POLITECNICO DI TORINO

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Master Thesis

Finite element analysis and redesign of the UMaine VolturnUS-S floating platform in MOST and Ansys.

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Abstract

In the last years, offshore energy is getting an increasing role within the renewable energies. The growth of this new type of energy has been possible thanks to the development of new technologies. One of the fundamental associated technologies which makes possible the implementation of offshore energy are the floating platforms, in which the wind turbines are sustained. This project focuses on the redesign and testing of an existing floating platform model, the UMaine VolturnUS-S. This model will be simulated in different static and dynamic conditions in order to understand its structural behavior. In addition, its geometry will be modified in order to ensure its structural stability in the conditions simulated. Parallel to that, a new process for validating the design will be developed and tested with this model. This new validation process, based on the standardized one, will try to simplify it in order to save time and computational costs. Finally, a study of the different critical parameters of the simulations performed for the validation process will be done in order to understand its real influence and importance at the time of validating the structural stability of the platform.

1. Introduction.

The use of fossil fuels has implied, since the industrial revolution, a transcendental change in the evolution of the humanity, leading to the biggest technological development in history and bringing to the people a welfare level as never seen before. However, in the last decades, some problems derived from the increasing global energy demand, and the excessive use of fossil fuels to satisfied it, has led to the apparition of some of the most critical challenges for the humanity: the climate change, the air pollution, the destruction of the environment and the end of some natural resources.

To reduce this problem, humanity has focused in renewable energies, a sustainable and clean alternative to fossil fuels, putting all its effort in its development. This type of energy englobes those sources which don't deplete natural resources as are replenished naturally. Furthermore, in opposition to fossil fuels, this kind of energies don't produce emissions that contribute to climate change and air pollution. However, renewable energies still face problems that makes it, in many cases, less competitive than the non-renewable ones. But the increasingly global awareness of the necessity of a fully implementation of these types of energy for the good of the planet and the humanity makes this kind of energies a firm intent of present and future.

Within the different renewable energy types, wind energy is for sure one of the most important one. This type of energy harnesses the power of the wind to generate electricity, using for this purpose wind turbines which convert the kinetic energy of the wind first into mechanical energy, and this finally into electrical energy through a generator. Wind energy can be classified in two categories according to the location of the turbines: onshore and offshore wind energy.

Onshore wind energy refers to the wind energy obtained by turbines on land. Its main advantages are its relative cheap cost, which allows the implementation of big wind farms; the less electric losses in the energy transportation, as the distance between the windmill and the consumer ports are low; and the easy and quick installation of the wind turbines [1].

However, its main disadvantages –the visual and noise pollution of its implementation and the inconstancy of the energy production due to the often poor inland wind speed and the physical blockages such as hills- are promoting offshore wind energy to be more and more relevant.

Offshore wind energy is the one obtained by turbines located over open water, usually in the sea. Its usual location, far out at sea, is the cause of its main advantages: its windmills can be larger and taller than the onshore ones and the wind farms that can be built are way larger, allowing for more energy collection. Also out at sea, the wind speed and forces are higher, so that the instant energy generated is bigger, and the consistence of the wind is also higher than inland. For last, but not less important, its impact in the environment is much lower.

Nevertheless, this type of wind energy has also its disadvantages, which basically are its transportation, building and maintenance costs, which are also sum to the higher breaking risk, as the weather –and so structural- conditions are more extreme. Anyway, high efforts are being done for solving these technological problems, as this offshore wind energy is seen as a highly promising renewable energy.

One interesting way to see the increasingly importance of the wind energy is attending to its last years' statistics. In less than 15 years, the global cumulative wind power has increased around a 425%, passing from 159 in 2009 to 837 GW in 2021 [3]. Although the weight of onshore wind energy in this favorable evolution has been, without any doubt, higher; the relevance of offshore energy has been year by year greater, as can be seen in the graph below. In it, the evolution of wind energy capacity in Europe in the last years is shown.

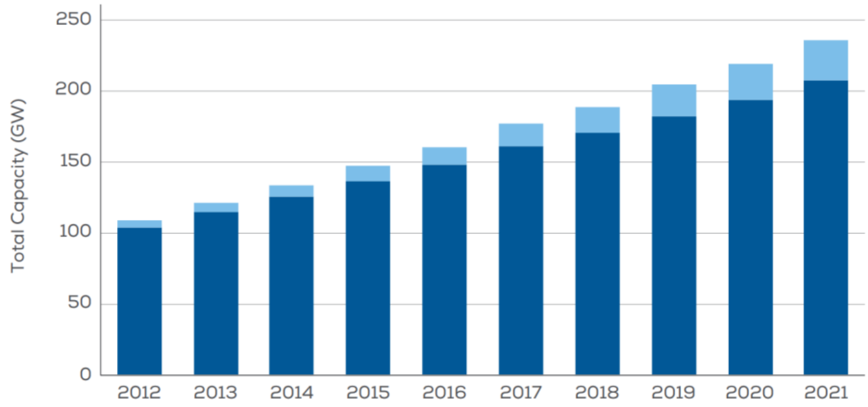


Figure 1: Wind energy capacity evolution in Europe,2012-2021 [4]

The progress in the implementation of wind energy is enhancing year by year. In that way, only in 2021, 93.6 GW of new wind power capacity was added worldwide, which means a growth of 12,4 % in the total installed capacity compared to the previous year [3]. The role of Europe in this increasing trend is substantial, becoming the third main wind energy producer only behind the US and China, with 17GW of new wind energy capacity installed in the last year. From all the European countries, the UK is clearly the one which contributes the most, with 6 GW, which means around 35% of all the European new wind energy installed.

Despite this positive trend, the capacity installed in Europe until now is far away from achieving the objectives defined in the 2030 Climate and Energy goals. In fact, the current total wind energy production (437 TWh) can only satisfied a 15% of the Europe Electricity consumption (2921 TWh). However, the future development previsions of wind energy, and specially the offshore one, give reasons to hope.

In that way, the offshore wind energy capacity was, in 2021, of 57 GW, which represented a 7 % of all the wind energy installations. However, since 2010, the global wind offshore market has grown nearly 30% per year, thanks to the fast technology improvements. Hence, around 150 new offshore projects are being developed around the world [2].

As said before, Europe's role in this development has been and need to continue being crucial. In that way, only in 2021, 17,4 GW has been installed there, of which 3,4% comes from offshore energy. The total offshore power installed in Europe is, nowadays, of 28 GW. The majority of this quantity is provided by the UK, followed by Germany, France and Netherlands.

Attending to the "Global Wind Report 2022", the annual global offshore capacity is expected to grow from 21.1 GW in 2021 to 31.4GW in 2026, which will imply an increment of the offshore new installations from 22% now to 24% in that dates. However, these good predictions are insufficient to ensure the objectives defined in the Paris Agreement targets and the net zero by 2050 goal [3].

Anyway, the technological improvements and economic efforts that are and will be done make the offshore energy as one of the most promising renewable energies in the next future. In the picture below, the European offshore evolution prediction for the next years is shown.

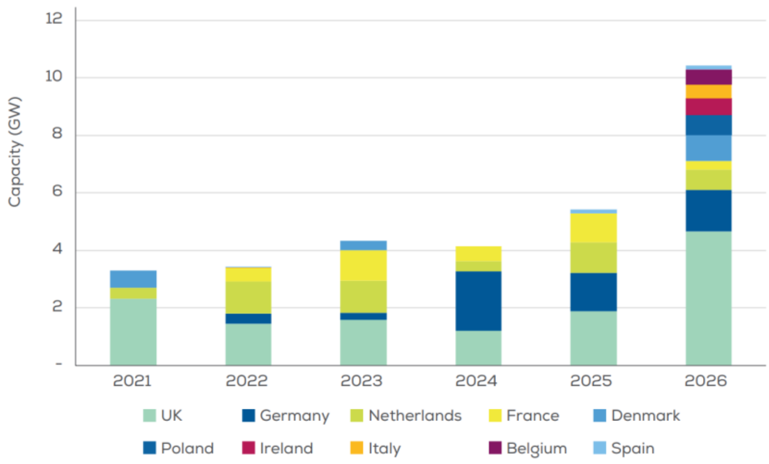


Figure 2: New offshore installations per country between 2022 and 2026, realistic expectations scenario [4]

As wind technology is improving at great strides (mainly due to the bigger turbines), the capacity factor –average input power over a year compared to the maximum rated power capacity- of offshore energy is increasing in a considerable way. Thus, nowadays, the offshore electricity production has similar capacity factors than other -considered until recently- more competitive technologies such as gas and coal fire generation; and already exceed the capacity factors of other clean energies as solar photovoltaics or the same onshore wind generation.

However, the offshore wind energy has a high variability, in time and location. Thus, its hour by hour fluctuation is of around 20%. Furthermore, the wind resource level highly depends on the geographical location, being higher near the poles. As shown in the picture below, the capacity factors are different in the different regions of the world, taking values between 45-65% in Europe's Atlantic seas, 40-55% in the US, 35-45% in China and Japan, 50-65% in South America and New Zealand, and 30-40% in India. The productivity on each region varies, also, over the year. In that way, the winter season is the higher productivity one in China, Europe and US, while in other regions such as India the productivity is higher in summer.

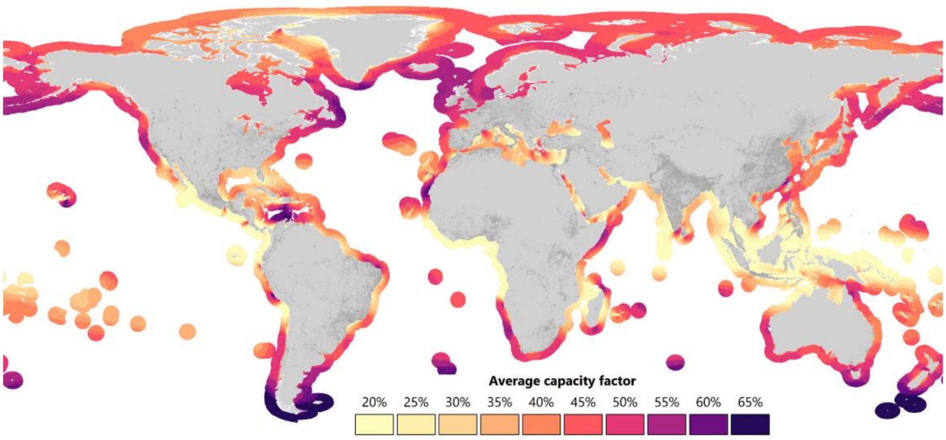


Figure 3:Average simulate capacity factors for offshore wind worldwide [5]

Until now, most of the offshore projects that have been developed and implemented are located in near shore locations, mainly due to its high efficiency electricity transportation. However, as times goes on and technology improves, more and more projects are developed in deeper waters, in places further away from the coast. The far-offshore energy, defined as the one installed in waters of more than 50 meters' depth, has the main advantages of a better wind quality and the vast space usable for that kind of projects, in comparison to the near-offshore energy in which the locations are much more exhausted and the proximity to the coast produces a lower quality of the wind.

The specific characteristics and conditions of this far-offshore spots make necessary the implementation of new technologies adapted to this environment. The main technological change with respect to the near-onshore energy is the type of platform used. While on near-onshore projects the fixed platforms are the most commonly used, the impossibility of implementing this type of platform in deep waters has led to the development of the floating platforms, which consist in rigid structures which support the turbine and are connected to the ground by mooring lines. In that way, the amount of material needed, and thus the cost of production, is much lower. In fact, nowadays, much companies are implementing this kind of solution even in less deep waters, (mostly in projects with a water deep of 50-60 meters).

Attending to its structural typology and mooring system, there are four main types of floating platforms: spar buoy, semi-submergible, barge and tension leg platform (TLP). Each of them has its own advantages and disadvantages, as explained below [6].

- **Spar buoy**: consist on weight-buoyancy stabilized structures with a cylindrical shape, connected to the ground by catenary mooring lines with drag-embedded anchors. Its simplicity makes it to have an easy fabrication, quite good stability and cheap mooring installation, as well as fast decommissioning and good maintainability and corrosion resistance. All of these characteristics make this system quite adequate for swallow waters (100 meters deep or more). However, it presents some disadvantages with regard to the other typologies, as its high costs of transport and repair.

- **Tension leg platform**: consist on vertically moored floating structures connected to the ground by tethers or tendons, anchored by suctions pile anchors. Its strong points are its higher stability compare to the other types, added to its low sensitivity to wave-induced motions. This implies a low buoyancy tank costs and complexity. Furthermore, it has a good corrosion resistance and a low footprint. Those characteristics makes it ideal for medium deep waters (50-60 meters). However, it has some disadvantages, concerned to the mooring typology, which are its high installation cost and the limitation in its possible locations, as its positioning in waters deeper than 60 meters is technically and economically unaffordable.

- **Barge:** consist on buoyancy stabilized mono-hull structures with a large water plane area and relative small draught; connected to the ground by a catenary mooring system. Its main advantages are its relative low anchor costs and the faster decommissioning time; as well as its relatively easy transportation and installation. However, has a lower stability compared to other typologies. Due to these characteristics, barges platforms are used in both swallow and deep water locations (beyond 50 meters).

- **Semi-submersible:** consist on buoyancy and free surface stabilized structures formed by a number of large columns linked to each other by bracings. These columns provide the ballast and flotation stability [7]. Although it doesn't present a high stability and its fabrication costs are high, is a popular option due to its high versatility of locations, as can be positioned in either shallow and deep waters. Moreover, this solution presents an easy and cheap transportation and installation, as well as low costs for the mooring system and of repair.

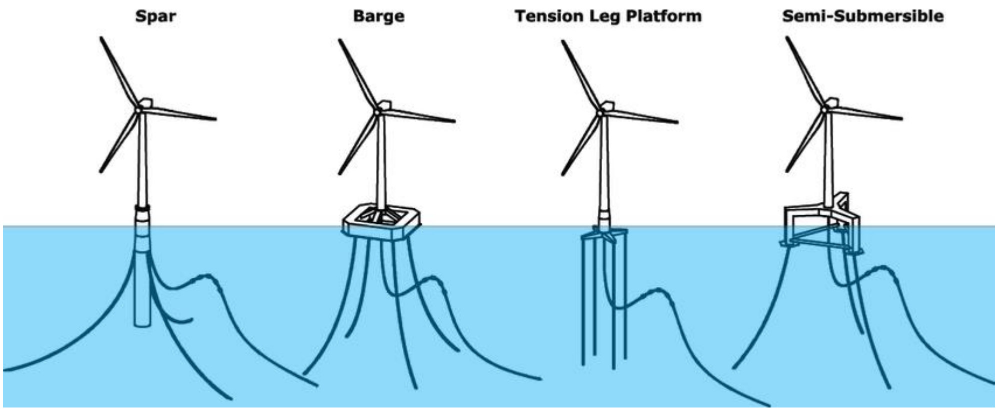


Figure 4: Main floating platform types

In this project, we focus on the development, design and validation of a semi-submergible platform, using as a base the model *UMaine VolturnUS-S* developed by the University of Maine. This model will be simulated, firstly, in the simplest situation, which is the hydrostatic case, in order to evaluate its structural behavior and consider possible re-design improvements if it is required.

Next step will consist on the validation of the model in the most extreme situations, which implies the realization of dynamical simulations which modeled the most extreme conditions defined by the standards. During the validation process, several re-designs will probably need to be implemented to ensure the structural stability of the platform, obtaining in that way the definite design.

As the standardized process of validation requires high times and computational costs, in this project a simplification of this process is suggested, implemented and evaluated with the platform.

2. Hydrostatic case. Simulation and re-design of the platform.

The objective of this section is to simulate the hydrostatic case in the *UMaine VolturnUS-S* reference platform. This primary case will serve us to settle the basis for future, more complex simulations, in which the dynamical loads will be include. It will help us also to understand the structural nature of the platform, and determine which points are more critical for its stability.

Once the basic geometry is simulated with the hydrostatic case, it may be necessary to redesign it for guarantee its stability with regard to the hydrostatic loads, and also for the dynamic case, in which the mechanical requests will be quite higher. The platform redesign will consist on adding internal structural ribs which will add robustness to the geometry, allowing it to withstand better the loads.

One problem which is presented at the time of making the hydrostatic simulation in the ANSYS software is how to model the buoyancy condition of the platform. In this chapter, we will also expose how to deal with this problem and explain the solution we have adopted.

2.1 UMaine VolturnUS-S Reference Platform. Definition and main characteristics.

The geometry from which we started to do the analysis is the *UMaine VolturnUS-S* reference floating platform. This structure, developed by the University of Maine, is a steel semi-submersible offshore platform designed to support the *International Energy Agency (IEA)-15-240-RWT 15-megawatt (MW)* reference wind turbine.

The kind of platform we will analyze is semi-submergible. These types of platforms are buoyancy and free-surface stabilized structures, in which a part of the hull is submerged, whereas the upper part is beyond the sea water level.

These kinds of platform often consist on a group of columns disposed in a symmetrical way with respect to the vertical axis, with a central column in which the tower of the turbine is supported. The columns are often connected by a base. Both the columns and the base are material-empty inside, and so, contains solid or water ballast there. This ballast allows to compensate the high values of hydrostatical pressure, which otherwise would damage the structure.

The main characteristics of these kinds of platform, which distinguishes them from the other ones, are a low stability and a complex fabrication, disadvantages which are compensated by its versatility, as it can work either in shallow or in deep waters; its relatively easy transportation and installation; the low mooring cost; and the low costs of repair.

The *UMaine VolturnUS-S* reference platform consist on three external columns, made of structural steel and empty inside. These columns are disposed in a radial way, in an external circumference whose center is a central column, also from steel and empty inside. The turbine tower is supported by this central column. The external columns are disposed in a symmetrical way with respect with this central column, so the angle between each two of them is of 120 degrees. The four columns are connected by a base, also made of steel and empty inside. Each external column is also connected with the central column by a tube located in the top. The platform is moored by a system based on three pre-tensed lines, which connect each of the external columns with the ground.

In a static condition, the platform is design to be submerged so that the sea water level is located at a distance of 15 meters from the top. In that way, platform protrude a height of 15 meters from the sea level, and the rest of 20-meter height is submerged. The measurements of the geometry are given in the following figure.

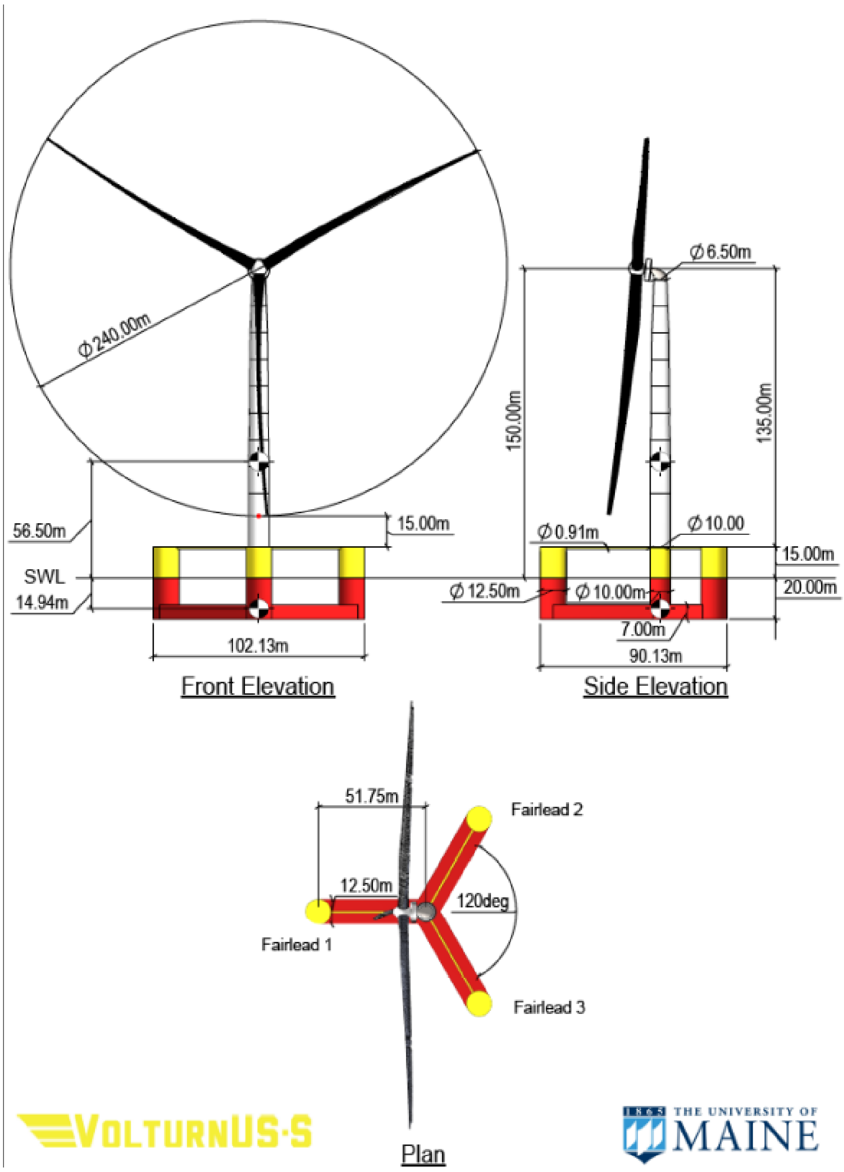


Figure 5: Layout of the VolturnUS-S platform. [7]

The platform's weight, with the ballast include, is of 17,839 t: of which 3,914 t is structural steel, and the rest is ballast. Part of the ballast is concrete, and the other one consist on water ballast. The concrete ballast is placed in the base of the three external columns, while the water ballast is placed inside the whole base, and also in the four columns. The exact distribution of these quantities are not given in the University of Maine's report, so we will estimate it basing on the structural design. The central column holds a weight of 2254 t, which is the sum of the tower and the RNA mass. With this configuration, the platform displaces a volume of 20206 m^3 of sea water, assuming a water density of 1025 kg/m^3 [7]. The general properties of the platform are given in the table below.

Parameter	Units	Value
Platform Type		Semi-submersible
Total System Mass	t	20093
Platform Mass	t	17893
Hull Steel Mass	t	3914
Ballast Mass (Concrete/Fluid)	t	2540/11300
Tower Mass	t	1263
RNA Mass	t	991
Hub Height	m	150
Freeboard	m	15
Draft	m	20
Vertical Center of Gravity from SWL	m	-14,94
Hull Displacement	m^3	20206

Table 1:Floating Offshore Wind Turbine General Properties[7]

The type of steel used for the hull is not even specified in the University of Maine's report, so it's also a design decision which corresponds to us. Due to the extremely high mechanical stresses to which the structure will be subjected, a high resistance steel for sheets and profiles (S450) is used. Its main properties are exposed in the table below.

Type	S450	
Density	7850	Kg/m^3
Young Module	210.000	N/mm^2
Shear rigidity's Module	81.000	N/mm^2
Poisson's coefficient	0,3	
Tensile yield strength	410	N/mm^2
Compressive yield strength	410	N/mm^2
Tensile Ultimate strength	550	N/mm^2
Thermal dilatation coefficient	$1,2 \cdot 10^{-5}$	$^{o}C^{-1}$

Table 2:S450 steel properties[8]

The thickness of the steel structure is not given in a direct way in the University of Maine's report, but it can be computed easily as the weight and density of the steel are known. However, we won't consider this as a fixed parameter, as it is critical for the structural stability, and it may need to be changed in the different simulations for allowing this stability.

2.2 Hydrostatic case modeling in ANSYS.

The hydrostatic model is the simplest case of study, as it only takes into account static loads, which have a stationary nature, and so, don't vary on time. The static loads which are taken into account in this simulation are: the gravitational force, the hydrostatic pressure, the tower and turbine weight and the mooring pretension force.

The first step to do is to determine the ballast configuration, which, as we said before, is not completely define in the University of Maine's report.

The ballast used in the platform is divided in concrete ballast and water ballast. As it is said in the report, the concrete ballast is equally distributed in the three external columns. Taking into account a concrete's density value of 2400 kg/m^3, and the columns dimensions, is possible to compute the height of the concrete's columns. In this way, the external columns are fill with concrete ballast until a height of 2,88 m.

The water ballast is applied inside the base of the platform, as well as in the four columns. In order to compensate the external hydrostatic effect in the base, which cause extremely high stresses and deformations in its thin hull, it is necessary to fill the whole volume of the base. This design decision makes also necessary to fill the four columns with water, until the ballast height is leveled.

With this configuration, the water ballast weight is a little bit higher than the theoretical value computed in the University of Maine's report. This imply an increment in the whole platform's weight, and so, an increment of the draft surface of the platform. In other words, it causes an increment in the platform's density, and so, it is more sunken. However, as the weight increment is not considerable, (less than 13%), the Sea Water level is considered to be the same. The thickness of the steel hull, for allowing its theoretical weight value, is of 45 mm. The new weight configuration is represented in the next table.

	Theoretical configuration	**New configuration**
Steel hull	3914	3914
Concrete ballast	2540	2540
Water ballast	11300	13664
Total platform	17839	20118
Increment		12,8%

Table 3: New weight configuration

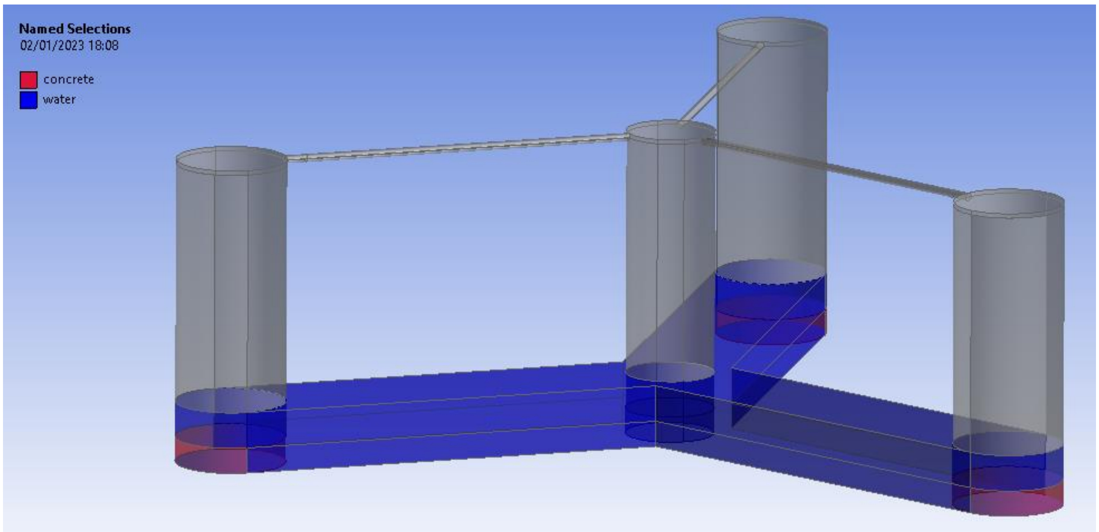


Figure 6: Ballast distribution

The external hydrostatic pressure is applied to the external faces of the platform, except in each surfaces which correspond with the concrete ballast. To simulate the rigidity of these faces, no load is applied there.

The internal hydrostatic pressure is modelled as a negative pressure applied in the external faces of the base, and in the part of the columns associated with the water ballast. The values of this internal pressure are given in ANSYS as an external data input, in which for each node, a hydrostatic pressure is computed using the law:

$$Ph.int(z) = -\rho water \cdot g \cdot z$$

where $\rho water$ is the sea water density, with a value of 1025 kg/m^3; g is the gravity acceleration, consider as 9,81 m/s^2; and z is the relative height coordinate with respect the Sea Water Level frame, in absolute value.

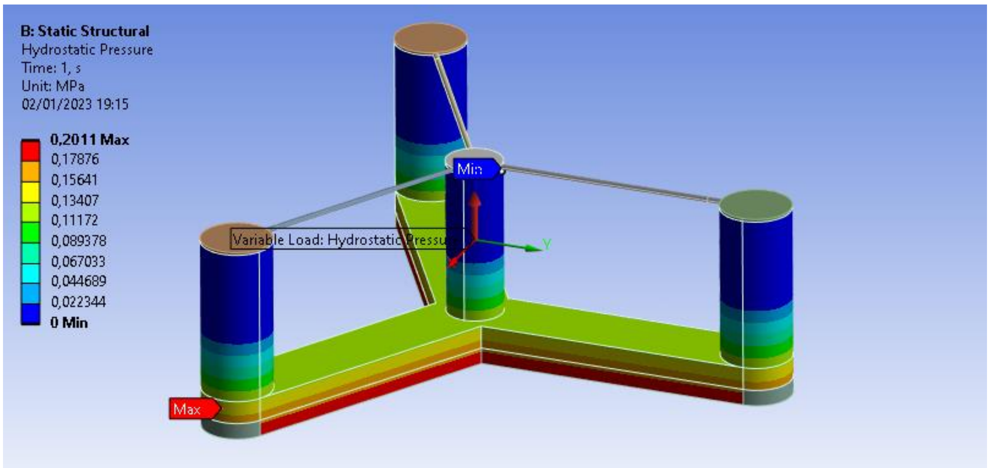


Figure 7: External hydrostatic pressure distribution

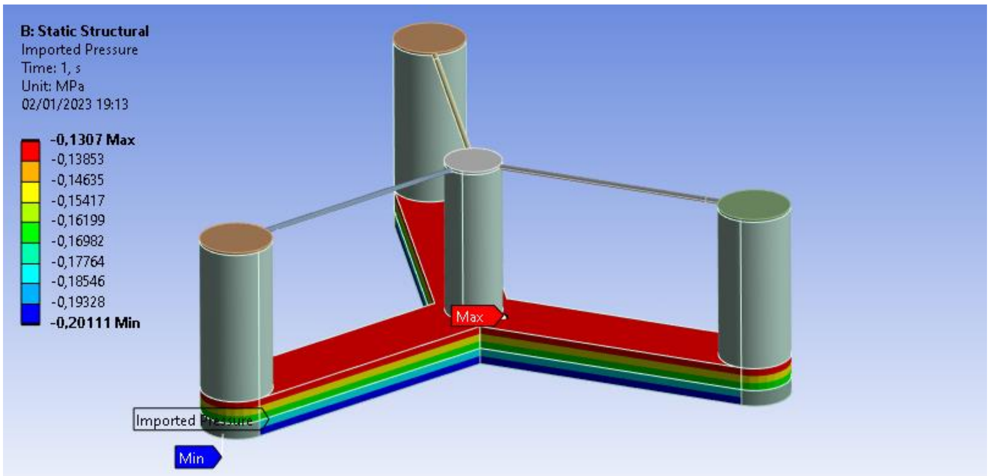


Figure 8: Internal hydrostatic pressure distribution

The turbine and tower weight is applied as a distributed surface force in the top face of the central column. For simulating the effect of the gravity force in the whole platform, it is necessary to include a point mass which simulates the weight of the ballast, located in the center of gravity of the platform which is situated in the central column at a distance of 14,94 meters below the sea water level.

To complete the model settings, it’s necessary to add a constraint which allows the simulation to converge to a solution. Because of the nature of the situation we want to model, based on a body which is floating in the water, the constraints which are normally used in the static analysis (such as fixed supports or displacements constraints) cannot be used in this case. The selection of a constraint which simulates the floating condition will be discussed in the next section.

2.2.1 Implementation of the buoyancy constraint in the hydrostatic model.

As said before, the election of a constraint which represent in a proper way the buoyancy of the platform is critical to obtain coherent results. The buoyancy condition is based on an equilibrium between the platform and the sea water, in which the displaced volume of water -due to the submerged volume of the platform- produces a buoyancy force in the platform, which compensates the negative vertical forces (gravity and the tower weight). In this way, the platform floats in a static equilibrium.

The way to represent the buoyancy condition in ANSYS is by activating the Inertia Relief option. This option allows to balance the total force applied in a static model using acceleration body forces over the whole structure. This acceleration compensates the vertical force applied in the body, obtaining a static equilibrium of the same nature of the buoyancy one.

The main problem when applying this type of condition is that it requires that the mass of the platform needs to be perfectly represented. In that way, the model is not under-constrained and the simulation converges to a solution. To facilitate this convergence, the "Weak Springs" ANSY's option needs to be activated. When this option is activated, the solver creates a number of artificial springs attached to the body, which allow a perfect static equilibrium. However, it must be checked that the magnitude of this spring forces is quite lower than the real forces applied in the model, so that its influence in the result is negligible. In that way, the Weak Springs don't distort the result.

In our particular case, the virtual acceleration generated with the Inertia Relief must compensate the vertical forces applied in the platform: the platform weight and the tower and turbine weight.

$$Platform\,weight + Tower\ forces = m_{platform} \cdot\ a_{I.Relief}$$

If we solve the original case, with the platform weight recomputed (20118 t), and a tower force value of $2{,}2\cdot 10^7$ N, the theoretical virtual acceleration computed is of 10,9 m/s^2. The value of the inertia relief acceleration computed by the solver and used in the simulation is 12,1 m/s^2. The reason of this difference of values means that the platform weight is not perfectly equilibrated, and justify the necessity of using weak springs. However, the low value of these weak spring forces confirms that the buoyancy state is properly modeled.

ANSY's Inertia Relief have also a physical interpretation which is interesting to underline. The virtual acceleration used in the simulation substitutes the buoyant force applied by the displaced water to the platform in the real situation. In this way, the buoyant force, which can be expressed as

$$F_B = \rho_{water} \cdot V_{displaced} \cdot g$$

is substituted by a virtual force, with expression:

$$F_{I.R} = m_{platform} \cdot\ a_{I.R}$$

The theoretical buoyant force, computed using the displaced volume given by the University of Maine's report, implies a virtual acceleration of 11,38 m/s^2, which differs with the one computed in the simulation because of the reasons explained before.

To end with this chapter, it's interesting to highlight the role of the hydrostatic pressure in the model defined in ANSYS. As it happens with the real case, in the model defined, the hydrostatic pressure is linked to the buoyant force which allows the platform to float. Hence, the external and internal hydrostatic pressure are implicitly represented in the virtual acceleration force generated by the Inertia Relief, and in the weight of the platform's ballast.

2.3 Analysis of the results of the hydrostatic simulation

To complete the simulation settings of the hydrostatic model, a convergence mesh analysis has been done, obtaining the mesh parameters showed in the table below. This mesh configuration will be used as well in the future simulations of the hydrodynamic cases.

Element size	**1,5308 m**
Mesh defeature size	**7,654 mm**
Curvature min size	**15,308 mm**
Curvature min angle	**30º**

Table 4:Mesh configuration parameters

The results obtained from the hydrostatic simulation show extremely high values both in stresses and deformations. These values exceed in a significant way the structural limits of the platform, and so, will be required to do a redesign of the structure.

In terms of stresses, the highest values are located in the top of the central column, the contact surface in which the tower and turbine weight is transmitted to the platform. In all this region, the stresses exceed the yield strength of the steel (410MPa), becoming up to six times this value in the points with the highest stresses (2500 MPa). The stresses reach the maximum value in the border of the top surface, in the regions of connection with the top tubes.

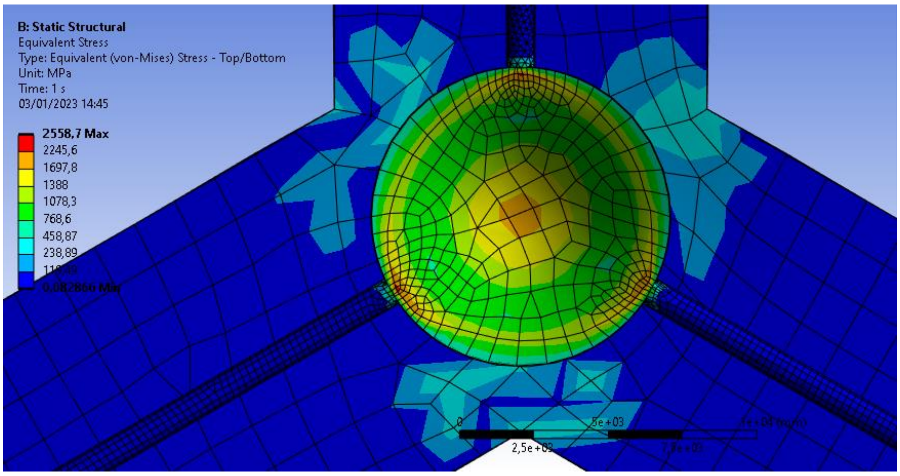


Figure 9: Stresses in the top surface of the central column

This result shows a trend which will be repeated in future simulations, even in the dynamical case, which is the relevance of the tower forces in the structural stability of the platform. The effect of these forces is quite higher than the one of the water ones (hydrostatic and hydrodynamic loads). As we can see in the figures below, the effect of the hydrostatic pressure is negligible compare to the effect of the tower weight.

Besides the top surface of the central column, stresses are also relevant in the upper and bottom corners of the base, due to the displacement of the central column, which generates stresses in the connection zones with the base. In these regions, the stresses exceed also the yield strength.

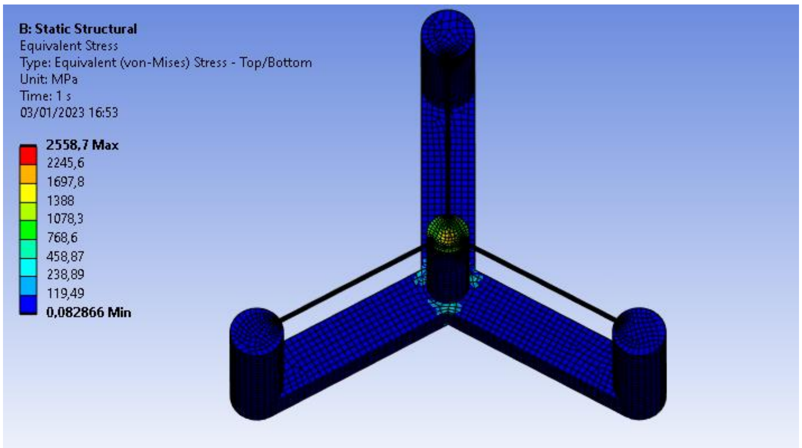


Figure 10:Stresses distribution in the platform (front view)

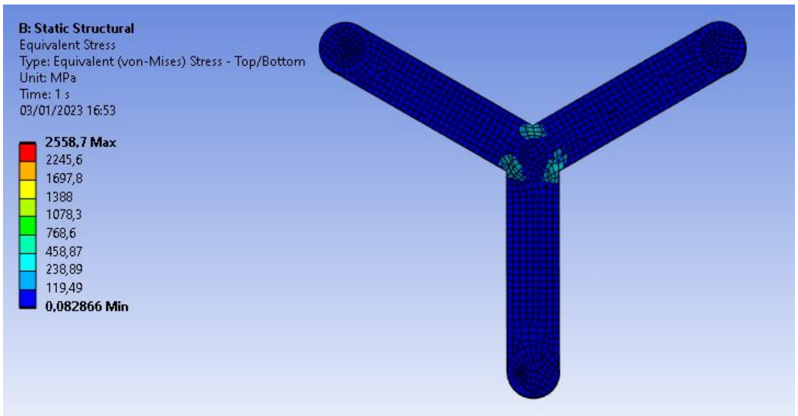


Figure 11: Stresses distribution in the platform (bottom view)

The effect of the high stresses in the top of the central column is an extremely high deformation on this surface, which basically means that the surface can't withstand the loads there, and would fail.

The results show the necessity to redesign the geometry in order to reduce the stresses in the central column to acceptable values, way lower than the yield limit, and so, guarantee the structural stability even in more demanding situations which will be simulated after. Two possible solutions ca be implemented [9]:

- Internal reinforcement of the platform adding structural ribs in the critical regions. These ribs will give robustness to the structure and allow to distribute the loads in a better, softer way so that the stresses in the platform decrease in a significant way.
- Filling the central column and other critical regions, with heave plates without interior free volume. This would heavily increase the rigidity of the structure, minimizing the stresses and deformations due to the tower forces and directly removing the effect of the hydrostatic pressure.

Although the second solution seems to be more effective in terms of structural stability, it's not chosen as the first option to develop as it requires high quantities of material, which compromise the floatability of the platform and also highly increase the costs of production of the platform. In this way, the redesign of the structure will consist in the reinforcement of the critical areas of the platform using internal ribs.

Lastly, it's interesting to understand the effect of the hydrostatic pressure in the stresses and deformations distributions in the platform. As said before, this effect is negligible compared to the one of the tower and turbine weight, and so, is not visible in the previous simulation. To watch the hydrostatic pressure effect, it's necessary to do a new simulation in which the tower loads are suppressed, so that the hydrostatic pressure is the only external effect, apart from the platform weight and buoyant force.

The results of this new simulation show that the effect of the hydrostatic pressure in the hull is concentrated in the column regions where exist a transition between the internal ballast and the gap zone.

In these areas, a big pressure difference exists, as it turns from zero in the surfaces in which the ballast is applied (in which the external and internal hydrostatic pressure compensates each other); to a significant value in the surfaces with a gap inside (in which the internal pressure is zero, and so, the difference of the pressures is equal to the external hydrostatic pressure).

This phenomenon produces a deformation in these areas, which is actually negligible (less than one millimeter), and a stresses distribution which doesn't compromise at all the structural stability of the platform (the maximum value is lower than 19 MPa). However, it's interesting to know how the hydrostatical pressure affects the platform, as its behavior with respect to the dynamical pressure of the waves will be similar.

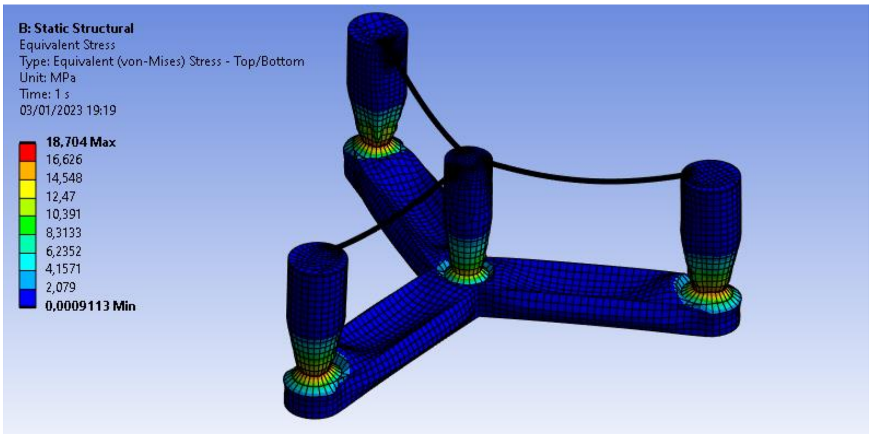


Figure 12: Effect of the hydrostatic pressures in the stresses distribution

2.4 Redesign of the platform

The redesign of the platform is based on the addition of internal ribs in those critical regions of the geometry in which the loads effects are appreciable and can produce a structural instability. The application of internal ribs in these regions will give the structure a higher robustness, and will allow a better distribution of the loads.

The regions in which internal reinforcements are considered necessary are: the central column, which carry the tower and turbine weight; the connection between the central column and the platform base; the external columns, in which the hydrostatic pressure effect is higher; and the inside of the platform base.

The central column is the part of the platform which mostly needs a reinforcement, as it holds the turbine tower, whose high weight is fully transmitted through its top surface. Due to the homogenous nature of this load, which is transmitted in a uniaxial way through the heave direction, the reinforcement distribution which is considered consist on four steel panels placed perpendicular and connected in the center, forming a cross. This distribution will give to the column a high stiffness, and allows to distribute the tower weight in a less concentrated way, reducing the stresses in the top surface.

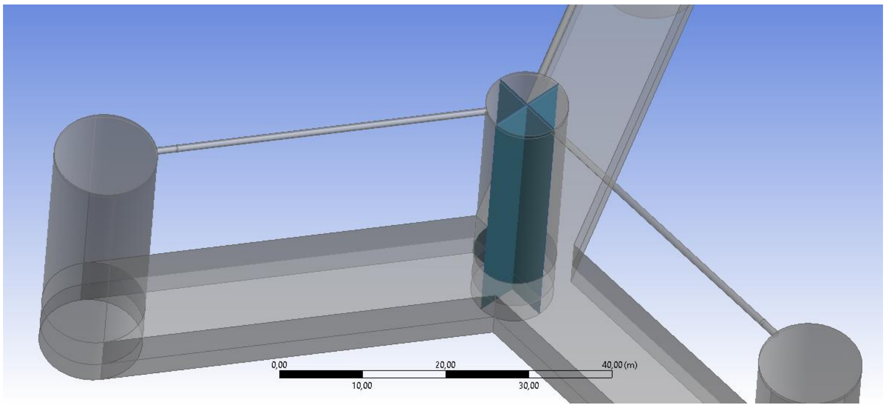


Figure 13: Internal ribs in the central column

Other region which needs internal reinforcement is the connection between the central column and the platform base. As shown in the hydrostatic simulation, this region is subjected to high stresses produced because of the central column sinking, due to the tower and turbine weight which has to withstand. The high stresses are mainly distributed along the corners of the base.

The easiest and most effective way to reinforce this section is to add three steel panels –one for each corner- to connect the base corners with the central column. This solution gives enough stability and robustness to the region, preventing the sinking of the central column with respect to the platform base.

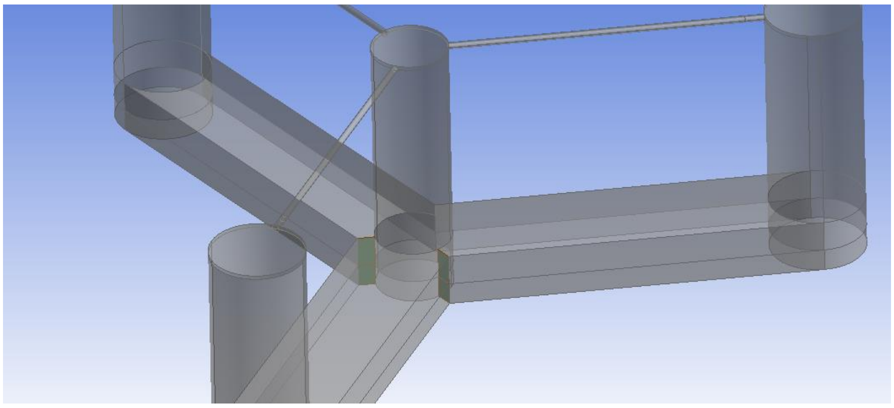


Figure 14:Internal ribs in the connection region

Next region which needs an internal reinforcement are the external columns. This part of the platform is mainly submitted to the sea loads (hydrostatic pressure and wave pressure). As we saw before, this loads are not significant in the static case, but needs to be reinforced to ensure their mechanical stability in the dynamic situation.

The nature of these kinds of loads is radial, as they are pressures which act on a cylindrical surface. Due to that, the reinforcement distribution which is considered consist on six steel panels symmetrically distributed with respect to the column axis. This hexagonal distribution gives the structure a high stiffness in the radial direction of the columns.

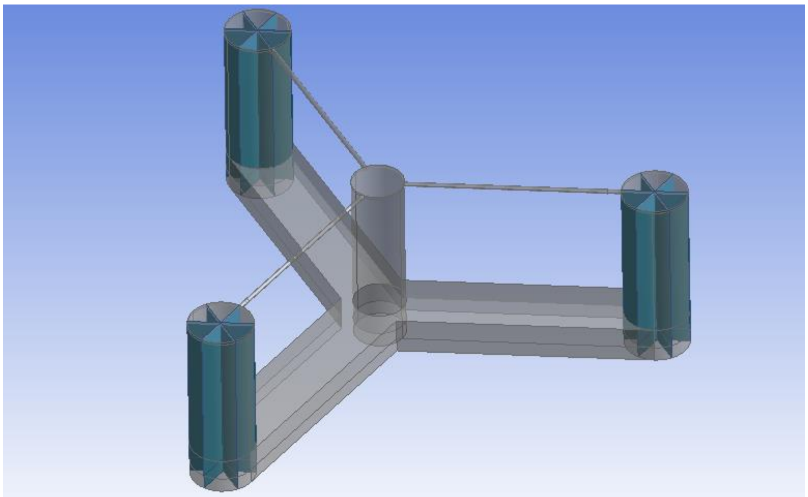


Figure 15: Internal ribs in the external columns

The last region which is reinforced is the platform base. There are two reasons to reinforce this part. The first one is the effect of the dynamical sea pressure to its surfaces, which can produce considerable deformations. The second reason is not less relevant. It has to do with the high bending loads transmitted from the external column to the base. The bending effect is increased in the base due to its great dimensions (each arm is around 50 meters long). Due to that, even not considerable loads in the external columns can produce relevant deformations in the base surfaces.

The reinforcement of the base consists on the addition of steel panels distributed along the length of each arm. In a first approximation, we consider to add two of this vertical panels per arm. This distribution will give enough robustness to the platform to avoid the bending effect and enough stiffness to reduce the pressure effects.

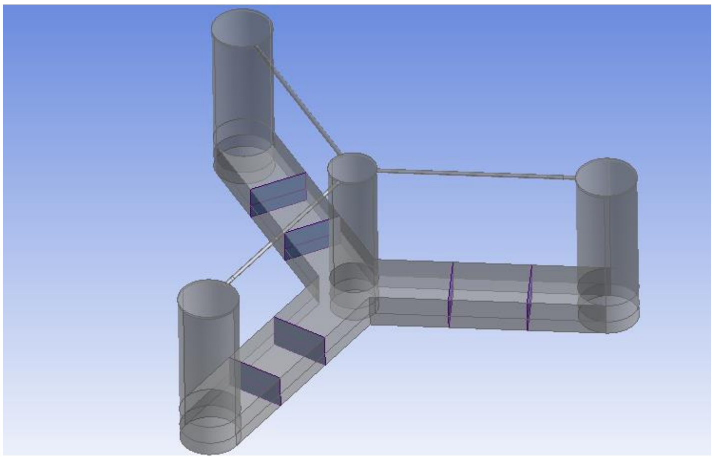


Figure 16:Internal ribs in the platform base

The final platform design consists, therefore, on a semi-submerged structure formed by three external columns with a reinforcement of internal ribs in hexagonal disposition; a central column, which holds the turbine tower, with an internal reinforcement of four ribs in a cross disposition; and a submerged base which connect the four columns, formed by three arms, each of them with two internal ribs.

This new design involves a significant increment of material needed, which can lead to a relevant weight increment and so, buoyancy problems. To minimize this problematic effect, it will be necessary to optimize the thickness of each platform region, so that the weight increment is compensated with the increment of stiffness of the structure. In that way, the amount of steel required to support the loads is drastically reduced.

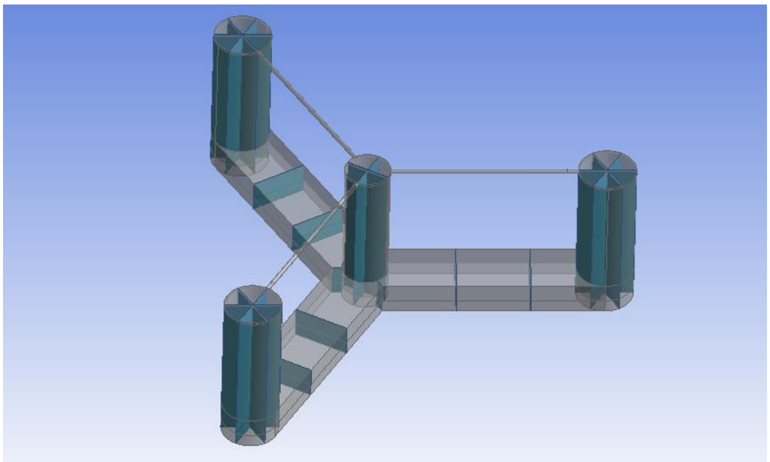


Figure 17: Platform final design

2.5 Hydrostatic simulation of the new platform design.

To understand the effect of the platform redesign, the static case is simulated, firstly without an optimization of the thickness of the different parts. In that way, all the parts are considered to have the same thickness, with the original value of 45 mm computed in the last simulation.

With that setting, the results of the hydrostatic simulation show significant changes with respect to the original geometry. First thing we can appreciate is a great reduction on the values of the stresses in the top surface of the central column. Thus, the maximum stress value obtained with this configuration (529MPa) is five times lower than the one obtained with the original geometry. Nevertheless, it continues to be an unacceptable value, as considerably exceeds the yield strength of the steel. The stresses values are insignificant in the rest of the platform.

To reduce even more the values of the stresses in this top surface, it will be necessary to increase its thickness, so that the tower and turbine weight is distributed among a higher volume of material. As it can be seen, this surface thickness will be probably the most critical design parameter.

Other relevant aspect that we can appreciate is the effect of the internal connection between the central column and the base, which avoid the sinking of the central column in the platform base. Thus, the stresses in the corners of the base, which were too high in the original geometry, are now way lower.

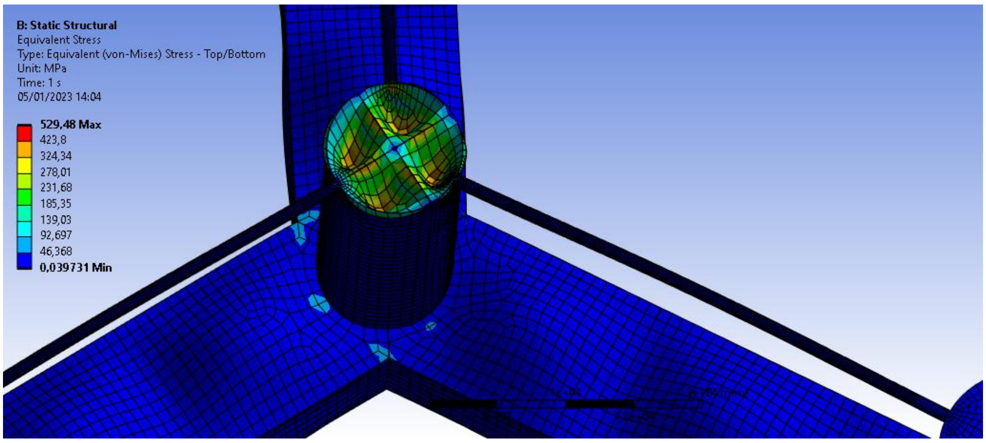


Figure 18: Stresses in the top surface of the central column

Nevertheless, the robustness of this connection produces a new effect hasn't seen in the original structure. Both the central column and the central part of the base experience a combined vertical down displacement, which produces a non-negligible bending moment in the arms of the base. This bending moment produces a deformation in the top and bottom surfaces of the arms. However, the internal ribs disposed inside the platform arms reduced this deformation in a way that there are not problematic for the structural stability of the platform.

The connection top tubes also experience this bending effect due to the central column sinking, but as happen with the base, its deformation isn't relevant for the structure stability.

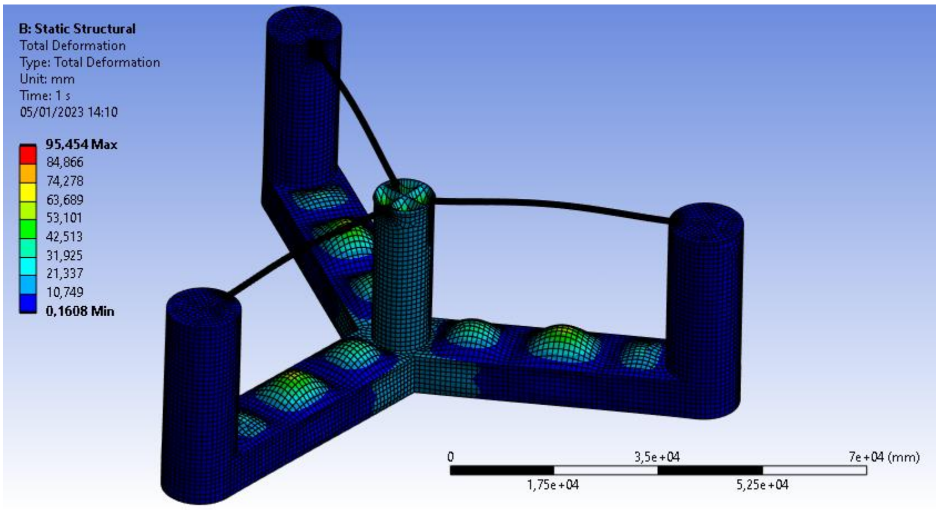


Figure 19: Deformations distribution in the platform

As seen in this simulation, the redesign of the platform has given robustness to the structure, but is still not enough to adequately withstand the loads even in the less extreme case –the hydrostatic one-. Moreover, the addition of internal ribs produces a high increment in the platform weight, from 3900 t of the original structure to 6000 t (considering a 45 mm thickness in all the platform). This excessive increment in the weight can produce buoyancy problems in the structure, which must be avoided.

These two reasons make necessary to do an optimization of the platform thickness. As the hydrostatic simulation shows, the different parts of the platform aren't subjected to the same efforts. Thus, it doesn't make sense to give the same thickness to all the elements of the platform, as it is totally ineffective.

The most critical thickness on the structure is the one of the central column top surface. With the original value of 45 mm, the stresses which must withstand are too high, exceeding the allowable limits. To reduce the stresses in this region, it's necessary to increase its thickness. Through an iterative simulation process, it's obtained an optimized thickness of 70 mm.

The rest of the platform is subjected to significate lower stresses, so its thickness can be reduced without losing structural stability. The thickness reduction can be higher in the internal ribs, as there are subjected to very low stresses; and must be lower in the external hull, which is directly subjected to the hydrostatic pressure.

The definitive thickness values of each platform region are shown in the following table:

Platform region	Thickness(mm)
Central column tap	70
Central column	35
External columns	35
Base	35
Internal ribs	15
Top connection tubes	30

Table 5: Thickness of the platform regions

With this definitive configuration, the results obtained of the hydrostatic simulation are finally acceptable. Just like happens in the other simulations, the higher stresses are located in the top surface of the central column, where the tower is sustained. However, the values obtained with this new thickness are quite lower. The maximum stress value, of 190 MPa, is more than two times lower than the steel yield limit, ensuring no structural instabilities in the platform, at least for the static case.

The stresses on the rest of the platform doesn't exceed in any case the value of 100 MPa, being, thus, irrelevant. The effect of the mooring pretensed force is also negligible.

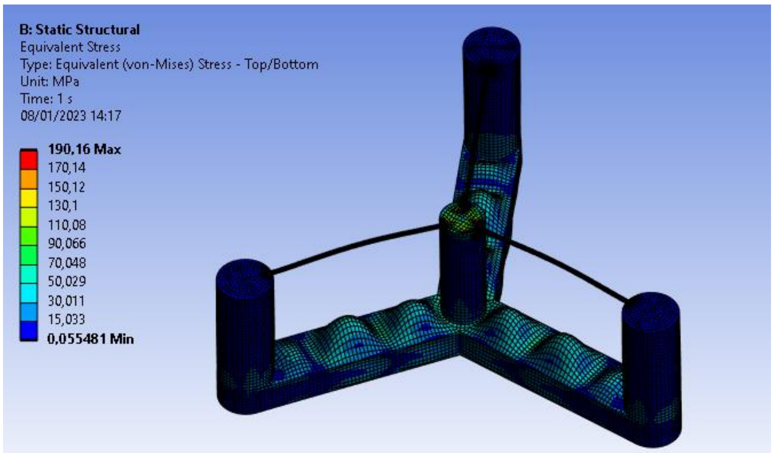


Figure 20: Stresses distribution in the new platform design

In terms of deformations, the base top and bottom surfaces are the parts which experiment higher values, due to the bending efforts located in that area. Due to the thickness reduction of the base, the values are higher than in the previous simulation. However, there are considered acceptable regarding the dimensions of the structure.

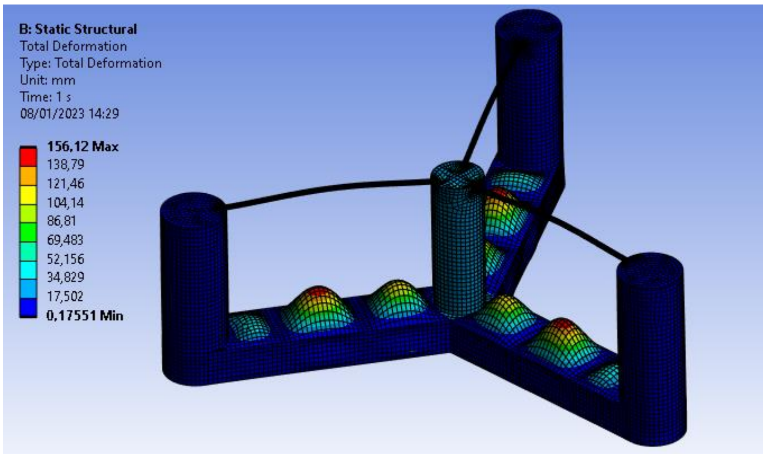


Figure 21: Deformations distribution in the new platform design

With this final simulation, the hydrostatic analysis of the platform is concluded, and the new design is totally defined. The next step to validate the model is to simulate it in the different dynamic cases defined in the standards.

3. Dynamic case

Once the hydrostatic analysis is completed and the platform is redesign to withstand this load case, we can proceed with the structural evaluation of the platform in more several cases. The dynamic simulations that must been performed in order to validate the structure are accurately characterized in the standards. In this work, a simplification of this standardized load cases is done in order to speed this validation process.

3.1 Standardized Design Load Cases.

For validating the platform design, it must be simulated in different dynamic conditions which represent all the possible situations in which the platform can be submitted during its working life. These dynamic situations are described in the designing standards *DNVGL-ST-0119 Floating wind turbine structures* [10] and *DNVGL-ST-0437 Loads and site conditions for wind turbines* [11], which defined the different Design Load Cases (DLC) that must be simulated for the platform validation.

The Design Load Cases in which the dynamic simulations are based are standardized cases which represent the different dynamic conditions in the platform. Each load case depends on the external environmental situation, as well as on the working situation of the turbine.

The environmental situation is defined by the sea and wind loads. These loads which affect both the platform and the turbine depend on the sea and wind conditions.

The sea conditions are defined, in a simplify way, by two parameters: the significant wave height (Hs) and its corresponding peak period (Tp). The significant wave height is a statistical value which represents a normalized wave height. The election of this value depends on the load case and are given by the standards. The peak period represents a normalized value of the time between two contiguous peaks. The direction of the waves, defined by the angle β of incidence between these and the platform, is another parameter used for modeling the DLC.

The wind conditions are defined by the significant wind speed in the turbine's hub height and its direction. The computation of these parameters depends on the wind model used (normal or extreme turbulent, extreme wind, etc.), which is specified for each DLC in the standards. As we will see later, wind conditions are neglected in our working case.

The Design Load Cases depend also on the operational situation of the turbine. The different working situations cover: normal power production (DLC 1), power production with occurrence of fault (DLC 2), start up condition (DLC 3), normal shutdown condition (DLC 4), emergency stop (DLC 5), parked situation (with and without fault occurrence) (DLC 6 and 7), and transport installation, maintenance and repair (DLC 8).

For a complete validation of the structural integrity of the platform, it must be done, for each design situation, an Ultimate Limit State (ULS) analysis and a fatigue analysis.

The ULS analysis validates the situations which involves the highest deformations, associated with the structurally most critical cases with respect to the collapse of the platform. The fatigue analysis is the structural analysis of the failure tendency of systems when subjected to cyclical loads. Due to the cyclic nature of the turbine loads and the sea and wind loads, this type of analysis is crucial for ensuring a correct structural behavior of the platform during its life time.

Due to the great number of different environmental and operational situations that must be analyzed, the number of simulations which must be done for a complete and correct validation of the platform design is extremely high. This requires huge computational and time costs, which makes the process quite expensive. Furthermore, these costs can increase if in one of the simulations a fail is detected, so that a redesign of the platform must be done, and all the validation process must be repeated.

Nevertheless, a much simpler validation process can be carried out as a first approach. This process, which is the one developed in this project, doesn't substitute the actual standardized validation process for the design of the platform, but allows to obtain a consistent design which won't have to be submitted to great changes during the complete validation process. This will significantly reduce the computational, time and economic cost of the process.

The simplify validation process consists on simulating the platform only in the most mechanical requested cases. In the case of the platform, these cases are associated to extreme sea conditions, in which the waves loads are predominant.

As shown in the standards, the extreme wave conditions are associated with the DLC 6. In those design load cases, the rotor of the turbine is blocked to protect its integrity. The significant wind speed and the significant wave height reach the highest values of all the simulations. If the platform is allowed to resist this cases without any structural instability, the design won't need severe changes in the rest of the validation process.

For doing these simulation, the software MOST, based on MATLAB, is used. This software computes the sea dynamical loads in the platform, which will later be used for its structural analysis. A significant limitation of this software is that it doesn't compute the wind loads in the turbine and tower, so these loads will be omitted in the structural analysis of the platform. However, in the DLC that will be simulated, in which the rotor is blocked, these kind of loads are not significant compare to the sea loads, and so, the result obtained should not be compromised.

The design load cases that will be simulated, with its simplifications made because of the software used, are shown in the next table:

DLC	**Wave Conditions**		**Load safety factor**	**Type of analysis**
	Height	**Direction**		
6.1	Hs_{50}	$\beta = 0º$	1,35	ULS
6.1	Hs_{50}	$\beta = +30º$	1,35	ULS
6.1	Hs_{50}	$\beta = -30º$	1,35	ULS
6.3	Hs_{1}	$\beta = 0º$	1,35	ULS
6.3	Hs_{1}	$\beta = +30º$	1,35	ULS
6.3	Hs_{1}	$\beta = -30º$	1,35	ULS

Table 6: DLC parameter definition

Each case is defined by a wave height and direction. The weight height is a statistical value obtained from an oceanographic dataset. In our case, the wave height used are the 50-year significant wave height (Hs_{50}) and the 1-year significant wave height (Hs_{1}).

The Hs_{50} represents a wave height value corresponding to a return period of 50 years, which means that has a probability of exceedance in the distribution of annual maximum of 0,02. The Hs_{1} is defined as the most probable highest value in one year, normally determined as the mode in the distribution of annual maximum.

With respect to the wave direction, its incident angle with respect to the platform covers a range of +/- 30º. Due to the symmetric pattern of the platform, with this range, the effect of all the possible wave directions are covered.

Finally, a load safety factor is applied in each simulation. The combination of this safety factor with the material factor determines the global safety factor of the platform for each case.

3.2 DLC simulation procedure

For doing the analysis of the behavior of the platform in the design load cases defined before, a procedure is developed, based on the use of two different software: MOST and ANSYS.

MOST ("*Matlab for Floating Offshore wind turbine"*) is a MATLAB-based software, developed by MOREnergy Lab of Politecnico di Torino. This software follows the same philosophy as FAST, but with a simplified structure focused on the optimization of floating offshore platforms. MOST uses Simulink to join aerodynamics and hydrodynamic models for offshore structures with control and electrical system dynamics models, and structural models for computing the mooring loads [12].

ANSYS is a simulation software based on the finite element method (for structural analysis) and the finite volume method (for fluid analysis). It is composed of different modules, each of them used for a different type of analysis. For this work, only the Static Structural module is used, since it's enough for the kind of analysis requested.

The simulation of each DLC is done using this two software in a cascade way, so that the output data obtained from the MOST simulation is used as input parameters in the ANSYS simulation.

MOST is the first software we must use. It allows to obtain the dynamical loads which affect the platform in each time instant. To achieve this, it simulates the sea state during an interval, defined by the wave state parameters (Hs and Tp) as well as by the turbine operational situation. With this data, it computes for each interval the loads in the model.

These loads, which are the output data used later in ANSYS, are classified in: hydrostatic pressures in the hull, nonlinear wave pressures in the hull, tower forces and moment applied in the top surface of the central column of the platform, and the mooring forces.

The loads values obtained with MOST are used, then, in ANSYS, as inputs of the model to simulate. As said before, for the structural analysis of the platform, the Structural static module is used. The reason for using this module instead of using other – dynamic- one is its simplicity and efficiency in terms of computational costs. Thus, instead of simulating the loads effect in each time instant of the previous MOST simulation (which with the standardized duration means 60000 time instants), it will be only simulated the times instant in which the loads effect is consider to be critical.

The ANSYS Static structural module is used, in this way, to simulate the structural behavior of the platform in the most critical instants of the simulation. The model used for simulate it is based on the Newton's law of motion for a floating body, adapted to the platform case:

$$m_{plat} \cdot a_{plat} = F_{hst} + F_{FK} + F_D + F_R + F_{drag} + F_{moor} + F_{turbine+tower}$$

where the Froude-Krylov (F_{FK}), the diffraction (F_D), the radiation (F_R) and the drag forces (F_D) are associated with the dynamic sea loads; while F_{hst} is the hydrostatic force, F_{moor} the mooring force and $F_{turbine+tower}$ the inertial forces of the turbine and tower.

The parameters of this expression must be adapted to the static nature of the simulation. Thus, the dynamic sea loads are implement in the platform as wave nonlinear pressures, whose values are obtained for each element of the platform mesh in each instant of the simulation, from MOST. The same happens with the hydrostatic force, which is also obtained as a pressure in MOST. The mooring and turbine and tower forces are obtained directly from MOST.

The platform acceleration is simulated in ANSYS by the inertia relief, using the same philosophy as in the hydrostatic case. Thus, this constraint allows the equilibrium of the system, giving the platform an instantaneous acceleration equal to the sum of the forces that affect the platform in each instant, divided by the platform mass.

The simulation procedure described before is synthetized in the following diagram:

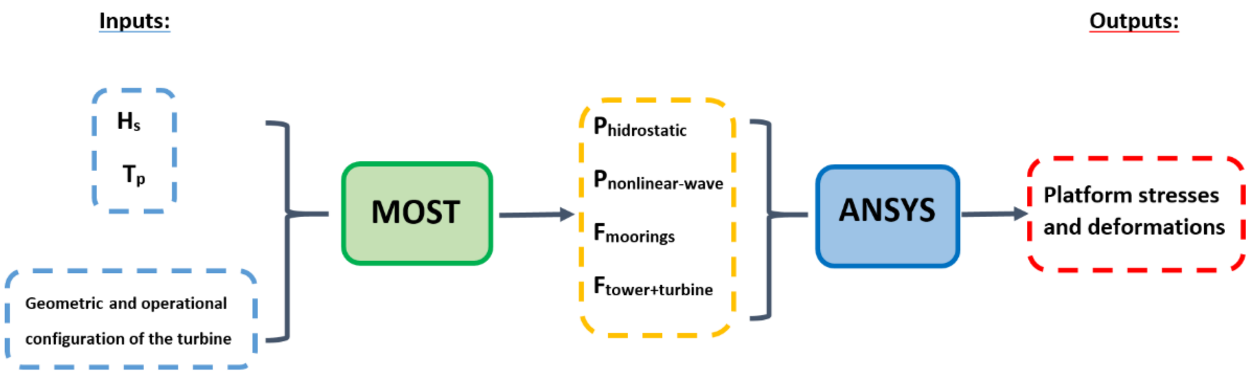


Figure 22: Simulation procedure diagram

As said before, the simulations that will be implemented in ANSYS represent the mechanical states of the structure in those time instants considered as the most critical ones. Those critical instants are associated to geometric configurations of the platform and load situations in which the mechanical requests are higher. Thus, it is necessary to decide which configurations and load cases will be considered as critical ones.

3.2.1 Critical parameters definition.

The critical parameters, which determine the time instants of the DLC simulation in which the platform has to be structurally analyzed, are associated to the situations in which the platform has higher mechanical requests.

The mechanical requests on each time instant depend, mostly, on the platform geometric configuration at that time instant. Thus, most of the critical parameters to consider are specific values of the platform geometry variables.

The critical parameters selected are considered to be the ones with higher influence in the structural stability of the platform. In the simulations carried out in this project, it will be verified the real impact of this parameters in the platform stability.

The variables which are considered to be critical for the structural analysis of the platform are:

- **Minimum heave**: The heave represents the displacement of the structure along its vertical axis. This variable is defined as the vertical coordinate of the center of gravity of the platform in a time instant, with respect to a fixed frame linked to its static equilibrium position. The minimum heave is the point in which the platform is supposed to be more submerged, and, thus, the effect of the hydrostatic pressure is higher. That's why it is considered as a critical parameter.

- **Maximum pitch**: The pitch represents the structure rotation about the lateral axis (perpendicular to the wind direction, and so, to the turbine hub). This variable is defined as the angle between the x axis in a time instant and the x axis of the fixed frame linked to the static case. As the tower and turbine inclination is associated with the pitch angle, when it reaches its maximum value the tower moments transferred to the platform are supposed to be more significant than in other configurations.

- **Minimum pitch**: As happens with the maximum pitch, this configuration is associated to a great inclination of the tower and turbine, which means high values on the tower moments transfer to the platform. As we will see later in the simulations, the negative pitch values are significantly higher, in absolute terms, than the positive ones. Thus, its effect in the structural stability will be higher. It is also interesting to remark that in this configuration, due to the platform inclination, some parts are also submitted to high sea pressures, which compromise even more the structural stability.

- **Maximum bending moment**: The bending moment transmitted by the tower to the platform is the one which can be decomposed into moments in the x and y axis. It has compressive and traction effects in the platform, which affects directly to the central column of the platform. As we will see later, when this variable reaches its highest value, the structural stability of the whole platform may be compromised.

- **Maximum torsion moment:** The torsion moment transmitted by the tower to the platform is the one associated with the vertical direction. Although its effect is significantly lower than the bending moment one, is interesting to evaluate the maximum torsion moment instant to see the torsion behavior of the platform.

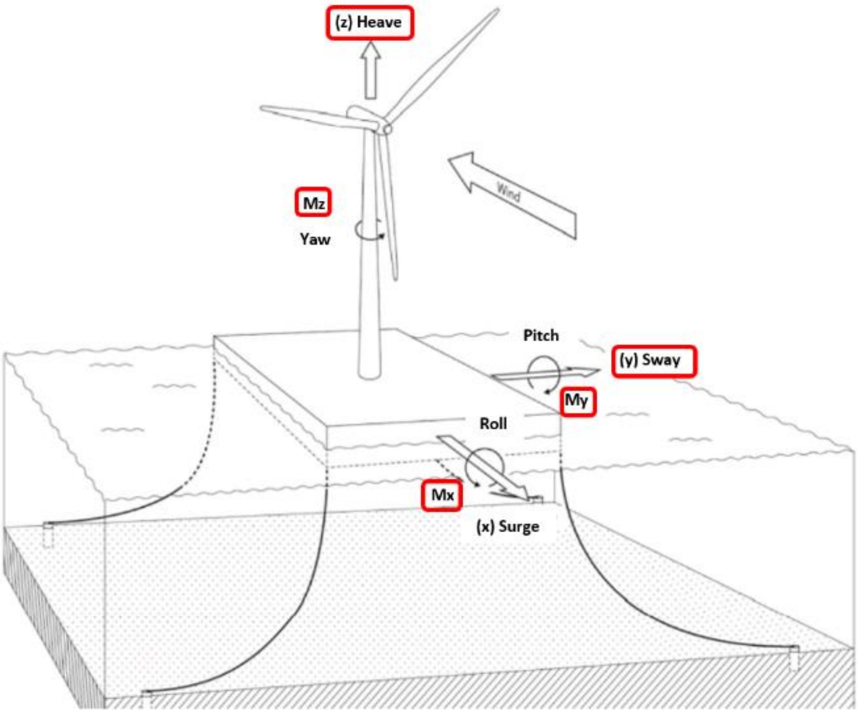


Figure 23: Critical parameters representation

As we will see later, the time instants in which the platform reaches lower heave values are similar to the ones in which the pitch is lower. These instants are, furthermore, associated to high bending moment values. To complete this analysis, is interesting to remark that the maximum tower force is not considered as a critical parameter because its components are not significantly changing in time, compare to the bending and torsion moments. Thus, it not defines a critical time instant to take into consideration.

Before starting with the DLC simulations, it is necessary to set the values of the input parameters of the MOST simulations, which are, basically, the significant wave height, H_S, and its associated peak period, T_P. For obtaining this values, a statistical study must be done with the sea data of the place where the platform is considered to be located.

3.3 Determination of the input parameters.

To determine the values of the simulation input parameters, it is necessary to do a statistical analysis of the oceanographic data of the area in which the platform would be located.

In our case of study, the location chosen for implementing the platform design is Hollandse Kust (west), a windfarm located in the Dutch part of the North Sea. The main reason to select this location is the quality, quantity and availability of its meteorological and oceanographic data.

Furthermore, the selected location is also interesting for other reasons: it is located in one of the European seas with more potential in terms of offshore energy implementation, due to its relatively shallow waters, its favorable wind climate and its proximity to great ports and energy consumers [13]. Moreover, the development and implementation of this wind farm is responsibility of the European Union, which its commitment and investment in these kinds of energy renewable projects are unquestionable, and increasing more year by year.

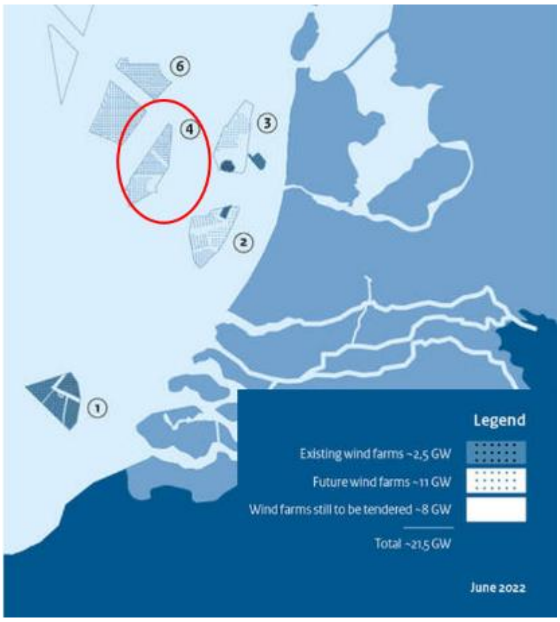


Figure 24: Platform location

The statistical processing of the oceanographic data for obtaining the wave parameters is defined in the standard *DNVGL-ST-0437 Loads and site conditions for wind turbines* [11]. As said there, the wave parameters H_s and T_P may be represented in terms of generic distributions.

The most typical generic distribution for the representation of the wave height H_s is the Weibull distribution. This distribution is often used for representing meteorological phenomena because of its precision and simplicity. Its general expression of the cumulative probability distribution is:

$$F(x) = 1 - e^{-(\frac{x}{\beta})^{\alpha}}$$

where β and α are parameters which have to be adjusted according to the data used, and the x variable corresponds, in our case, to the significant wave height, H_s. The data used to fit this distribution corresponds to one natural year sea state data, as determined in the standard. The parameters obtained for the wave data of our location are: β = 1.9143255; α= 1.29258825.

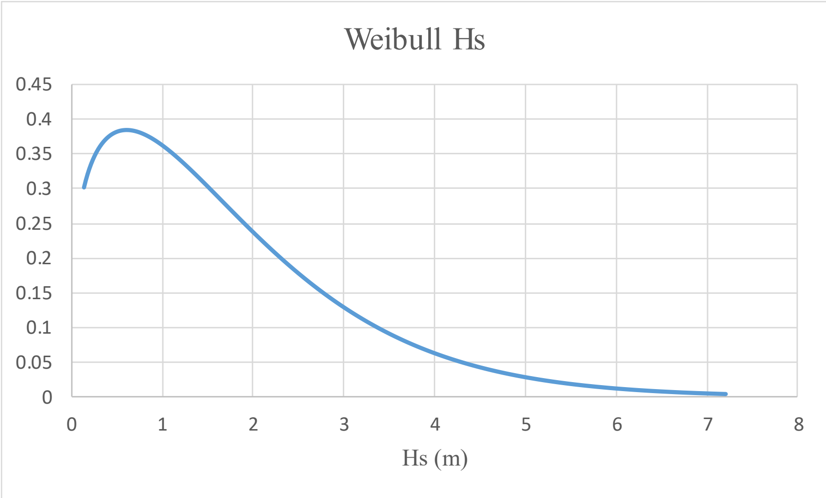


Figure 25:Weibull distribution of the analyzed data

The parameters which must be computed from the Weibull distribution for our simulations are the wave height value corresponding to a return period of 50 years, H_{s50}, and the 1-year significant wave height H_{s1}.

As explained in the standard, the significant wave height with return period T_R in units of years is defined as the (1- 1/T_R) quantile in the distribution of the annual significant wave height. For a returning period of 50 years, the quantile associated is of 0,98, which corresponds in our distribution with a wave height of 5.53 m. Its associated peak period is of 9,18s.

The 1-year significant wave height is computed as the median of the annual maximum wave height. It takes a value of 1.44 m, with a corresponding peak period of 5,27 s. The values of the input parameters for the simulation of the DLC are, thus:

H_{s50}	5.53 m
T_{P50}	9,18s
H_{s1}	1.44 m
T_{p1}	5,27 s

Table 7: Input parameter values

As it can be seen, the values of the wave heights and peak periods aren't too high, and seems to be lower than in other offshore energy locations in which the extremes events are of a higher magnitude. However, this fact doesn't actually rest importance to the validation procedure which will be carried out, as, like the standard *DNVGL-ST-0119* [10] said, "the maximum responses in a semi-submersible are often not governed by the maximum wave height and associated wave period. Waves with shorter period often give the highest response".

The reasoning can be applied with the DLC 6.3, whose parameter values are lower than the ones of the DLC 6.1, but even so, its structural effect on the platform must be checked.

3.4 Simulation of the DLC 6.1 with 0º direction.

For the simulation of the DLC 6.1 with 0º wave direction, the MOST software must be configured according to the case specifications. The sea state which must be simulated has a significant wave height of 5,53 m; with a corresponding peak period of 9,18s. The incidence wave direction has an angle of 0º with respect to the surge axis of the platform and turbine. The rotor of the turbine is blocked.

The simulation is configured with a duration of 60 minutes, as recommended in the standards [14], with an interval between time steps of 0,1 s, which means the obtainment of 36000 time instants with its respective output data. For removing the undesirable transient effect of the beginning of the simulation, the first minute of the simulation is removed, so that the results are considered valid only up to this time instant.

The most significant results obtained from the simulation are shown in the graphics below.

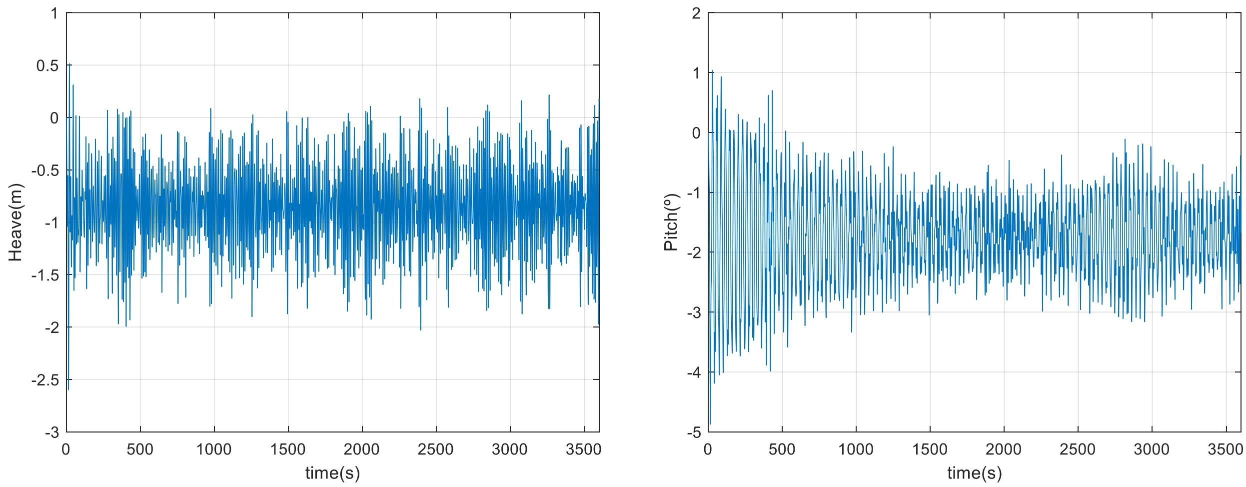


Figure 26: Heave and pitch values in time

The heave variable takes values from -2 to 0,25 meters. Its minimum value is of -2,029 m. The pitch takes values between -4 and 0,7 º. As it can be appreciated the negative values reached are bigger than the positive ones. In this way, the balancing movement of the platform is not symmetric with respect the sway axis. The inclination of the tower is higher forward than backward because its geometric and inertial configuration. Thus, the bending moments transmitted by the tower are higher in negative pitch angle configurations of the platform. The pitch's maximum value is of 0,93º, while its minimum value is of -4,05º.

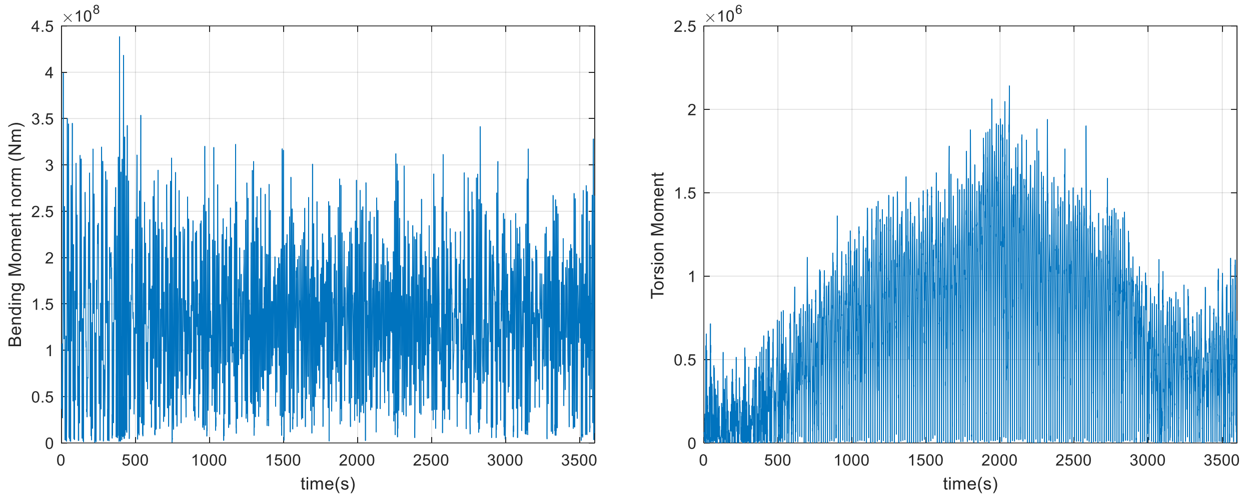


Figure 27: Bending moment norm and Torsion moment in time

The bending moment norm is the quadratic norm of the bending moment vector, (components M_x and M_y). It takes values between 0 and 4,4 · 10^8 Nm. The peak values of this norm are associated to minimum, negative values of the pitch angle. It reaches a minimum value of 4,38 · 10^8 Nm.

As it can be seen in the graphics, the torsion moment values have a magnitude order two times lower than the bending moment. Thus, its effect in the structural stability of the platform is much lower. It reaches a maximum value of 2,14 · 10^6 Nm.

To end with the simulation overview, is interesting to analyze the time variation of the tower forces and of the mooring forces. As it can be seen in the graphics below, none of these forces experiment big changes along the simulation time. They have, in contrast with the other loads, a quite stationary behavior. Furthermore, it magnitude order is way lower than the other loads. For these loads aren't consider as critical variables in the static analysis, as said in the section 3.2.1.

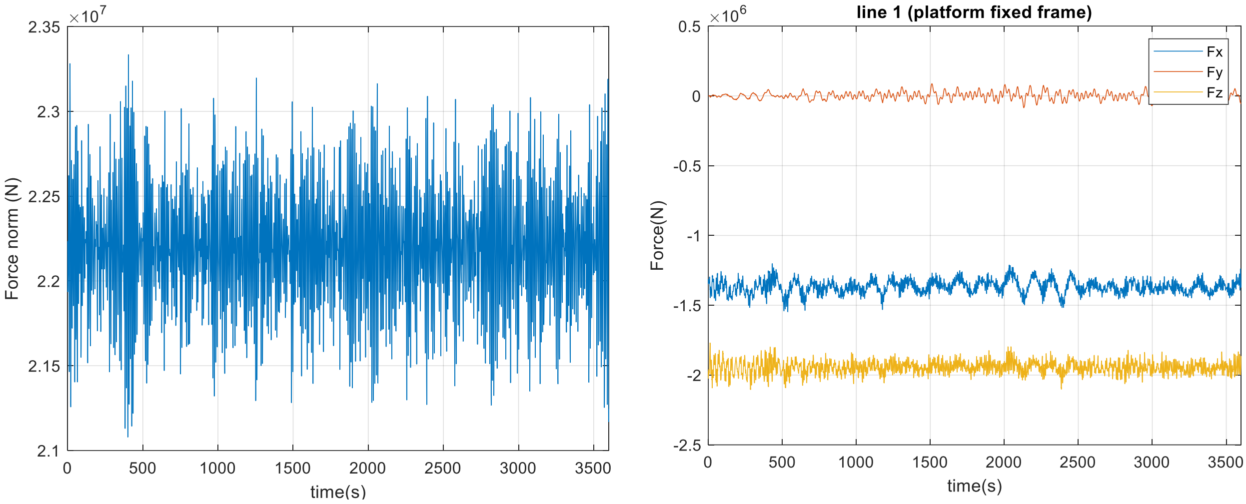


Figure 28:Tower forces norm and Mooring forces in time

The output values of the critical parameters obtained with this simulation are shown in the next table:

Min heave	-2,029 m
Max pitch	0,93º
Min pitch	-4,05º
Max bending moment norm	$4{,}38\cdot10^{8}$ Nm
Max torsion moment	$2{,}14\cdot10^{6}$ Nm

Table 8: Parameters of DLC 6.1 with 0º direction

Once we have the output parameters of the MOST simulation, which are also the input parameters for the ANSYS model, it is time to proceed with the structural simulations and analysis.

3.4.1 Structural analysis of DLC 6.1 with 0º wave direction in the minimum heave situation.

In this analyzed case, the heave reaches its most negative value, and thus, the submerged part of the platform is submitted to higher hydrostatic pressures. This effect is increased in those parts of the platform inclined backwards because of the negative pitch associated with this situation. That produces that points with the same z coordinate in the platforms frame have not equal pressure, as they have in the hydrostatic case (see figure 3). Because of that, the effect of the hydrostatic pressure is more significant in the most submerged column, as shown in the figures bellow. The most submerged point of the platform presents, in this time instant, the highest hydrostatic pressure value of all the simulation.

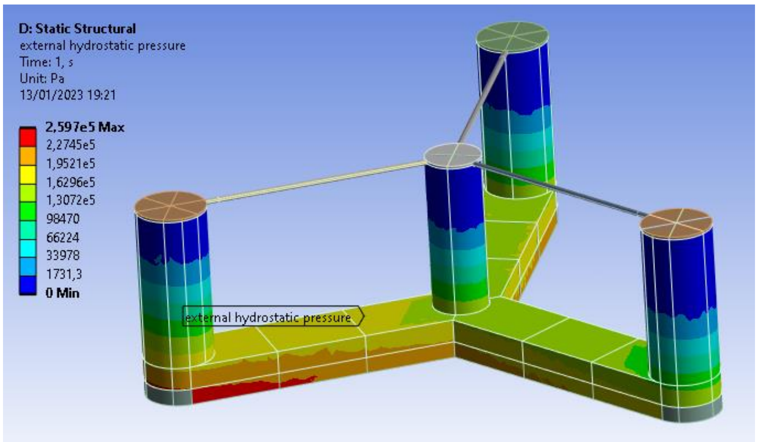


Figure 29: External hydrostatic pressures in the min heave situation

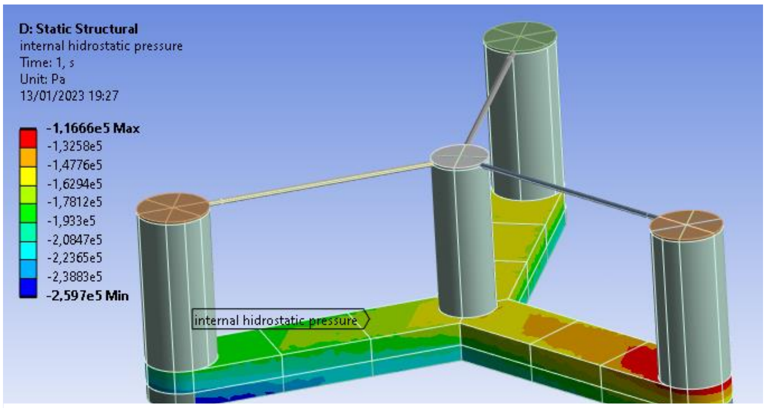


Figure 30:Internal hydrostatic pressures in the min heave situation

The dynamical sea loads are modelled as wave nonlinear pressures, with a distribution in the platform shown in the figure bellow. In contrast to the hydrostatic pressure, this type of load takes negative values in some of the platform regions, due to its complex nature which covers the sum of different nonlinear forces. This can produce a more complex structural response of the platform, compare to the one produced by hydrostatic pressure. However, as we can notice, its values have one order of magnitude lower than the hydrostatic ones, and so, its effect is lower.

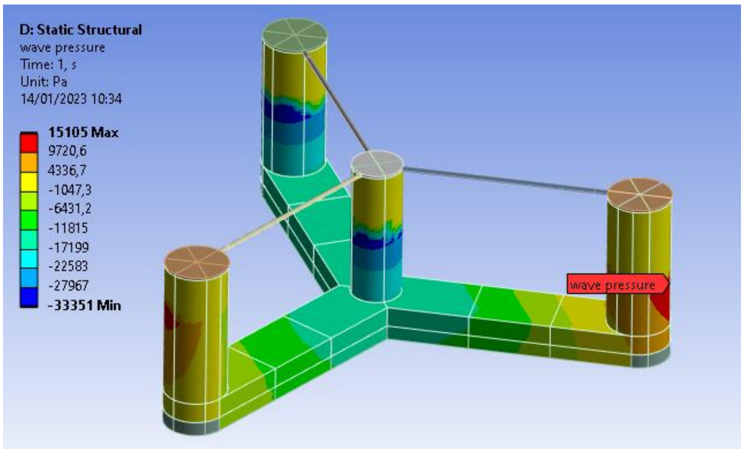


Figure 31: Wave nonlinear pressures distribution

To finish with the structural simulation set up, the external direct loads are shown in a table. As we can notice, the pitch bending moment reaches a high value, because of the platform configuration with a negative pitch value. However, it is far from the maximum. With respect to the tower force, its main contribution is provided by its z component, which corresponds to most of the turbine and tower weight. Its values are quite similar to the one of the hydrostatic case, and so, it shouldn't cause structural problems in the structure.

Finally, the mooring forces have similar values to the ones of the hydrostatic case. Each mooring force can be decomposed into a negative vertical component (around $2 \cdot 10^6$ N) and a longitudinal component (around $1,5 \cdot 10^6$ N). Its magnitude order is lower than the one of the tower forces, and thus, its effect in the structural stability is insignificant.

$F_{tower}x$	$-1,7167 \cdot 10^6$ N
$F_{tower}y$	41547 N
$F_{tower}z$	$-2,3217 \cdot 10^7$ N
Mx	$-3,924 \cdot 10^6$ N·m
My	$-2,4077 \cdot 10^8$ N·m
Mz	$-3,1543 \cdot 10^5$ N·m
$F_{mooring1}$	$2,42 \cdot 10^6$ N
$F_{mooring2}$	$2,56 \cdot 10^6$ N
$F_{mooring3}$	$2,39 \cdot 10^6$ N

Table 9: Values of the input forces and moments

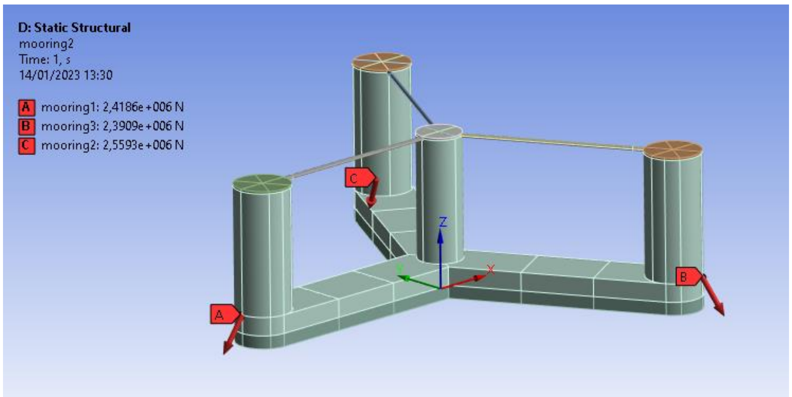


Figure 32:Mooring forces in the platform

The results obtained of the simulation of the minimum heave situation show an extreme increment of the stresses values with respect to the hydrostatic case. The stresses come to exceed 1200 MPa in the most critic zones, and are beyond the allowed limit in many of the regions of the platform. The reasons of this increment is the effect of the moment of the turbine and tower on the central column, as well as, in a smaller way, the effect of the wave nonlinear pressures. This two loads weren't taking into account in the hydrostatic case.

As specified in the section 3.1, a load factor must be applied in the obtained results. This load factor (1,35 for this DLC), has to be combined with the material factor (specified in the standard [10], and with a value of 1,1), to obtain the global safety factor of the analysis. Applying this safety factor to the structural limit of stability of the platform (which is the yield limit of the steel, 410 MPa), we obtain the maximum stress value allowed in the platform: 276 MPa.

In the regions where the stresses exceed the stablished limit, a redesign process must be done, based on recomputing its thickness to reach the structural stability of the platform, as it was done in the hydrostatic case. The regions in which thickness must be recalculate are: the top surface of the central column, the top connection tubes, the top surface of the base, and the internal ribs of the external columns and of the central column.

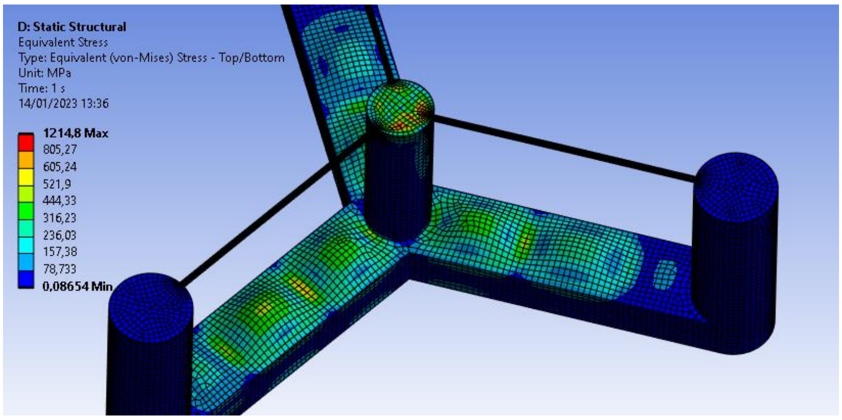


Figure 33:Stresses distribution in the minimum heave situation

3.4.1.1 Computation of the new thickness values.

The optimization of the platform thickness is done element by element, beginning with the one with the highest requests and going downstream. In each of the steps of the process, the reduction in the stresses is analyzed in order to verify the effect of this redesign. Attending to that proceeding, the thickness is re-computed in this order:

- **Top surface of the central column:** Same as happened in the hydrostatic case, this area is submitted to the highest stresses, as it is the region in which the tower forces and moments are transmitted to the platform. As it can be seen, the stresses in all the region are quite higher than the safety limit. Stresses are higher in the compressive side, as in this zone the effect of the tower force is added, conversely to the traction side in which the contributions have opposite sign. As is logic, the thickness increment of this part has to be higher than in any other one.

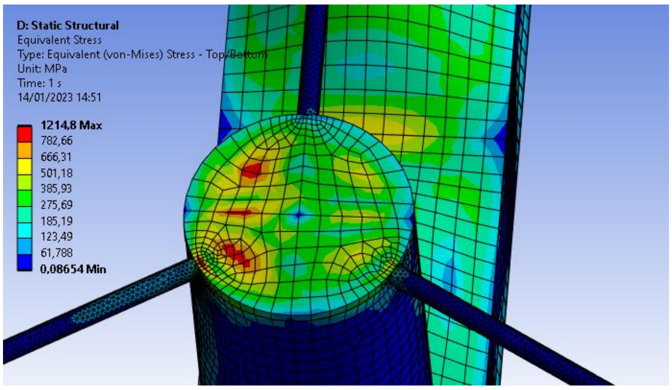


Figure 34: Stress distribution in the top surface with the original thickness

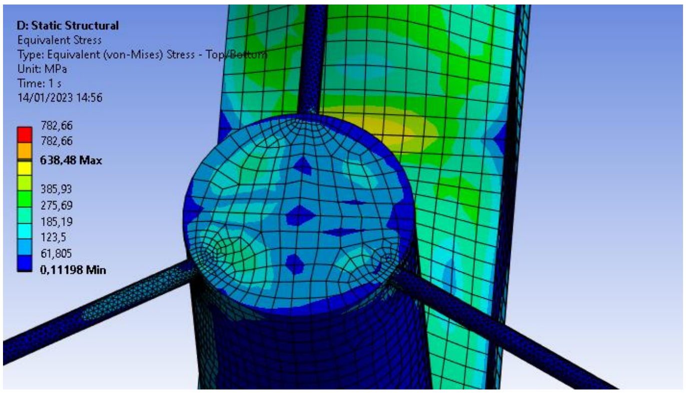


Figure 35: Stress distribution of the top surface with the new thickness

- **Connection top tubes**: After the central column top surface, this section has the highest stress values. The reason of it is its location near to the region where tower and platform are connected and the moments and forces are transferred. Due to that, part of these tower loads are transmitted to the tubes, producing excessive stresses in its extremes.

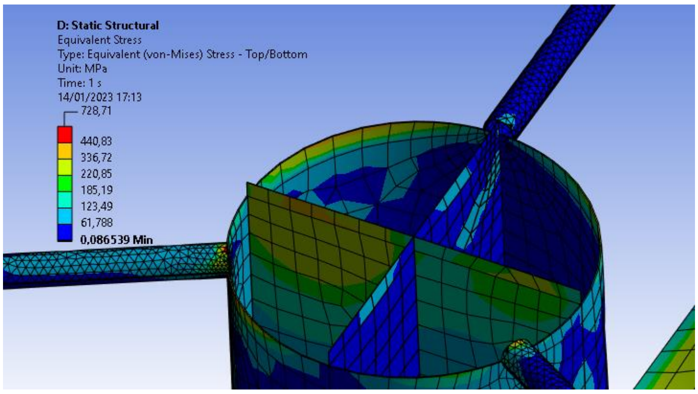


Figure 36:Stress distribution in the tubes with the original thickness

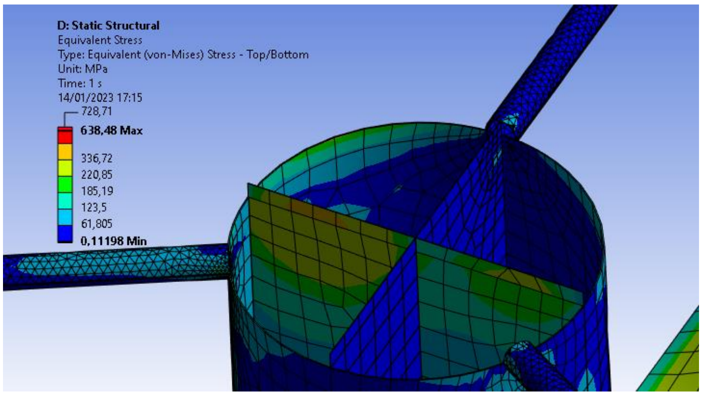


Figure 37:Stress distribution in the tubes with the new thickness

- **Platform hull:** The stresses in the hull surpass the safety limit in the top surface of the platform base. The cause of these high values are the effect of the wave pressures in this region, added to the bending effect caused by the sinking of the central column with respect to the platform base. The central column experimented also excessive stresses on near its top surface (see last figure), because this is the region where the tower loads are transmitted from the top surface to the rest of the column. In the rest of the external hull, stresses are lower than the limit, thanks to the effect of the internal ballast.

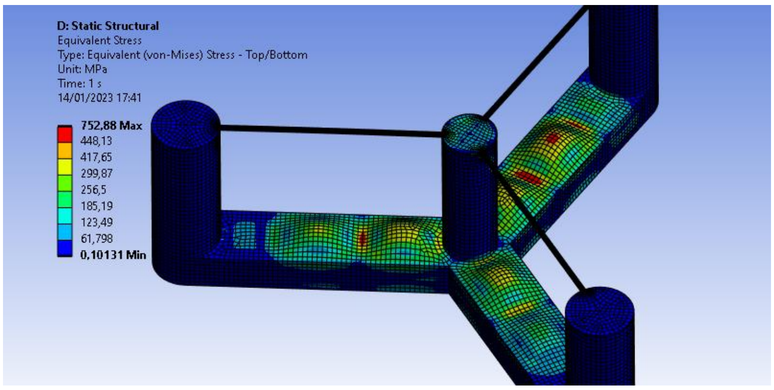


Figure 38:Stress distribution in the hull with the original thickness

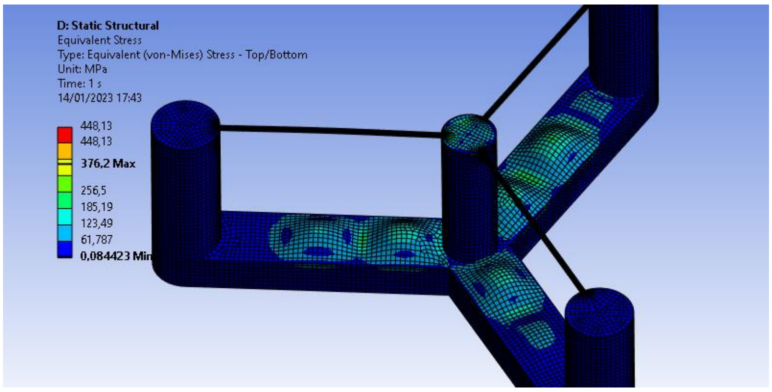


Figure 39:Stress distribution in the hull with the new thickness

- **Internal ribs of the central column:** This part presents stresses beyond the safety limit in its top areas, which are connected directly to the top surface. Part of the tower loads are transmitted from the top surface to these elements, which are designed to distribute these loads so that the efforts that the external hull has to support are reduced. In order to correctly resist these loads, the thickness of this internal ribs must be increased.

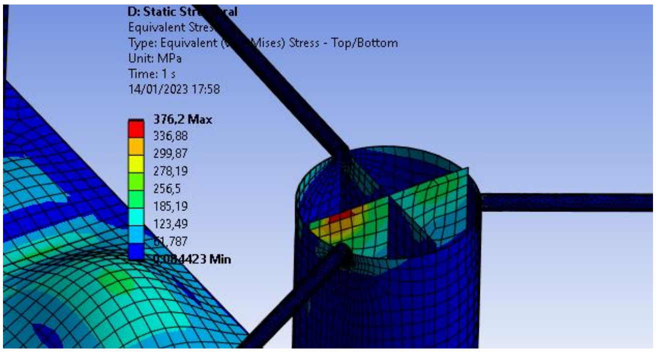


Figure 40:Stress distribution in the central column ribs with the original thickness

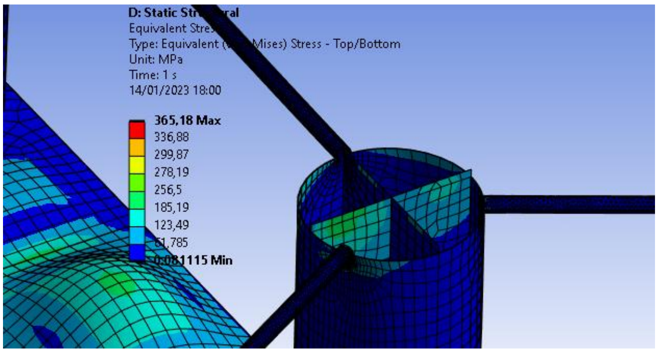


Figure 41:Stress distribution in the central column ribs with the new thickness

- **Internal ribs of the external columns:** As happens with the ribs of the central column, this element are submitted to stresses beyond the limit in its top. In this case, the problematic values are located around the connection between the top tubes and the external column. In this zones, the high loads of the tubes are transmitted to the internal ribs. To guarantee its structural stability, its thickness must be increased.

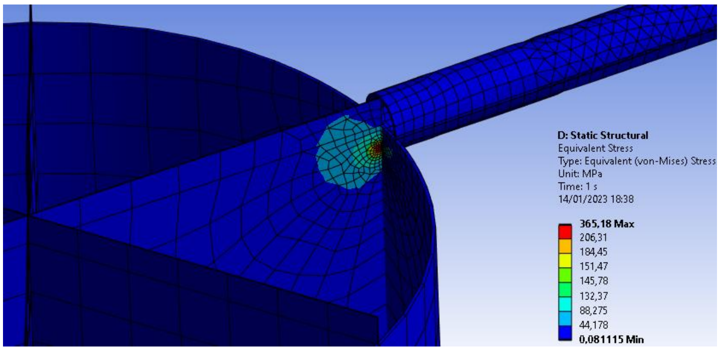


Figure 42: Stress distribution in the external cylinder ribs with the original thickness

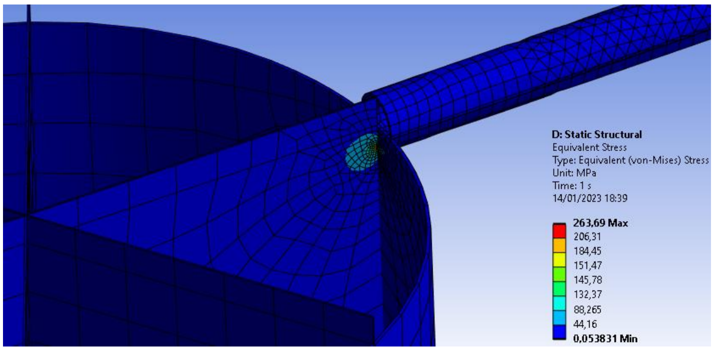


Figure 43:Stress distribution in the external cylinder ribs with the new thickness

In the table below, the original and new thickness of each critical element are compared. As it can be seen, the central cylinder top surface is the one with the highest thickness, 145 mm. This element is also the one in which the increment is higher, as the new thickness is 2 times the original one. For the rest of the elements, the increment is not so significant.

Element	Original thickness (mm)	New thickness (mm)
Central cylinder top surface	70	145
Top connection tubes	30	50
Platform hull	35	55
Ribs of the central column	15	25
Ribs of the external columns	15	35

Table 10: New thickness values of the platform

The re-dimensioning of the platform thicknesses allows to have a satisfactory structural response in the minimum heave situation, in a way that all the points of the platform have values below the safety limit. However, this increment on the thickness has a negative consequence, as it produces a rising in the platform weight. This may cause problems in the buoyancy stability of the platform.

Thus, the new steel structure has a weight of 6051 t, which means an increment in the whole structure weight of 25% with respect to the original design proposed by the University of Maine.

This fact would need to be considered in further studies. For this analysis, the magnitude of the weight increment won't be considered to be significant for the buoyancy stability of the platform.

The results obtained with the new re-dimensioned platform are much more reasonable than the ones of the previous design. As it can be seen in the picture below, the values of the stresses in all the points of the platform are beneath the fixed safety limit (276 MPa).

The maximum stress is reached in the central cylinder top surface, with a value of 263 MPa. The regions in which the stresses are bigger are the mentioned top surface, and the top surface of the platform base, especially in the connection points with its internal ribs.

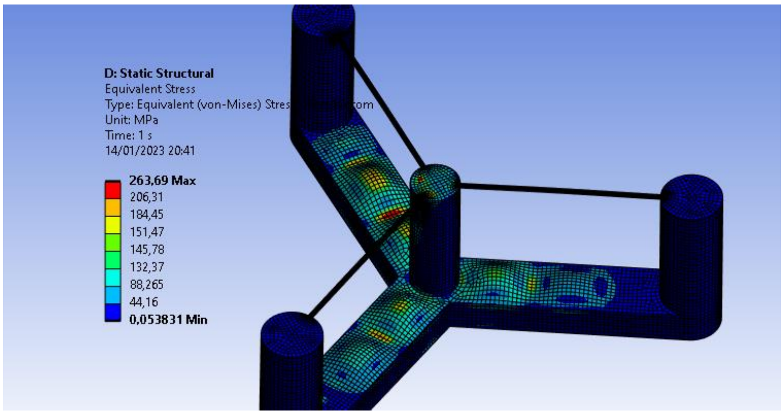


Figure 44: Stress distribution with the new thickness configuration

With respect to the deformations, the only region in which they aren't negligible are in the top and bottom surface of the base. The wave pressure effect in that region is now added to the bending effect which caused its deformation in the hydrostatic case. Thus, the deformation in this zone is higher, although its values remain inside an acceptable range.

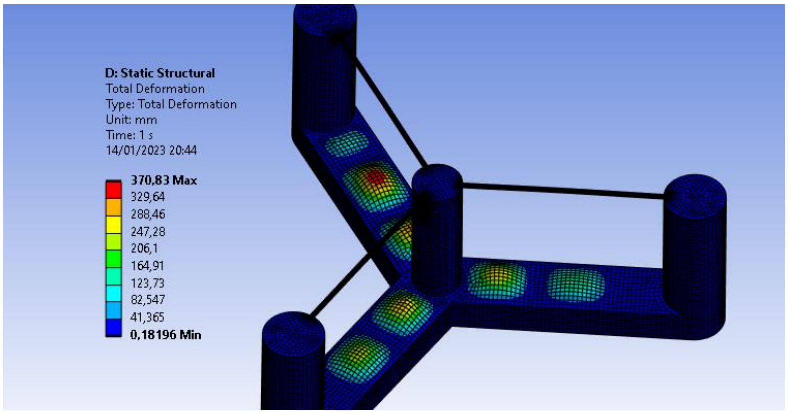


Figure 45:Deformation distribution with the new thickness configuration

3.4.2 Structural analysis of DLC 6.1 with 0º wave direction in the maximum pitch situation.

In this situation, the pitch angle reaches its maximum positive value (0,93º). As said before, the positive pitch angle range (from 0 to 0,93º) is way lower than its negative range (0 to -4,05º). For this reason, the load effects in the platform should be different in these two different configurations, as will be shown below.

In the maximum pitch configuration, the platform is slightly inclined with respect to the sway axis. This inclination makes the hydrostatic pressure to be higher in the points of the platform more submerged. However, contrary to the minimum heave situation, the differences between points of the same height aren't big at all. In fact, this situation is pretty similar to the hydrostatic one in terms of hydrostatic pressure's distribution.

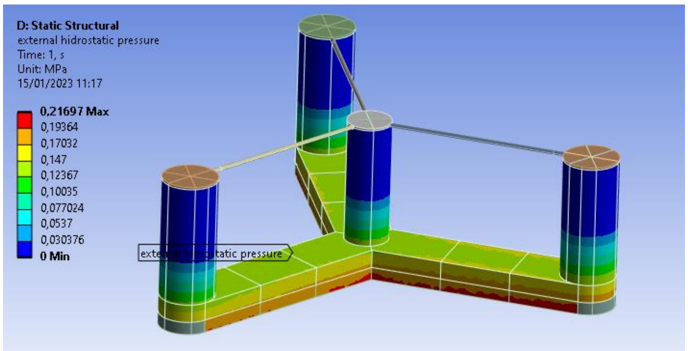


Figure 46: External hydrostatic pressures in the maximum pitch situation

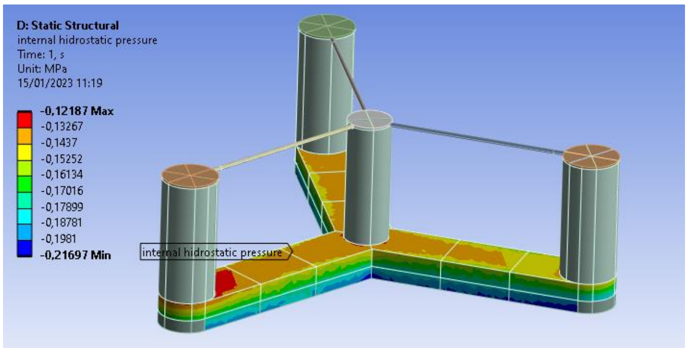


Figure 47:Internal hydrostatic pressures in the minimum pitch situation

The wave nonlinear pressures are, as happens with the minimum heave situation, an order of magnitude lower than the hydrostatic pressures. With respect to the turbine and tower moments transmitted to the platform, there are lower than in other situations, as they depend basically on the tower inclination with respect to the sea level, which in this case is not too high. Mooring and tower forces take similar values to the previous situation analyzed.

$F_{tower}x$	$1,4248 \cdot 10^6$ N
$F_{tower}y$	-5385,3 N
$F_{tower}z$	$-2,3217 \cdot 10^7$ N
Mx	$6,7737 \cdot 10^5$ N·m
My	$8,2827 \cdot 10^7$ N·m
Mz	$4273,9 \cdot 10^3$ N·m
$F_{mooring1}$	$2,44 \cdot 10^6$ N
$F_{mooring2}$	$2,44 \cdot 10^6$ N
$F_{mooring3}$	$2,35 \cdot 10^6$ N

Table 11: Values of the input forces and moments

The results obtained show a lower stresses distribution in the whole platform, which seems to be logic as the structure thickness has been re-dimensioned to withstand correctly a higher request situation. Thus, the stress safety limit established is not exceeded in any point of the structure. The maximum stress (163 MPa) is located in the top surface of the base, in which the contribution of the dynamic pressures has a higher effect. The central cylinder top surface is also submitted to the highest stresses of all the platform, together with the base top surface.

The maximum deformation (246 mm) is reached in the base arms. In this region, as specified before, the stresses are higher. This, combined with the fact that in this region the bending effects are potentiated, makes this zone to be more deformed than any other one. However, as it happens with the minimum heave case, the magnitude of this deformations are insignificant in comparison to the platform dimensions.

As it can be seen, this situation is less demanding than the minimum heave one. The slightly inclination of the platform makes this configuration to be similar to the hydrostatic case.

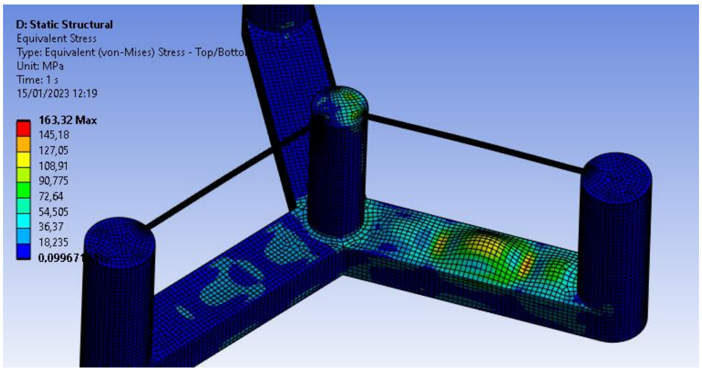


Figure 48: Stresses distribution in the maximum pitch situation

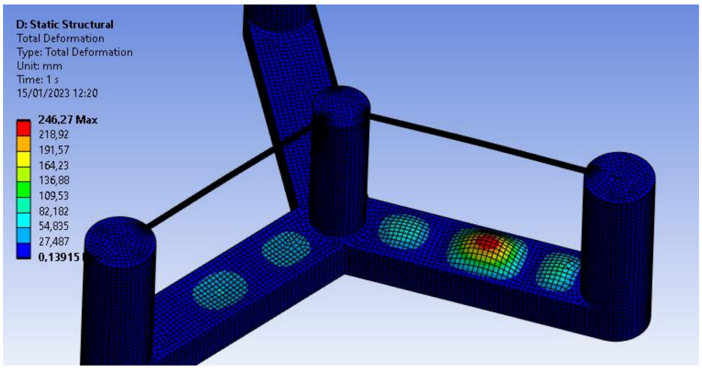


Figure 49 Deformations distribution in the maximum pitch situation

3.4.3 Structural analysis of DLC 6.1 with 0º wave direction in the minimum pitch situation.

In this situation, the pitch angle reaches its maximum negative value, -4,05º. As said before, negative pitch angles get considerable higher values than the positive ones, and so, the load effects are more significant in this negative pitch cases.

The minimum pitch configuration is the most extreme situation in terms of the structure inclination. Because of that, the hydrostatic pressures present big differences between points with the same height, as shown in the picture below.

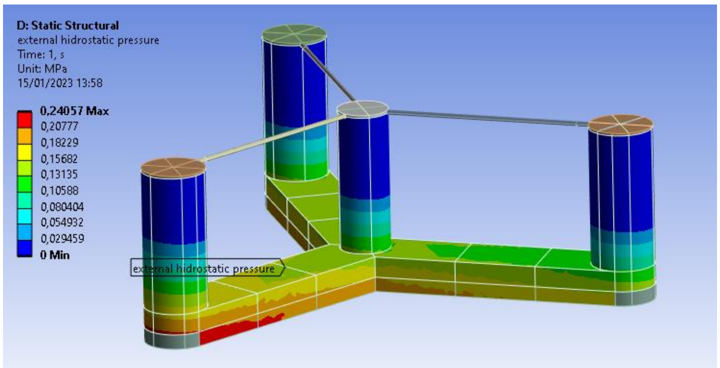


Figure 50: External hydrostatic pressures in the minimum pitch situation

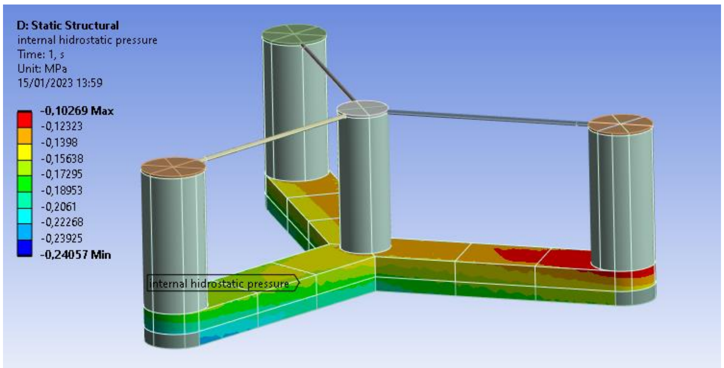


Figure 51:Internal hydrostatic pressures in the minimum pitch situation

Due to the inclination of the structure in this situation, the turbine and tower moments transmitted to the platform are extremely high. If we compare the moment values with respect to the ones of the maximum pitch situation, we can notice that the pitch component of the moment (M_y) increases by an order of magnitude. Due to the influence of this moments in the structural stability of the platform, this situation should be more critical than the one described in the last section.

The rest of the loads take similar values to the other situations analyzed. The dynamic wave pressures are, as happen in all the simulations, an order of magnitude lower than the hydrostatic pressures, and take either positive and negative values.

$F_{tower}X$	$2{,}9095 \cdot 10^6$ N
$F_{tower}Y$	25790 N
$F_{tower}Z$	$-2{,}187 \cdot 10^7$ N
Mx	$1{,}532 \cdot 10^6$ N·m
My	$-3{,}449 \cdot 10^8$ N·m
Mz	$-41248 \cdot 10^4$ N·m
$F_{mooring1}$	$2{,}35 \cdot 10^6$ N
$F_{mooring2}$	$2{,}41 \cdot 10^6$ N
$F_{mooring3}$	$2{,}38 \cdot 10^6$ N

Table 12: Values of the input forces and moments

The obtained results show stresses beyond the safety limit in various regions of the platform. The maximum stress value (421 MPa) is located in the upper zone of one of the external columns, near its connection with a top tube. This top tube experiments a traction effort from the central column to which is linked, caused by the tower bending moment. The traction is transmitted to the external column, which experiment in its connection region a high stress value.

As told before, the significant increment of the stresses values in all the platform is linked to the raise of the bending moment. As a consequence, the situations in which these moments are higher are the most critical ones in terms of structural stability.

Other regions in which the stresses overpass the safety limits are the top surface of the central column, the central column, the platform base, the top tubes and the internal ribs of the central column. The thickness of all these sections must be, again, re-dimensioned in order to achieve stresses below the limit in the whole structure. The new thickness values obtained are shown in the table below.

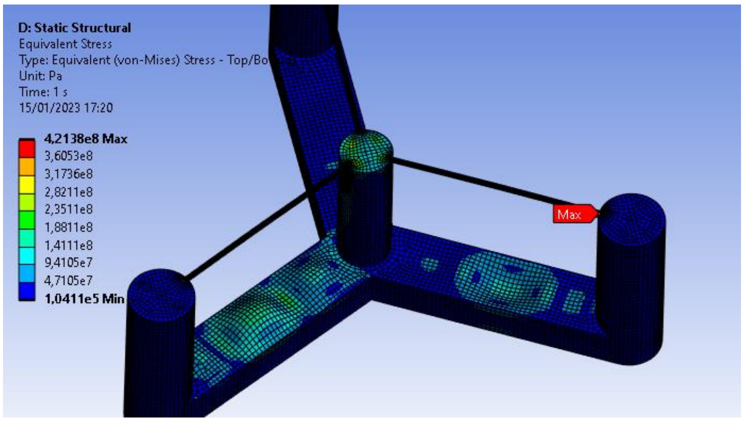


Figure 52: Stresses distribution in the minimum pitch situation

Element	**New Thickness (mm)**
Central cylinder top surface	165
Top connection tubes	70
Platform hull	75
Ribs of the central column	35

Table 13: New thickness values of the platform

The regions which present higher thickness increments are the platform hull, as is the region in which the highest stress is located; and the top connection tubes, which are submitted to great loads due to its connection with the central column in which the moments are transmitted. The top surface of the central column doesn't need, in this case, a big increase.

With this new configuration, the stresses values are reduced along all the platform. The stresses stop being relevant in the external and central columns, as a consequence of its considerable thickness increment. Same happens to the top tubes. In all these regions, the stresses take values below 100MPa, more than the half part of the limit allowed. The only region in which the stresses are more relevant is the central cylinder top surface, in which the maximum value is located. This maximum value, 275 MPa, is approximately the same than the safety limit, so all the platform is considered to be structurally ensured in this situation.

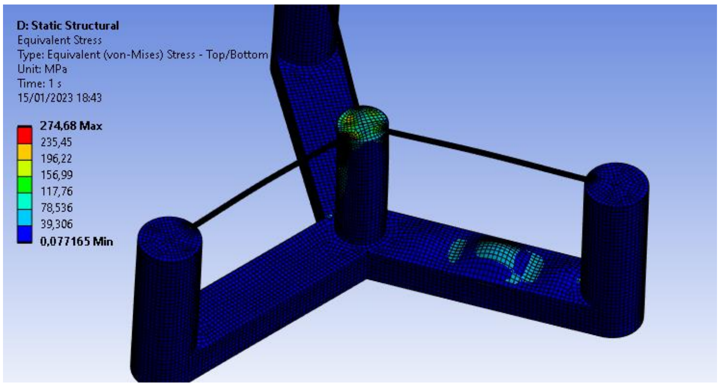


Figure 53: Stress distribution with the new thickness configuration

The deformations are drastically reduced in all the platform. As it can be seen in the picture below, its maximum value is reduced by more than three times with respect to the maximum pitch situation. Taking into consideration that the solicitations in this situation are quite higher than in the last situation, this reduction can be considered as a significant improvement.

The maximum deformation is reached in the base arm, in which the bending effect caused by the sinking of the central column into the base is higher. In contrast to the other situations analyzed, it is observed a higher –but still insignificant- bending deformation in the central column, as well as in the external columns, as a consequence of the moments transmitted from the tower and turbine, whose magnitude is, in this situation, higher than in the other ones.

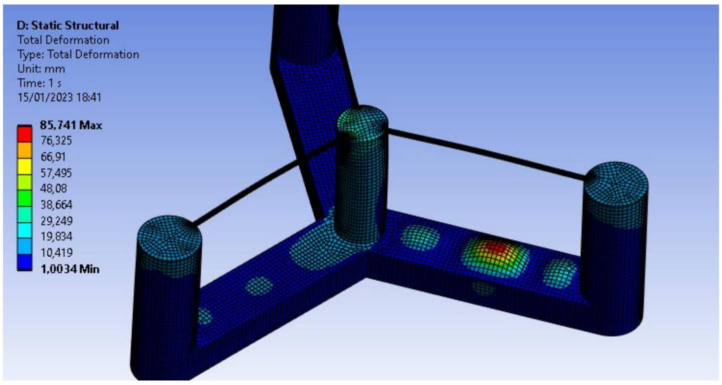


Figure 54: Deformation distribution with the new thickness configuration

3.4.4 Structural analysis of DLC 6.1 with 0º wave direction in the maximum bending moment norm situation.

The maximum bending moment norm situation is associated to an instant in the balancing period of the structure in which the pitch is minimum (-3,87º). Thus, the load characteristics of this situation will be quite similar to the ones of the minimum pitch situation.

In that way, the hydrostatic pressure distribution presents a big variation between points of the platform of the same height, due to the high inclination which presents the structure in this configuration (see the figures below).

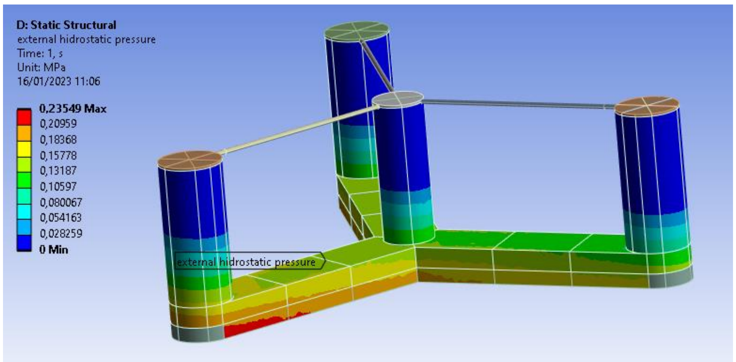


Figure 55: External hydrostatic pressures in the maximum bending moment situation

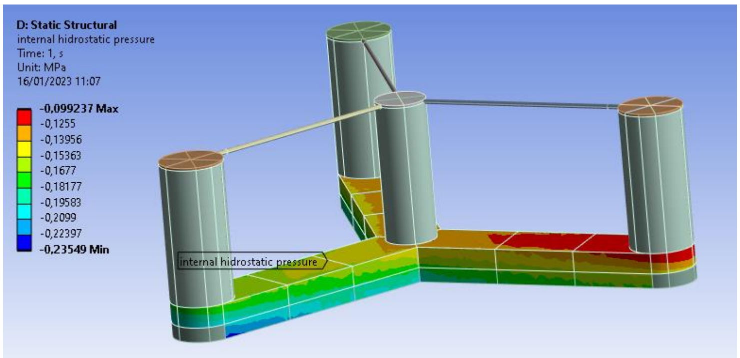


Figure 56:Internal hydrostatic pressures in the minimum bending moment situation

The analyzed situation represents the instant in the simulation in which the norm of the bending moment vector reaches its maximum value. This vector can be divided in two components, M_y and M_x, each of them with its own contribution in the mechanical solicitations on the structure. It is possible that the maximum norm situation doesn't correspond to the situation in which the sum of the contributions in the platform is the maximum. However, this parameter is considered as a good approach to the phenomena which want to be evaluated.

The wave pressures distribution looks pretty similar to the other situation analyzed. In the same way, the tower force norm, as well as the mooring forces, take values which don't vary in a significant way with respect to the ones of the other simulations.

$F_{tower}x$	$-3,744\cdot10^6$ N
$F_{tower}y$	-65019 N
$F_{tower}z$	$-2,178\cdot10^7$ N
Mx	$6,3651\cdot10^6$ N·m
My	$-4,3835\cdot10^8$ N·m
Mz	$3,194\cdot10^5$ N·m
$F_{mooring1}$	$2,38\cdot10^6$ N
$F_{mooring2}$	$2,23\cdot10^6$ N
$F_{mooring3}$	$2,4\cdot10^6$ N

Table 14: Values of the input forces and moments

The results obtained shows stresses beyond the limit in some regions of the platform. The central cylinder top surface is the most solicited section, as it is the zone in which the bending moment of the turbine and tower is transmitted to the platform. Even with the thickness increments done until now, the stresses in this region reach up to 353 MPa. The stresses in both the traction and compression zones of this surface exceed the safety limit. Thus, a new thickness re-dimensioning is needed.

Other parts which need a thickness increment are the top tubes, the platform hull, the internal ribs of the central and external columns, and the top surfaces of the external columns. This last region, which haven't needed to be re-dimensioned before, requires now a thickness increment as a consequence of the high traction stresses transmitted by the top tubes.

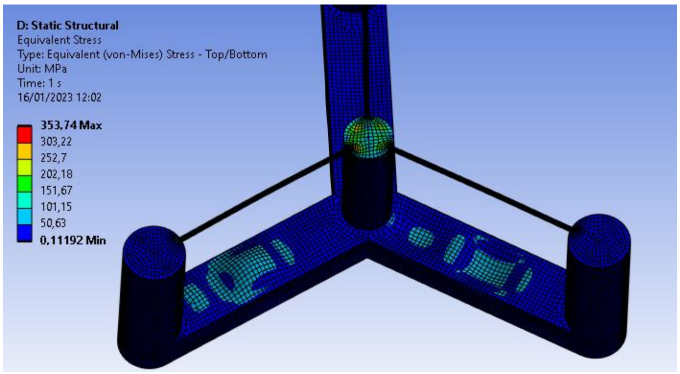


Figure 57: Stresses distribution in the maximum bending moment situation

Element	**Thickness(mm)**
Central column top surface	190
Top connection tubes	85
Platform hull	80
External columns internal ribs	45
External columns top surface	35

Table 15: New thickness values of the platform

With this new thickness configuration, the stresses are reduced in a considerable way all along the platform, in a way that they don't exceed the established limit in any point. Stresses are only considerable in the central column in which the bending moment is directly transmitted, as well as in the platform base, where the bending effect is combined with the wave pressure effect. It is in this region in which the deformation is higher, as happens with the other situations. However, its magnitude (114 mm) is not high enough at all to compromise the structural stability of the platform.

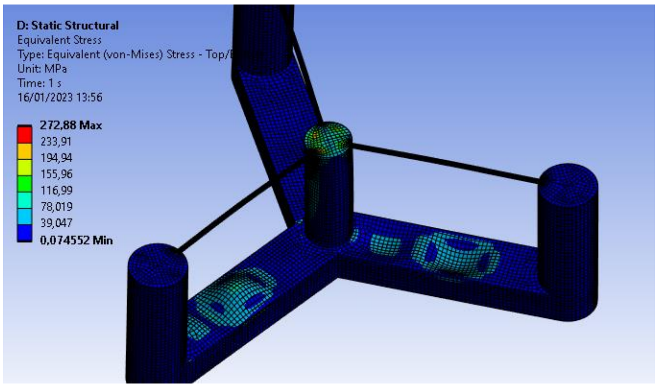


Figure 58: Stress distribution with the new thickness configuration

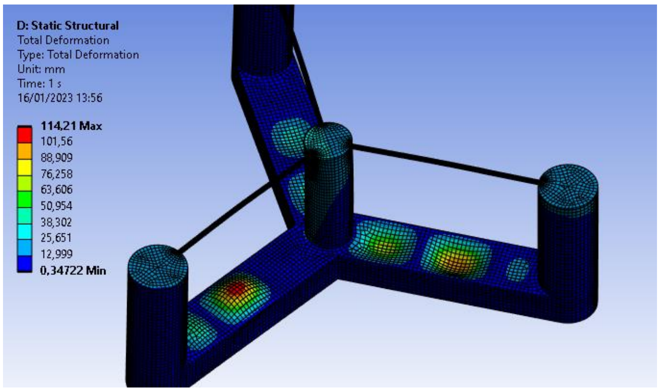


Figure 59:Deformation distribution with the new thickness configuration

3.4.5 Structural analysis of DLC 6.1 with 0º wave direction in the maximum torsion moment situation.

In this situation, the torsion moment reaches its maximum value, $2{,}14 \cdot 10^6$ N·m. Even so, this value is still two orders of magnitude lower than the bending moment one, and so, its importance in the structural stability of the platform is small.

This case is different to the other analyzed ones, as it represents a geometrical configuration in which the inclination of the structure is not significant. As seen before, the level of inclination of the platform is directly linked to the structural solicitations in the platform, as the bending moment value depends on this inclination. Thus, the case analyzed doesn't represent a critical situation with respect to the structural stability of the platform. However, it is interesting to analyze this situation in order to study the platform behavior with respect to the torsion loads.

The geometrical configuration in the maximum torsion moment situation is characterized by a heave value of -0,71 m, and a pitch angle of -0,81º. As the platform is only slightly inclined, the hydrostatic pressure is distributed homogeneously along points of the same height, similarly to the hydrostatic case. Because of this inclination also, the bending moment doesn't take an extreme value at all. Tower and mooring forces remain similar to the other analyzed situations.

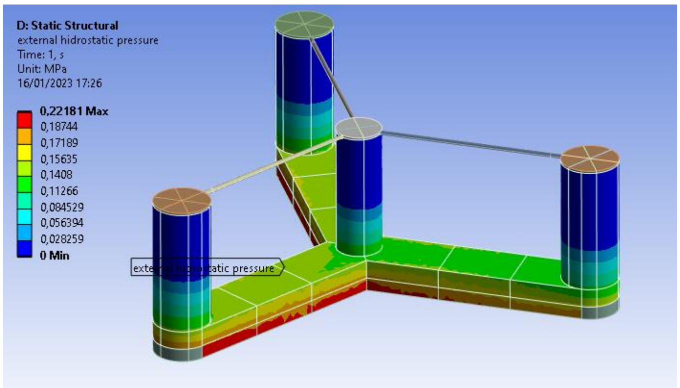


Figure 60: External hydrostatic pressure in the maximum torsion moment situation

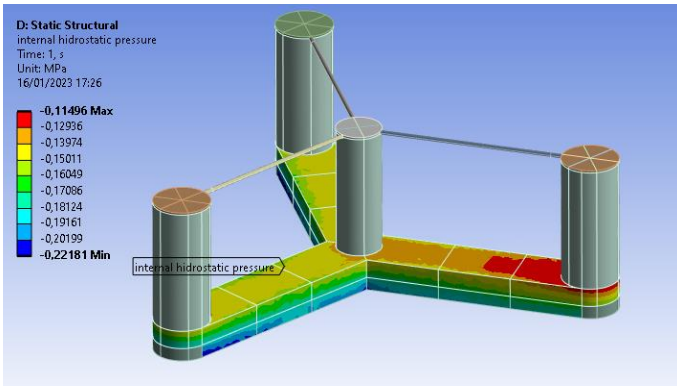


Figure 61:Internal hydrostatic pressure in the maximum torsion moment situation

$F_{tower}x$	$-8{,}42\cdot10^{5}$ N
$F_{tower}y$	$-5{,}1477\cdot10^{5}$ N
$F_{tower}z$	$-2{,}184\cdot10^{7}$ N
Mx	$-4{,}7598\cdot10^{7}$ N·m
My	$-1{,}1972\cdot10^{8}$ N·m
Mz	$-2{,}1409\cdot10^{6}$ N·m
$F_{mooring1}$	$2{,}46\cdot10^{6}$ N
$F_{mooring2}$	$2{,}48\cdot10^{6}$ N
$F_{mooring3}$	$2{,}34\cdot10^{6}$ N

Table 16: Values of the input forces and moments

Unlike the other analyzed cases, in which the most solicited region in term of stresses is the central column top surface, in the maximum torsion moment situation the regions with the biggest stresses are the ribs which connect the central column with the platform base. The main objective of these elements is to give enough structural rigidity in this connection zone, so that the relative displacements between the central column and the base are not too great to produce structural instabilities in the platform.

In the analyzed situation, in which the effect of the torsion moment is bigger, the connection ribs largely prevent the rotation of the central column with respect to the rest of the platform. As a consequence of that, these elements absorb and transmit the torsion loads from the central column. This torsion strain, added to the bending ones, produces high stresses in this zone. However, the values of these stresses are far beyond the safety limit, and don't exceed 130 MPa.

Other regions with considerable stresses are the top surface of the central column, the base hull and the internal ribs in the central and external columns. As said before, the geometric configuration of the platform in this situation, with not a big inclination, produces low bending loads in the platform, so the stresses aren't critical at all.

With respect to the deformations, the platform hull is the region in which they are higher (maximum of 41 mm). Other regions in which the deformation is visible are the central column, in which the bending moment produces a little flection, and the external columns which experiment the same effect. However, they aren't significant at all for the structural stability of the platform. The torsion moment doesn't have a real impact in any of the elements deformation.

As it can be seen, the structure is oversized with respect to the torsional effects of the load cases. The predominant load is, in fact, the bending moment transmitted caused by the tower and turbine inertia.

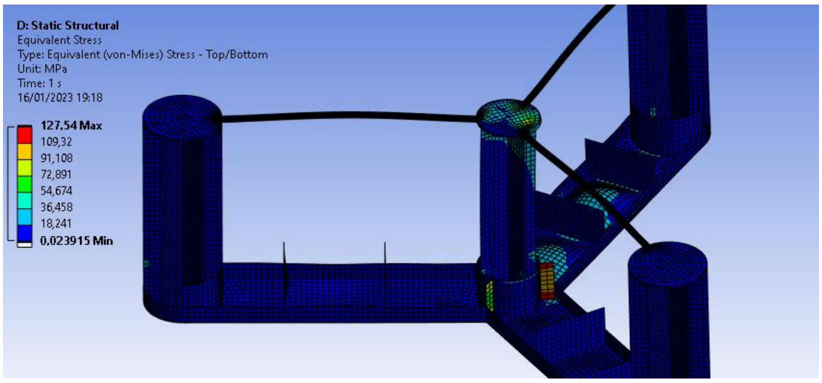


Figure 62: Stresses distribution inside the platform hull in the maximum torsion moment situation

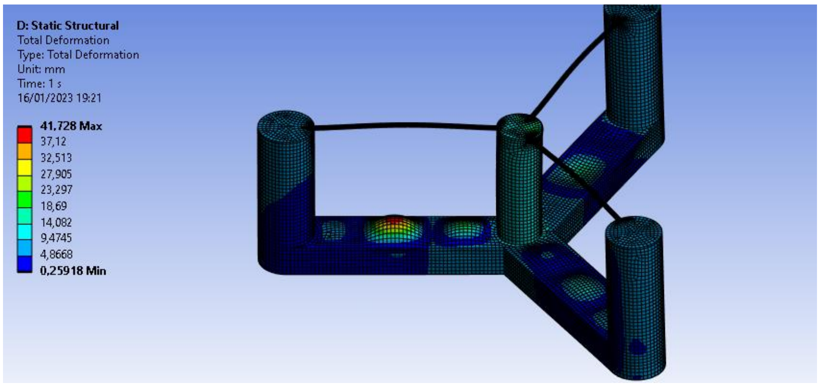


Figure 63: Deformation distribution in the maximum torsion moment situation

3.4.6 Analysis and comparison between the different critical situations of the DLC 6.1 with a wave direction of 0º.

Once we have done an exhaustive analysis about the structural stability of the platform in each of the critical situations of the DLC studied, it's interesting to evaluate and compare these situations in order to understand how the different external parameters associated to the DLC analyzed affects the structural behavior of the platform. For doing this, we will compare all the significant parameters used in the MOST and ANSYS simulations.

First thing to analyze is the geometrical configuration of the structure in each critical situation. Among all the six parameters which serves to defined the platform configuration in each instant of the simulation, only two of them are considered relevant with respect to the structural stability of the platform: the pitch angle and the heave. Also the yaw angle will be analyzed in order to understand its relation with the torsion loads.

The pitch angle is the parameter that represents in a most significant way the inclination of the structure with respect to the sea water level. This is due to the orientation of the turbine and tower considered, which forms 90 degrees with respect to the sway axis associated to the pitch angle; which implies a quite higher variation in this orientation than in the orthogonal one. This effect is even higher in this specific DLC, in which the wave direction is aligned with the surge axis (β=0º).

As we can see in the graph below, the pitch's negative range (associated to the forward inclination of the platform) is considerably greater than its positive one (associated to the backward inclination). The reason of it is the geometrical configuration of the structure, in which the turbine and tower are oriented onward, in a way that the inertia effect during the forward balancing is higher than the negative one and, thus, it's harder to change the platform movement when is inclined forward. We can also notice how the pitch configuration influences in the bending moments transmitted by the tower and turbine to the platform, as its highest values are associated to situations in which these moments are considerable.

The heave is other relevant parameter with respect to the structural stability of the platform, as it represents its level of buoyancy/sinking in each time instant. The main loads associated to this parameter are the hydrostatic pressures on the hull, as its magnitude depends on the level of submersion of the hull. Thus, the minimum heave represents the situation during the simulation in which the influence of the hydrostatic pressure is bigger. Moreover, the minimum heave instant is associated to a structural configuration in which the pitch takes a negative and significant value, so that the effect of the high hydrostatic pressure is summed to the one of the considerable bending moments. As it can be seen, the value of the heave in its minimum is quite bigger –in absolute terms- with respect to the other critical situations analyzed. The situations in which the heave takes a low absolute value (maximum pitch, maximum torsion moment) are associated to low pitch configurations in which the bending moment is less considerable.

In addition to these two important parameters, it's consider interesting to analyzed the influence of the yaw angle in the torsion moment value, and understand the real impact of this parameter in this kind of solicitation; as it represents the spinning of the platform with respect to the heave axis. For that purpose, the yaw angle is represented in the five critical situations analyzed. As it can be seen, the value of the yaw angle in the maximum torsion moment is not the highest one, but, in fact, is lower than in other cases analyzed. Thus, is not find a direct relation between this geometric parameter and the magnitude of the torsional loads. This loads will be lately analyzed in more detail.

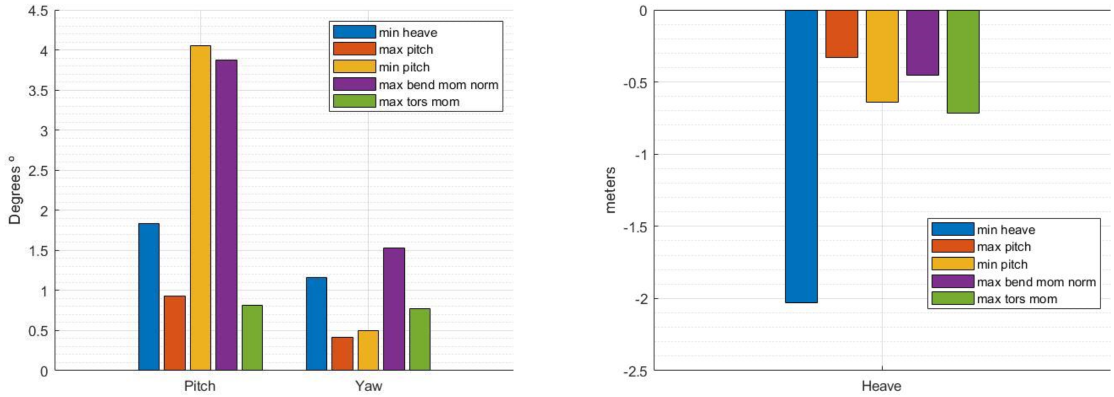


Figure 64: Pitch, yaw and heave values of the situations analyzed of the DLC 6.1 with 0º wave direction

Next thing to analyzed are the loads which are involved in the situations analyzed. It can be classified in two types, with respect to its nature and the way they affect the structure: the tower and moment loads, and the hydrostatic and wave nonlinear pressures. Mooring forces aren't taking in consideration in this analysis because its influence in the structural stability of the platform is null.

From all the loads transmitted by the turbine and tower, the bending moments are the ones with a higher magnitude, and thus, a more critical effect in the structure stability. The bending moment is quantized in the analysis done by its quadratic norm, as an approach to its real magnitude and effect in the platform. The bending moment vector can be decomposed, with respect to the platform associated frame, in two components: M_x, associated to the platform spin with respect to the surge axis; and M_y, associated to the platform spin with respect to the sway axis.

As we can see in the graphs below, the values of the M_y component are extremely higher than the M_x ones, and thus, its effect in the stresses distribution of the platform is much more considerable. It's also possible to notice how the variation in this M_y component between the different critical cases analyzed are much higher than the ones of M_x. The mainly reason of that is the geometric configuration of the turbine and tower with respect to the platform. The tower and turbine are oriented in a way that have symmetry with respect to the x-z plane. With respect to the y-z plane, in contrast, it doesn't have this symmetry, as most of the turbine is situated onwards this plane. As a consequence of that, the effect of the tower and turbine inertia is quite higher in the balancing movement of the structure associated to the inclination of the structure (pitch turn), than in the turn movement around the x axis. This difference between M_x and M_y is even higher in this DLC in which the direction of the wave is aligned to the x axis, and so the inertial excitation in the orthogonal direction is null. Thus, in this case the M_x values are depreciable compare to the M_y ones, which are basically equal to the bending moment norm. We can conclude, so, that in this case the moment norm is a very good approach to quantify the bending effect.

The inertial configuration of the structure is also the responsible of the considerably higher forward inclination with respect to the backward one during the balancing movement of the platform (higher pitch negative values than positive ones, see figure 64). This effect also affects to the bending moment values, as the distance between the center of gravity of the platform and turbine, and the region of the platform in which the moment is transmitted, increases when the inclination is higher. Thus, the bending moment value depends on the inertial state of the structure during the simulation, as well as on its geometrical configuration.

With respect to the torsion moment, it takes much lower values than the bending moment ones. As we can see in the figure below, the order of magnitude of these moments are two times lower than the bending moments one, and so, its logical to think that its effect in the structural stability of the platform is minimum. This fact can be verified attending to the results of the simulations done of the critical cases analyzed, as the most committed situations (minimum pitch and maximum bending moment norm), have the lowest torsion moment values. Moreover, the torsion moment is negligible during most part of the simulation, and so, the mean torsion moment value is very low.

It is not found a direct relation between the torsion moment and the platform configuration, as the situations in which this moment is high don't correspond to situations in which the yaw angle is big. The torsion moment magnitude is more related to the inertial excitation state of the structure, as it can be seen in the figure 27. That explain the slow variation of this moment during the simulation, compare to other loads, as the bending moment or the tower or mooring forces.

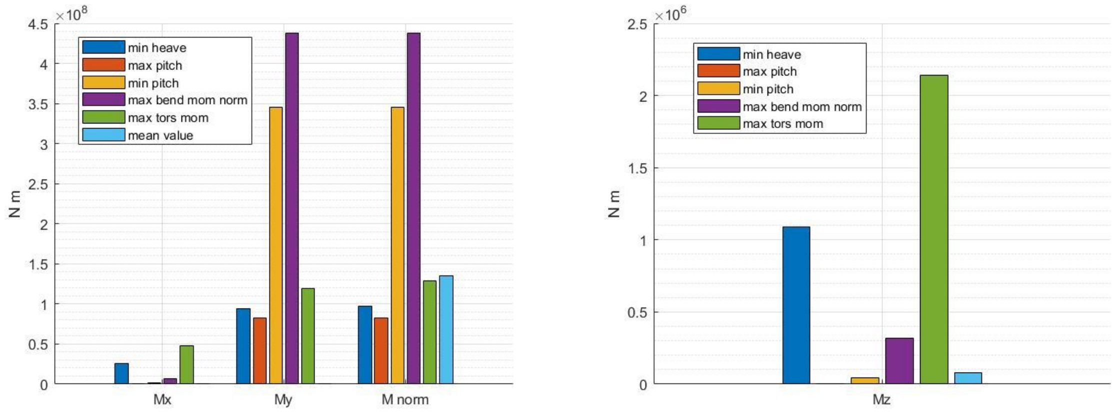


Figure 65: Bending and torsion moment values of the situations analyzed of the DLC 6.1 with 0º wave direction

With respect to the tower and turbine forces transmitted to the platform, we can see that its component in the vertical direction is quite higher than in the x direction one. Its contribution in the y axis is, directly, negligible.

The nature of this type of forces is inertial, as there are linked to the tower and turbine mass and movement. Thus, this forces can be expressed as the sum of two contributions: the tower and platform weight, and its longitudinal acceleration. As we can see in the figure 66, the nacelle acceleration is in all the situations lower than 1,5 m/s^2, which means at least six times lower than the gravity acceleration. That's why the contribution of the weight in these forces is more significant. For that reason, and because of the relative low inclination of the platform during all the simulation, the z component takes much greater values than the x component. In this way, F_z is more associated to the turbine and tower weight, while F_x is more associated to the instantaneous acceleration. F_x is higher in those situations in which the inertial state of the structure is bigger, while F_z doesn't even change and takes values near to the weight one ($2{,}2 \cdot 10^6$ N).

The z component of the tower and turbine forces in one instant is also related to the heave value of the platform in each instant, as it directly contributes to the sinking of the structure. In this way, the value of F_z in the minimum heave situation is slightly higher than in the other ones.

As we can also see in the figure 66 the longitudinal acceleration of the platform is mainly associated to the inertial situation of the structure, and so, it reaches its maximum value in the maximum bending moment situation. It also depends on the geometrical configuration of the platform, being higher in the extremes of the balancing movement (maximum and minimum pitch).

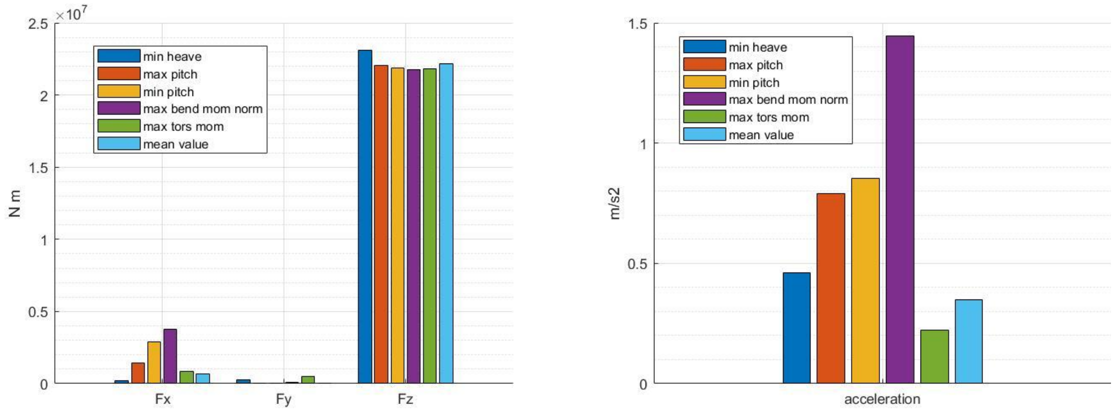


Figure 66: Tower and turbine forces and acceleration values of the situations analyzed of the DLC 6.1 with 0º wave direction

The other group of loads to analyze are the pressures, whose contribution in the structural instabilities are way lower. Attending to its nature, two types of pressures are independently analyzed: the hydrostatic pressures and the wave nonlinear pressures. To quantified this loads, their extreme values in each situation are taken, to have an idea of its contribution in the load state of each situation.

In the case of the hydrostatic pressure, the maximum value corresponds to the most submerged point of the platform. The situations which present higher hydrostatic pressure values are the ones in which the platform is more submerged. As the level of submersion depends on the sinking of the platform (associated with the heave) and its inclination (associated to the pitch), the situation with higher hydrostatic pressures are the minimum heave and the minimum pitch ones. Despite this, there aren't significant changes between cases. Furthermore, and due to the internal ballast which compensates these pressures, its effect on the stability of the structure is null.

The wave pressures are associated to the dynamic loads of the sea. Although its order of magnitude is lower than the hydrostatic ones, its effect in the structural stability is quite higher as the internal ballast doesn't compensate them. As a consequence of it, these loads are the main responsible of the maximum deformations in the platform in all the situations analyzed. This deformation is always located in the top or bottom surfaces of the platform bases. As we can see in the graph below, the wave pressures are higher in the maximum moment situation, and so, the maximum deformation is achieved in this situation.

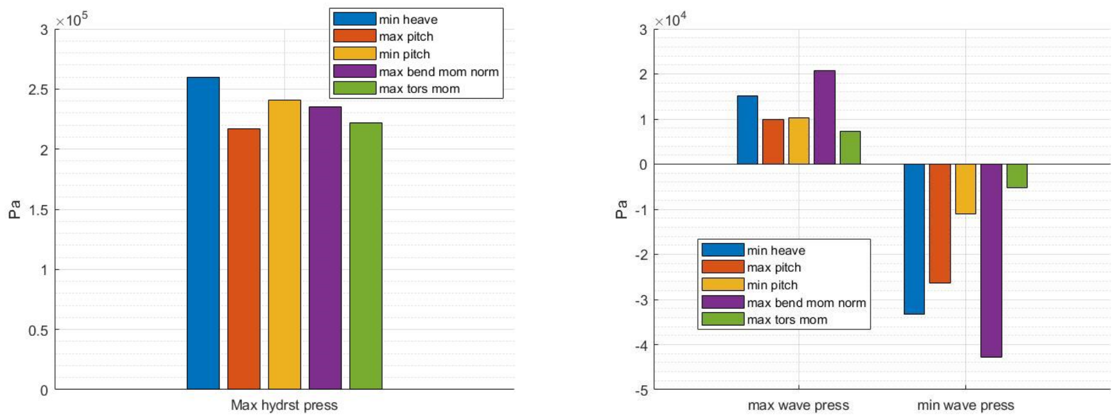


Figure 67: Hydrostatic and wave pressure values of the situations analyzed of the DLC 6.1 with 0º wave direction

Once we analyze and evaluate the relations between the geometric and dynamical parameters of each critical situation, is useful to understand and compare the results obtained in each of its correspondent static simulations. To do it, we take the most significate values on both the stresses and deformation results.

For the stresses evaluation, the values of the maximum and mean stresses on each situation are valuated. Both variables are directly associated to the structural solicitation state of the situation concerned.

As seen before, the solicitations in the structure depend, greatly, on the bending moment magnitude. Thus, the situations which have higher bending moment presents higher maximum stresses, and so, are more critical with respect to the structural stability. These situations correspond to the ones in which the onward inclination of the platform and/or its dynamic excitation are higher (minimum heave, minimum pitch and maximum bending moment). However, and because of the successive redesigns done, the maximum values don't exceed in any case the safety limit established.

With respect to the mean stresses values, they are also highly linked to the structural solicitations in the platform, and so, depend basically on the bending moment. Thus, they are higher in the minimum heave, minimum pitch and maximum bending moment situations. However, its values are ten times lower than the maximum ones, which means that the critic regions of the platform with respect to its static stability are highly focalized, so the main part of the platform is far from the risk of structural fail. As seen when analyzing the critical situation static simulations, these problematic regions are the top surface of the central column (which most of the times have the maximum values), the top tubes, and focalized regions of the hull and the internal ribs. The fact that the highest stresses are only concentrated in several small regions produce the oversized of the thickness of the platform.

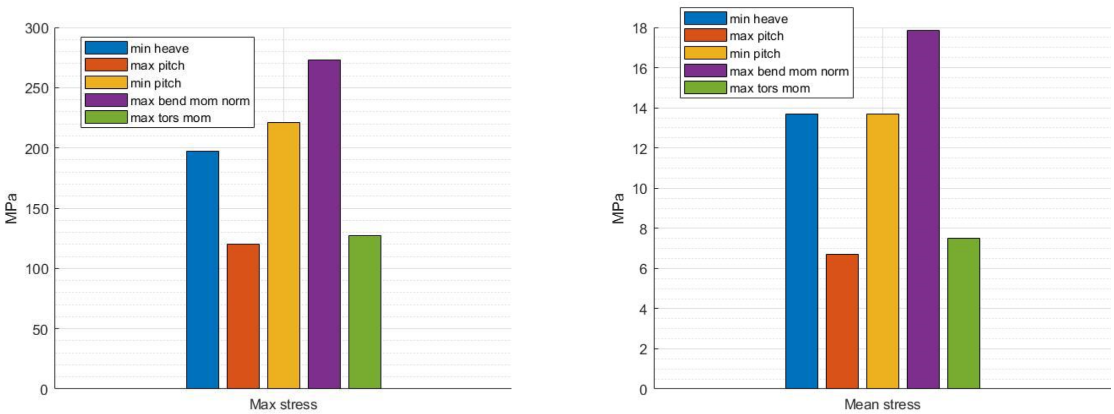


Figure 68: Maximum and mean stress values of the situations analyzed of the DLC 6.1 with 0º wave direction

For the deformations evaluation, the values of the maximum deformation, the deformation in the central column and the mean deformation of the platform are analyzed.

The maximum deformation of the structure is not explicitly related with the maximum stress reached, but with the effect of the wave pressures on the hull. In fact, the point with maximum deformation is not locate in the central column top surface, but on the top surface of the platform base.

As explained before, the high dimensions of this surface enhance the bending effect in this zone produced both by the wave pressure and by the sinking of the central column. The deformation of the central column, however, is limited by its internal reinforcement which provides it a high stiffness.

The highest values are reached in the situations in which the wave pressures are higher –minimum heave and maximum bending moment-. Nevertheless, these values don’t suppose a structural risk to the platform, as are relatively inside the allowed limits, if we take into account the great dimensions of the structure.

The central column deformation is directly associate to the dynamic loads transmitted by the tower and turbine. Thus, it is higher in the situations associated with bigger values of the bending moment. Nevertheless, its magnitude is quite low due to the high stiffness of the region.

The mean deformation mainly depends also to the bending moment, and takes similar- but lower- values to the central column deformation ones. Both of them are irrelevant for the structural stability of the platform. The reason of this low values obtained is the internal reinforcement done in the platform which gives enough rigidity in its critical regions, as well as the thickness increment in those regions, which reduces the stress values and its effects.

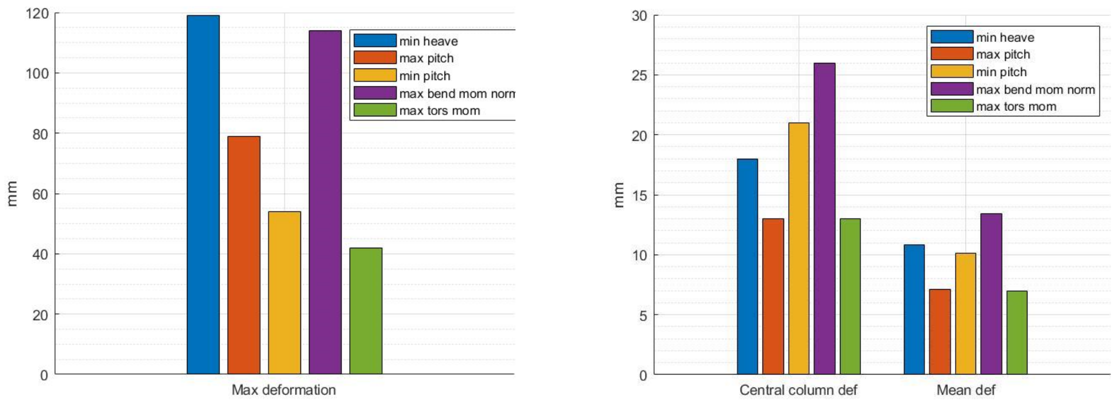


Figure 69: Maximum, mean and central column deformation of the situations analyzed of the DLC 6.1 with 0º wave direction

3.5 Simulation of the DLC 6.1 with 30º wave direction.

The configuration of the MOST simulation for this load case is given by the next input values: significant wave height of 5,53 m, with a corresponding peak period of 9,18s; an incidence wave direction with an angle of 30º with respect to the surge axis of the platform and turbine; and blocked condition of the turbine's rotor.

The simulation is configured with a duration of 60 minutes with an interval between time steps of 0,1 seconds. The first minute of the simulation is removed to avoid the transient effect of the beginning of the simulation. The main results obtained are shown below.

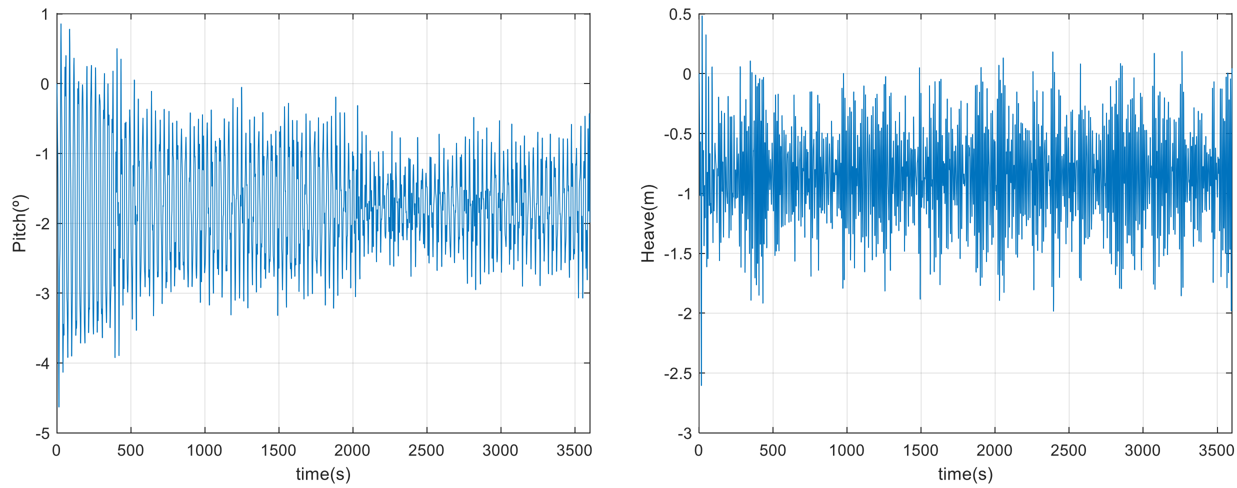


Figure 70: Heave and pitch values in time

Both the pitch and the heave have a similar tend compare to the DLC with $\beta = 0º$, but its positive and negative limits take slightly lower values. The reason of this –almost irrelevant- reduction is that the balancing movement of the platform is, in this case, slightly mitigated because of the orientation of the waves. In this case, waves impact in a transverse direction with respect to the orientation of the tower and turbine (x axis), so that the inertial balancing dynamics of the platform is not as amplified as when waves are aligned with the x axis.

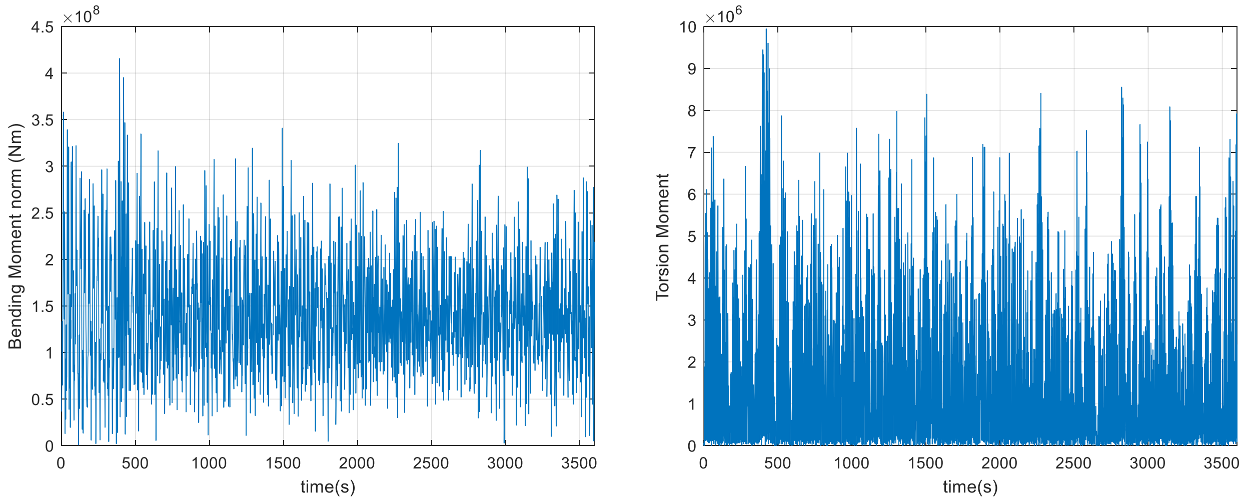


Figure 71: Bending moment norm and torsion moment values in time

The bending moment norm takes values between 0 and $4,2 \cdot 10^8$ Nm. The peak values of this norm are associated to minimum, negative values of the pitch angle. It reaches a minimum value of $4,16 \cdot 10^8$ Nm.

This parameter takes similar values to the ones obtained in the load case with 0º wave direction. However, the its impact in the structural solicitations of the platform are higher. This is because, in this case, the M_x component takes higher values than in the last case, and so, its effect is higher. Thus, the sum of the two contributions produces, in the critical situations, highest stresses in the platform. As a consequence, a new thickness re-dimension must be done. In this case, only the central column top surface must be swelled, from 190 mm to 200 mm.

With respect to the torsion moment, it present higher maximum values that in the case of 0º wave direction, reaching a maximum of $9,95 \cdot 10^6$ Nm. Moreover, it presents a much faster dynamic trend than in the last case simulated, resembling in this case to the other loads ones. The reason of this notable increment in the torsional dynamics is the transversal orientation of the waves, which increases the inertial torsional excitation.

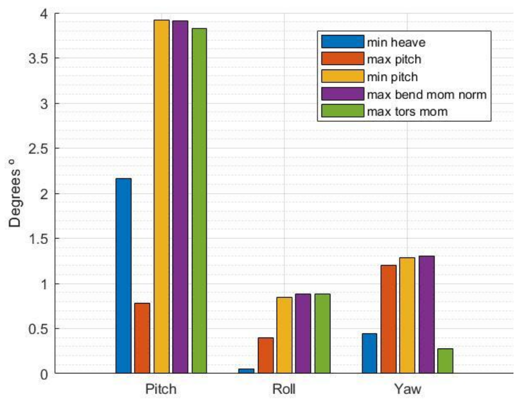
With respect to the rest of the loads –mooring forces, tower and turbine forces and hydrostatic and wave pressures-, they don't present relevant variations with respect to the previous case.

3.5.1 Analysis and comparison between the different critical situations of the DLC 6.1 with a wave direction of 30º.

A static structural analysis is done for the five critical situations, in the same way as described in the section 2.4. The results obtained of these simulations are evaluated and compared, so the main conclusions are exposed below.

With respect to the pitch angle, its highest values are associated to the situations in which the solicitations are greater (higher bending moment), as are, in this case, the ones of minimum pitch, maximum bending moment norm and maximum torsion moment. This last situation is remarkable, as have, in this case, considerable high values in all the load types that intervene: bending and torsion moments, tower forces and hydrostatic and wave pressure.

In this load case, it's decided to introduce a new geometrical parameter, the roll angle, which represents the inclination of the structure with respect to the z-y plane. Due to the misalignment between the wave direction and the x axis, the inclination of the platform stop being only relevant in the x-z plane, and so the structure presents a tridimensional balancing movement. As we can see, the situations with highest solicitations present a high inclined geometrical configuration, and so, high values of yaw and roll angles



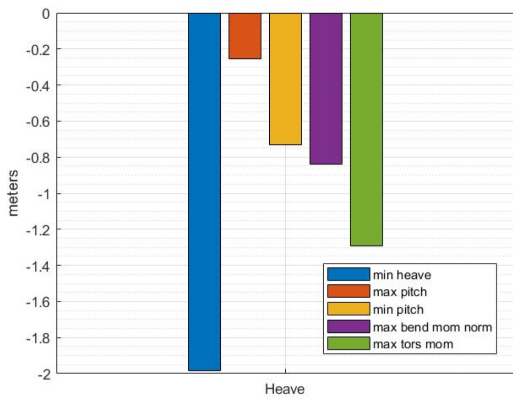
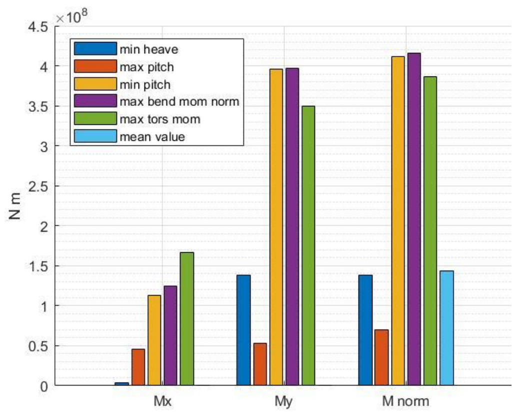


Figure 72: Pitch, yaw, roll and heave values of the situations analyzed of the DLC 6.1 with 30º direction

With respect to the bending moment, it can be appreciated a considerable increment of the M_x values with respect to the 0º wave direction case, being one order of magnitude higher in this case. This supposes a bigger impact of this contribution in the structural stability of the platform. The reason of this change is the new orientation of the wave's incidence, which are in this case misaligned with the orientation of the turbine and tower. As a consequence, the inclination in the y-z plane stop to be irrelevant, which implies that the M_x components of the bending moment stop also to be insignificant in those situations in which this inclination is considerable.

However, the M_y component is still, and by large, the predominant one, as the inclination and inertial dynamics in the x-z plane are quite higher. But the increment of the M_x component implies higher structural solicitations in the most critical situations, and so, stresses exceed the established stress limit in those cases. To solve this problem, the thickness of the central column top surface must be increased from 190 mm to 200 mm.

As we said before, the dynamic response of the torsion moment is, in this case, faster and so, similar to the other types of load ones. Because of that, the highest torsion moment values are, in this case, more distributed among all the simulation time (in the case before, the highest values were concentrated between approximately the second 1500 and 2500, see figure 27). Thus, the situations in which high torsion moments are combined with high bending moments are more recurrent. That is what happens, in this case, in the minimum pitch, maximum bending moment and maximum torsion moment situation.



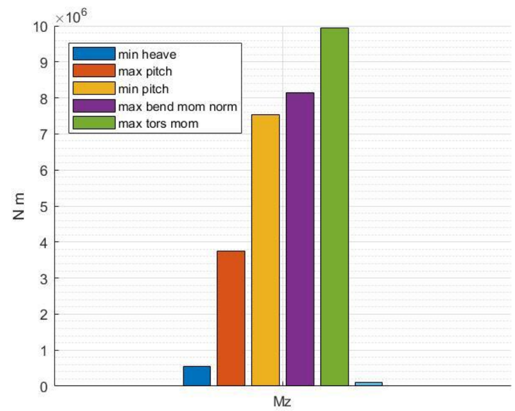


Figure 73: Bending and torsion moment values of the situations analyzed of the DLC 6.1 with 30º wave direction

With respect to the tower and turbine forces, it can be observed an increment in the F_y component, associated to a higher inertial effect in the y axis. Same happens with the longitudinal acceleration, whose y component increases in this case.

However, the F_x component is higher than the F_y due to the bigger inclination on the y axis, and the F_z component, mainly associated to the turbine and tower weights, is quite predominant. The effect of these forces in the structural stability of the platform continues being quite low.

Both the inertial forces and the acceleration are higher in the critical situations associated with highest solicitations: minimum pitch, maximum bending moment and maximum torsion moment.

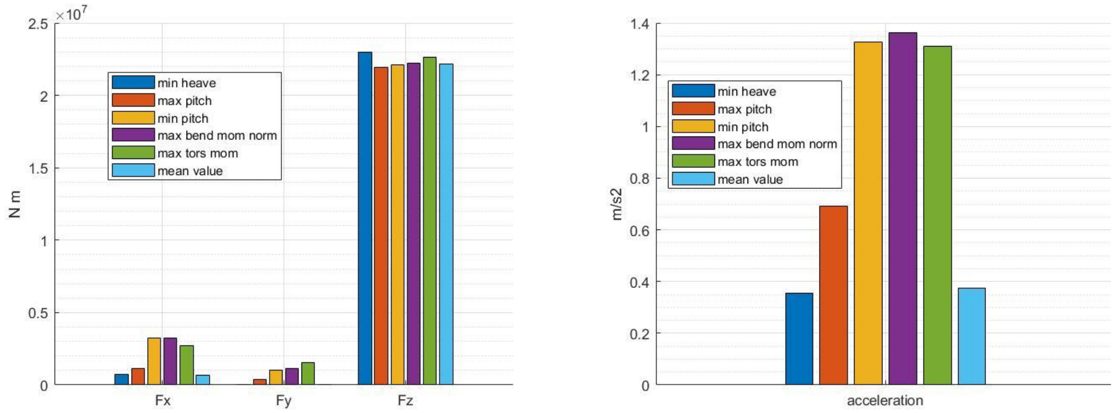


Figure 74: Tower and turbine forces and accelerations values of the situations analyzed of the DLC 6.1 with 30º wave direction

The hydrostatic pressure takes maximum values a bit higher than in the previous case due to the higher combined inclination of the platform which makes the most submerged point to be deeper with respect to the sea water level. This effect is incremented because of the higher effect of the bending moment, but, however, is actually irrelevant. The wave maximum and minimum pressures are higher in the minimum heave, maximum bending moment and the maximum torsion moment, and so, in fact, should have higher deformations in the surfaces of the base.

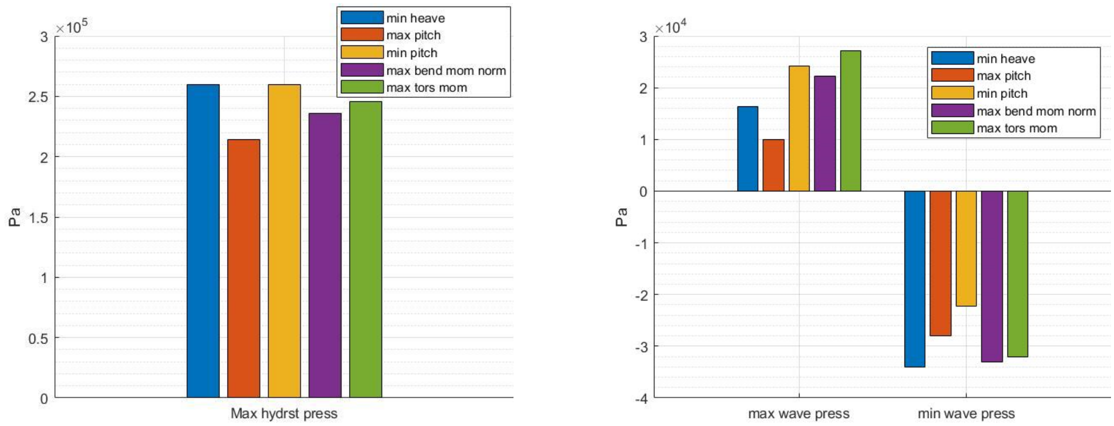


Figure 75:Hydrostatic and wave pressure values of the situations analyzed of the DLC 6.1 with 30º wave direction

As a consequence of the bigger bending effects due to the higher inclination of the platform, the maximum stress values reached in the critical situations are higher, and also, near the safety limit. However, with the new redesign, all critical situations are out of any structural risk.

The three critical situations present very similar maximum values, as its load conditions are practically equal. However, the mean stress value is considerably higher in the situation of the maximum bending moment, which means that, as happens with the previous case, this situation presents the highest structural solicitations.

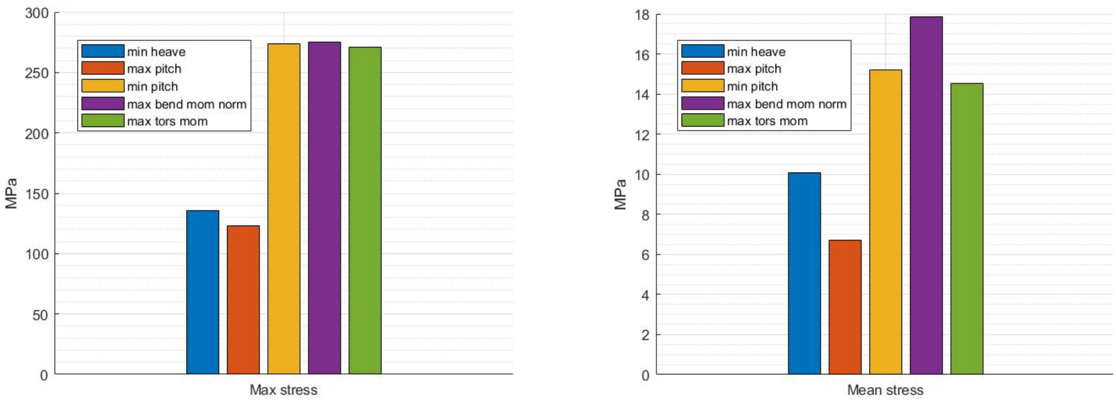


Figure 76:Maximum and mean stress values of the situations analyzed of the DLC 6.1 with 30º wave direction

With respect to the deformations in each situation, the maximum values are associated, as happens in the case with 0º wave direction, to the wave pressure magnitude in the top and bottom surfaces of the base, and so, are linked to this region deformation. Because of that, minimum heave, minimum pitch, maximum bending moment and maximum torsion moment reach bigger values.

The central column deformation, directly linked to the bending moment effect, is higher, thus, in the maximum bending moment situation. The mean deformation values follow the same trend, being higher in those cases in which the maximum deformation is higher because of the bending moment effect.

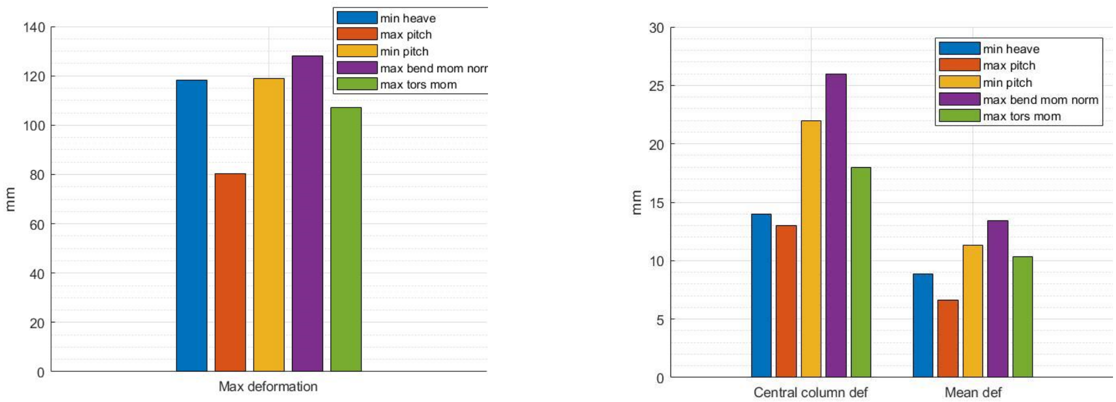


Figure 77: Maximum, mean and central column deformation of the situations analyzed of the DLC 6.1 with 30º wave direction

3.6 Simulation of the DLC 6.1 with -30º wave direction.

The simulation done in MOST for this case follows the same configuration as the other ones from the DLC 6.1: significant wave height of 5,53 m, with a corresponding peak period of 9,18s; an incidence wave direction which in this case has an angle of -30º with respect to the surge axis of the platform and turbine; and blocked rotor of the turbine.

The simulation has a duration of 60 minutes, with an interval between time steps of 0,1 seconds. The first minute of simulation is eliminated to avoid the undesirable transient situation in the beginning of the simulation. The main output results of this simulation are exposed below.

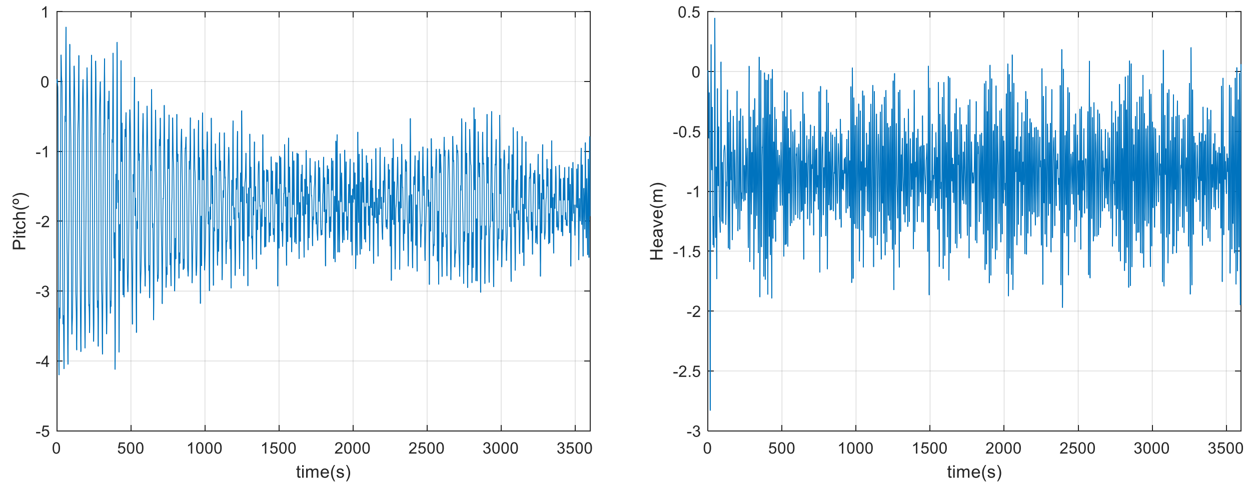


Figure 78: Heave and pitch values in time

Pitch and heave parameters take similar values to the ones obtained in the other cases analyzed. The pitch maximum positive value is, in this case, 0,78, and its maximum negative one -4,12. The heave minimum value is of -1,97. The pitch takes only positive values at the beginning of the simulation, being negative in most part of the time. This is because of the inertial configuration of the structure, with the turbine and tower oriented in the positive x axis (and, thus, asymmetrical with respect to the z-y axis). Due to this configuration, the structure trends to incline forwards. This tend increases during the simulation until the structure reached a semi-steady state.

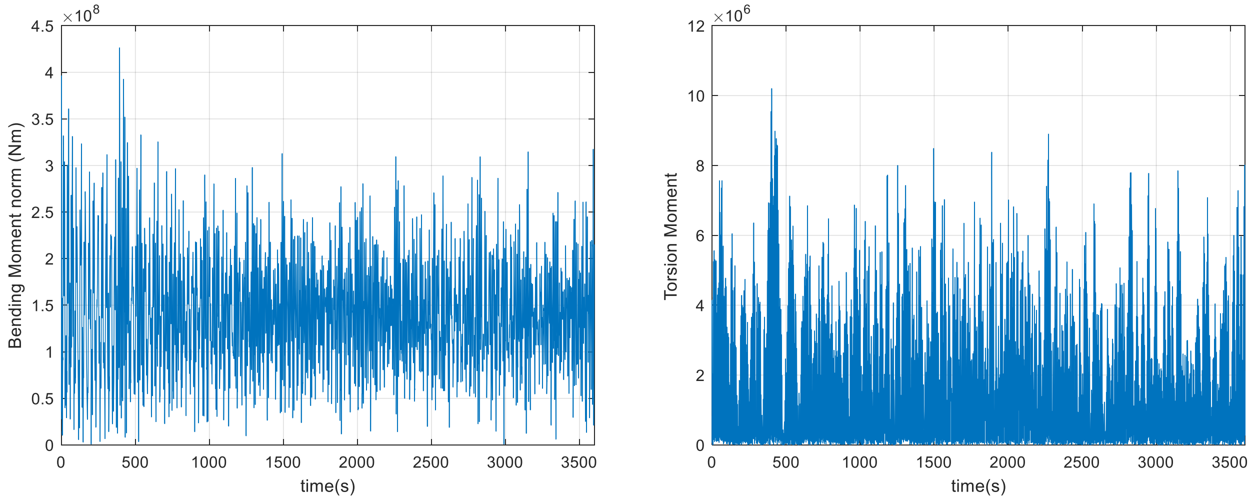


Figure 79:Bending moment norm and torsion moment values in time

The bending moment norm takes a maximum value of $4,26 \cdot 10^6$ N·m, and a medium value of $1,5 \cdot 10^6$ N·m. The bending moment values oscillates which this trend along all the simulation. The highest values are associated to the configurations in which the pitch takes also big negative values.

The torsion moment has, as happens with the 30º wave direction case, a higher dynamic response, and so, its values oscillate between negligible minimum values and maximum values which are near the global maximum. Furthermore, the global maximum is, in this case, higher than in the other ones, reaching a value of $1,02 \cdot 10^7$ N·m.

With respect to the rest of the loads –mooring forces, tower and turbine forces and hydrostatic and wave pressures-, don't present relevant variations, as happens with the other cases.

3.6.1 Analysis and comparison between the different critical situations of the DLC 6.1 with a wave direction of -30º.

A static structural analysis is done for the five critical situations, in the same way as described in the section 2.4. As a curious aspect, in this case simulated, the minimum pitch situation coincides with the maximum bending moment norm one. Thus, the number of critical situations to analyzed is reduced, in this case, to four. The main results obtained are shown below.

The pitch angle takes its highest negative value in the situation of maximum bending moment norm, in which the inclination of the platform is higher.

The roll angle is substantially more significant than in the 0º wave direction case, due to the transversal orientation of the waves. This angle takes its highest value in the maximum torsion moment situation, and so, its M_x component of the bending moment is higher in this situation.

In the most solicited situations in terms of bending moments, the roll angle takes considerably lower values than in the 30º wave direction case. Thus, its M_x contribution is, in this case, a little bit lower.

The yaw angle presents, in this case, a high value in the situation of maximum torsion moment, in contrast to the other cases analyzed in which this angle takes the lowest value in this situation. In this way, we can conclude that the magnitude of the torsion moment doesn't depend on the platform geometric configuration, but on the dynamical situation in each instant.

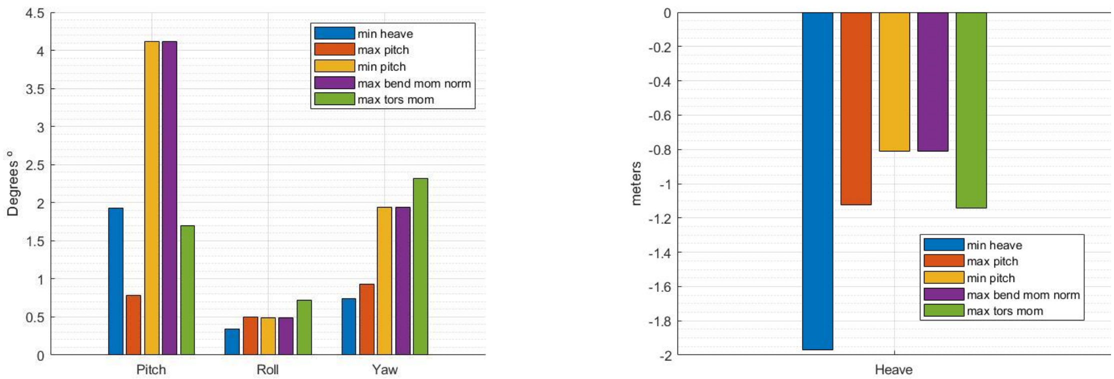


Figure 80: Pitch, yaw, roll and heave values of the situations analyzed of the DLC 6.1 with -30º wave direction

With respect to the bending moment, there is a considerable increment of the M_x values, as happens in the 30º case, due to the higher inclination in the y axis as a consequence of the misaligned orientation of the waves with respect to the x axis. However, in contrast to the 30º case, the highest M_x values aren't associated to high values on M_y (maximum torsion moment situation), and the maximum bending moment situation doesn't have a high M_x contribution. Even though, the structural solicitations in the platform are quite similar to the 30º case due to the high predominance of the M_y component, whose higher values with respect to the previous case compensates the lower M_x values.

The torsion moment takes considerable values in most of the critical situations, compared to the mean value of the simulation. As said before, the higher recurrence of this big values along all the simulation time is caused by the faster torsional dynamics due to the misalignment of the wave direction.

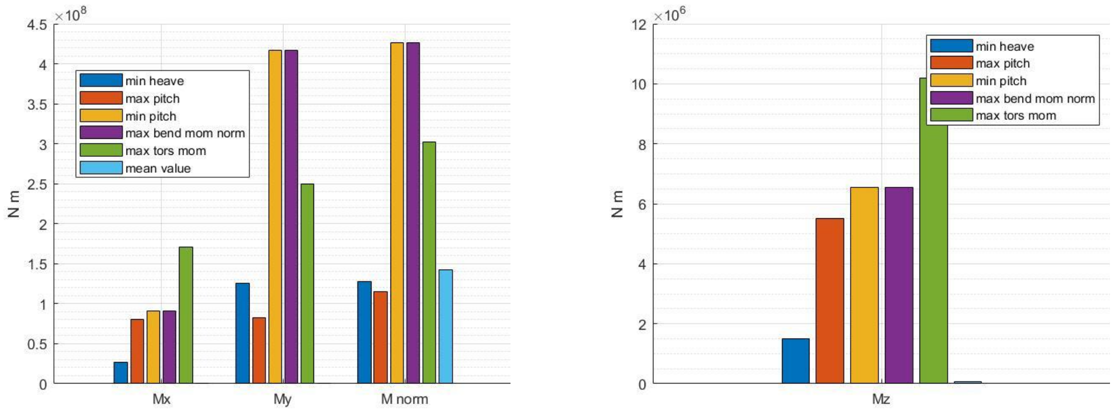


Figure 81: Bending and torsion moments values of the simulations analyzed of the DLC 6.1 with -30º wave direction

The tower and turbine forces present not only considerable values on the F_z and F_x components as happens with the 0º case, but also in the F_y component because of the higher inclination in the x axis. The F_y values are higher in the maximum torsion moment situation, in which the roll is higher; while the F_x values are higher in the maximum bending moment situation, in which the minimum pitch is higher. In the same way, the longitudinal acceleration presents its higher values in the configurations whit bigger inclination.

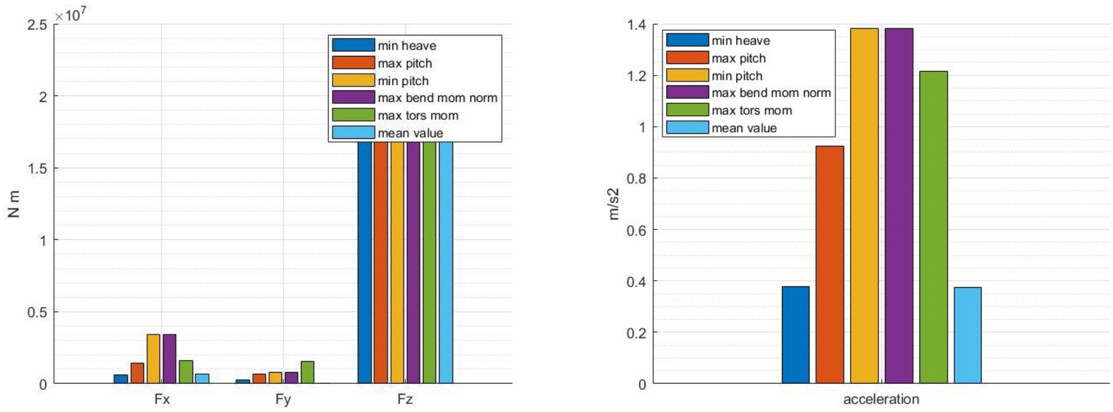


Figure 82: Tower and turbine forces and acceleration values of the situations analyzed of the DLC 6.1 with -30º wave direction

The maximum stress reaches it maximum value in the situation of highest structural solicitations, which corresponds, as happens in the other cases, to the maximum bending moment one. However, these solicitations are significantly lower than in the previous case, as the M_x component is lower. Thus, the maximum stresses reached in this case are considerably beyond the safety limit. The mean stresses are also a little bit lower than in the 30º case.

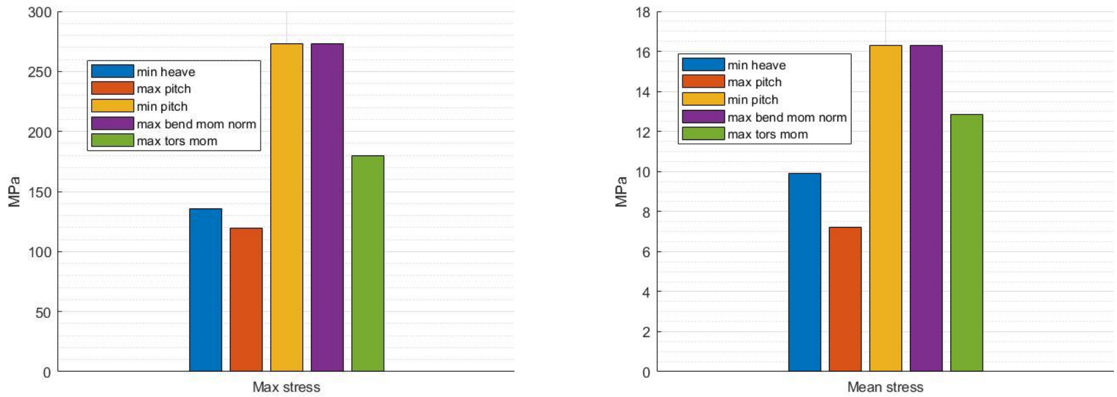


Figure 83: Maximum and mean stress values of the analyzed situation of the DLC 6.1 with -30º wave direction

The maximum deformations are located in the top and bottom surfaces of the base, and are higher in those situations in which the wave pressure is greater: minimum heave, minimum pitch (maximum bending moment norm), and maximum torsion moment. The central column deformation is higher in the maximum bending moment situation, but takes values slightly lower than in the other cases. The mean deformation takes quite similar values than on the other cases.

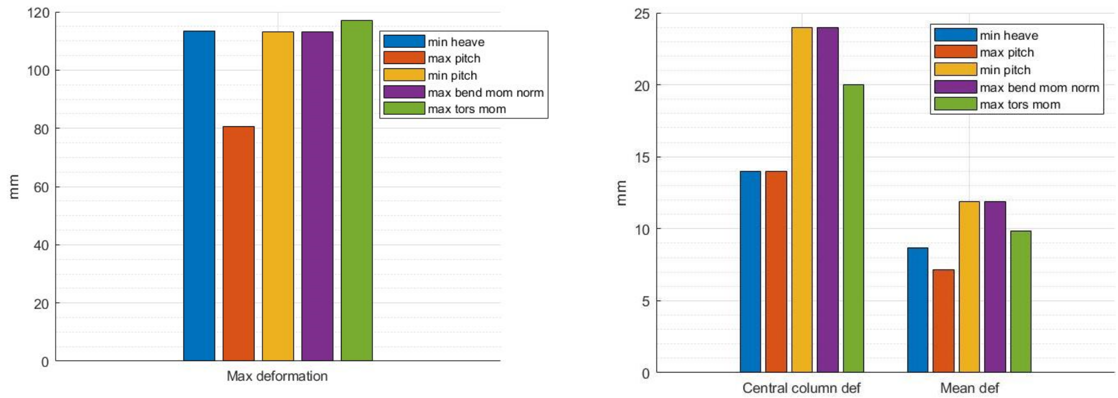


Figure 84:Maximum, mean and central column deformation of the situations analyzed of the DLC 6.1 with -30º wave direction

To finish the analysis of these load cases, a briefly comparison between the results obtained from the three cases are done. The main conclusions are exposed in the next section.

3.7 Analysis and comparison between the DLC 6.1 with 0º, 30º and -30º wave direction.

To compare the different DLC 6.1 cases, it's interesting to evaluate the main parameters which intervene in the simulations: the geometric configuration variables, the main external loads and the main results –maximum and mean stresses; and maximum, mean and central column deformations-.

With respect to the geometric configuration, the pitch and the roll angles are the main and only two geometric parameters which have real influence in the load case. The pitch angle is related to the inclination of the platform with respect to the y axis, which is by far the most relevant inclination. This inclination is, at the same time, associated to the M_y component of the bending moment of the tower and turbine. Thus, due to the higher values of the pitch, the M_y component is by far the highest and more relevant load. For this reason, the pitch inclination is considered as the most relevant geometric parameter of the load cases.

For the cases analyzed, the minimum pitch value (in absolute terms) takes values around 4 º, which supposes M_y values around $4{,}2 \cdot 10^8$ N·m. The percentage difference of the pitch between cases is of around 5%, which implies variations in the M_y components around 10%.

The roll angle represents the inclination of the structure with respect to the x axis, which is considerably lower. Thus, the M_x component, associated to this inclination, takes much lower values, and so, its relevance in the structural stability is, as well, lower. In the case of 0º wave direction, the roll value is insignificant, because of the alignment between the wave and turbine and tower directions, which implies almost null inclination of the platform with respect the x axis. Thus, the M_x component in this case is also irrelevant. In the cases of +/- 30º, the transverse orientation of the waves produces higher roll values, which means higher M_x values, and so, higher structural solicitations. The percentage difference of the roll angle is around 70%, which implies variation of 95% of the M_x component between the cases.

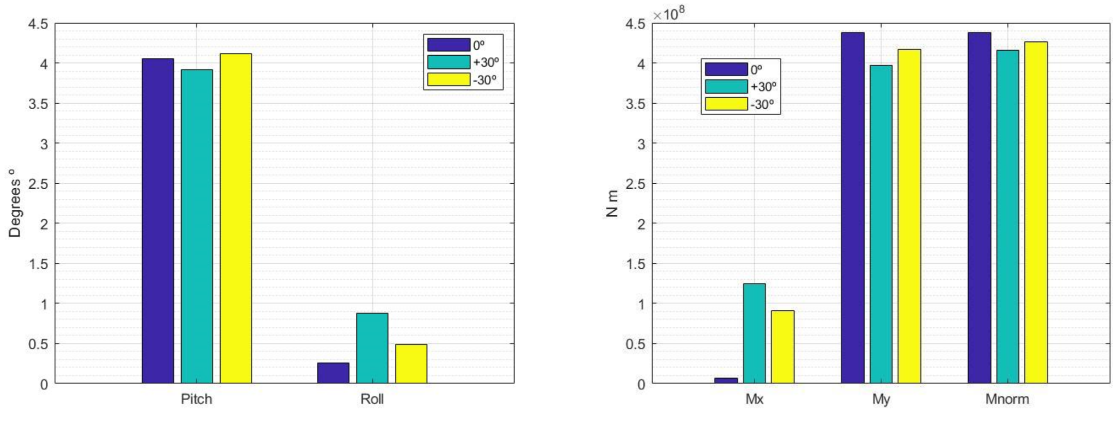


Figure 85: Pitch, roll and bending moments comparison between the different DLC 6.1 cases

With respect to the external loads associated to the heave axis, the F_z component of the turbine and tower inertial force, associated to their weight, doesn't present relevant variations at all between cases. It takes values around $2{,}3 \cdot 10^7$ N. The torsion moment M_z, instead, present big variations between the 0º direction, in which is insignificant, and the other cases. The reason of it is the transverse orientation of the waves which causes higher torsional excitation in the structure. Thus, the torsion moment is not associated to any specific geometric parameter, but on the specific dynamic excitation in each instant of the simulation.

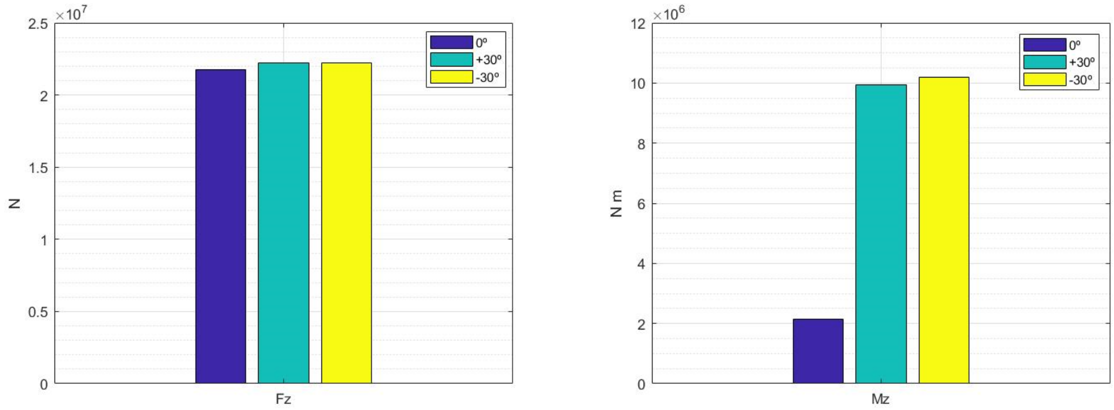


Figure 86: Fz and torsion moment comparison between the different DLC 6.1 cases

The tower and turbine transverse forces are components associated to the inertial acceleration of turbine and tower. Its composition in each instant depends, basically, on the geometrical configuration of the structure, and so, on the pitch and roll angles associated to the y and x inclination. For that reason, the F_y component takes much lower values than the F_x ones, as the inclination associated to the first is much lower than the one associated with the last. Furthermore, due to the insignificant x inclination in the 0º case, its F_y component is almost null. However, this case takes the highest F_x component, due to the highest y inclination sum to the bigger dynamical excitation in the x component (due to the alignment between the wave and turbine and tower direction).

With respect to the longitudinal accelerations, they are directly linked to the tower and turbine inertial forces. In fact, the 0º case, which presents the highest forces, is also the case with highest longitudinal acceleration. However, all the case present similar acceleration values.

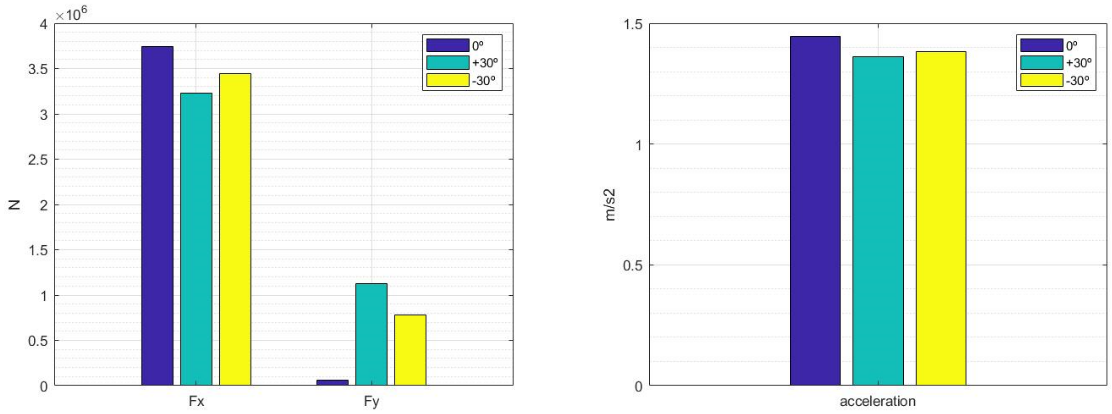


Figure 87: Fx, Fy and acceleration comparison between the different DLC 6.1 cases

The results obtained depend on the platform geometric configuration and on the loads magnitude (both linked as explained before). In the case of the maximum stresses, they depend basically on the bending moment contributions M_x and M_y, whose magnitude depend on the platform inclination. Thus, the maximum stresses are higher in the +/- 30º wave direction cases, in which the x inclination is not irrelevant, and so, the M_x values are considerable.

Even if the magnitude of the M_y is considerable higher than the M_x one, the effect of this last component is also relevant in the maximum stresses, as can be seen in the figure below. Thus, the

0º case, with higher M_y values, presents a maximum stress of around 250 MPa, while the other cases have a maximum value around 275 MPa. The mean stress is similar in the three cases, and takes a value around 15 MPa. This big difference between the maximum and the mean stresses shows that the high stresses are focused in small regions of the platform, and so the redesign of the platform based on the thickness increment is, in any case, oversized.

With respect to the deformations, the maximum values are related to the wave pressure, and so, they are not so relevant to analyzed, as also takes acceptable values that don't compromise the structural stability. The central column deformation is linked to the value of the maximum stress in each case, and so, it's a little bit higher in the 30º case. Thus, a percentage variation of around 8 % in the maximum stress values implies a variation of around 15 % in this deformation. The variation of the mean deformation values is not significant in any case.

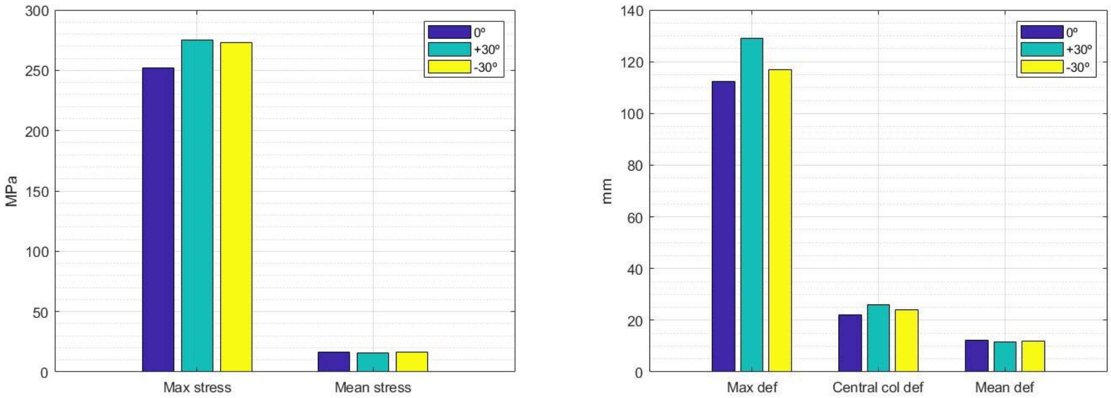


Figure 88: Stresses and deformations comparison between the DLC 6.1 cases.

With this briefly comparison, the analysis of the DLC 6.1 cases is concluded. In the next section, an analysis of the DLC 6.3 cases will be done, following the same methodology as done in this section.

3.8 Simulation, analysis and comparison of the DLC 6.3 with 0º, 30º and -30º wave direction.

The DLC 6.3 modeled a situation in which the turbine is parked with an idling rotor, and the meteorological conditions represented a state of 1- year return period. As defined in the standards, this statistical state is characterized by the medium of the annual maximum values of the climate variables. For our simplified case, these variables are the wave height, which takes a value of H_{s1} = 1,44 m, and its correspondent peak period, T_{p1}, with a value of 5,27 s. These values represent a more probable situation than the 6.1 one, and so, a less extreme one. However, it is important to check if this smoother situation implies less structural solicitations in the platform, because, as said in the section 3.3, the structural response magnitude and the waves magnitude are not always linked.

The results obtained with MOST show some differences from the ones of the 6.1 cases. The main difference is the faster dynamics of the simulated parameters due to the highest frequency of the waves, which implies that these parameters reach before its semi-stationary condition. Because of that, the values of all parameters along the simulation are much more uniform, and the variation between relative maximums and minimums are, in this case, much lower.

Due to the lower wave height, some of the parameters reach lower maximum and minimum values than in the 6.1 case. The wave nonlinear pressures are the ones in which this difference is greater, reaching significant lower maximum and minimum values. This fact directly impacts in the maximum deformation values, reached, as in the previous case, in the top and bottom bases of the platform, and whose mainly cause are these wave pressures.

To analyze the DLC 6.3 cases, the values of its main geometric parameters, loads and results are compare.

With respect to the geometric configuration, the pitch and the roll are the only relevant variables from a dynamical point of view. The pitch angle, related to the y inclination of the structure, reaches quite similar, but higher values with respect to the 6.1 cases. In that way, the minimum pitch takes values (in absolute terms) between 4,1 and 4,2º. However, the M_y component of the bending moment takes values which are considerably lower because of the lower dynamical-inertial excitement, due to the smaller waves. The maximum M_y value is of $2{,}87 \cdot 10^8$ N·m and correspond to the 30º wave direction (4,17 º pitch angle).

The percentage difference of the pitch between cases is of around 1,5%, which implies variations in the M_y components around 7,5%. As explained before, the values variation between cases are, for this DLC, lower.

The roll angle, related to the x inclination of the structure, follows the same trend as in the 6.1 cases. In this way, its value is practically inconsiderable for the 0º case, due to the alignment between the wave and turbine direction which implies an insignificant inclination of the structure in the x axis. This inclination is relevant in the +/- 30º cases, in which the roll angle takes values around 1º, similar to the ones of the 6.1 cases. However, as happen with the M_y components, the M_x values –related to the roll inclination- present lower values than in the previous cases. The maximum M_x value is of $5 \cdot 10^7$ N·m and is associated to the -30º wave direction case (0,99º roll angle).

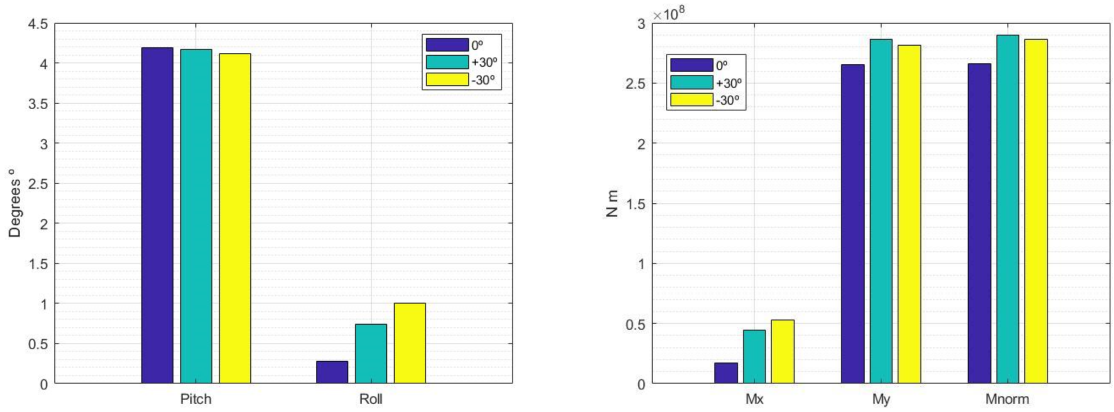


Figure 89: Pitch, roll and bending moments comparison between the different DLC 6.3 cases

With respect to the loads associated to the heave axis, the values of the F_z component of the turbine and tower forces are quite similar to the ones of the DLC 6.1, as they depend basically on the turbine and tower weight, which doesn't change. It takes values around $2.2 \cdot 10^7$ N. The torsion moment M_z is only considerable in the +/- 30º cases, in which the misalignment of the waves produces higher torsional excitation. However, its values, around $6 \cdot 10^6$ N·m, are lower than in the 6.1 cases.

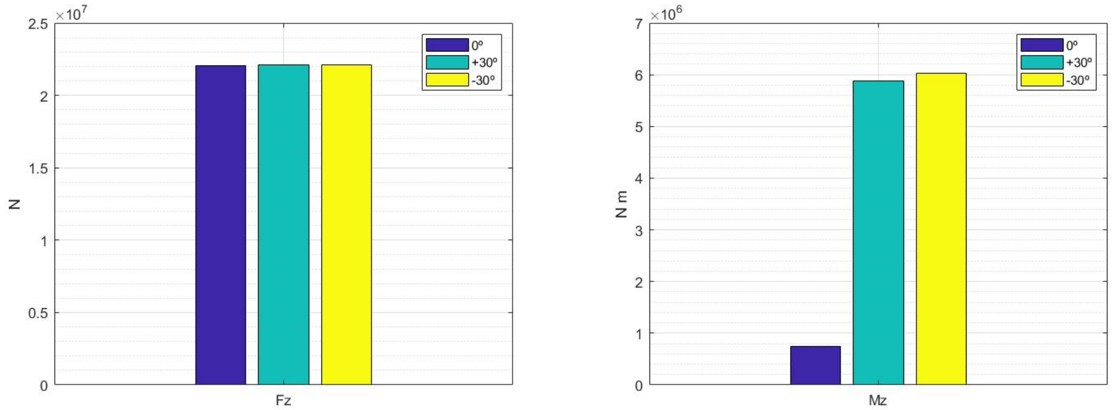


Figure 90: Fz and torsion moment comparison between the different DLC 6.3 cases

With respect to the transverse components of the turbine and tower forces, F_x and F_y, they depend, respectively, on the platform inclination with respect to the y and x axis. Thus, the F_x component takes higher values than the F_y one. In the case of the 0º wave direction, the F_y is almost inexistent as the inclination in x is null. As happens with the bending moments, the maximum values are lower than in the DLC 6.1 cases, because of the less extreme sea conditions.

In the same way, the longitudinal accelerations associated with these forces are also way lower than in the previous case. Thus, the longitudinal acceleration takes values between 0,35 and 0,5 m/s^2, almost three times lower than in the 6.1 cases. These lower dynamical loads will imply lower structural solicitations in the platform, as seen below.

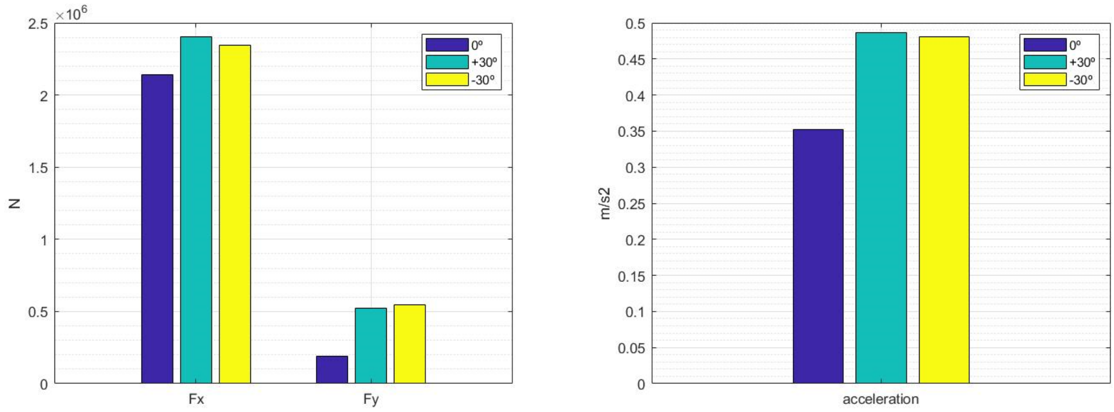


Figure 91: Fx, Fy and acceleration comparison between the different DLC 6.3 cases.

The maximum stresses, which depend basically on the bending moment magnitude, present considerably lower values than in the DLC 6.1 cases. Thus, in the 30º wave direction case, in which the stresses are higher, its maximum value is not higher than 180 MPa, almost 100 MPa beyond the safety limit. The stresses are higher in the +/- 30º cases than in the 0º one, as the effect of the M_x component is considerably greater. The mean stresses, which depends more in other loads as the hydrostatic and wave pressures, take values much more similar to the 6.1 cases.

The maximum deformations of the platform are associated to the wave pressure magnitude, which is, in these cases, much lower, as the wave conditions are smoother. This implies a significant reduction in the maximum deformation values, which don't exceed the 32 mm, that is, up to five times lower than in the previous cases. The mean and central column deformation take similar, but lower values than the 6.1 cases.

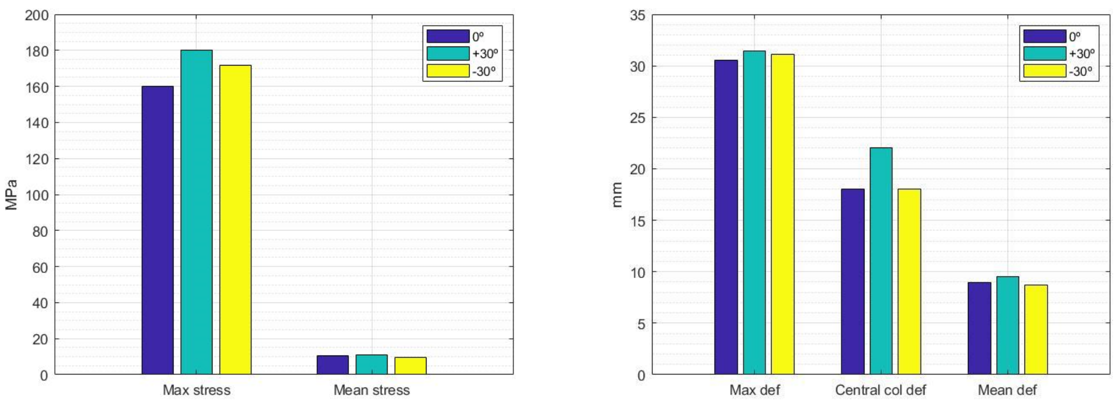


Figure 92:Stresses and deformations comparison between the DLC 6.3 cases

As a conclusion, the DLC 6.3 presents lower structural solicitations than the DLC 6.1, due to the smoother wave conditions. Because of that, its weight in the validation process of the platform design should be lower, at least for our particularly case of study. However, it mustn't be neglected as it gives interesting information about the platform behavior in conditions that are more similar to the normal operational ones.

4. Conclusions.

As it can be seen, this work has followed two main lines of development. On one side, a design process of a floating offshore platform has been done, simulating it in the most extreme conditions to validate it. On the other hand, a simplified validation process has been developed, using the designed platform to evaluate it. Both work lines are quite associated and are developed in parallel in the project. However, the work conclusions can be grouped separately in those two main development lines.

With respect to the platform design, the original model, developed by the University of Maine and which on we have initially based, has needed successive re-designs. For implementing these re-designs, two different strategies have been followed. On one side, internal structural reinforcements have been added in order to increment the platform's rigidity. On the other side, the geometry has been re-dimensioned in order to reduce the stresses in the most solicited regions, by increasing its thickness. Both strategies have been carried out in order to obtain a definite design able to submit all the possible load conditions.

The first design step, which consisted on the evaluation of the original model under the hydrostatic case –the one which lowest loads-, showed that the structural stability of the original platform wasn't guaranteed even in this case. Thus, the high weight of the tower and turbine produced the collapse of the central column. To solve this situation, it has been necessary to change the internal geometry of the platform, implementing internal reinforcements which give a sufficient rigidity to those most critical regions. With this re-design, a more robust model is obtained, which can resist the hydrostatical loads with no problem. Moreover, the optimization of the platform thickness allows to get a platform weight similar to the original one, avoiding problems related to the buoyancy of the structure.

The next design step consisted in the simulation of the re-designed platform in the dynamic critical situations. As seen in the successive cases analyzed, the first platform re-design is not able to withstand the high dynamic loads in most of the critical situations. Consequently, it needed to be subjected to new re-designs, this time based on the thickness increment of its critical regions. Although the final design obtained is able to resist all the dynamical situations which may occur, the final thickness of the platform is way excessive, in terms of the structure's weight and the quantity of steel needed. This would implied problems of buoyancy in the platform, as well as a highly, unaffordable, increment in the fabrication costs of the platform due to the amount of steel needed. For solving these problems, a new re-design must be done, mainly based in the reinforcement of the central column, lowering in this way the required steel. However, this new design falls outside the reach of this work, being material for possible future projects.

The other work line of the project is the development of a simplified structural validation process, which doesn't pretend to substitute the standardized one, but to speed the tasks of designing of the platform, reducing in that way the temporary, computational and economic costs.

The procedure developed consists on the dynamical simulation of the platform in the most extreme meteorological conditions that can be given, described in the standards and which correspond to the DLC 6.1 and DLC 6.3. For doing these simulations, the MOST software is used. Due to the characteristics of this software, some simplifications have to be done, as the not consideration of the areodynamical loads on the turbine, which the software doesn't integrate at the time of computing the platform solicitations. However, due to the nature of the cases wanted to be simulated, in which the turbine is blocked and the wave conditions imposes the wind ones, this simplification is assumed to be admissible.

The loads obtained from these simulations are used as inputs of the structural analysis of the most critical situations, simulated in ANSYS. One of the main goals of the project was to analyze the different situations considered as critical ones, evaluating in each one the structural behavior of the platform.

From the analysis done it's possible to conclude that the parameter which influences the most in the structural stability of the platform is the bending moment transmitted from the tower and turbine, and which produces by far the highest stresses in the structure.

The M_y component of this bending moment is the one which higher magnitude, and thus, the one which influences the most in the structural stability. Its value is associated to the angle of inclination of the platform with respect to the y axis, which is described by the pitch angle parameter. In that way, the maximum value –in absolute terms- of this pitch angle needs also to be considered as a critical parameter. Due to the geometrical and inertial disposition of the tower and turbine, asymmetric with respect to the x-z plane and with most of its mass distributed forwards, the balancing movement of the platform is higher forward than backward. In fact, the negative values of the pitch (related to the forward inclination) are considerably higher than the positive ones, and thus, its relevance in the structural stability are much higher.

The M_x component of the bending moment is a magnitude lower, and so, its impact in the structure is smaller. It is associated to the x inclination of the platform, described by the roll angle, and which is only relevant when the wave direction is misaligned with respect to the turbine and tower direction (x axis).

Other parameters which at first seemed to be interesting to evaluate were the heave and the torsion moment. The heave is directly related to the level of buoyancy of the platform. It is, thus, associated with the hydrostatic pressure magnitude, but is not relevant in the structural stability of the platform as the effect of this load is insignificant compare to the ones of the tower and turbine. The torsion moment is not as important as the bending moment one, as its magnitude is considerable lower and its effect is almost irrelevant.

To conclude, we can appreciate the strongly relation between the geometric disposition of the platform and its dynamical state in each time. Thus, the maximum structural solicitations are happened when the bending moment is maximum, which means a combination of high M_y values –related with a big negative pitch- and considerable M_x values –associated with high roll values-. All the other parameters considered in the first instance have a much lower relevance in the structural stability of the platform, at least for the cases simulated.

On the other hand, with respect to the load cases simulated, we can confirm that the DLC 6.1 is more relevant than the DLC 6.3, at least in order to validate the platform design, as represent load cases in which the structural solicitations are considerably higher. However, it doesn't rest importance to the DLC 6.1, as these last cases represent conditions which are more similar to the normal operation ones, and thus, are useful to understand the behavior of the platform in the most commons dynamical situations. Both are, thus, important and necessary to perform a complete-first approximation validating process.

5. Future lines

The possible future working lines based on this project can be categorized in two groups, associated to the two main lines of the project: the development of a platform design, in one hand; and the development of a simplified validation process for the platform design, in the other one.

With respect to the platform design, the definite design obtained in this work presents some relevant disadvantages which hinder its real implementation. The main problem with the current structure lies in the excessive thickness of its elements, which implies an extremely high weight of the platform with respect to the original model. This would involve problems related to the buoyancy and stability of the platform, as well as an unreasonable increment of the production costs due to the big amount of steel needed.

For solving this problem, a new re-design of the platform is needed. This future re-design should be based on the reinforcement of the most critical regions, specially the central column in which the bending moments of the tower and turbine are transmitted. With a new, more optimized, disposition of the internal ribs in this region, it will be surely possible to considerably reduce the thickness of the whole platform, allowing thus to have a much lighter model in which the buoyancy and production cost problems are no longer exist.

With respect to the validation process, the results obtained seems to be satisfactory enough. However, for a complete development of the procedure, it must be necessary to compare its results with the ones of the standardized validation process. In, fact, the simplifications done in the DLC simulations haven't been correctly evaluated in this project, being matter for future works. In addition, it would be interesting to integrate the wind loads of the turbine and tower in the platform's module of the MOST software, allowing us, in that way, to make more complete and accurate simulations of the different load cases. Once these loads are integrated, a comparison between the simplified simulations done in this work and the new ones, with the wind loads added, can be done, evaluating the real impact of the wind loads in the structural stability of the platform, and verifying –or not- if these loads can really be neglected in the simulations done. To complete the designing validation, a fatigue test must be also done, following the procedures given by the standards.

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