulation considers no ballast inside the tank, the rigidity and inertia of this part decrease, therefore a hinge may appear in a random location and not at the ballast level.

This parameter also affects the seakeeping of the FOWT (especially in heave) since the mass is reduced tremendously, thus changing the *COG* of the entire structure (ballast represents 85% of the total FOWT mass).

The final parameter analyzed is **gravity** (Fig. 10 fifth tower), which can influence the internal energy in a rate of 4% (Fig. 8), and the collision force is maintained almost the same (Fig. 11). This parameter affects also the long-term FOWT dynamic response; especially in heave (because buoyancy is counteracting the gravity force). This parameter is also linked to the catenary mooring response. However, it is recommended to study the effects of gravity in more detail in a future analysis. An example of such analysis was done by Le Sourne et al. (2015), who demonstrated that during the collision event of a ship with a OWT supported by a fixed jacket, the gravity effects can be neglected. In the case of a FOWT this parameter may be, however, very important regarding the post collision behavior, when the risk of collapse and fairlead rupture increases.

In conclusion, the following simulations are run taking into account all parameters, except gravity, for the sake of simplicity, at least during the initial impact (5–10 seconds simulation).

3.3 *Results for the two ships*

Figure 12 compares the FOWT internal energy resulting from collisions with the OSV and the container ship.

It is important to notice that the collision with an OSV seems to be the most dangerous, especially at high speed. It is observed that the OSV transfers a huge amount of its initial kinetic energy into internal energy, compared to the container ship. This is because the OSV has a displacement comparable to that of the FOWT, while the container ship is around 25 times heavier.

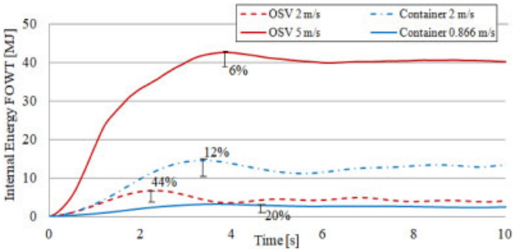


Figure 12. Internal energy time history (two vessels at different speeds).

Table 5. Results comparison.

Property	OSV		Container ship	
u_1 [m/s]	2	5	0.866	2
KE_1 (initial) [MJ]	12	75	75	400
V_1 [m/s]	0.12	1.12	0.813	1.88
V_2 [m/s]	0.46	0.94	0.427	0.83
KE_1 (final) [MJ]	0.043	3.76	66.1	353.4
KE_2 (final) [MJ]	0.92	3.88	0.756	2.86
E_{intern} (FOWT) [MJ]	4.05	40.1	2.38	13.5
Other mechanisms [MJ]	6.98	27.26	5.76	30.24

It is also remarkable that both ships induce an elastic response on the tower, which cannot be neglected when developing a simplified tool. Such elastic response is mainly due to the contribution of the first bending natural modes of the tower subjected to a concentrated shock load.

This can be seen as restoring internal energy for each simulation (it reaches a maximum peak at the beginning but then decreases to a more constant value). This elastic restoring is about 6% for the impact of the OSV at 5 m/s, but 44% at 2 m/s, and 12% and 20% for the impact of the container ship at 2 m/s and 0.866 m/s, respectively. This trend shows that the lower the initial kinetic energy, the more significant the elastic response of the collided structure.

Results are summarized in Table 5, where the subscript 1 represents the ship and 2 the FOWT, u is initial velocity and V is final velocity.

It is shown that the OSV transfers most of its initial kinetic energy at both speeds, but especially at 5 m/s. In this case 40.1 MJ are absorbed by plastic deformation of the FOWT, i.e. 53.5% of the total initial kinetic energy. Only 5% is kept as kinetic energy of the ship. The remaining 41.5% is transferred into other mechanisms, such as FOWT kinetic energy, mooring system, hydrodynamic damping, etc.

The container ship keeps around 88% of the initial kinetic energy at bothspeeds. The FOWT deformation energy in both cases is small: 3.2% if cruising at 0.866 m/s and 3.4% at 2 m/s. Around 8.5% of the initial kinetic energy is transferred into other mechanisms, including FOWT kinetic energy, mooring system, hydrodynamic damping, etc. meaning that these effects cannot be neglected.

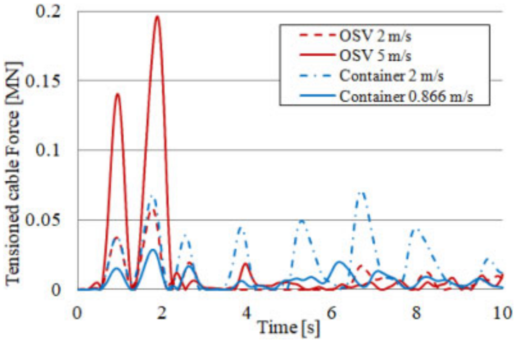


Figure 13. Cable response time history during the collision (two vessels at different speeds).

3.4 *Mooring response*

The mooring system influences the FOWT response because it generates a restoring force depending on the collision direction. After the impact, some lines get in tension and prevent the floater from drifting.

As a catenary mooring system is considered in this study, the worst collision scenario during which only one line is taut does not lead to mooring line rupture. Indeed, after 10 seconds, the tension level is still very small as shown in Figure 13.

The normal reaction in a mooring line is non-linear, especially at the very early contact where the cable oscillates. In a longer response, the behavior of the cable could be predicted using a simplified method (based on the quasi-static catenary model – Cruz & Atcheson (2016)), especially for the higher energy collision scenarios, where the FOWT absorbs more kinetic energy, tensioning the mooring cables.

Although this force might not seem very appealing to the problem studied (in terms of energy and deformation), it influences the seakeeping behavior of the FOWT. This characteristic by its own makes the mooring system an important parameter to include in the study of ship-FOWT collision. Moreover, it worth to note that the overall response of the FOWT is also influenced by the weight of the mooring lines which must be taken into account in the simulation.

3.5 *Collision force and crushed area*

The FOWT collision resistant force depends mainly on the dissipation of the striking ship kinetic energy through FOWT deformation mechanisms (such as plastic crushing, local plastic buckling and mooring line tension) and floating bodies' external dynamics which are governed by the hydrodynamic forces acting on both the ship immersed hull and the wind turbine floater.

As shown in Table 5, where the resulting deformation energies have been plotted, the OSV transfers clearly more energy into the FOWT plastic deformation as the order of magnitude of the ship mass is similar to that of the FOWT. The resulting collision

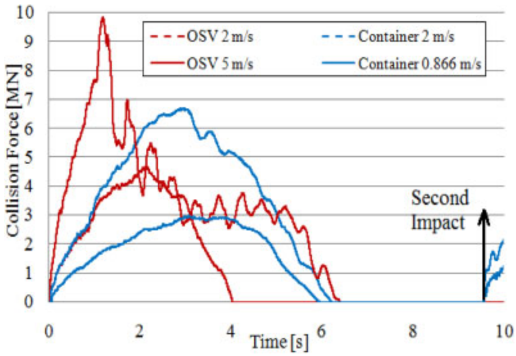


Figure 14. Collision force time history (2 vessels at different speeds).

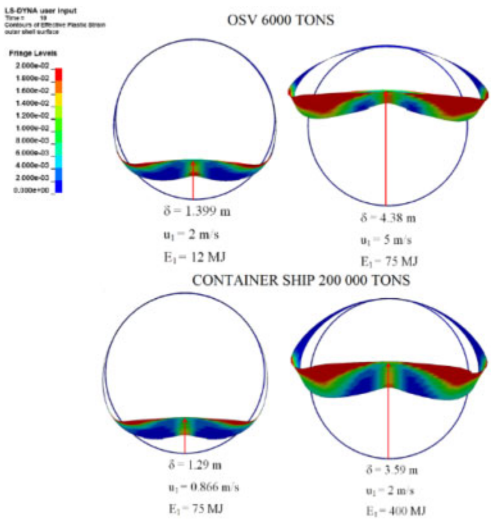


Figure 15. FOWT crushed area (two vessels at different speeds).

force plotted in Figure 14 reaches 10 MN, while it does not exceed 3 MN when the container ship strikes the FOWT at 0.866 m/s. In these scenarios the initial kinetic energy is the same (75 MJ).

Figure 15 shows the crushed area of the FOWT when impacted by the two ships at different speeds. Taking as an example the same initial kinetic energy 75 MJ, the OSV travelling at 5 m/s deforms the FOWT much more (4.4 m) than the container ship at 0.866 m/s (1.29 m).

The container ship at 2 m/s causes a penetration of 3.6 m, smaller than the deformation caused by the OSV at 5 m/s, with a penetration of 4.38 m. This confirms that the similar masses of the impacting bodies (and sufficient initial kinetic energy) lead to a more damaging situation for the FOWT. The OSV travelling at 2 m/s causes almost the same damage as the container ship at 0.866 m/s.

The subsequent contacts are also appearing faster for the container ship, this is because the ship keeps

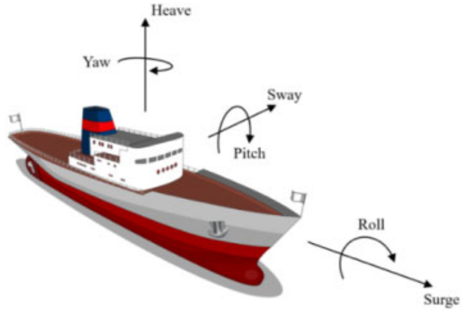


Figure 16. Example of ship translations and rotations.

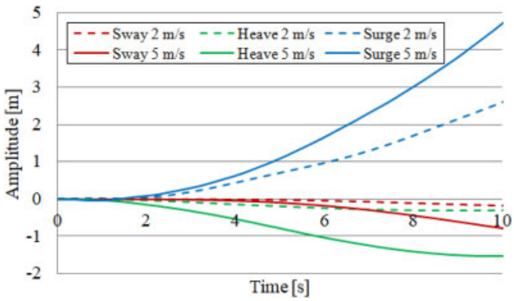


Figure 17. Translational response of FOWT time history (OSV at 2 m/s and 5 m/s).

a high kinetic energy, compared to the OSV, which transfers most of its initial kinetic energy to the FOWT.

Since the OSV seems to cause the most damage, for next analyses, only the OSV at 2 m/s and 5 m/s is used.

3.6 *Seakeeping response*

Seakeeping is known as the reaction of a floating body when it is subjected to waves (or any force that can change its current position). Translational movements along X, Y and Z axes are known as*surge, sway* and *heave*, and rotational ones are *roll, pitch* and *yaw* (Fig. 16).

These motions are important to predict the loadings on the nacelle, rotor and blades of the FOWT. Excessive motions would cause the capsizing of the floating structure, which would be the worst case scenario in a collision event.

Figure 17 and 18 present the translation and rotation time histories for a collision with an OSV at the two velocity cases studied (5 m/s and 2 m/s).

FOWT surge motion, which is obviously the most important as it correspondsto the direction of the collision, is responsible for the mooring line tension. Additionally, it is interesting to observe the movements in other directions as well, especially for the 5 m/s collision, where movements in heave and pitch are more noticeable. The pitch reaction endangers the FOWT, because it can accelerate the nacelle and consequentlylead to the failure of the turbine generator.

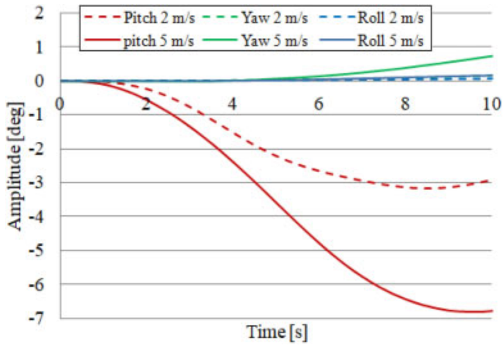


Figure 18. Rotational response of FOWT time history (OSV at 2 m/s and 5 m/s).

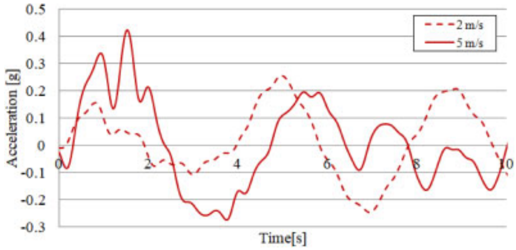


Figure 19. Accelerations at the generator time history.

3.7 *Nacelle response*

Bela et al.(2017) explain that electrical equipment is sensitive to high accelerations. Therefore, even if the FOWT can withstand a collision at higher speeds, the top accelerations can cause significant damage to the wind turbine generator. They also suggest limiting the axial accelerations on the generator between 0.2 g to 0.3 g at normal operation, so that any acceleration over this limit is considered as potentially dangerous.

Figure 19 shows that the longitudinal accelerations at the tower top (generator) reach up to 0.4 g, for the collision with the OSV at 5 m/s. considering the aforementioned limits; this means that the wind turbine generator may be damaged in such collision scenario. However, for 2 m/s scenario, the accelerations never exceed 0.26 g.

3.8 *Hydrodynamic and restoring forces*

The hydrodynamic characteristics of each colliding object (both the FOWT and the ship), obtained from *Hydrostar* seakeeping code calculation, are given to *LS-Dyna* as *.mco* files and *MCOL* subroutine solves the equations of motion of both floating bodies – see (Ferry, 2002). The rigid body mass matrix, hydrostatic matrix, buoyancy parameters, added mass matrix are the main parameters to define before running the simulation. It is also desirable toinclude in *MCOL* data files viscous damping parameters as well as wave radiation damping matrices calculated at different frequencies.

Figure 20 shows the time evolution of the virtual work of the hydrodynamic and wave forces (for the collision with an OSV at the speeds studied).

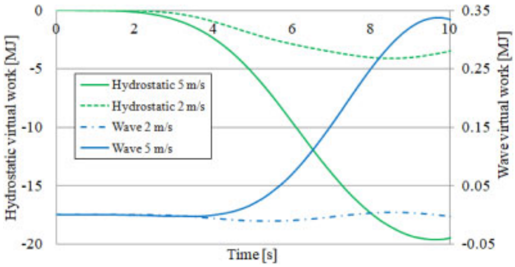
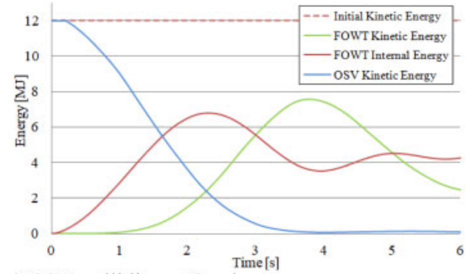
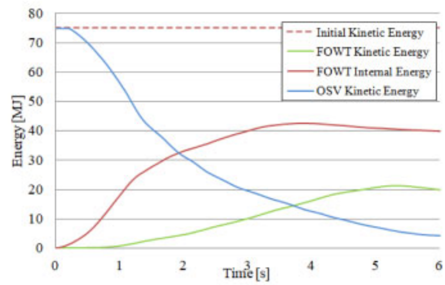


Figure 20. Virtual work by hydrostatic and wave restoring forces time history (OSV at 2 m/s and 5 m/s).



a) OSV colliding at 2 m/s



b) OSV colliding at 5 m/s

Figure 21. Energy balance time history (OSV at 2 m/s and 5 m/s).

The hydrostatic restoring virtual work corresponds to the heave displacement (Fig. 16), this is: if the FOWT sinks, the hydrostatic restoring forceincreases (as negative force), while opposite if the FOWT heaves upwards. The mooring system is then responsible of the restoring of the tower in surge, pitch, roll and yaw.

On the other hand, the energy evolution of the wave forces represents the energy dissipated through wave radiation, which is in the order of 20 times lower than the hydrostatic restoring work.

3.9 *Energy balance*

As it has been mentioned before, several forces act in the dynamics of the FOWT during and after a collision with a ship.

Figure 21 shows how the most significant forces maintain the energy balance in the first 6 seconds, which are crucial at the initial contact.

Table 6. Deformable OSV particulars.

Property	Value	Unit
Type	Bulbous bow	
Length	78	m
Breadth	17.6	m
Depth	13.8	m
Double bottom height	1.4	m
Total weight	5000	t

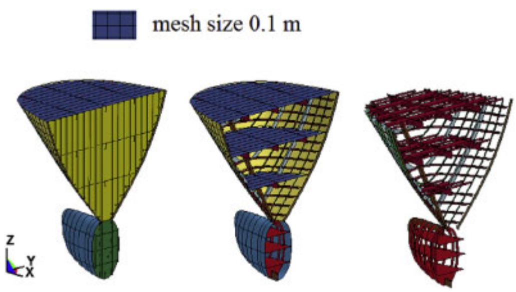


Figure 22. FE model of the deformable OSV. Bela et al. (2017).

The initial kinetic energy is transferred mainly to plastic deformation occurring in contact area and in the floater just above the ballast tank. It is noticed that at low collision speed, the elastic contribution is more significant (first peak in the internal energy curve) while at high speed the deformation is mainly plastic.

It is also noticeable how the kinetic energy of the FOWT increases when the ship has already transferred at least half of its initial kinetic energy, when a high deformation level is reached. This is due to the rigid-body surge, heave and pitch movements of the FOWT.

4 SIMULATIONS WITH A DEFORMABLE SHIP

As aforementioned, first simulations were run considering the striking ship as rigid. However, in real life the ship will deform as well and the deformation energy will be shared between the two structures. In order to quantify the part of energy absorbed by the ship, numerical simulations have been performed considering a deformable OSV, with main particulars defined in Table 6 and Figure 22.

All the other conditions from previous simulations are kept, hydrodynamic calculations with *MCOL*, lumped mass on top of the tower, solid ballast in the tank and mooring system as cable beam elements, but gravity loads are not considered.

As expected, the energy dissipated by the FOWT decreasesgreatly when the striking ship is deformable (from 40 MJ to 9 MJ at 5 m/s). Moreover, after some time, half of the total internal energy has been dissipated by plastic deformation of the ship bow, for both speeds (Fig. 23).

At lower collision speed (2 m/s), the contact occurs only at the bow area, but for a collision at 5 m/s,

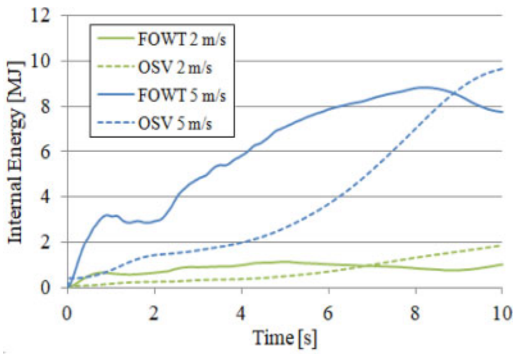


Figure 23. Internal energy time history for OSV and FOWT.

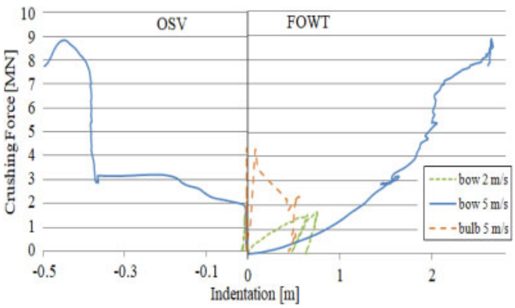


Figure 24. Crushing force vs indentation.

Table 7. FOWT tower indentation (m).

	2 m/s	5 m/s
Rigid bow	1.4	4.4
Deformable bow	0.76	2.6

the bulb collides the tower at a second impact. The bow impact is clearly the most important in terms of deformation, both for the OSV and FOWT. Finally, Figure 23 also indicates that in the case considered in this study, the ship bow indentation is greatly smaller than that of the FOWT, being the collision much more damaging for the FOWT integrity.

Figure 24 illustrates the crushing forces as function of the local indentation for the two velocities, showing the difference between the ship (on the left) and FOWT (on the right).

Moreover, it is interesting to note that the indentation of the FOWT is almost half when a deformable bow considered, as shown in Table 7.

5 CONCLUSIONS

This study is an initial step for building a simplified analytical method in order to study the crashworthiness of a FOWT in the pre-design stage.

As a first approach, non-linear finite element simulationswere run consideringthe striking ship as rigid, which gave some insights of the FOWT behavior upon a collision event:

- The initial kinetic energy is of great importance in the FOWT response (i.e. ship mass and initial velocity), this determines the type of deformation and dynamic behavior.
- The main deformation modes governing the FOWT are: plastic indentation in the collided area, beam-like elastic response of the overall FOWT, plastic deformation near the ballast-level, surge displacement and turning pitch moment.
- Taking into account the effects of hydrodynamic forces is necessary when studying ship-FOWT collision as the floater external dynamics governs the FOWT crushing response.
- Some other parameters are important to take into account during such analysis: ballast and nacelle massesas well asaction of the mooring cables.
- Gravity does not influencethe early-time response of the FOWT; however, this parameter should probably affect the post-collapse response of the FOWT and mooring system.
- A collision at a speed near 5 m/s or more, would be very dangerous for the FOWT integrity, regardless the ship size.
- Since the electrical equipment is sensitive to high accelerations, the tilting response and surge displacement of FOWT may cause significant damage to the generator.

When the ship deformability is taken into account, it appears that the structure might not suffer such a great deformation. Furthermore, it is observed that in a longer response, the ship may absorb half of the dissipated energy, even if resulting bow indentation is very small in comparison to that of the FOWT. For a 5 m/s collision, the bulb also impacts the FOWT, causing additional deformation to the tower. This means that considering the ship as rigid is very conservative for the FOWT reaction analysis.

It is understandable that this type of analyses require several simulations in order to widely understand the crashworthiness of a FOWT. For the complete risk analysis of a floating wind farm, a lot of scenarios, involving different types of ships at different velocities, will have to be considered. It is thus clear that a simplified tool based on analytical formulations, coupling internal and external mechanics, may be useful not only in FOWT early design stagebut also for ship traffic regulation purpose.

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