LiftWEC

DEVELOPMENT OF A NEW CLASS OF WAVE ENERGY CONVERTER BASED ON HYDRODYNAMIC LIFT FORCES

Deliverable D6.2

Transportation and Maintenance LiftWEC ULS Assessment

Deliverable Lead	University of Strathclyde
Delivery Date	29th January 2020
Dissemination Level	Public
Status	Final
Version	**1.3**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

Document Information

Project Acronym	LiftWEC
Project Title	Development of a new class of wave energy converter based on hydrodynamic lift forces
Grant Agreement Number	851885
Work Package	WP6
Related Task(s)	T6.2
Deliverable Number	D6.2
Deliverable Name	Transportation and Maintenance LiftWEC ULS Assessment
Due Date	29th January 2021
Date Delivered	29th January 2021
Primary Author(s)	Abel Arredondo Galeana (UoS)
Co-Author(s)	Nicolas Clave (Innosea), Remy Pascal (Innosea), Weichao Shi (UoS), Feargal Brennan (UoS), Paul Lamont-Kane (QUB)
Document Number	LW-D06-02

Version Control

Revision	Date	Description	Prepared By	Checked By
1.0	5/01/2021	Internal working draft	AAG	NC, WS, FB
1.1	7/01/2021	Internal draft for review	AAG	NC, RP, WS, FB
1.2	11/01/2021	Draft for consortium Review	AAG	NC, RP, WS, FB, PLK
1.3	29/01/2021	Submission to EU	AAG	NC, RP, WS, FB, PLK

EXECUTIVE SUMMARY

This document constitutes Deliverable '*D6.2 Transportation and Maintenance LiftWEC ULS Assessment"* of the LiftWEC project. LiftWEC is a collaborative research project funded by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 851885. It is the intention of the project consortium that the LiftWEC project culminates in the development of one or more promising configurations of a Wave Energy Converter operating through the use of one or more rotating hydrofoils that generate lift as the primary interaction with the incident waves.

In this report different scenarios for transportation and maintenance of LiftWEC are presented. It is the intention of this report to identify loading scenarios that occur in non-operating conditions (transport and maintenance) and that could risk the structural integrity of LiftWEC.

Up to this point, thirteen candidate LiftWEC configurations remain. As such, three configurations are here introduced: 1) supported with a monopile, 2) supported with a frame and 3) supported with a floater. The weight of the substructures of each configuration is computed considering a fixed water depth, hydrofoil span and radius.

It is to note that determining transportation and maintenance loads accurately is a significant challenge, hence here, some selected scenarios are presented as illustrative examples. This analysis has the aim to highlight critical areas of the structure that need to be considered during transportation and maintenance. The analysis is performed with Aqwa Ansys, Solid Edge, analytical methods and the online solver SkyCiv. Results are analysed in terms of structural integrity of the device.

It is worthy to note that a limit state is a condition beyond which a structure or a part of a structure exceeds a specified design requirement. For example, ULS can be defined as a condition where a loss of structural resistance occurs. Additionally, partial safety factors can be considered to account for abnormal operating conditions. As such, in this deliverable, we defined the threshold for the ULS as a fraction of the yield stress level. This threshold however can be refined to meet future design specifications.

The deliverable sets out the path to identify what additional measures need to be considered when transporting and maintaining LiftWEC from a structural perspective.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

TABLE OF CONTENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

1 INTRODUCTION

LiftWEC is expected to undergo several transportation and maintenance cycles during its lifetime. During these manoeuvres, LiftWEC can be exposed to different types of loading than those occurring during operating conditions. As noted in the NASA report of handling and transportation of space vehicles (*NASA SP-8077),* it is desirable that the design of a device is governed by the operational loads rather than by the transportation and handling loads. Hence it is important to characterise and understand non-operational loads in order to attenuate any potential structural damage that can occur during transportation and maintenance.

1.1 LITERATURE REVIEW

To understand the type of loads that LiftWEC could experience during transportation and maintenance, it is useful to study guidelines and standards of more established industries that deal with cargo designed for remote and extreme locations. For example, the aerospace and the offshore wind industries.

1.1.1 Aerospace

According to the *Transportation and Handling loads manual for space vehicle design criteria* (*NASA SP-8077, 1971*), adequate assessment of loads during maintenance and transport is needed during the design process, in order to avoid local damage to the structure or accumulated fatigue from cyclic loads. Several factors need to be considered, such as transportation and handling medium, speed of transport vehicle, weather conditions (pressure, temperature, winds, etc.) and dynamics during transport (acceleration, decelerations).

Furthermore, *NASA SP-8077 manual* specifies that loads encountered during transportation and handling are extremely difficult to predict accurately. This is due to the complexity of the operations. However, transportation and handling operations are typically carried out with success, in part due to load attenuation systems that are implemented during these operations.

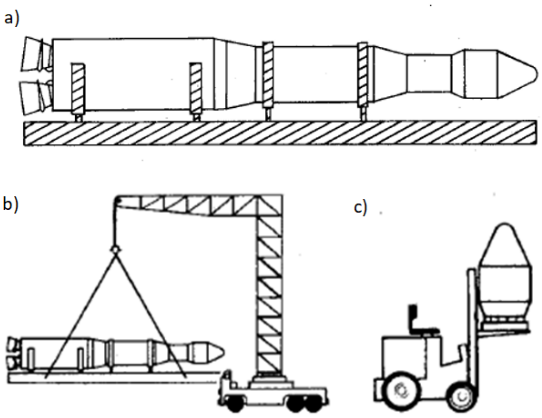


Figure 1: Examples of transportation and maintenance operations on space cargo, a) Rocket in platform, b) crane lifting operation, c) forklift operation, from NASA SP-8077, 1971

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

1.1.2 Offshore wind

The DNV-GL *Transport and installation of wind power plants standard* (DNVGL-ST-0054) addresses the requirements and guidelines for offshore wind power plants. This entails transportation and lifting operations offshore.

The standard recommends that the transportation and installation procedures of an offshore wind farm should be carefully planned and should incorporate risk management methods. The design stages to stream down the risks and hazards during transport and installation operations are: initial concept, design basis, preliminary design, detailed design, manufacturing, testing prior to transportation and maintenance and final transport and installation. At this stage, in LiftWEC, there are thirteen candidate configurations and so we equivalently are at the initial concept and design basis stages.

Different transportation and installation operations are addressed in the DNV-GL guideline, such as road transport and offshore transport, as well as load out operations, such as skidded load outs or lifted load outs. Pre-assembly operations are recommended to reduce the operational cost of offshore installations. Figure 2 shows an example of transportation and lifting operations for maintenance in offshore wind. Figure 2a shows an example of road transportation, whilst figure 2b shows the loading out of a jack-up rig to the seabed and figure 2c, shows the loading out of a rig onto a barge.

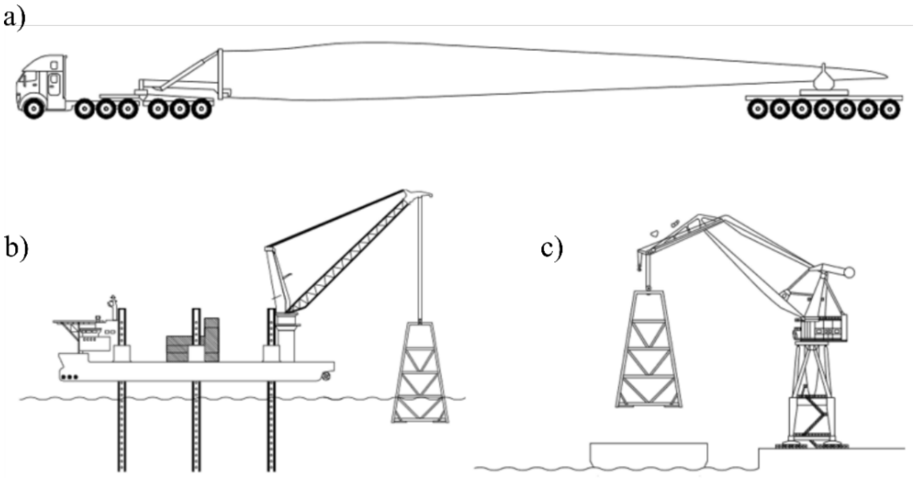


Figure 2: Examples of transportation and maintenance operations on offshore wind structures a) road transport of turbine blade, b) loading out of jack-up rig and c) loading of rig onto barge, from DNVGL-ST-0054

1.2 LIFTWEC CONFIGURATIONS

We consider three configurations of LiftWEC: 1) monopile supported, 2) frame supported and 3) supported by a floater. We consider initially a hydrofoil span (S) of 30 meters. The span is selected based on the results obtained from deliverable *D6.1 Extreme Event LiftWEC ULS Assessment*. The water depth is 50 m. The material for the hydrofoils and support structures is offshore steel with a yield stress (σ_{yield}) of 350 MPa (Brennan & Tavares, 2014) and a density (ρ) of 7850 kg/m^3 (The Engineering ToolBox, 2021).

1.2.1 Hydrofoil cross-section

The hydrofoil cross-section consists of a NACA 0012 profile with a chord length of 3 meters. The height of the section is 0.12c and the thickness (th) of the walls is $0.016c$. The hydrofoils have two equally spaced spars away from the aerodynamic centre (AC), which is located at $0.25c$, as shown in Figure 3.

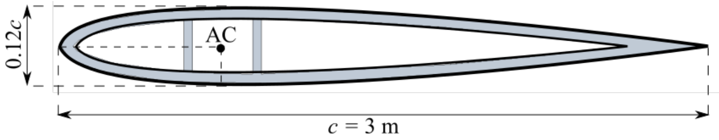


Figure 3: LiftWEC hydrofoil cross-section

1.2.2 Monopile supported configuration

A LiftWEC configuration supported by a monopile is introduced in Figure 4. The radius of the LiftWEC rotor is 3 m. The monopile has an outer diameter (OD) of 3 m and internal diameter (ID) of 2.6 m. The height of the monopile is 53 m, assuming a 50 m water depth. It is assumed that one third of the monopile is embedded in the soil. The rotor is supported by a bracket structure with bearings at each side. The central shaft is connected to bearings, which are inserted in the bracket structure. Lateral spokes support the hydrofoils. The central shaft is hollow with an OD of 1.2 m and ID o 0.9 m.

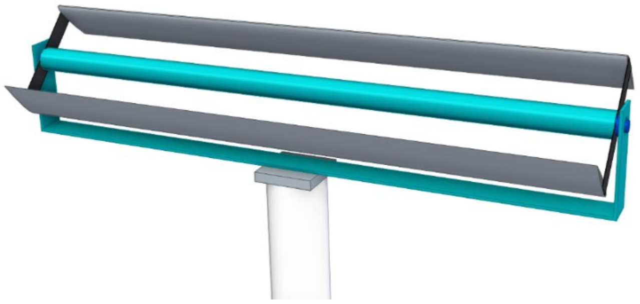


Figure 4: Rendering of LiftWEC rotor, with hydrofoils, spokes and rotor supported by a monopile

The computed volumes and masses of the substructures are shown in Table 1. The total mass of device (without monopile) is approximately 260 tonnes. The mass of the monopile is 734 tonnes.

Table 1: Substructures of LiftWEC in monopile supported configuration and their corresponding unit volume, density, total mass and percentage mass. The material selected is offshore structural steel.

Substructure	Quantity	Unit volume (m^3)	Density (kg/m^3)	Total Mass (Tons)	Percentage of total mass (%)
Hydrofoils	2	9.0	7850	142	12.9
Rotor	1	15.1	7850	118	10.7
Spokes	4	0.1	7850	2	0.2
Support bracket	1	13.1	7850	103	9.4
Monopile	1	94	7850	734	66.8
Total	1	561.6	7850	1099	100.0

1.2.3 V-frame support configuration

A LiftWEC configuration supported by a frame is introduced in Figure 5. The v-frame structure can be, similarly retractable to the support structure of CycWEC (Siegel, 2019) or fixed and independently transported. The dimensions of the rotor are the same as those of the monopile case. The frame is built with solid bars with a diameter of 1 m.

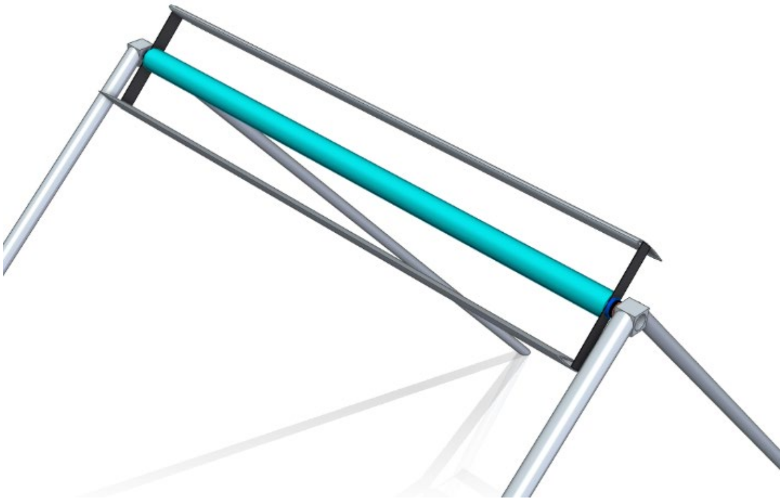


Figure 5: Rendering of LiftWEC rotor supported by a pair of v-frames

The computed volumes and masses of the substructures are shown in Table 2. The total mass of device (without v-frames) is approximately 260 tonnes. The mass of each v-frame is approximately 500 tonnes.

Table 2: Substructures of LiftWEC in frame supported configuration and their corresponding volume, density and mass. The material selected is offshore structural steel.

Substructure	Quantity	Unit volume (m^3)	Density (kg/m^3)	Total Mass (Tons)	Percentage of total mass (%)
Hydrofoils	2	9.0	7850	142	11.3
Rotor	1	15.1	7850	118	9.5
Spokes	4	0.1	7850	2	0.1
Frame	2	63.0	7850	986	79.0
Total	1	561.6	7850	1,248	100.0

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

1.2.4 Floating configuration

Finally, a LiftWEC configuration supported by a floater is presented in Figure 6. The dimensions of the rotor are the same as the previous ones. The floater is constructed with 3 cylinders of an OD of 3 m and a height (H) of 5 m. The connecting rods of the floater have a 1 m diameter.

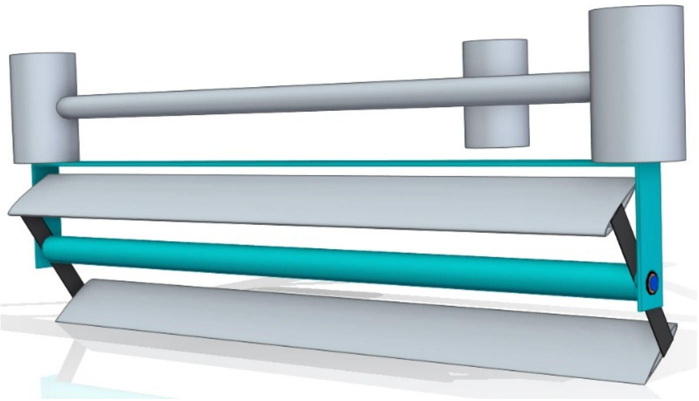


Figure 6: Rendering of LiftWEC rotor with floater, hydrofoils, spokes and rotor.

The computed volumes and masses of the substructures for the floating configuration are shown in Table 3. The total mass of device (without floater) is approximately 260 tonnes. The mass of the floater is estimated to be 276 tonnes. We note that in this exercise the floater is made of steel with thin walls inside. However, the mass of the structure can be reduced if the cylinders are redesigned and built from a different material.

Table 3: Substructures of LiftWEC in floater supported configuration and their corresponding volume, density, and mass. The material selected is offshore structural steel.

Substructure	Quantity	Unit volume (m^3)	Density (kg/m^3)	Total Mass (Tons)	Percentage of total mass (%)
Hydrofoils	2	9.0	7850	142	22.1
Rotor	1	15.1	7850	118	18.5
Spokes	4	0.1	7850	2	0.3
Support bracket	1	13.1	7850	103	16.1
Floater	1	35.2	7850	276	43.1
Total	1	561.6	7850	641	100.0

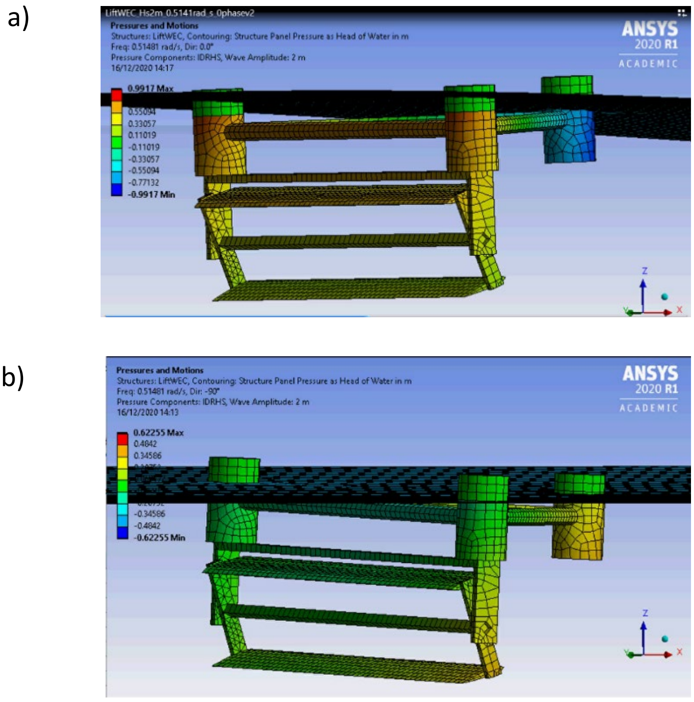
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

2 TRANSPORT

2.1 ENVIRONMENTAL CONSIDERATIONS

During transport, environmental conditions could impact the loading on the structure. As such, it is important to consider their effect prior to transport. As one example of environmental conditions, we show the effect of the direction of a wave on the pressure contours of a LiftWEC device supported by a floater. The device is free to roll and pitch, but constraint in all other degrees of freedom. The hydrofoils are fixed and do not rotate. Two wave directions are studied, one at 0° (figure 7a) and one at 90° (figure 7b), where 0° indicates a wave whose crest is parallel to the span of the hydrofoils and 90° indicates a wave whose crest is orthogonal to the span of the hydrofoils. The selected wave properties are $H_s = 2$ m and $T_p = 10$ s.

It is observed that when the wave is at 0°, the structure is loaded equally in the front, and the loading decreases from top to bottom. When the wave is at 90°, the structure is loaded asymmetrically, with high pressure appearing first on one side and then on to the other one. Although this is only an illustrative example, it highlights the importance of the direction of the wave and its interaction with the structure. As such, other examples of weather conditions need to be assessed to identify sources of non-operational cycling loading. This will help designing strategies to mitigate this type of loading prior to transportation operations. The software utilised to carry out the simulations of Figure 7 was Ansys Aqwa.



a)

Pressures and Motions
Structures: LiftWEC, Contouring: Structure Panel Pressure as Head of Water in m
Freq: 0.51481 rad/s, Dir: 0.0°
Pressure Components: IDRHS, Wave Amplitude: 2 m
16/12/2020 14:17

b)

Pressures and Motions
Structures: LiftWEC, Contouring: Structure Panel Pressure as Head of Water in m
Freq: 0.51481 rad/s, Dir: -90°
Pressure Components: IDRHS, Wave Amplitude: 2 m
16/12/2020 14:13

Figure 7: Floater structure subject to; a) wave at 0° and b) wave at 90° with respect to frontal face of rotor

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

2.2 WET TRANSPORT

We illustrate an example of wet towing and the type of loading that the structure can undergo during this type of operation. The device is towed laterally, to prevent lift force generation in the hydrofoils and therefore more instability. Hence, the recommended setup for towing is illustrated in Figure 8.

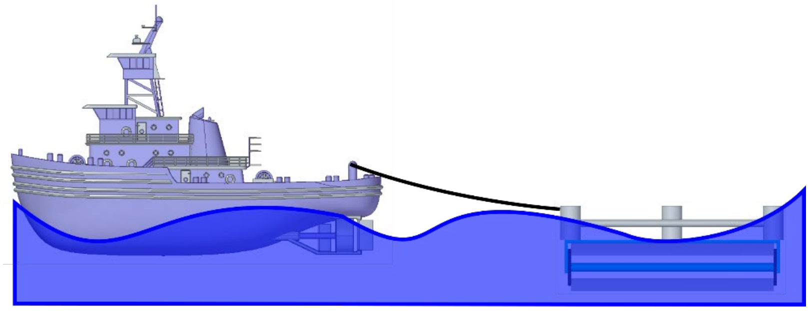


Figure 8: Schematic of towing operation of LiftWEC structure with floater

The drag force due to towing is estimated with

$$D = \frac{1}{2}\rho U^2 A C_D,$$

where ρ is the density of the fluid, U is the towing velocity, A is the frontal area in the direction of towing and C_D is the drag coefficient.

We take a conservative approach, and we assume that the device is fully submerged. We note that D increases according to the square of the towing velocity, hence the towing velocity is crucial to increase or attenuate the loads in the structure. In this analysis, we consider the drag generated by the three floating cylinders (1, 2 and 3 from Figure 9), two connecting rods (1 to 2 and 2 to 3 from Figure 9) and the two flat plates that hold the central shaft of the assembly. The frontal area of each floating cylinder is 15 m^2, of each connecting rod is 15 m^2 and of each flat plate is 7.35 m^2. Two drag coefficients are considered, one for the cylindrical shapes ($C_D = 0.62$) and one from the lateral flat face of the bracket ($C_D = 1.2$) from White (2016). The density of water is $1025\ \mathrm{kg/m^3}$. Hence the total estimated drag force is approximately $D \approx 32U^2\ \mathrm{kN}$.

Assuming a towing velocity of $1.5\ \mathrm{m/s}$, which is within the range of speeds for a tugging vessel according to *Deliverable D7.3 Assessment of Preliminary configurations*, we apply a lateral distributed load of 7.2 kN/m to the structure. Results are shown in Figure 9. The highest area of Von Misses stresses lies in the bracket substructure connecting the floater and the rotor. Table 4 shows different towing speed versus the estimated drag force and maximum Von Misses Stresses on the structure. The maximum allowable stress level considered in this deliverable is 280 MPa, as such, it is observed in Table 4, that LiftWEC should survive wet towing under submerged uniform flow conditions.

Table 4: Towing speed versus maximum Von Misses stresses

Towing Speed (m/s)	Estimated drag force (kN)	Maximum Von Misses Stresses (MPa)
1.5	72	1.6
2.5	200	4.7
3.5	392	9.1
4.5	648	15.1

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

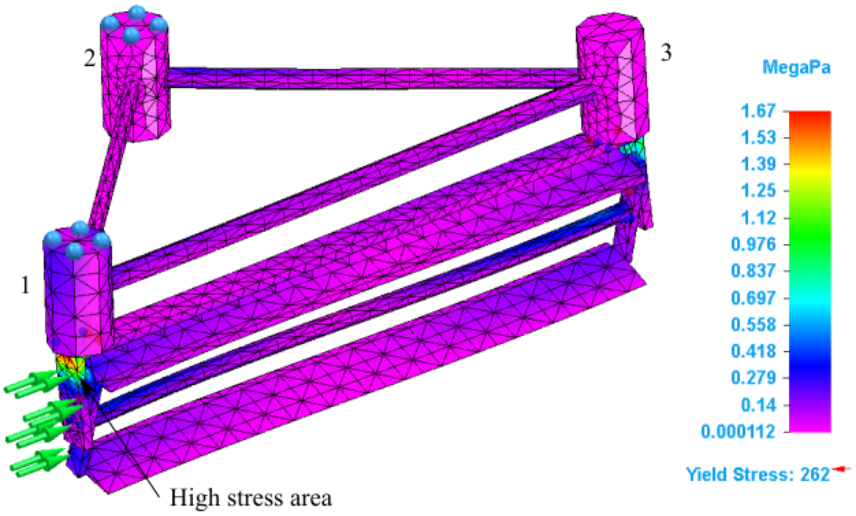


Figure 9: Von Misses stress on floating LiftWEC structure towed at 1.5 m/s

2.2.1 Effect of waves in wet transport

The effect of incident waves during wet transport is now studied with a quasi-steady analysis. We consider the maximum and minimum horizontal velocity components for two cases: case 1, with a wave of $H_s = 2$ m and $T_p = 10$ s, and case 2, with a wave of $H_s = 4$ m and $T_p = 10$ s. The maximum and minimum horizontal wave velocity components are added and subtracted, respectively, to the towing speed velocity. The wave velocity components are computed considering intermediate water depths and Airy wave theory. The maximum and minimum estimated drag forces and maximum and minimum Von Misses Stresses are shown in Table 5.

Table 5: Wave effect in towing speed induced drag forces and stresses

Towing Speed (m/s)	Wave height (m)	Wave period (s)	Maximum estimated drag force (kN)	Minimum estimated drag force (kN)	Maximum Von Misses stresses (MPa)	Minimum Von Misses stresses (MPa)	Percentage change between maximum wave and maximum uniform flow stresses (%)
1.5	2	10	142.5	25.6	3.3	0.6	106
1.5	4	10	236.7	2.7	5.5	0.1	244
2.5	2	10	309.5	114.9	7.2	2.7	53
2.5	4	10	442.8	53.3	10.3	1.2	119
3.5	2	10	540.5	268.2	12.5	6.2	37
3.5	4	10	712.9	167.8	16.5	3.9	81
4.5	2	10	835.6	485.5	19.4	11.3	28
4.5	4	10	1047.0	346.4	24.3	8.0	61

We note that for all the tested cases, the maximum estimated drag force and maximum Von Misses stresses are higher than those computed in uniform flow conditions, whilst the minimum drag force and stresses are lower. The last column of Table 5 shows the percentage difference between the maximum Von Misses Stresses due to the waves and due to uniform flow (Table 4). It is observed that

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

although the percentage change is always higher for larger amplitude waves, the stress levels remain below the allowable stress level (280 MPa) when the towing speed is low (1.5 m/s). However, with increasing towing speed, the effect of the waves becomes more significant and their effect on the structure should be carefully assessed. We also note that shorter waves ($T_p < 10$ s) will induce higher magnitude wave velocity components and therefore higher drag forces and stresses. This shows the importance of considering wave conditions prior to transport, so the design of the device is dictated by operational requirements rather than by wave climate conditions, as pointed out in Section 1.

2.3 DRY TRANSPORT

We consider alternative scenarios, where dry transport is performed. In this scenario the structure could be secured to a lorry or a cargo ship. Both scenarios are depicted in Figures 10a and 10b, respectively.

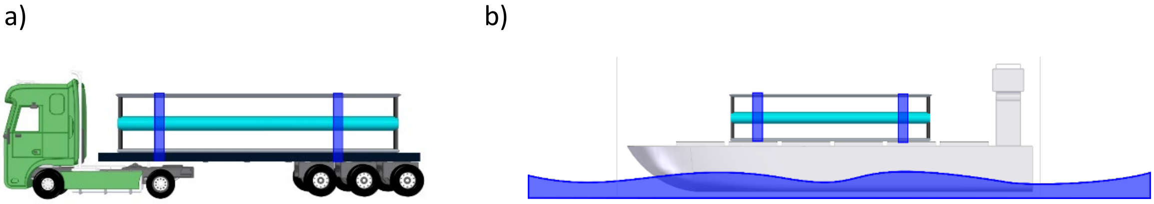


Figure 10: a) Dry transport of LiftWEC rotor in lorry and in b) cargo ship

We model this type of scenario through beam analysis, following a similar approach to the structural analysis developed in *Deliverable D6.1 Extreme Event LiftWEC ULS Assessment*. By assuming two point loads acting on a beam, which is fixed at both ends, we can compute the bending stresses that the structure can undergo. We consider two heavy duty ratchet straps rated to 5 kN each (Nationwide Trailer Parts, 2021). Therefore at each attachment point a force of 5 kN is applied. Each strap is positioned away from each other at a distance d, with the midpoint of d coinciding with the midpoint of the hydrofoil span. The online solver SkyCiv is utilised to compute the maximum bending moments on a 30 m length hydrofoil, for a range of d between 0 to 20 m, in increasing intervals of 5 m. From *Deliverable D6.1 Extreme Event LiftWEC ULS Assessment*, hollow squared cross-sections of dimensions 0.36 x 0.36 m are considered for this analysis.

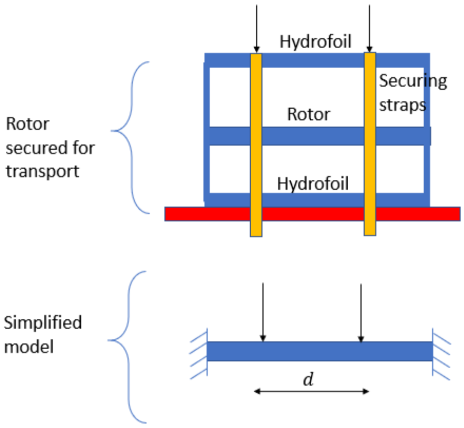


Figure 11: Point load scenario for dry transport on LiftWEC rotor

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

Results show that the straps should be separated as much as possible from the centre of the foil. This will reduce the maximum bending stress on the hydrofoil. As shown in Table 6, the maximum bending stresses are found to be between 10 to 20 MPa. This level of stress remains below the allowable stress level of 280 MPa. Hence this analysis shows that dry transport static loads do not pose a significant risk on the LiftWEC structure.

Table 7: Maximum bending moments and stresses in top hydrofoil as a function of the distance (d) between ratchet straps

Distance between straps ($\boldsymbol{d}$) in meters	Maximum bending moments in top hydrofoil (kN)	Maximum bending stresses in top hydrofoil (MPa)
0	37.5	17.4
5	36.5	16.9
10	33.3	15.4
15	28.1	13.0
20	20.8	9.6

3 MAINTENANCE

3.1 LIFTING OPERATIONS DURING MAINTENANCE

During the maintenance stage, LiftWEC and its support structure may be lifted with a crane. Possible lifting operations include the load out to a boat in a quayside or the onsite lifting installation and removal of substructures offshore (heavy maintenance operations). Other lifting operations may be required depending on the transportation and installation processes selected.

Lifting operations can induce high stresses in the lifted components and these must be assessed and time limited. Lifting of large and heavy components is usually achieved using an intermediate spreader bar enabling a more secured and safe lifting (see Figure 12a and b).

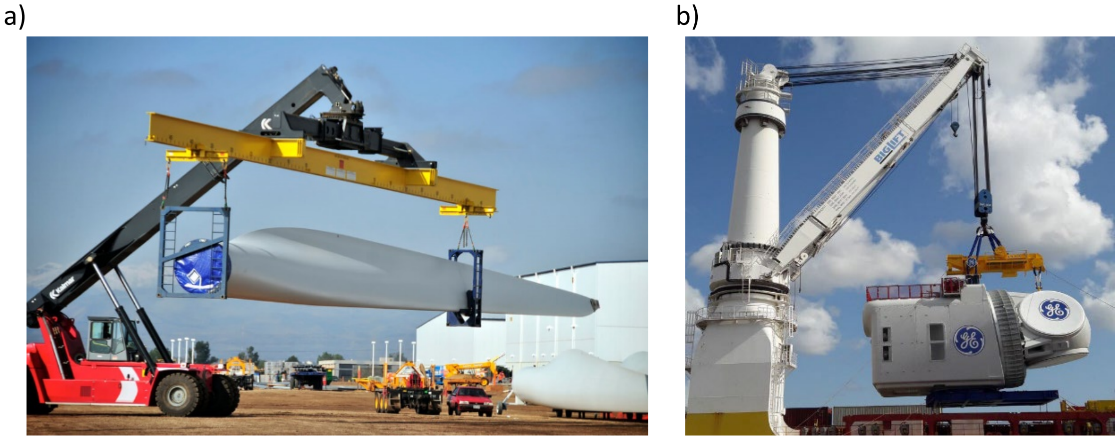


Figure 12: Lifting operations with crane and intermediate spreader of a) turbine blade and b) nacelle

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

3.1.1 Safety factors for lifting operations

Safety factors should be considered for lifting operations structural assessment, to take account of uncertainties on the lifted structure characteristics, lifting equipment and lifting execution. Recommendations are provided in the DNVGL-ST-N001 “Marine operations and marine warranty”. At this early stage of the project, the following factors will be considered based on this standard:

- Mass contingency factor $\gamma_{mass} = 1.15$, to consider the uncertainties on structural mass.
- Lifting factor $\gamma_{lift} = 2.00$, to consider structure COG shift, dynamic amplification factor and consequence factor.

3.1.2 LiftWEC lifting case modelling

The lifting of LiftWEC with a spreader bar can be modelled initially by two lifting points on the central shaft of the rotor, as illustrated in figure 13. The main parameters to consider are the total weight of the structure, the distance between the lifting points (D) and the LiftWEC equivalent cross-section to be considered. This model is similar to the analysis presented to carry out the dry transport analysis.

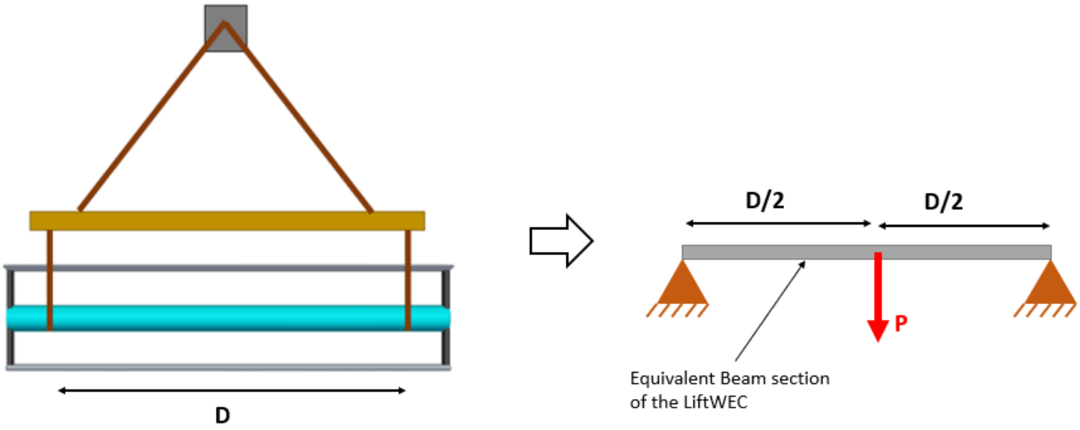


Figure 13: LiftWEC lifting case modelling scheme

3.1.3 LiftWEC lifting strength assessment

In lifting operations, bending is induced in the structure. The maximum bending moment occurs at the middle of the distance between the lifting points. This generates stresses in the rotor and in the hydrofoils. Maximum bending and shear stresses can be determined with the following equations:

$$\sigma_{b,max} = \frac{M_{b,max}\, h}{2\, I} \text{ and}$$

$$\tau = \frac{P_{LW}}{A_{LW}},$$

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

where the maximum bending moment ($M_{b,max}$) is defined as

$$M_{b,max} = \gamma_{lift} \frac{\gamma_{mass}\, m\, g\, D}{2}$$

and the LiftWEC factored weight is defined as

$$P_{LW} = \gamma_{lift}\, \gamma_{mass}\, m\, g.$$

In the previous equations, g is the gravity constant, h is the height of the cross-section, A_{LW} is the section area, I is the section moment of inertia, m is the total mass of LiftWEC (rotor, hydrofoils, spokes) considered as 260 tons from tables 1-3 (without support structure), and D is the distance between the lifting points.

The hydrofoil equivalent sections are squared hollow sections as considered in *Deliverable D6.1 Extreme Event LiftWEC ULS Assessment*, whilst the rotor has a circular hollow cross-section. The hydrofoil and central shaft cross-sections are illustrated below, in two conditions. One where the sections are vertically aligned and one where they are horizontally aligned.

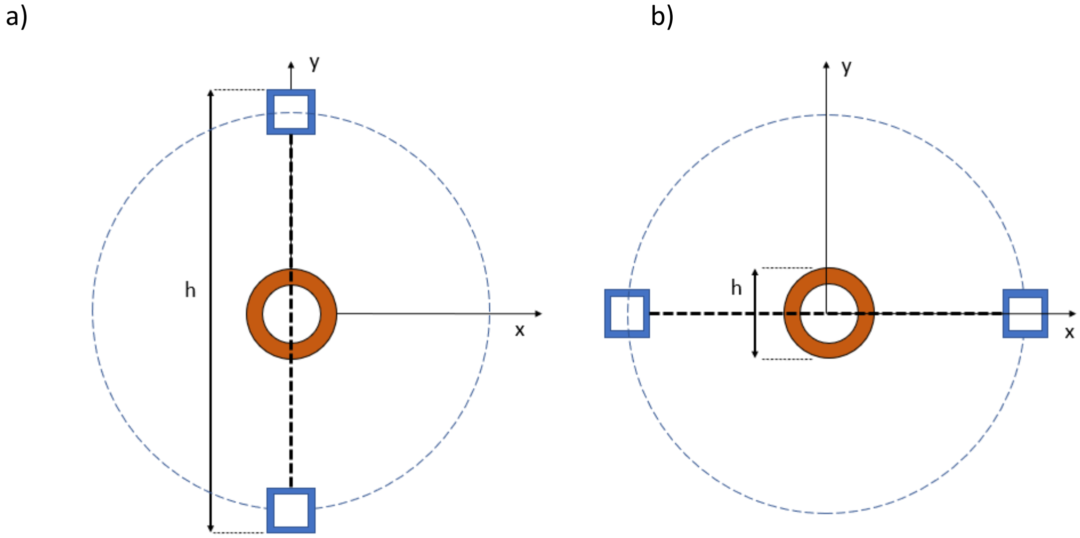


Figure 14: LiftWEC cross-sections in a) vertically and b) horizontally aligned orientations

The maximum allowable stress is defined here for offshore steel grade (Brennan & Tavares, 2014) and a typical material factor of 1.25 (Eurocode), such that

$$\sigma_a = \frac{f_y}{1.25}.$$

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

The utilisation ratio of the Von Mises stresses is defined to evaluate the structural strength of the section:

$$UC = \frac{\sqrt{\sigma_b^2 + 3\,\tau^2}}{\sigma_a},$$

we recall that UC is the ratio between the effective maximum stress in the structure over the admissible stress. When $UC < 1$, the criterion is structurally safe.

Results for a two lifting point configuration with the hydrofoils aligned vertically and horizontally are presented in Table 6. The assessment is carried out by considering the hydrofoil sections and the rotor section in combination. The design bending moment is defined for the total factored weight of the structure.

Table 8: Results for a two lifting point operation, with LiftWEC component vertically or horizontally aligned.

Hydrofoils orientation	Max bending moment [kN.m]	Moment of inertia [m4]	Shear stress [MPa]	Max bending stress [MPa]	Allowable stress [MPa]	Utilisation ratio [-]
Vertical	6.45 e4	1.154	10	178	280	0.64
Horizontal	6.45 e4	0.075	10	522	280	1.86

Results show that the LiftWEC lifting operations should not damage its structure for a vertical hydrofoil orientation. This is because the maximum bending stresses remain below the allowable stress level (280 MPa). However, a horizontal lifting configuration may damage its structure, because the bending stress is higher in this direction. Thus, the vertical hydrofoil configuration is preferred for lifting operations of LiftWEC.

3.1.4 Monopile lifting case modelling

During transportation to site, monopiles are generally stored horizontally on the deck. The monopile is then lifted by 2 hooking points from this horizontal position and rotated to vertical position where it can be immersed in water and driven in the soil. In some cases, the monopiles can be stored on deck in a vertical position, simplifying the lifting operations.

Figure 15 Horizontal monopile lifting (2 points)

Thus, the structural integrity of the monopile should be checked in horizontal configuration (bending moment) and vertical configuration (traction force). The horizontal configuration assessment follows the same methodology as described for the lifting of LiftWEC (see previous section). The vertical configuration assessment is achieved by considering the normal strength of the monopile section only supported at its top extremity.

3.1.5 Monopile lifting strength assessment

The following equations are used to define the governing stresses in the structure:

- Bending stress and shear stress in horizontal configuration (as in section 3.1.2):

$$\sigma_{b,max} = \frac{M_{b,max}\, h}{2\, I} \text{ and } \tau = \frac{\gamma_{lift}\, \gamma_{mass}\, m_{MP}\, g}{A}$$

- Normal stress in vertical configuration:

$$\sigma_{n,max} = \gamma_{lift} \frac{\gamma_{mass}\, m_{MP}\, g}{A_s}$$

where, m_{MP} is the monopile design mass and A_s is the monopile cross section area. The maximum allowable stress is defined here for offshore steel grade (Brennan & Tavares, 2014) and a typical material factor of 1.25 (Eurocode).

$$\sigma_a = \frac{f_y}{1.25}$$

Utilisation ratio of the Von Mises stresses is defined to evaluate the structural strength of the section:

$$UC = \frac{\sqrt{\sigma_b^2 + 3\,\tau^2}}{\sigma_a}$$

Table 9: Monopile strength during typical lifting operations

Max bending moment [kN.m]	Weight [kN]	Cross section area [m^2]	Moment of inertia [m4]	Max bending stress [MPa]	Shear stress [MPa]	Max normal stress [MPa]	Allowable stress [MPa]	Utilisation ratio horizontal /vertical [-]
1.76 e5	1.35 e4	1.76	1.73	152	8	8	280	0.81/0.04

Results show that the monopile lifting operations should not damage its structure. This is because the maximum bending stresses and normal stresses remain below the allowable stress level (280 MPa).

3.1.6 Floating structure lifting modelling

A triangular floating structure could be lifted with 3 hooking points. Two lifting configurations are considered: one, with a lifting hooking point on each column and one with lifting hooking points at each brace centre. The modelling of those cases is presented in Figure 16a and b, respectively.

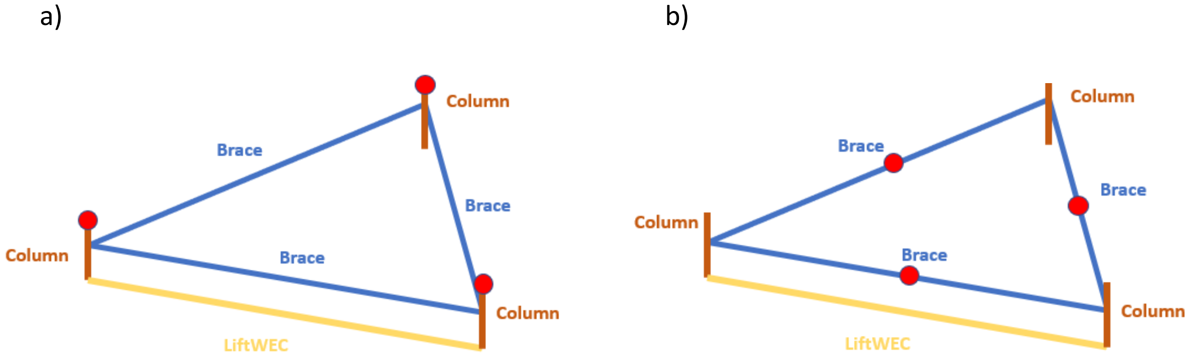


Figure 16: Hooking points on a) columns and at b) brace centres. Hooking points are highlighted in red.

3.1.7 Floating structure lifting assessment

The centre of gravity (COG) of the full assembly (floating structure and LiftWEC) is not centred as the LiftWEC is fixed to 2 of the 3 columns only. This should be considered in the structure assessment for lifting operations. For the column hooking configuration (Figure 16a) the normal strength of the vertical columns should be checked. For the brace hooking configuration (Figure 16b), bending strength of the braces should be checked.

On a further stage of the design, stress verification at the joints of the floating structure should be performed as these areas can be source of amplified stresses.

We compute, the normal stresses in the column hooking configuration, such that:

$$\sigma_n = \gamma_{lift} \frac{\gamma_{mass}(m_{LW}/2 \ + m_s/3)g}{A_s}$$

where m_{LW} is the LiftWEC mass, m_s is the floating structure mass and A_s is the column cross section area.

Table 10: Floating structure strength in the columns hooking points configuration

Traction hooking point [kN]	Cross section area [m²]	Max normal stress [MPa]	Allowable stress [MPa]	Utilisation ratio [-]
6.16 e3	0.91	7	280	0.02

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

For the braces hooking configuration, the bending stresses and shear stresses are computed, such that

$$\sigma_b = \frac{M_{b,max}\, r}{2\, I} \text{ and } \tau = \frac{\gamma_{lift}\, \gamma_{mass}\, m\, g}{A}$$

where

$$M_{b,max} = \gamma_{lif}\ \gamma_{mass}\, \frac{l_b}{2} . \left(\frac{m_c}{2} + \frac{m_{LW}}{4}\right) + \frac{l_b}{4} . \frac{m_b}{2}$$

and m_c is the single column mass, m_b is the single brace mass, l_b is the brace length, r is the brace external radius, A is the brace cross section area and I is the brace cross section moment of inertia and m is a third of the total mass of the structure, which is the fraction of total mass supported by each hooking point.

Table 11: Floating structure strength in the braces hooking points configuration

Max bending moment [kN.m]	Cross section area $[m^2]$	Moment of inertia [m4]	Shear stress [MPa]	Max bending stress [MPa]	Allowable stress [MPa]	Utilisation ratio [-]
3.59 e4	0.15	0.017	20	478	280	3.79

Results show that the lifting operations with hooking points on the columns is safer for the floating structure than the lifting with hooking points on centre of the braces. However, this assessment does not consider local stresses in the structure and should be refined in a further stage of the design.

4 CONCLUSIONS

This work presents the Transportation and Maintenance LiftWEC ULS Assessment analysis, by means of representative scenarios that could be encountered during these operations. Loads during transport and maintenance are extremely difficult to predict accurately, hence the estimations presented here aim to serve as a guideline for further analysis prior to final deployment of the device.

We presented three different configurations, monopile, submerged v-frame and floater supported LiftWEC, which represent a summary of the thirteen remaining configurations that are subject to evaluation in the LiftWEC project. The masses of each structure were computed by defining structural steel as the material and by means of computational aided design (CAD) drawings.

The effect of the wave direction climate and towing velocity is presented for the floating LiftWEC to illustrate how the direction of the wave might impact the loading on the structure and how the towing velocity can impact the stresses on the structure during wet transport. A dry transport analysis is carried out based on similar assumptions as those utilised in *Deliverable D6.1 Extreme Event LiftWEC ULS Assessment.* It is shown that the LiftWEC structure should be resilient to this type of transportation method.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.

Lifting analysis, which occurs during maintenance, is carried on the rotor and hydrofoils, in two different configurations, one where the foils and rotor are aligned horizontally and one where they are aligned vertically. Results show that the stresses are less severe when the cross-sections are aligned vertically, therefore this is the recommended setup to perform a lifting operation of LiftWEC.

Lifting analysis was also carried out in a couple of the support structures, the monopile and the floater. It is shown that during lifting operations, the monopile is resilient to the maximum bending stresses. Regarding the floater, it is concluded, that lifting hooking points from the columns are preferred as opposed to lifting from the braces.

Finally, this deliverable constitutes a set of representative examples of transportation and maintenance operations and possible scenarios of non-operation loading of the LiftWEC structure, with the aim to highlight possible areas and conditions of structural concern, that need to be dealt with prior to full installation and deployment.

5 BIBLIOGRAPHY

Arredondo-Galeana, A., Shi, W., & Brennan, F. (2020). *LiftWEC: D6.1 Extreme Event LiftWEC ULS Assessment.*

Brennan, F., & Tavares, I. (2014). Fatigue design of offshore steel monopile wind substructures. *Proceedings of Institution of Civil Engineers, 167*, 1-7.

Flannery, B. (2020). *LiftWEC: D7.3 Assessment of preliminary configurations.*

Nationwide Trailer Parts. (2021, January 06). Retrieved from https://www.nationwide-trailer-parts.co.uk/collections/ergo-ratchet-straps-5000kg

The Engineering ToolBox. (2021, 01 06). Retrieved from https://www.engineeringtoolbox.com/metal-alloys-densities-d_50.html

Transport and installation of wind power. DNVGL-ST-0054. (2017). DNV-GL.

Marine Operations and Marine warranty, DNVGL-ST-N001 (2016). DNV-GL

Transportation and handling loads. NASA SP-8077. (1971). NASA.

White, F. M. (2016). *Fluid Mechanics, 8th edition.* Singapore: McGraw Hill.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851885. This output reflects the views only of the author(s), and the European Union cannot be held responsible for any use which may be made of the information contained therein.