PORT SAID ENGINEERING RESEARCH JOURNAL
Faculty of Engineering - Port Said University
Volume17 No. 1pp: 164:174

Structural Design of a Floating Foundation for Offshore Wind Turbine in Red Sea

Karim R. Hussein[*1], *Arwa W. Hussein*[*2], *El-SayedH.Hegazy*[*3], *Ahmed A. Amin*[*4]

ABSTRACT

WindFloat concept is a recent innovation that appears beside the main categories of offshore wind turbine. The structural design of such structure is not explicitly given in the classification societies rules. This paper gives a methodology to calculate the scantlings of thefloating foundation of the WindFloat using a combination of the available guidelines and rules for wind turbines. A computer program has been developed to calculate the scantlings of the floating foundation according to DNV rules taking into account the hydrostatic pressure only. A 3D Finite Element Analysis is performed for two loading conditions to check the adequacy of the calculated scantlings taking into account allenvironmental loads in the Red Sea, axial force and tower weight.Environmental loads: wave, wind, current and sea level are calculated by using a developed program. To check the significance of the environmental loads in Red Sea, Finite Element Analysis is repeated for each load individually. The results showed that the hydrostatic pressure gives the highest stresses on the columns which justifies why it is the only load considered in the DNV rules.The results obtained for both loading conditions considered have been used to identify the critical areas in the column supporting the tower, and hence determine the structural enhancement required to avoid any undesirable response.

LIST OF SYMBOLS

A	Projected area	m^2
A_d	Rotor disc area	m^2
a	Horizontal water particle acceleration	m/s^2
b_f	Flange width	mm
b_{eff}	Effective width	mm
C_D	Drag coefficient calculated	-
C_M	Inertia coefficient calculated	-
C_s	Shape coefficient	-
D	Depth below still water surface including tide	m
D_b	Bracings diameter	m
D_c	Column diameter	m
D_h	Horizontal member diameter	m
D (z)	Projected width at height z	m
d	Mean water depth	m
E	Modulus of elasticity	MPa
F	Wave loads	N/m
F_{axial}	Axial force	N
$F_D(z)$	Design Sea current loads	N/m
f_a	Axial flow induction factor	-
g	Acceleration of gravity	m/sec^2
H	Significant wave height	m
H_z	Hydrostatic head	m
h	Height above sea water level	m
h_{hub}	Hub height	m
h_w	Web height	mm
K	Wave number	m-1
Ka	Correction factor for aspect ratio of plate	-
Km	Bending moment factor	-
K_{pp}	Fixation parameter for plate	-
K_{ps}	Fixation parameter for stiffeners	-
K_r	Correction factor for curvature perpendicular to stiffeners	-
L_{eff}	Effective length	mm
L	Distance between ring frames	m
P_d	Hydrostatic pressure	N/m^2
R	Radius of the rotor	m
S	Distance between stringers	m
T	Time	sec.
t_f	Flange thickness	mm
t_h	Horizontal member thickness	mm
t_{shell}	Column shell thickness	mm
t_w	Web thickness	mm
$U_c(z)$	Wind induced current speed at elevation z	m/s
U_{c0}	Wind induced current at sea surface	m/s
U	Water particle velocity	mm
V	Wind speed at hub height	m/sec
V(h)	Wind speed at specific height	m/sec
V_{hub}	10-min. mean wind speed at hub height	m/s
W	Frequency	sec^{-1}
X	Distance of propagation	m
Y	Distance from water entrapment plate	m
Z	Distance from sea water level, positive upward	m
Z_{calc}	Calculated section modulus	mm^3
Z_g	Ring frame section modulus	mm^3
Z_s	Stringer section modulus	mm^3
Z_{req}	required section modulus by the rules	mm^3
A	Power law exponent	-
ρ_{air}	Density of air	$N.s^2/m^4$
ρ_{water}	Sea water density	N/m^3

**Naval Architecture and Marine Engineering, Faculty of Engineering, Port Said University.*
1 karim.raed@gmail.com
2 a.w.hussein@gmail.com
3dr_elsayed_hegazy@yahoo.com
4 ahmedamin_ceb@yahoo.com

σ_{jd}	Equivalent design stress for global in-plane membrane stress	-
σ_y	Minimum yield strength	N/mm^2
Θ	Angle between stringers	degree

LIST OF ABBREVIATIONS

ABS	American Bureau of Shipping
API	American Petroleum Institute
DNV	Det Norske Veritas
FEA	Finite Element Analysis
FEM	Finite Element Modeling
MW	Mega Watt
SEQV	Von Mises Equivalent stress
TLP	Tension Leg platform
WEP	Water Entrapment Plate

1. INTRODUCTION

Wind energy is a renewable and clean source of power that may provide electricity from other types of power plants and thus reducegreenhouse gases which produce global warming. There are two types of wind turbines: onshore and offshore.Offshore wind turbines usually generate more energy than onshore turbines because coastal wind energy is usually much more reliable and of greater force than inland wind energy due to the open spaces increasing the ability to use wind. Offshore wind turbines are gaining attention for their ability to capture the immense wind resources available over coastal waters. There are two types of offshore wind turbines: Fixed and floating offshore turbines.The former are limited in water depth to approximately 30~50m and the latter are extended in water depth to approximately 60~900 m [1].

There is a good opportunity in Egypt to install floating offshore wind turbines in the Red Sea, precisely in the Gulf of Suez, since the wind speed there can reach 30 m/sec at 50 m height above the sea level; in this region the average water depth is about 490 m. Therearea number of offshore wind turbine floating foundation concepts in various stages of development.They fall into the main categories shown in Fig.1 which represent (A) the Spars concept, (B) tension leg platform (TLP) and (C) the Hybrid spar/TLP (single tendon).

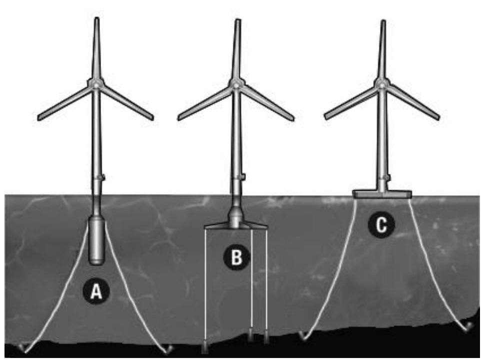

Figure 1, Floating wind turbine concepts

In 2009, a new concept was developed by Marine Innovation & Technology called WindFloat. The WindFloat foundation is a semisubmersible attached with 4-6 mooring lines, and can withstand up to 10 MW wind turbine. Waves and wind induced motions are not the only parameters to consider in the floater type. Economics play a significant role [2]. WindFloat is completely installed onshore and towed out to its position fully commissioned. It has simplicity in the design when compared to other concepts. WindFloat is a floating foundation for large wind turbines based on a small column-stabilized semi- submersible platform with one column supporting the tower for a large wind turbine and the other two stabilized column are spread out so as to form an equilateral triangle between the three column centers. These columns are connected to each other with a truss structure composed of main horizontal members connecting columns and bracings as shown in Fig.2[3].

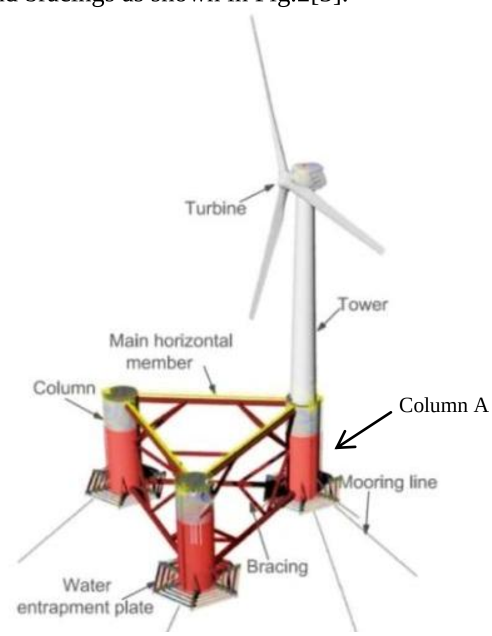

Figure 2Main components of the WindFloat

A horizontal water entrapment plate (WEP) is located at the base of each column to provide additional hydrodynamic inertia to the structure due to the large amount of water displaced as the platform moves.Permanent water ballast, inside the bottom of the columns is used to lower the platform to its target operational draft. An active ballast system, which is located in the upper half of each column, moves water from column to column to compensate for the mean wind loading on the turbine. This movable ballast compensates for significant changes in wind speed and directions. It aims at keeping the mast vertical to improve the turbine performance. Up to 200 ton of ballast water can be transferred in approximately 30 min using two independent flow paths with redundant pumping capability [3]. Table 1 shows the advantages and disadvantages of each concept mentioned above [1].

The objective of this paper is to review different codes used to find the structure scantlings of the WindFloat which can withstand the extreme Red Sea conditions. In these codes the hydrostatic pressure is the only environmental load that is taken into account and there aren't any formulae given in these codes for calculating the stiffeners of the WEP. A program was developed to design a WindFloat according to DNV guidelines by using the commercial software called MATLAB. It was necessary to develop a Finite Element (FE) modelto check the rule-based design by finite element analysis (FEA) and take into account the other environmental loads such as: wave, current, wind, sea level and axial force on the rotor blades. For this purpose a computer program was developed to calculate the different environmental loads which will be used in the finite element analysis.

Table 1 Advantages and disadvantages of different types of floating wind turbine

	Advantages	Disadvantages
Spar	• Good heave performance due to its deep draft. • Reduced vertical wave existing force.	• Bad pitch and roll motion due to the reduced water plane area.
(TLP)	• No heave and angular motion occurs.	• High cost of mooring installation. • The change in tendon tension due to the change in the environmental effects. • Structural frequency coupling between the mast and the mooring system.
Hybrid spar/TLP	• Good stability in operational and transit conditions. • Cheaper to tow out, install and commission.	• Bad heave performance due to its shallow draft.
WindFloat	• Minimized ocean floor & environmental impacts • Lower installation & insurance costs. • Static and dynamic stability provides sufficiently low pitch performance. • Its design and size allow for onshore assembly. • Its shallow draft allows for depth independent siting and wet tow (fully assembled and commissioned) to sites not visible from shore.[4] • Simplicity in design	**No Disadvantages till now**

2. ENVIRONMENTAL LOADS

The design of an offshore wind turbine is based on the environmental conditions to be expected at a proposed site over the project's lifetime (typically 20 or more years). The main environmental conditions for offshore wind turbines which may contribute to structural damages are mainly waves, wind, current, ship and ice impact, earthquakes, temperature, tides, and wake turbulence as shown in Fig.3. They also include the variation in hydrostatic pressure and buoyancy on members caused by changes in water level due to waves and tides. In this paper the environmental loads which are taken into account are: wave, current, hydrostatic pressure and wind.

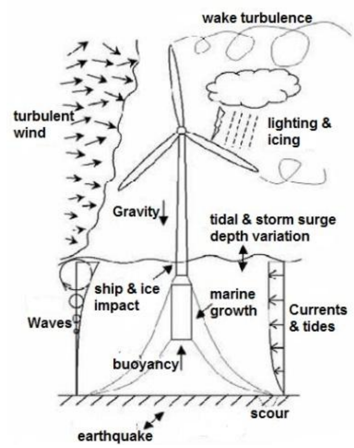

Figure 3Loads acting on offshore wind turbine

2.1. Wave loads

There are two types of waves: regular and irregular waves. Regular waves may be described by deterministic waves which are idealistic. The corresponding theoriesinclude Airy wave theory, second-order stokes wave theory, fifth-order stokes wave theory and the stream function theory. Irregular wave theories are described by energy density spectra, (e.g. JONSWAP and Pierson-Moskowitz spectra)[5]. The first step to calculate the wave loads is to convert the spectrum back into individual sinusoids. The sinusoids have amplitude and frequency that can be derived from the energy density given by the spectrum [6].

Airy wave theory is applicable to define the wave kinematics parameters for deep and transitional water waves [7].Semi empirical formulae such as Morison's equation is used only for determining the horizontal wave loads actingon a vertical cylinder having a diameter less than 20% of the wave length [8, 9]:

$$F = C_D . \rho_{water} . \frac{D_c}{2.g} |u|. u + C_M . \rho_{water} . \frac{\pi . D_c^2}{4.g} . a \quad (1)$$

For vertical cylinders which have diameters greater than 20% of the wavelengths the incident flow field, diffraction forces and the hydrodynamic interaction of structural members are to be accounted for in the design.

Linear wave theory is valid only up to the still water level,then the water particle velocity (u) and acceleration (a) are computed by using the formulae of linear wave theory corrected with the Wheeler stretching formulation as follows [6]:

$$u(x,z;t) = H\pi w \frac{\cosh . k(z+d)}{\sinh(k.d)} \cos(k.x - 2\pi wt) \quad (2)$$

$$a(x,z;t) = 2H(\pi w)^2 \frac{\cosh . k(z+d)}{\sinh(k.d)} \sin(k.x - 2\pi wt) \quad (3)$$

Fig.4 shows the flowchart that is used to calculate the wave loads and hydrostatic pressure loads.

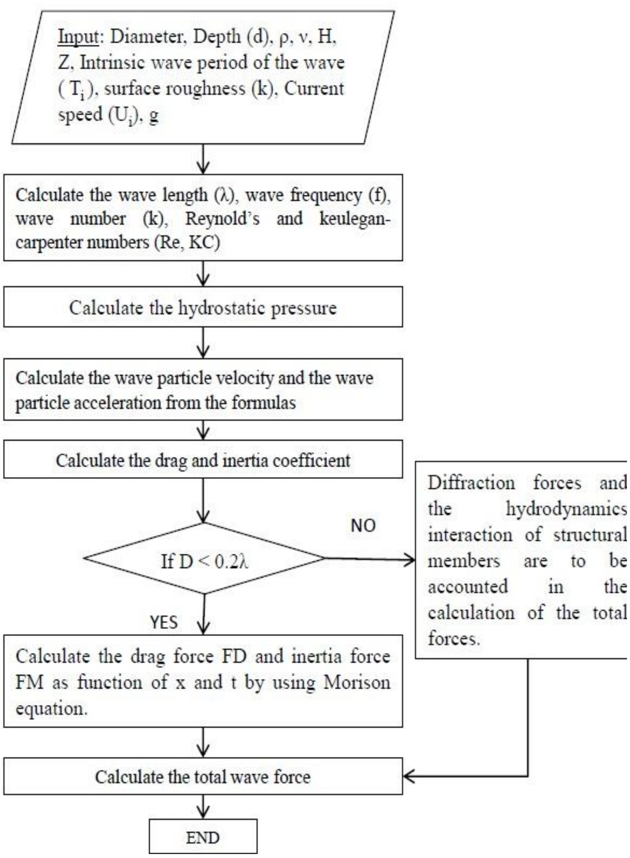

Figure 4Flowchart to calculate the wave loads and hydrostatic pressure

2.2. Current loads

Currents are very important in the design of offshore structures because they affect the forces acting on the structure. Several categories of current are described [7], but the main category is the wind generated current. The current speed varies with depth of water and the current profile can be obtained by[7]:

$$U_c(z) = U_{c0}\left(\frac{z+d}{d}\right) \quad (4)$$

The current load is given by:

$$F_D(z) = C_D . q_D(z) . \left(\frac{D(z)}{2}\right) \quad (5)$$

where

q_D (z)Design sea current pressure at elevation (z), m

$$q_D(z) = \frac{\rho_{water}}{2.U_D^2(z)} N/m^2$$

2.3. Hydrostatic pressure

Hydrostatic loads act in a direction normal to the contact surface; they may be external due to the surrounding water or internal due to the ballast waterwhichis located into each column as shown in Fig.5. Each column is divided into 4 separate tanks by one horizontal and one vertical bulkhead; the lowest tank is a static ballast tank and the upper one is to maintain the WindFloat in a stable condition to withstand any loading condition during the installation, operation and maintenance.

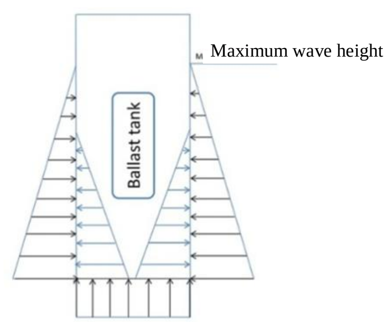

Figure 5Ballast tanks in the column

The design hydrostatic pressure to be used is calculated by[7]:

$$p_d = \rho_{water} . H_z \quad (6)$$

$$H_z = D + \frac{H}{2}\left(\frac{\cosh[k(d-D)]}{\cosh . kd}\right) \quad (7)$$

2.4. Wind load

Wind speed varies with time. It also varies with the height above the sea surface. For these reasons, the average time for wind speed and the reference height must always be specified.The wind shear (the increase of mean windspeed with height) and wind turbulence intensity (fluctuations in wind speed on a relatively fast timescale) are dependent on the wind turbine class and the design wind condition.The wind shear profile is calculated by[8]:

$$V(h) = V_{hub} \left({}^{h}/_{h_{hub}} \right)^{\alpha} \qquad (8)$$

The wind acts on three main areas as follows:

1- On the air gap of the WindFloat columns.
2- On the mast of the wind turbine along its height above the sea level.

Wind load on both areas defined above is given by [8]:

$$F_w = \frac{\rho_{air}}{2g} . C_s . A . V(h)^2 \qquad (9)$$

3- The axial force acting on the turbine blades is given by [10]:

$$F_{axial} = 2A_d \rho_{air} V^2 f_a (1 - f_a) \qquad (10)$$

A sub-program was developed to evaluate the wind force acting on the subjected area and the rotor blades as mentioned above. The flowchart of the sub-program is shown in Fig.6.

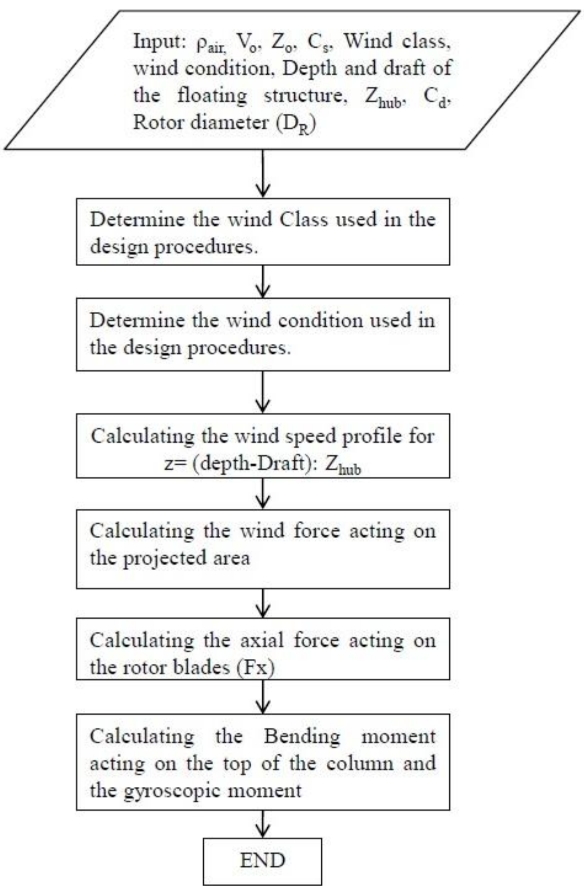

Figure 6Flowchart of wind loads calculation

3. STRUCTURAL DESIGN CODES

The structural design of WindFloat structure is not given directly in the classification societies rules. This section demonstrates the rules and the guides which may be used to determine the minimum required section modulus of the floating structure of the WindFloat, as follows:

-DNV-OS-J101, Design of Offshore Wind Turbine. (Det Norske Veritas)

This guide is applicable to the design of complete structures, including substructures and foundations, excluding wind turbine components such as nacelles and rotors. It gives the impact of environmental effects on offshore wind turbine and how to calculate the loads generated from these effects. Formulae for calculation of the required section modulus of different components are given [9].

- DNV, Buckling strength of shells - Recommended practice for planning, designing and constructing floating production system [11]. This guide reports the different buckling modes for stiffened cylindrical shell, and the required geometry of the stiffeners and their proportions.

- ABS Guide for buckling and ultimate strength assessment for offshore structure [12](American Bureau of Shipping).This guide gives the criteria for calculating the buckling limit state of orthogonally stiffened cylindrical shell subjected to axial loading, bending moment, radial pressure or a combination of these loads. It also gives the geometry and the scantlings proportions required for designing a cylindrical shell after calculating the minimum required moment of inertia *I* which is based on the axial and circumferential load acting on shell.

-API Recommended Practice for planning, designing and constructing fixed offshore platforms [13] (American Petroleum Institute). This gives the allowable stresses for cylindrical members and the sequence for calculating the circumferential ring size as well the effective width of the shell.

4. RULE-BASED STRUCTURAL DESIGN OF WINDFLOAT

The design basis for the WindFloat and the requirements that must be addressed by design teams in this new technology is explained by (D. Roddier et al. 2009) [2]. Stiffened cylindrical shells are used in the fabrication of the floating structure for WindFloat as shown in Fig.7.The columns are orthogonally stiffened by a ring frame as shown in Fig. 8 and stringer stiffeners as shown in Fig.9[14]. The geometry of the ring frame and stringer are as shown below to prevent the local instability [12].
According to the codes mentioned abovefor calculating the minimum required section modulus, only the hydrostatic pressure is considered[9].

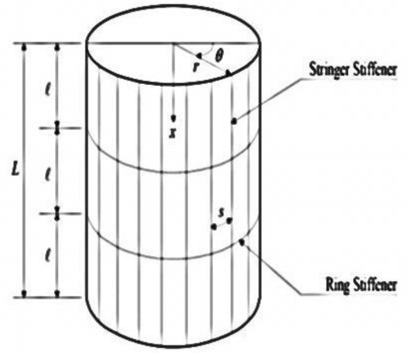

Figure 7 Orthogonally stiffened cylinder[12]

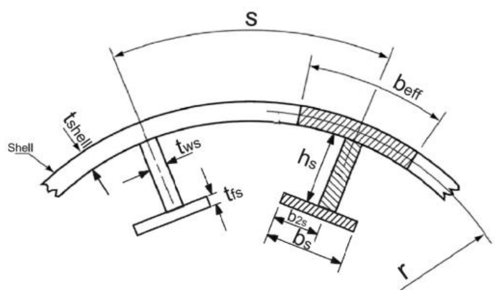

Figure 8Stringer stiffened shell

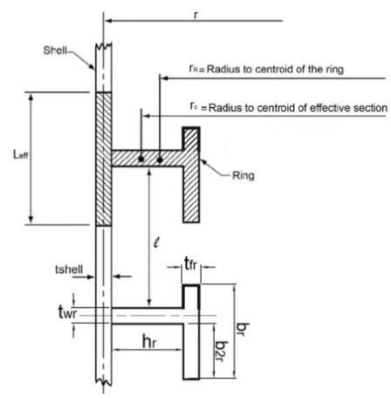

Figure 9Ring stiffened shell

A MATLAB Program has been developed to calculate the structural scantlings of the floating foundation according to the rules and guidelines available. The procedure is explained in the flowchart shown in Fig.10.

The equations used in this procedure are as follows:

1- Calculate the hydrostatic pressure (P_d) acting on the column perpendicular to its axis [7] from equation 6.
2- The frame spacing between stringers is chosen to satisfy the continuity with the hexagonal WEP
3- Calculate the thickness of the main horizontal members and bracing to satisfy the buckling requirements[11]:

$$\frac{D_{b,h}}{t_{b,h}} < 300 \qquad (11)$$

4- Calculate the column shell thickness according to DNV-OS-J101 as given by [9]:

$$t_{shell} = \frac{15.8\, K_a\, K_r\, s\sqrt{P_d}}{\sqrt{\sigma_{pd\,1} K_{pp}}} \qquad (12)$$

where

σ_{pd1} Design bending stress, N/mm^2 $= 1.3*(\sigma_{yd} - \sigma_{jd})$
σ_{yd} Design yield stress, N/mm^2

5- Calculate the minimum required section modulus of the stringers according to DNV as given by[9]:

$$Z_s = \frac{l^2\, P_d\, s}{K_m\, \sigma_{pd\,2} K_{ps}} . 10^6 \qquad (13)$$

where

σ_{pd2} Design bending stress, N/mm^2 $= (\sigma_{yd} - \sigma_{jd})$
σ_{yd} Design yield stress, N/mm^2

6- Calculate the section modulus of the ring frames as given by [9]:

$$Z_g = \frac{s^2\, P_d\, l}{K_m\, \sigma_{pd\,2} K_{ps}} . 10^6 \qquad (14)$$

7- Assume a web depth (h_{web}) for the flanged stiffeners that satisfy the buckling requirements by using the formulae given by[11]:

$$h_w \le 1.35\, t_w \sqrt{\frac{E}{\sigma_y}} \qquad (15)$$

8- Assume a flange width (b_f) for the flanged stiffeners that satisfy the buckling requirements by using the formulae given by[11]:

$$b_f \le 0.4\, t_f \sqrt{\frac{E}{\sigma_y}} \qquad (16)$$

9- Calculate the effective breadth (b_{eff}) and the effective length (L_{eff}) described in Fig.8&9.
10- Assume the scantlings of the WEP and the closed plates of the column as shown in Figs.11 and 12 respectively, sincethe structural design of these components has to be carried out numerically as design codes do not provide specific guidelines for such components[15].

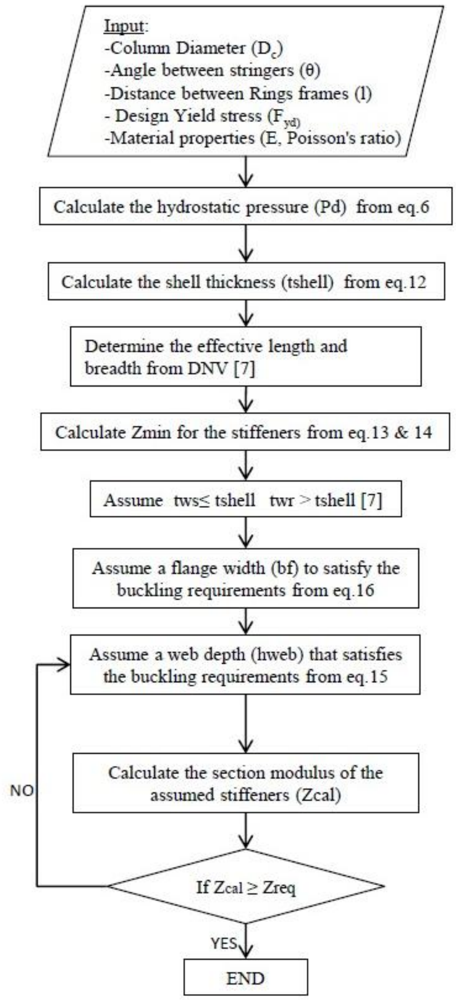

Figure 10Flowchart for the developed program for scantlings calculation

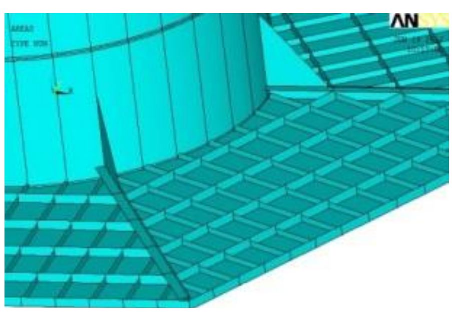

Figure 11 Construction of WEP

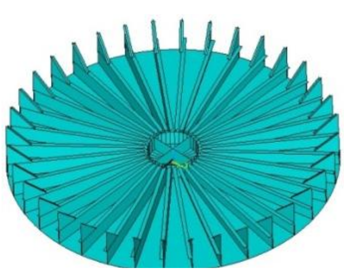

Figure 12 Bottom and top plate construction

5. CASE STUDY

The application is performed on an existing WindFloat that can withstand up to 10 MW wind turbine[16]. The developedprograms have been applied to carry out the structural design of thefloating foundation of WindFloat in Red Sea. The main dimensions of the floating foundationare summarized in table 2[16]. The input given in table 3 defines the average sea state for a 100 year return period[17].It is to be noted that the operating draft given in table 2 corresponds to 2917 tonnes light weight plus 4134 tonnes of ballast distributed in all columns of WindFloat;this condition is defined as 100% ballast condition.

Table 2: Main Dimensions of the floating foundation of the WindFloat[16]

Items	Dimensions (m)
Column diameter	10.7
Pontoon diameter	1.8
Bracing diameter	1.2
Length of heave plate edge	13.7
Column center to center	56.4
Operating draft	22.6
Air gap	10.7
l (distance between rings)	3.36

Table 3: Average sea state for a 100 year return periodfor Red Sea[17]

Average Depth (m)	490
Current speed (m/sec)	1.5
Wind speed at 10 m above sea level (m/sec)	10.7
Peak period (T) (sec.)	15
Significant wave height (H)	5
Tide range (m)	±1

The relation between the shell thickness (t_{shell}), effective breadth (b_{eff}) and the angle between stringers (ϴ) is plotted in Fig.13 using the developed program at constant hydrostatic pressure and constant diameter. To have an effective breadth (b_{eff}) of the stringer of not more than 1 m as conventionally adopted is ship structures as shown in step 1 in Fig.13, an angle of 10 degrees is selected as shown in step 2 in Fig.13. Consequently, the thickness of the shell is 23 mm as shown in step 3 in the same figure.

Table 4 summarizes the results obtained from eq.11 &12 that are used to calculate the thicknesses of the main components of the floating structure of the WindFloat which are shown in Fig.2, and the results of the section modulus (Z) obtained from eq.13 & 14.

The thicknesses of the web and flange of the ring and stringer are assumed to be as shown in table 5 and by taking into account that the thickness of the ring web is greater than the shell thickness (t_{shell})[9].

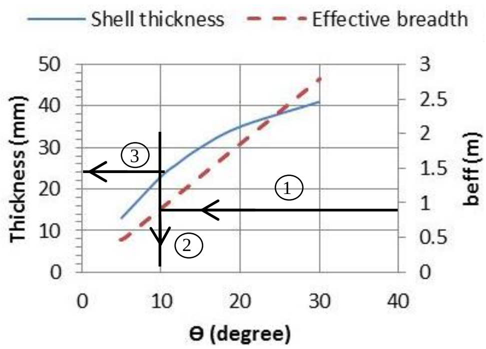

Figure 13Shell thickness vs. angle between stringers

Table 4:Scantlings of the main components of the floating foundation

Items	Outputs
Column thickness	23 mm
Horizontal membersthickness	10 mm
Bracing thickness	8 mm
Heave plate thickness	20 mm
required section modulus for ring frame	6.4E+5mm^3
Required section modulus for stringer	2.3E+6mm^3

Table 5: Assumed thicknesses for ring frame and stringer

	Ring	Stringer
Web Thickness (mm)	24	17
Flange Thickness (mm)	20	20

The depth of each stiffener is then determined according to buckling requirements[11]giving the maximum value of the web depth.

The scantlings of the ring frame and stringer are calculated using the developed program; the results are summarized in table 6. The effective length of the stringer (L_{eff}) is calculated according to the DNV and API recommendations. The effective breadth of the ring frame (b_{eff}) is assumed to be equal to the frame spacing (s) according to the same recommendations. The depth of the ring frame and stringer (h_w) are calculated to give minimum section modulus.

Table 6 shows the ratio between the section modulus calculated ($Z_{cal.}$) according to the selected dimensions, and the section modulus required (Z_{req}) by the rules. If this ratio equals to 1, this means that the corresponding dimensions are the minimum dimensions that can be used.

Table 6: Stiffener dimensions (mm) for t_{shell}=23mm

Items	Stringer	Ring frame
L_{eff}	-	1500
b_{eff} = s	934	-
Web depth (h)	326	326
Web thickness	17	24
Flange thickness	20	20
Flange width (b)	276	95
b2	234	46
Ratio (Z_{calc}//Z_{req})	1	2.2

It is clear from the results given in table 6 that the ratio between the calculated section modulus and the required section modulus is equal to 1 for the stringer and equal to 2.2 for the ring frame. The ratio of 2.2 for ring frame is due to considering the depth of the ring frame equal to the depth of the stringer web to facilitate the construction and welding process. However this high ratio is required for ring frames since they represent the main structure member in the column.

6. FINITE ELEMENT ANALYSIS

A static strength assessment is performed by means of 3D FEM for the floating structure of WindFloat usingthe commercial software ANSYS version 13.0.The model geometry is shown in Fig.14

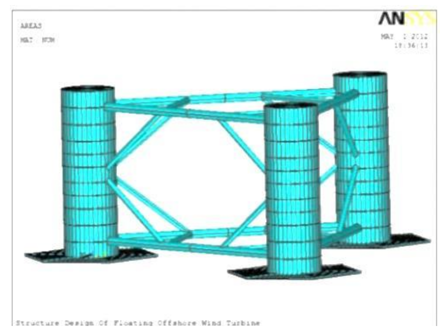

Figure 14WindFloat model geometry

The element SHELL281 is adopted. It consists of eight nodes as shown in Fig.15. Element COMBIN14 is used for modeling the springs that are used circumferentially under each column to simulate the boundary conditions under the column that represent the water effect, this element is a spring damper element that has no mass and is an uniaxial tension-compression element with up to three degrees of freedom at each node.Zero linear motion in x, y, and z directions were applied as boundary conditions circumferentially at each node in the end of the spring element.Normal tensile strength steel with yield strength equal to 235 MPa, modulus of elasticity (E) equal to 210000 MPa and Poisson's ratio 0.3 is used.A static analysis was performed to calculate the von Mises equivalent stress (SEQV) at each point.SEQV stress allows any arbitrary three dimensional stress state to be represented by a single positive stress value.

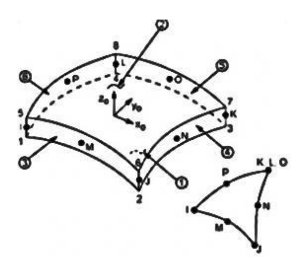

Figure 15Element shell281

6.1. Loading conditions

All loads previously presented acting on the WindFloat are applied to perform the FEA for the two loading conditions shown in table 7, where the loading condition 1 (LC 1) representsthe installation condition of the WindFloat with 25% ballast water in the columns;this generates a draft equal to 14.3m. Loading condition 2 (LC 2) representsthe operating condition of the WindFloat with 100% ballast water in the columns which generates a draft equal to 22.6m.

Table 7: Loading conditions

Loading condition	Bal-last	Height of ballast water (m)	Draft (m)	Turbine status
LC 1	25%	4.48	14.3	Installation
LC 2	100%	17.94	22.6	Operating

For each loading conditionthe different environmental loads are applied.These loads are used in the FEA as well as the weight of the tower and rotor as shown in table 8 appointed 854 tonnes[2] acting on the top of one column, namely column A as shown in Fig.2

Table 8:Loads acting on columns

Columns	Vertical load components	LC 1	LC 2
A	Tower weight (MPa)	0.094	0.094
	Hydrostatic pressureon WEP (MPa)	0.104	0.048
B& C	Tower weight (MPa)	-	-
	Hydrostatic pressure on WEP (MPa)	0.104	0.048

As the ballast is increased, the hydrostatic pressure at the base of all the columns decreases from 0.104MPa in LC 1 to 0.048MPa in LC 2.

6.2. Results and discussion

FEA was performed and five vertical paths on each column were specified to calculate the SEQV on the WindFloat as shown in Fig.16.

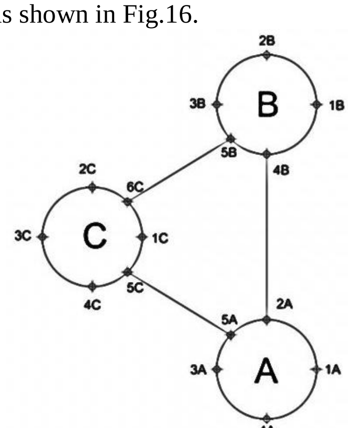

Figure 16Sketch for all paths

6.2.1. Effect of each load acting individually on WindFloat

FEA was performed for each load acting individually on the WindFloat to estimate the predominant load acting on the WindFloat. Table 9 shows the maximum value and position of SEQV for each load individually.

Table 9: Maximum value and position of SEQV for each load individually

		Hydrostatic pressure		Waves & Wind		Axial Force		Tower Weight	
	Path	***σ_{max} MPa***	***y (m)***	***σ_{max} MPa***	***y (m)***	***σ_{max} MPa***	***y (m)***	***σ_{max} MPa***	***y (m)***
Column A	***1A***	61	1.7	0.9	0	3.2	33.6	46.5	32
	2A	127.1	1.7	6	16	3.1	32	68.2	32
	3A	64.7	1.7	1.3	0	3.5	33.6	46.7	32
	4A	93.9	1.7	0.7	16	14.5	33.6	48.5	32
	5A	123.7	1.7	2	18	8.8	33.6	68	32
Column B	***1B***	61	1.7	0.7	13.4	0.2	0	1.3	0
	2B	93.9	1.7	0.2	6.7	7E-2	13.4	0.9	0
	3B	64.5	1.7	1.7	0	0.3	32	1	0
	4B	124.8	1.7	5.6	16	1.4	17	4	16
	5B	123.7	1.7	2.1	16	0.3	32	1.4	32
Column C	***1C***	66.6	1.7	2	33.6	1.1	15	1.6	0
	2C	89.7	1.7	0.8	20	0.1	0	0.6	1.7
	3C	63.4	1.7	0.6	0	0.2	0	1.1	0
	4C	89.7	1.7	1.4	13.4	0.7	20.1	1.1	13.4
	5C	123.7	1.7	3.9	16	3	16	4	16
	6C	124.8	1.7	3.5	16	0.5	23.5	1.4	32

The response of each of the applied loads has been studied individually to examine the importance of each. The most significant load is found to be the hydrostatic pressure since it results in SEQV equal to 127.1 MPa at a position between the WEP and the lower horizontal member in the path aligned with connection between the bracings, horizontal members and columns (path 2A). The stress due to the wind axial force and moment due to operation of the wind turbine does not exceed 6% of the resultant stress in column A. The stress due to the weight of the tower and blades results in 21% of the resultant stress in column A. it has been noticed that columns B and C are not significantly affected by the tower weight; the effect is only seen around the connection of the bracing and horizontal members.

6.2.2. Effect of simultaneous action of different loads on WindFloat

FEA was performed for all loads acting simultaneous on the WindFloat in the installation condition (LC 1) and the operating condition (LC 2). The results obtained for the Von- mises stress in LC 1 and LC 2 are not realistic as shown in Fig.17, since the values obtained are between 230 and 666MPa in LC 1 and between 230 and 645 which exceeds the ultimate strength of the steel.

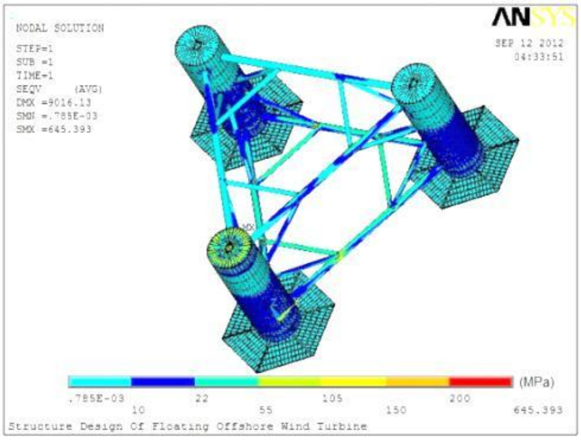

Figure 17SEQV for the WindFloat in LC 2

Critical areas showing unacceptable stress values require structural enhancement to withstand the load conditions under consideration; these are the top plate of column A, the top plate's stiffeners of column A, outer shell of the top part of column A, the stiffeners located in the middle area of column A and the joint between the lower horizontal member and the bracing of column A respectively. No critical areas have been detected in the other two columns B and C. The proposed enhancement consists of increasing thethickness of the top plate and the upper part of column A supporting the tower from 23 to 46 mm, increasing thickness of the brackets and stiffeners from 20 mm to 25mm and increasing thickness in the middle area of the column supporting the tower from 23 to 46 mm. The range of Von-Mises stress has greatly improved after enhancement as shown in Fig.18.

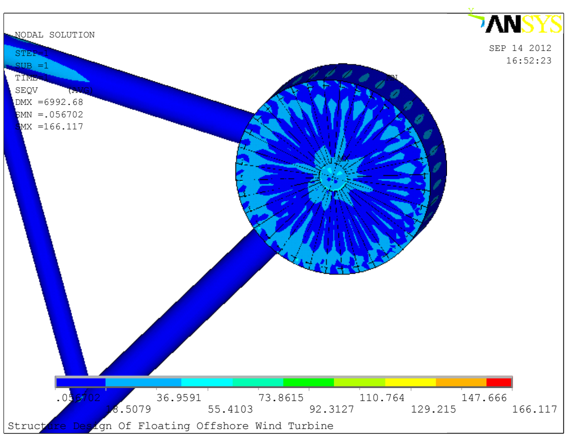

Figure 18 SEQV in the top plate of column A in LC 2 after reinforcement

Table 10 shows the maximum value and position of SEQV for both loading conditions after enhancement.

Table 10: Maximum value and position of SEQV for both loading conditions after enhancement

		LC 1		LC 2	
	Path	σ_{max} ***(MPa)***	***y (m)***	σ_{max} ***(MPa)***	***y (m)***
Column A	***1A***	32.45	1.7	24.4	33
	2A	34.1	33	35.3	33
	3A	32.34	1.7	20.3	33
	4A	48.4	1.7	24.5	33
	5A	30.4	33	31.6	33
	Center of the top plate	100	33.6	110	33.6
Column B	***1B***	27.3	1.7	12.1	1.7
	2B	50.2	1.7	23.3	1.7
	3B	31.8	1.7	15	1.7
	4B	12.6	1.7	11	4.5
	5B	18.5	1.7	13	13.5
Column C	***1C***	30	1.7	17.7	1.7
	2C	49	1.7	21.8	1.7
	3C	29.5	1.7	13.4	1.7
	4C	48.6	1.7	21.1	1.7
	5C	19.2	1.7	13.6	13.5
	6C	19.5	1.7	17.6	13.5

7. CONCLUSION

This paper studied the structural design of a Floating Foundation for Offshore Wind Turbine in Red Sea.

The scantlings of the structure are calculated to comply with the DNV rules and satisfy the buckling requirements. A computer program was developed to carry out the structural design of a WindFloat and making the necessary buckling checking. A 3D FEM is developed using ANSYS to perform a FEA for the static strength assessment of the structure in the installation and operation conditions. From the analysis given in this paper the following conclusions can be reached:

- The range of stresses in the column supporting the tower (column A) is higher than the ranges in the other columns in both studied loading conditions.
- The hydrostatic pressure is the predominant load that generates a high stress level in the WindFloat.This is a good argument support the formulae given by the DNV rules which takes into account he hydrostatic pressure only in the calculation of minimum section modulus of stiffeners.

- The weight of the tower results in 21% of the resultant stress in the column supporting the tower.
- The wind axial force and the weight of the tower subjected to the column supporting the tower have a very small effect on the stress level in the other column.
- The top part of the column supporting the tower is subjected to unacceptable SEQV in both operating conditions, whereas the two other columns are safe.
- The middle part of the column supporting the tower is a critical area in the operating condition.
- A structural enhancement consisting of an increased thickness in the top plate of the column supporting the tower and in its stiffeners is proposed to obtain acceptable stress values.
- The ranges and distribution obtained of Von-Mises stress in the identified paths in both loading conditions are approximately similar.
- The suitability of the WindFloat in the Red Sea should be studied from the economical point of view.

REFERENCES

[1] W. Musial, S. Butterfield, and B. Ram, "Energy from Offshore Wind," presented at the Offshore Technology Conference, Houston,Texas, 2006.

[2] D. Roddier, C. Cermelli, and A. Weinstein, "WindFloat: A Floating Foundation For Offshore Wind Turbines.Part I: Design Basis and Qualification Process," presented at the OMAE, Hawaii, USA, 2009.

[3] D. Roddier, C. Cermelli, A. Aubault, and A. Weinstein, "WindFloat: A floating foundation for offshore wind turbines," *Journal of Renewable and Sustainable Energy*, 2010.

[4] M. I. A. technology, "Principle power WindFloat Brochure," 2009.

[5] R. G. Dean and R. A. Dalrymple, *Water Wave Mechanics for Engineers and Scientists*: Prentice Hall, Inc., 1984.

[6] J. V. D. Tempel, "Design of Support Structure for Offshore Wind Turbines," PhD, Delft University, 2006.

[7] *Guideline for the Certification of Offshore Wind Turbines*, 2005.

[8] *Guide for Building and Classing Offshore Wind Turbine Installation, ABS*, 2010.

[9] *Design of Offshore Wind Turbine Structures, Recommended Practice DNV-OS-J101* 2007.

[10] T. Burton, D. Sharpe, N. Jenkins, and E. Bossanyi, *Wind Energy Handbook*: British Library Cataloguing, 2001.

[11] *Buckling Strength of Shells, Recommended practice DNV-RP-C202*, 2002.

[12] ABS, "Guide for Buckling and Ultimate Strength Assessment for Offshore Structures," ed: ABS, 2004.

[13] *Recommended Practice 2A-LRFD for Planning, Designing, and Constructing Fixed Offshore Platforms.*, 1997.

[14] *Recommended practice 2A-WSD for planning, designing and constructing fixed offshore platforms-working stress design*,2000.

[15] A. Aubault, C. Cermelli, and D. Roddier, "WindFloat: A Floating Foundation For Offshore Wind Turbines.Part III: Structural Analysis," presented at the OMAE, Hawaii, USA, 2009.

[16] C. Cermelli, D. Roddier, and A. Aubault, "WindFloat: A Floating Foundation For Offshore Wind Turbines.Part II: Hydrodynamics Analysis," in *OMAE*, Hawaii, USA, 2009.

[17] E. M. Authority. (2005)*http://www.ema.gov.eg/*.