XROTOR

X-shaped Radical Offshore Wind Turbine for Overall Cost of Energy Reduction

D4.1

Design basis of mechanical structure and analysis

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September 2021

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101007135

X-SHAPED RADICAL OFFSHORE WIND TURBINE FOR OVERALL COST OF ENERGY REDUCTION

Project acronym: **XROTOR**
Grant agreement number: 101007135
Start date: 01st January 2021
Duration: 3 years

WP4 Design of Mechanical Structure and Analysis
T4.2 – Establishment of a design basis
D4.1 Design basis

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30.09.2021

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Document Information

Version	Date	Description	Prepared by	Reviewed by	Approved by	Dissemination Level
1.0	30.09.2021	Final version	A Silva Adriana Correia da Silva	M. Muskulus Michael Muskulus	W. Leithead	PU – Public

The XROTOR Project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 101007135. For more information on the project, its partners, and contributors please see https://XROTOR-project.eu.

Executive Summary

This document provides an overview of the relevant design parameters for a novel X-rotor shaped wind turbine at a representative North Sea site, focusing on the structural design. This includes a definition of environmental conditions, as well as of the scope of the design and how it will be verified. In order to facilitate comparison with previous design efforts, the site conditions and design choices have been adapted from work performed for the DTU 10 MW offshore wind turbine and the UpWind design basis.

Acknowledgement

This work has been carried out as part of the EU Horizon 2020 project "X-shaped radical offshore wind turbine for overall cost of energy reduction" (XROTOR), grant agreement no. 101007135. Contributions from Delft University of Technology (C.S. Ferreira) and University of Strathclyde (D. Campos-Gaona) are kindly acknowledged.

Contents

1 Introduction 1
2 General Remarks 1
3 Rules and Regulations 1
4 Environmental conditions 2
  4.1 North Sea Center conditions 2
  4.2 Water levels and clearances 2
  4.3 Marine growth 3
  4.4 Wind and wave distributions 3
    4.4.1 Extreme values 4
  4.5 Wind shear 5
  4.6 Turbulence intensity 5
  4.7 Soil data 5
    4.7.1 Soil structure interaction 6
5 Wind turbine data 6
  5.1 Blades 6
6 Aerodynamic loads 7
7 Structural design 7
  7.1 Materials 7
  7.2 Corrosion allowance 7
  7.3 Limit states and code checks 7
  7.4 Connections 8
  7.5 Electrical components 8
  7.6 Shaft, bearings and other components 9
  7.7 Load modelling 9
  7.8 Lumping of load cases 10
  7.9 Blades structural design 11
8 Final remarks 11
9 References 12

1 Introduction

This document provides an overview of the relevant design parameters for a novel X-rotor shaped wind turbine at a representative North Sea site.

The goal is to both define the conditions the wind turbine will be designed for, as well as to define the scope of the design and its verification. This shall be done with sufficiently detailed information such that third parties can perform their own wind turbine designs in a comparable manner. In order to facilitate such comparison, the site conditions have been adapted from choices made for the DTU 10 MW offshore wind turbine [1] and for the UpWind support structure design basis [2].

Within the project two design phases will be performed. The basis for the first phase basic design is documented here. For the advanced design, additional considerations apply that are also mentioned here, but which have not been completely fixed. These will be provided later through additional documents.

2 General Remarks

For the basic design phase, the rotor configuration is assumed to be the one developed during the X-rotor feasibility study [3][4]. Therefore, the main objective of this design basis is to facilitate the design of the support structure for the X-rotor turbine. The structural design will be performed in a sequential manner: Aerodynamic loads have been determined with a rigidly supported rotor and will be used as inputs to a load and analysis model for the support structure. Later these assumptions will be reviewed in the light of more accurate load and control models being available, and the rotor design will be verified and updated.

3 Rules and Regulations

The design shall be performed according to DNV rules. The approach used will be a semi-probabilistic format using safety factors. The main standards and guidance documents that are relevant are indicated in the following table.

Table 1 Standards and guidelines

Document	Title	Comment
DNVGL-ST-0126	Support structure for wind turbines	Main design document
DNVGL-ST-0437	Design loads and load combinations	Environmental models and load cases
NORSOK N-004	Design of steel structures	ULS design of the support structure
DNVGL-RP-0005	Fatigue design of offshore steel structures	FLS design of the support structure
DNV-RP-C202	Buckling strength of sheels	Buckling checks
DNVGL-ST-0361	Machinery for wind turbines	Bearings, brakes, connections, etc
DNVGL-ST-0376	Rotor blades for wind turbines	Rotor blade design
API RP 2A-LRFD	Planning, designing and constructing fixed offshore platforms	Geotechnical design

4 Environmental conditions

It is proposed to develop the design for a representative North Sea site. Two choices are recommended here.

Table 2 Reference sites

Name	Character	Notes
NSC (North Sea Center)	Representative site	Previously used for 10 MW DTU offshore wind turbine. Only simplified information available (no directionality of environmental loads). Investigated during MARINA - Platform European project.
K13 (K13 Deep Water Site)	Similar wave conditions Larger wind speeds	Previously used for the UpWind jacket design. Well documented (full wind and wave roses available). Investigated during UpWind FP7 European project.

The NSC site is a representative site in the middle of the North Sea and shall be considered the primary site for which the Xrotor concept shall be evaluated. The annual mean wind speed is high enough to make it interesting for wind energy applications, and its wave climate is typical for harsh offshore conditions.

The K13 site features similar wave conditions and somewhat larger wind speeds. It is extensively documented in the UpWind Design basis [2], so this information is not repeated here. It is considered an interesting alternative for which the Xrotor concept could be evaluated for, especially in comparison with a design for the NSC site.

4.1 North Sea Center conditions

This site is located at 55.13N, 3.43E and described in more detail in [5] and [1].

4.2 Water levels and clearances

The mean sea level is assumed to correspond to a water depth of 40 m. *For the ADVANCED design phase alternatively a depth of 50 m can be considered, for comparison purposes.* The following table lists some choice for the water levels, consistent with [1].

Table 3 Water levels

Water levels	Value
50-year tidal range	5 m
Lowest astronomical tide LAT	-2.5 m
50-year positive storm surge	3 m

We assume the following minimum clearances, based on the DNV criteria:

Table 4 Water clearance

Clearance	Value
Airgap	2.5 m
Blade clearance (including 4.7 m radius secondary rotor)	7.5 m

4.3 Marine growth

Marine growth is modelled according to DNVGL-ST-0437:

Table 5 Assumed marine growth

Depth	**Thickness**	**Density**
-2 m to 40 m below MWL	60 mm	1325 kg/m3

4.4 Wind and wave distributions

The 1-hour mean wind speed distribution at 10 m height is assumed to be a Weibull distribution.

$$f_{\mathrm{U}}(u) = \frac{\alpha_U}{\beta_U}\left(\frac{u}{\beta_U}\right)^{\alpha_U - 1} \cdot exp\left[-\left(\frac{u}{\beta_U}\right)^{\alpha_U}\right]$$

with parameters:

Table 6 Wind speed - Weibull distribution parameters

Parameter	**Value**
α_U	2.299
β_U	8.920

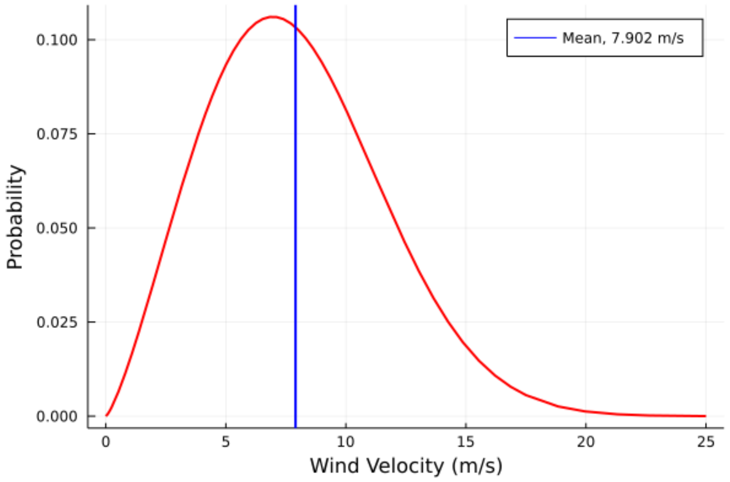

Figure 1 - The 1-hour mean wind speed distribution at 10 m height

The unconditional distribution of the significant wave height is given by the Lonowe model, a hybrid lognormal and Weibull distribution, as explained in [5].

However, the conditional distribution of the significant wave height is assumed to be a Weibull distribution,

$$f_{\mathrm{HC}}(h|u) = \frac{\alpha_{HC}}{\beta_{HC}}\left(\frac{h}{\beta_{HC}}\right)^{\alpha_{HC} - 1} \cdot exp\left[-\left(\frac{h}{\beta_{HC}}\right)^{\alpha_{HC}}\right]$$

with parameters α_{HC} and β_{HC} that are functions of the wind speed:

$$\alpha_{HC} = a_1 + a_2 \cdot u^{a_3}$$

$$\beta_{HC} = b_1 + b_2 \cdot u^{b_3}$$

where the coefficients are:

Table 7 Wave height – conditional Weibull distribution parameters

Parameter	**Value**
a_1	1.755
a_2	0.184
a_3	1.0
b_1	0.534
b_2	0.07
b_3	1.435

The conditional distribution of peak period is a log-normal distribution:

$$f_{T_p}(t|h|u) = \frac{1}{\sqrt{2\pi}\sigma' t} \cdot exp\left[-\frac{1}{2}\left(\frac{ln(t) - \mu'}{\sigma'}\right)^2\right]$$

with parameters σ' and μ' that are functions of H_s and U (see [5] for details). The conditional mean peak period is given by:

$$\mu_{T_p}(h,u) = \mathrm{t}(h)\left(1 + \theta\left(\frac{u - v(h)}{v(h)}\right)^{\gamma}\right)$$

where,

$$t(h) = e_1 + e_2 \cdot h^{e_3}$$

$$v(h) = f_1 + f_2 \cdot h^{f_3}$$

is a polynomial fit. The coefficients and parameter values are:

Table 8 Peak period conditional log-normal distribution parameters

Parameter	**Value**
θ	-0.477
γ	1.0
e_1	5.563
e_2	0.798
e_3	1.0
f_1	3.5
f_2	3.592
f_3	0.735

4.4.1 Extreme values

Given the above distributions, the extreme values have been estimated. The distribution of the annual maximum of the wind speed has been determined by assuming $n = 8760$ independent 1-hour intervals per year and calculating the exact distribution function. The characteristic annual wind speed is then the mode of this distribution. A conversion factor of 0.9 has been used to express this as a 10-minute mean wind speed.

Table 9 Wind extreme values

Return period	Value at 10 m (1 hr)	Value at 10 m (10 min)	Value at 70 m (10 min)
1 yr	23.4 m/s	26.0 m/s	31.5 m/s
5 yr	25.1 m/s	27.8 m/s	33.8 m/s
10 yr	25.74 m/s	28.6 m/s	34.7 m/s
50 yr	27.2 m/s	30.3 m/s	36.8 m/s
100 yr	27.9 m/s	31.0 m/s	37.6 m/s

For the wave height we use the Lonowe distribution and assume $n = 2920$ independent 3-hour intervals. Again, using the exact distribution leads to the values in the table below. The maximum wave heights have been calculated according to. It should be noted that these values are somewhat larger than the ones obtained with the environmental contour method in [5]. The last column shows the mean of the conditional peak period distribution (see [5] for details).

Table 10 Wave extreme values

Return period	Hs	Hmax	Tp(Hs)
1 yr	7.6 m	14.1 m	11.7 s
5 yr	8.6 m	16.1 m	12.6 s
10 yr	9.1 m	16.9 m	13.1 s
50 yr	10.1 m	18.8 m	14.1 s
100 yr	10.5 m	19.6 m	14.5 s

4.5 Wind shear

To extrapolate the wind speeds to different heights a logarithmic wind profile is assumed:

$$U(z) = U_{10}\left(\frac{z}{10}\right)^{\alpha}$$

Where $\alpha = 0.1$ has been chosen [1].

4.6 Turbulence intensity

For simplicity, the turbulence intensity is taken to be the characteristic value of 12 percent for a medium turbulence intensity site.

For the ADVANCED design a more accurate turbulence intensity curve, e.g. the DNV Normal turbulence Model, can be considered.

4.7 Soil data

No soil information is available for this site. To be comparable with work done on the DTU 10 MW offshore wind turbine in [1], the same simplification is used and it is assumed that the site has a single sand layer:

Table 11 Soil conditions

Type	Friction angle	Saturated unit weight	Effective unit weight	Tip bearing factor	Shaft friction limit	Tip resistance limit
Dense sand	35 degrees	20 kN/m3	10 kN/m3	50	115 kPa	12 MPa

For the basic design the piles are assumed to be open-ended. *This can be reconsidered in the ADVANCED design phase*.

4.7.1 Soil structure interaction

A simplified foundation design shall be performed. Design pile loads shall be determined and ULS soil capacity shall be checked (laterally and axially), as well as ULS and FLS pile capacity.

For the proposed piled jacket foundation, the soil-structure interaction shall be modelled with p-y, t-z, and q-z curves. These curves can be derived from the API approach, as described in DNVGL-ST-0126 App. F and in API 2A-LRFD. The p-y curve for fatigue assumes cyclic loading and initial modulus of subgrade reaction according to Figure F-5 in the DNV standard. The curves can be suitably linearized for the analysis.

Scour protection is assumed.

For the ADVANCED design the stress distribution in the pile and the influence of local scour (of size 1.3D) shall be checked.

5 Wind turbine data

The X-rotor concept is based on the preliminary design [3][4] with two blades. Its key parameters are:

Table 12 X-Rotor key blade configuration parameters

Parameter	**Value**
Upper blade length	100.0 m
Lower blade length	65.3 m
Design tip-speed-ratio	5.0
Rated wind speed	12.5 m/s
Upper blade coning angle	30 degrees
Lower blade coning angle	50 degrees

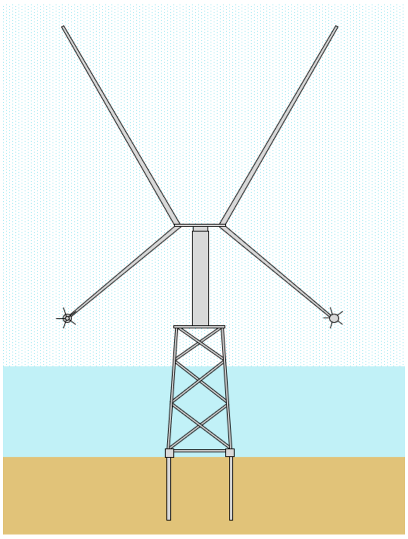

Figure 2 - X-Rotor illustrative representation

For the ADVANCED design phase, a three-bladed version of the X-rotor concept can be alternatively considered.

5.1 Blades

The chord lengths of the upper and lower blades are 10 m and 14 m, respectively, at the blade roots. These reduce linearly to 5 m and 7 m at the blade tips. There is no twist.

More information about the blades can be found in [6].

6 Aerodynamic loads

For the aerodynamic loads, reference is made to the load model report (X-rotor deliverable D2.1a) [6].

7 Structural design

The main concept to be considered is a steel offshore jacket with access platform / transition piece. The substructure could be a (relatively short) steel cylindrical tower. The main structural material considered are ductile offshore steels:

7.1 Materials

Table 13 Material properties

Property	S235	S355
Density	7850 kg/m3 8500 kg/m3 (incl. secondary steel)	7850 kg/m3 8500 kg/m3 (incl. secondary steel)
Yield strength	235 MPa	355 MPa
Young's modulus	210 GPa	210 GPa
Shear modulus	80.8 GPa	80.8 GPa
Poisson's ratio	0.3	0.3

To account for secondary steel, we have assumed that the density is increased by ca. 8 percent everywhere.

7.2 Corrosion allowance

A corrosion allowance is to be considered in the splash zone. For ULS calculations the full allowance is to be subtracted from the nominal element properties, for FLS calculations half the amount is to be subtracted.

Table 14 Corrosion parameters

Parameter	Value
Assumed corrosion rate	0.3 mm / year
Corrosion allowance	6.0 mm (ULS) 3.0 mm (FLS)

7.3 Limit states and code checks

Table 15 Limit states and code checks

Type	Notes
FLS	Based on characteristic cumulative damage with design fatigue factor. Hot spot stress approach for joints. Miner's rule. SN-curves "in air" (assuming coating) and "in seawater" (assuming cathodic protection) according to DNVGL-RP-0005. Stress concentration factors by Efthymiou (DNVGL-RP-0005 App. B). Local joint flexibility shall be modelled by springs or short elastic elements, following the standard approach due to Buitrago. Design fatigue factor 3.0 in all zones* (for simplicity). Thickness correction for welded joints (DNVGL-ST-0126 Sect. 4.11.2.1).
ULS	Design of tubular members and joints according to NORSOK N-004. D/t ratio < 120 shall be observed. Basic material safety factor 1.10

Type	Notes
SLS	For simplicity, verticality of the wind turbine will be assumed. Maximum acceleration horizontally: 0.5 g (for the electrical components). Maximum acceleration vertically: 0.2 g (for the electrical components). Cans and stubs are to be designed according to NORSOK N-004 Sect. 6.4. *For the ADVANCED design a ship collision with a service vessel at 0.5 m/s head-on, including fendering effects.*
ALS	*For the ADVANCED design a ship collision with a service vessel at 2.0 m/s laterally, including fendering effects.*
Buckling	Global (column) buckling shall be checked according to DNV-RP-C202. *For the ADVANCED design also local buckling, including at openings, shall be checked.*

* *For the ADVANCED design and more informed cost modelling, this should be repeated with DFF 2.0 or DFF 1.0 and a corresponding inspection plan. Also, SCFs for tubular girth welds with thickness or conical transitions shall be considered then.*

7.4 Connections

Full penetration welds will be assumed for all connections at joints, between plates and for T-connections. *For the ADVANCED design only: Bolted flange connections will be designed and checked according to Eurocode EN 1993- 3-1 Sect. 6.4*

7.5 Electrical components

For the basic design the following parameters are assumed representative for the electrical components, after discussion with X-rotor WP5.

Table 16 Electrical components - assumptions

Component	Quantity	Mass	Dimensions (W/D/H)
Power electronic convertor	2	3 tons	2.5 x 1.5 x 3.0 m
Transformer	1	20 tons	6.5 x 2.5 x 3.0 m (doors closed) 8.5 x 5.0 x 3.0 m (doors open)
Switchgear	1	2 tons	1.5 x 2.0 x 3.0 m
Rotary transformer	1	26 tons	D: 0.9 tower diameter H: 0.25 tower diameter
Cables etc	1	3 tons	Evenly distributed over height

The rotary transformer is assumed to be cylindrical with a diameter that is 90 percent of the tower diameter, and with a height that is 25 percent of it.

These values and the modelling of the electrical components will be updated for the ADVANCED design once more accurate estimates become available.

7.6 Shaft, bearings and other components

Table 17 Other mechanical components - assumptions

Component	Considerations
Brake	Braking shall bring the rotor to standstill (DNVL-ST-0361 Sect. 7.4.5). Check that dynamically magnified braking moment does not damage the structure.
Rotor lock	This must be designed to reliably prevent rotation without brake engaged, against an annual gust and a gust during erection or standstill. Either redundant locking or a safety factor of 1.15 applies.
Shaft / Drivetrain	Static and fatigue analysis shall be performed. The shaft shall be modelled with rotating masses and torsional springs. Usually torsional, axial and bending modes shall be considered checked for resonances. Dynamic simulation with run-up in torque-driven mode.
Pitch system	This shall be based on comparable data (mass, max. pitch rate) from literature.
Access system	Access by ladder will be assumed. These will not be designed individually but modelled as secondary steel masses (included in the allowance defined above).
J-tube	The J-tube for the cables will not be designed individually. For simplicity, this detail will not be modelled in the basic design phase.

7.7 Load modelling

General considerations on the number and choice of load cases.

Table 18 Load model considerations

Item	Considerations
Binning	Wave heights should generally be resolved with 1 m bins, but 0.1 m bins between 0 m and 1 m (DNVGL-ST-0126). Wind speeds should generally be resolved with 1 m/s bins.
Wave theories	For FLS linear wave theory will be used. For ULS Stokes 5th order is recommended (DNVGL-ST-0437).
Directionality	According to DNVGL-ST-0126 eight wave directions shall be considered. Due to symmetry, this is reduced to two directions: frontal and diagonal. The worst of these two scenarios will be used. It is assumed that wind and waves are co-directional. For the ADVANCED design the assumption of co-directionality and the possible effect of misalignment will be checked.
Lumping	The basic design will use a simplified set of load cases as described elsewhere in this document. For the ADVANCED design the lumping methodology shall be revisited.
Frequency constraints	Although current standards specify that resonances need to be avoided, due to the special nature of the turbine no strict limits will be prescribed for the design.
Design lifetime	The design lifetime is assumed to be 20 years.
Drag and inertia coefficients	For simplicity, we assume a single Cd = 0.8 and Cm = 1.6.
Vortex shedding	Potential cross-vibrations due to vortex shedding are not checked.

Item	Considerations
Vibrations in secondary structures	Vibrations in secondary structures (such as J-tubes or ladders) are not checked
Mesh sensitivity	A mesh sensitivity study shall be performed to determine the accuracy of the finite element/ flexible multibody model used

Load cases will be based on the DNV rules but shall be adapted to the concept, where necessary. *In particular, the definition of gust (ECD/EOG) might need to be reconsidered, therefore such loading will only be evaluated for the ADVANCED design phase.*

Due to limitations of the aerodynamic load modelling, for the basic design no transient loads will be available. Aerodynamic loads will be available as azimuth-dependent average load functions, where the effect of atmospheric turbulence is neglected.

The following load cases shall be evaluated in the basic design phase:

Table 19 Assumed design load cases

Designation	Intent	Comments
DLC1.1	Extrapolation of extreme loads during operating conditions	Lumped environmental conditions
DLC1.2	Fatigue during operating conditions	Lumped environmental conditions
DLC1.6	Survival under severe sea state	-
DLC6.1	Extreme loads during extreme winds and waves	-
DLC6.4	Fatigue and extreme loads during idling	-

In contrast to the design of a horizontal axis wind turbine, ambient turbulence is estimated to be not that important. Therefore DLC1.1 can be assumed to encompass the otherwise important DLC1.3 as well.

Start-up, emergency stop, and failure cases will be developed and evaluated during the ADVANCED design phase once the control strategy of the turbine has been further developed.

7.8 Lumping of load cases

During the basic design phase, the load cases can be lumped. For simplicity, for each wind speed we assume the mean of the conditional significant wave height and the mean of the conditional peak period. This results in the following minimal set of environmental conditions and their occurrence probabilities:

Table 20 Lumped load cases

U at 10 m (10 min)	Hs	Tp	p
< 3.5 m/s	-	-	0.084
4 m/s	0.9 m	7.6 s	0.063
5 m/s	1.0 m	7.5 s	0.077
6 m/s	1.2 m	7.4 s	0.088
7 m/s	1.4 m	7.3 s	0.094
8 m/s	1.5 m	7.3 s	0.095
9 m/s	1.7 m	7.3 s	0.092
10 m/s	2.0 m	7.3 s	0.084

U at 10 m (10 min)	Hs	Tp	p
11 m/s	2.2 m	7.3 s	0.074
12 m/s	2.4 m	7.3 s	0.063
13 m/s	2.6 m	7.4 s	0.051
14 m/s	2.9 m	7.5 s	0.040
15 m/s	3.2 m	7.5 s	0.030
16 m/s	3.4 m	7.6 s	0.021
17 m/s	3.7 m	7.7 s	0.015
18 m/s	4.0 m	7.9 s	0.010
19 m/s	4.3 m	8.0 s	0.006
> 19.5 m/s	-	-	0.006

7.9 Blades structural design

The integrity of the blades shall be checked according to DNVGL-ST-0376. The following table contains some relevant considerations:

Table 21 Blade design considerations

Item	Considerations
Extreme loads	An extreme load envelope shall be established in the main directions (flapwise and edgewise bending).
Fatigue loads	Fatigue loads shall be evaluated with bending moment rainflow counting matrices in the main directions (flapwise and edgewise bending).
Root attachment	The total mass of the root attachment bolts shall be specified. No root connection analysis will beperformed.
Tower clearance	The tower clearance load case shall allow min. 30 percent of clearance with respect to the unloadedstate.
Model	For the basic design, a beam model can be employed for the analysis, together with a safety factor of 1.25 on strains/stresses.

8 Final remarks

This document will be updated in case that it is found that the design work shows that some assumptions have to be reconsidered. In case this happens, the newer versions will be posted on the project / partner websites along the previously published versions.

9 References

1. Velarde J (2016): *Design of monopile foundations to support the DTU 10 MW offshore wind turbine*. Master thesis. Delft University of Science and Technology / Norwegian University of Science and Technology NTNU.

2. Fischer T et al. (2010): *Upwind Design Basis*. Technical report. Endowed Chair of Wind Energy (SWE), University of Stuttgart.

3. Amiri AK (2021): *X-Rotor, an innovative offshore wind turbine: background and draft design configurations*. Internal report. University of Strathclyde.

4. Leithead et al (2019): The X-Rotor offshore wind turbine concept. *Journal of Physics: Conference Series* **1356**: 012031.

5. Li et al (2015): Joint distribution of environmental condition at five European offshore sites for design of combined wind and wave energy devices. *Journal of Offshore Mechanics and Arctic Engineering* **137**: 031901.

6. Ferreira C (2021): Aero-elastic dynamic model capable of modelling the X-Rotor: XROTOR aerodynamics loads by actuator cylinder model. Technical report. Delft University of Technology.