STRENGTH ANALYSIS OF A LARGE-SIZE SUPPORTING STRUCTURE FOR AN OFFSHORE WIND TURBINE

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ABSTRACT

The offshore wind power industry is the branch of electric energy production from renewable sources which is most intensively developed in EU countries. At present, there is a tendency to install larger-power wind turbines at larger distances from the seashore, on relatively deep waters. Consequently, technological solutions for new supporting structures intended for deeper water regions are undergoing rapid development now. Various design types are proposed and analysed, starting from gravitational supports (GBS), through monopiles and 3D frame structures (jackets, tripods), and ending with floating and submerged supports anchored to the seabed by flexible connectors, including TLP type solutions.

The article presents the results of examination of an untypical large-size gravitational support intended for waters with the depth of up to 40 m. Firstly, a general concept of the new design is presented, while the next basic part of the article describes the support design in detail and provides its strength analysis. The examined support has the form of a large steel container consisting of conical segments. The strength analysis was conducted using the finite element method (FEM), in accordance with the standard DNVGL-ST-0126. Modifications introduced to the most heavily loaded structural node of the support, which was the set of base bottom trusses, is also included. The results of the performed analysis prove that the presented concept of supporting structure for a 7MW turbine meets fundamental strength criteria. The nonlinear buckling analysis was performed to evaluate the critical force acting on the support, which turned out to be 1.44 times as large as the maximum load of the wind turbine. Potentially important issues for further analyses have been identified as those resulting from the asymmetry of basic loads acting on the support.

Keywords: Renewable energy sources, offshore wind power industry, supporting structure, strength analysis, FEM, computer simulation, numerical calculations, CFD, conceptual design, buckling, thin-walled structure

1. INTRODUCTION

The offshore wind power industry sector is undergoing rapid development, as a result of EU policy on energy production from renewable sources. In two recent decades, the wind energy conversion technologies have been shifted from a sort of niche sector to one of most dynamically developing power industry branches. Following the publication of EU policy objectives concerning power industry development in years 2020 to 2030 [1], the development of the wind energy sector is included to strategic directions, and a substantial potential for development is seen in offshore installations [2, 3]. The trend in offshore wind power industry development is illustrated by the diagram in Fig. 1, which presents the annual and cumulated power of offshore wind turbines installed in EU countries.

Further dynamic development of this sector will be possible, provided that several technological challenges concerning production and installation of new wind farms of large-power turbines (100 MW and more) will be solved [6]. These farms should be situated at a large distance from the seashore and, consequently, on relatively deep waters. At present, the technological advancement level provides real opportunities for commercial investment project execution only on coastal waters. At the end of 2015, the average distance of wind farms connected to electric networks from the seashore was 43.3 km, and the average water region depth

was 27.1 m [4]. The most recent trends in the offshore wind power development are shown in Fig. 2.
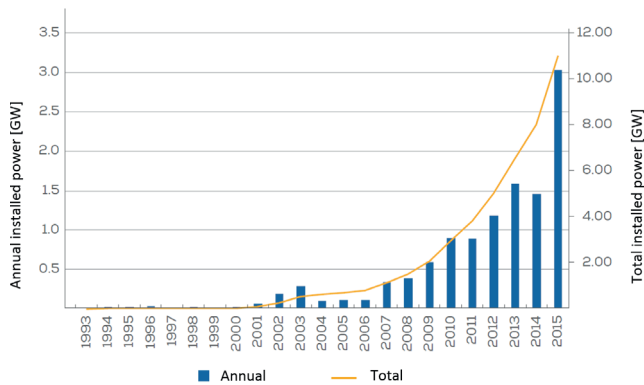

Fig. 1. Annual and cumulated power of offshore wind turbines installed in EU countries UE [4, 5]
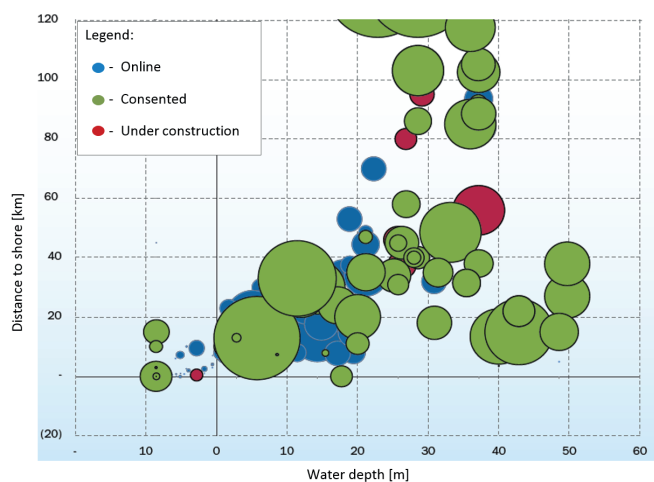

Fig. 2. Average water region depth and distance from the seashore – for wind farms: connected to the electric networks, accepted, and under construction [4]

For water regions with depths of up to 20 m, the most frequently used foundation form is a monopile driven into the seabed, while for the depths exceeding 30 m several support designs have been adopted from the offshore oil rig industry. The latter supports usually have the form of 3D frames or tripods. The offshore wind power industry development trends clearly lead towards deeper water regions. However, the main problem here is the lack of effective technical solutions for supporting structures, although the literature on supports for offshore wind turbines provides descriptions of various foundation types, such as monopiles [7-9], tripods [10,11], jackets [12-13], gravitational supports [14-16], etc. The solutions proposed for much larger depths, exceeding 50 m, include floating supports, [17-20], partially or fully submerged supports with flexible connectors [21], and supports with submerged displacement hulls, a so-called Tension Leg Platform (TLP) solution [22-23]. What is noteworthy is huge technological progress in the field of numerical simulations, supported by experimental tests [24-37]. Visible progress is

also observed in technologies of structure production [38-40] and structure operation monitoring [41-45]. All these factors affect considerably the dynamics of offshore wind power industry sector development.

This article proposes a concept of gravitational type foundation intended for waters with the depth of up to 40 m. For these waters, neither conventional solutions nor concepts of new type floating structures have been used so far. Obviously, the proposed supporting structure can be adapted to other water depths, but this adaptation would require new strength analyses. The general solution concept was proposed within the framework of the research project AQUILO oriented on verifying various concepts for offshore wind turbine foundations on the Baltic Sea. In the present concept, the supporting structure has the form of a large-size thin-walled steel container, ballasted with so-called pulp (mixture of sand and water). The strength analysis for the new support was conducted in accordance with the standard DNVGL-ST-0126 [46]. In the article, Section 2 presents the design assumptions, while Section 3, being the main part of the article, describes the FEM model based strength analysis of the examined structure. The presented results also include the assessment of the critical force coming from wind turbine load, and the presentation of changes introduced to the main structural node of the design. Section 4 provides conclusions from the research and indicates possible directions of its further continuation.

2. DESIGN ASSUMPTIONS

The supporting structure is intended for a 7 KW offshore wind turbine to be operated on North Sea or Baltic Sea waters, at the depth of up to 40 m. The structure was designed as a very untypical support of gravitational type, having the form of a thin-walled steel container. The general plan of the support with the installed column and turbine is shown in Fig. 3. The horizontal axis of the turbine is situated 100 m above the surface level of the 40-meter deep water region. The design also includes a 70-meter high intermediate column, similar to that used in monopile designs. This column rests on the foundation consisting of three conical segments. The end cross-sections of the first 30-meter high cone have the shapes of regular dodecagons inscribed in circles of 5.5 m (top) and 7.0 m (bottom) in diameters. The next segment, situated below, increases the diameter of the circle in which the regular bottom cross-section dodecagon is inscribed to 12.0 m, while the base of the lowest segment, lying on the seabed, is inscribed in the circle of 40 m in diameter.

While typical gravitational supports are made of concrete [16, 47], the presented structure is designed in the form of a thin-walled steel container. The structural shape of the container is similar to that of stiffened panels used in modern shipbuilding and offshore industry. The article describes the research activities concerning the support segment to the height of 70 m above seabed (underwater part and intermediate column). The support is designed as a container, playing the

function of a displacement hull, which is delivered to the foundation place via towing. Then the support is submerged by flooding the ballast tanks. Proper stability of the support standing on the seabed is ensured by ballasting the container with pulp to the height of 25 m. Other ways of transport and setting of the support seem to be more difficult and more expensive. The assumer lifetime of the support is 50 years.
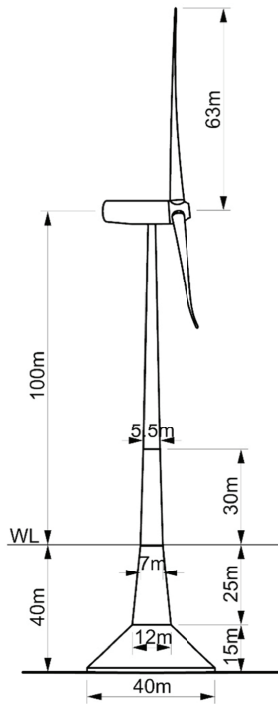

Fig. 3. General plan of the concept of gravitational supporting structure (steel container with internal ballast)

3. STRENGTH ANALYSIS OF THE UNTYPICAL OFFSHORE WIND TURBINE SUPPORTING STRUCTURE

The strength analysis was conducted in accordance with the standard DNVGL-ST-0126 [46]. The designed structure was subjected to maximal loads calculated for the assumed location and time of operation. The calculations were performed using the FEM model and the ANSYS software. The environmental loads were calculated with the aid of computational fluid dynamics (CFD) codes and the simulation platform STAR-CCM+. Sections 3.1 to 3.4 present the obtained strength analysis results, while the main results of maximal deflection and stress calculations are shown in Section 3.5, along with the calculated critical force which initiates buckling. This force was assessed by increasing the maximal wind turbine load until the load capacity limit was obtained. To meet requirements included in relevant regulations, some changes were introduced to the most heavily loaded structure fragments. The multi-variant analysis of the effect of selected design parameters on the support strength was also performed to decrease the level of global column deflections and local stresses in the structure.

3.1 AIM OF ANALYSIS

The strength analysis aimed at verifying the overall strength of load carrying elements of the untypical offshore wind turbine supporting structure. An important element of the analysis was identifying most heavily loaded regions and introducing changes to the initial design of the structure to reduce maximal support deflections and stresses at most heavily loaded structural nodes. The final stage of the analysis was calculating the critical force and identifying structure destruction forms.

For the purpose of strength calculations, the FEM model of the examined support was created. The support structure was modelled using shell elements, while the intermediate column was modelled using beam elements, and the nacelle was modelled using the mass element.

The numerical model of the support having the form of a large-size thin-walled container was based on shell elements (shell181), which are four-node elements with 6 degrees of freedom at each node. The FEM model described the geometry of the examined object very precisely. The elementary grid size was 150 mm, and respected the principle of at least three nodes over the span of each structural element. Modelling low stiffeners with the aid of shell elements provided the opportunity to connect the stiffener nodes with those of the truss webs through which they pass. This enabled more precise modelling of conditions of cooperation between these elements in the global model. Structural elements which were not involved in carrying global loads, inner walls in ballast tanks for instance, were excluded from the analysis. The FEM model of the examined offshore wind turbine supporting structure is shown in Fig. 4.
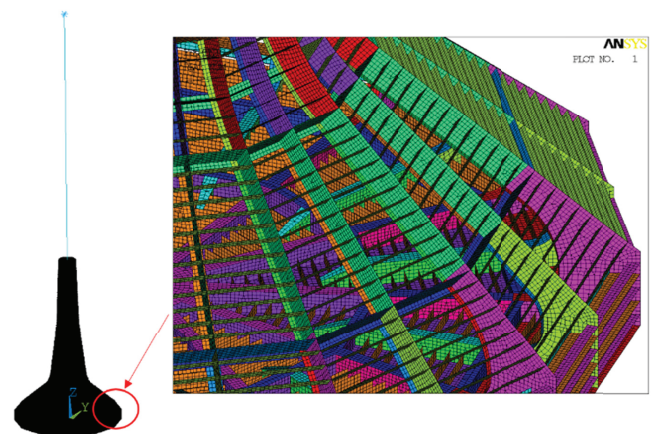

Fig. 4. FEM model of the offshore wind turbine supporting structure (hidden external plating)

3.2 MATERIAL MODEL

The structure of the support was designed to be made of normal-strength steel, Category B, according to the requirements in the standard DNV-OS-B101 [48]. Chemical composition and strength of this material, labelled as S235J0, meet the requirements of the standard EN 10025-2 [49]. At the same time the most heavily loaded region of the supporting structure, which is the passage of vertical trusses into base bottom trusses, was designed to be made of higher-strength steel NV A27, Category A, for truss webs, and of high-strength steel EH32, Category E, for truss flanges.

The computer simulations performed to verify the strength of the examined structure made use of linear-elastic models, while critical loads were calculated using isotropic material models with nonlinear stress/deformation characteristics for the above steels NVA, NV A27, and EH32. A sample material curve for steel NVA is shown in Fig.5. The Young's modulus was assumed equal to 2.06e5 MPa, the Poisson's number v=0.3, and the density 7.85 t/m³. The yield points for steels NVA, NV A27 and EH32 were assumed equal to, respectively, 235 MPa, 265 MPa and 315 MPa. For all steels, the tangent plastic hardening modulus was equal to 200 MPa.
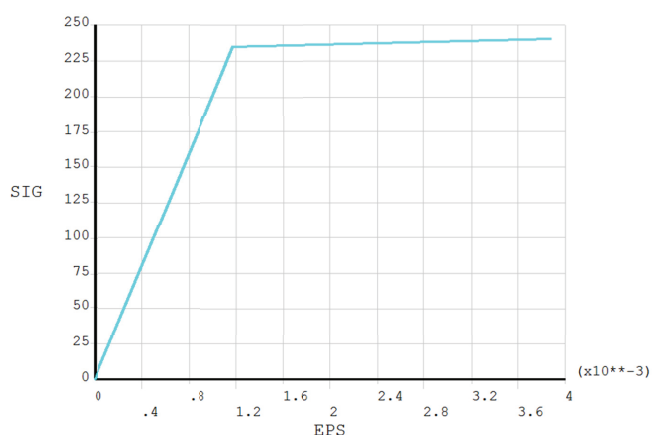

Fig. 5 Stress/deformation curve for the material model of NVA steel

3.3 LOADS AND BOUNDARY CONDITIONS

The performed strength analysis took into consideration the following loads and boundary conditions:
a) Self-weight of the structure.
b) Environmental loads (dynamic action of wind, waves, and sea current) corresponding to the maximal loads generated by the heaviest storm on the Baltic Sea in recent 50 years, for the unprotected support location and water depth of up to 40 m. The maximal loads were calculated using CFD codes and the simulation platform STAR-CCM+. The assumptions adopted in these calculations are collated in w Tab.1

Tab. 1 Assumptions for CFD simulations performed to determine environmental loads (wind, waves, sea currents)

Name	Value
Type of CFD analysis	Implicit unsteady
Time step	dt = 0.02 [s]
Turbulence model	k-epsilon
Wave model	Irregular wave (Jonswap)
Significant wave height	$H_{1/3}$ = 9.01 [m]
Wave period	T=11.3 [s]
Frequency	f=1200 [-]
Peak shape parameter	p=4.14 [-]
Spectrum width A	A=0.07 [-]
Spectrum width B	B=0.09 [-]
Water region depth	T_w = 40 [m]

The strength calculations were performed taking into consideration maximal values of environmental loads obtained from CFD storm simulations, for the irregular wave and Jonswap wave spectrum. A sample free surface shape obtained in the environmental load calculations is shown in Fig. 6, while Fig.7 shows the time history of the total transverse force. In both CFD and FEM calculations, the coherent global coordinate system was used with the origin at the centre of the circle circumscribed about the base bottom. The assumed direction of hydrodynamic loads was the same as that of the horizontal load coming from the wind turbine rotor. The maximal value of the calculated transverse force, corresponding to the average of 1% of maximal force peaks, was equal to F_x=6350 kN, while the total moment acting on the structure, which corresponded to the maximal value of 1% of loads for irregular wave, was equal to My=56800 kNm.
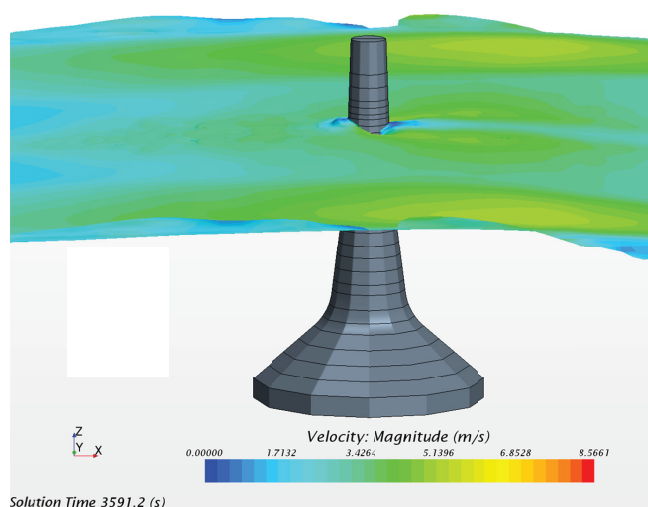

Fig. 6. Sample free surface of the wave being the support load (CFD simulation)
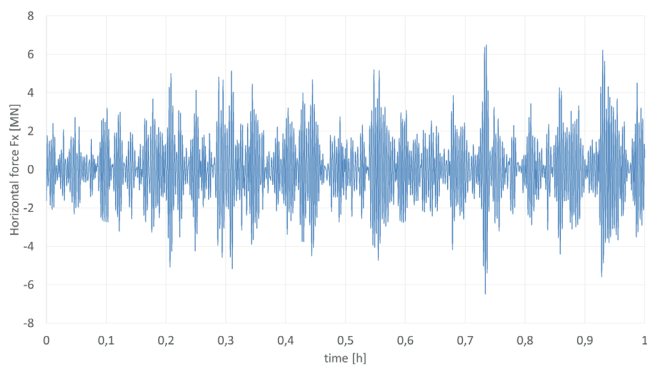
Fig. 7. Time-history of the calculated support load coming from the horizontal force F_x generated by the action of irregular wave, for Jonswap wave spectrum (CFD simulation)

c) Loads from the 7 KW wind turbine were assumed taking into account the safety factor k=1.35. The horizontal force from the examined turbine was equal to F_x = 2.9 MN. The remaining loads are protected by confidentiality provisions of the turbine producer and cannot be published.

d) Hydrostatic loads of seawater (ρwody = 1.025 t/ m³) and inner ballast (pulp, ρpulpy = 1.7 t/m³). The assumed submergence of the column at calm water was T_w=40 m. The wave height $H_{1/2}$=10m was also considered. The conservatively assumed resultant water head was equal to H_w=50 meters, while the hydraulic head of the inner pulp ballast was H_p=25m.

e) The soil stiffness was modelled in accordance with "Annex G" to the standard DNVGL-ST-0126 [46]. Each seabed element within the elliptic area of action was attributed with stiffness corresponding to the structure/ seabed interaction. The effective support area was A_{eff}=896 m².

3.4 RESULTS

The most important results of the presented offshore wind turbine supporting structure strength calculations are the total deflection and the reduced Huber-Mises stresses. The maximal calculated deflection occurs at the nacelle node and is equal to 2268 mm (Fig.8a), while the maximal total deflection of the support part situated under the intermediate column is observed in the section linking the support with the intermediate column and is equal to 261 mm (Fig.8b). The maximal values of the reduced Huber-Mises stresses occur in main vertical trusses and are equal to 235 MPa (Fig.9). The calculated values are within the design criteria, according to the standard DNVGL-ST-0126 [46]. Nevertheless, due to non-uniform stress distribution, some modifications were introduced to the design of the structure at the concept development stage – see Section 3.6.
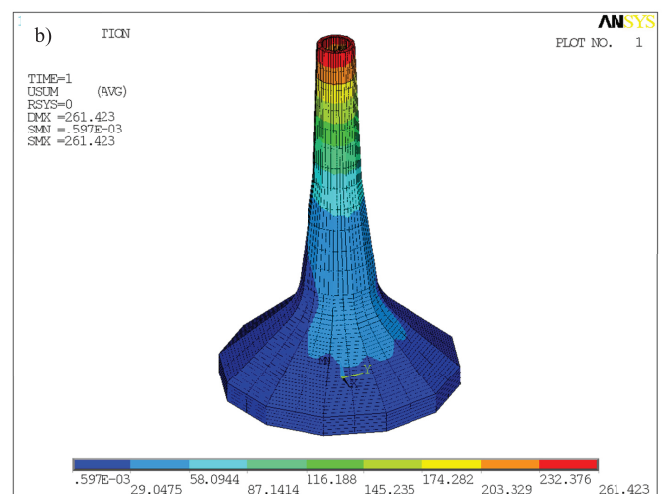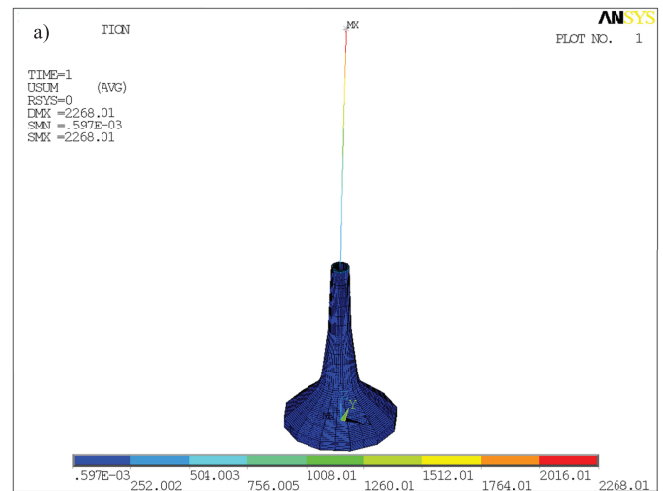

Fig. 8. Total deflection of the offshore wind turbine supporting structure (a), and total support deflection below the intermediate column (b) [mm]
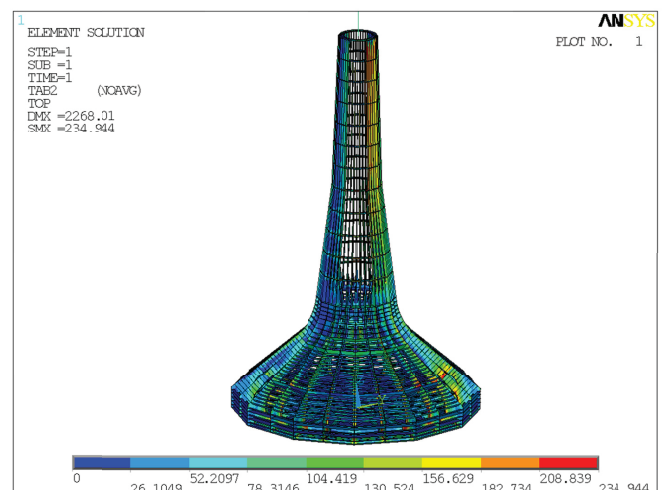

Fig.9. Reduced Huber-Mises stresses in the offshore wind turbine supporting structure [MPa]

It is noteworthy that the maximal stresses refer to a relatively small area of the structure. Its part situated on the

windward side of the turbine is subjected to relatively low stresses, which results from the nature of loads from waves and wind turbine, always acting in the wind direction.

Additionally, within the framework of the structure strength analysis, the fatigue life was assessed for the most heavily loaded region of the structure. This assessment based on local stress calculations and the so-called local stress approach. Although it was beyond the scope of the required calculations, a conclusion was made that the most heavily loaded node has sufficient fatigue life.

The last results discussed in this article refer to the nonlinear buckling analysis. For the horizontal force Fx, the amplification factor "n" was assumed which was the ratio of the set force and the maximal load of the wind turbine propeller, equal to F_x=2.9 MN. The factor n determines how many times the maximal force from the wind turbine was amplified. Figure 10 shows a diagram of maximal turbine node displacement in the horizontal x-axis direction, as a result of n-fold amplification of the turbine load. The calculations were conducted at forced displacement input. The obtained results indicate that at the load amounting to 1.44 of the maximal turbine force, the load carrying ability of the structure reaches its limit. The calculations were performed taking into account geometrical and material nonlinearities. The maximal calculated turbine load which can be carried by the structure is Fx= 4.18 MN. Further load increase leads to buckling of the plating and truss webs in the region of structure passage from column to conical base. Local deformations for the critical load are shown in Fig. 11 and Fig. 12.
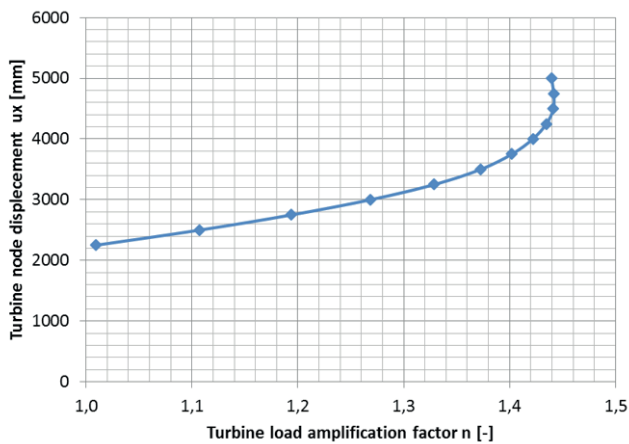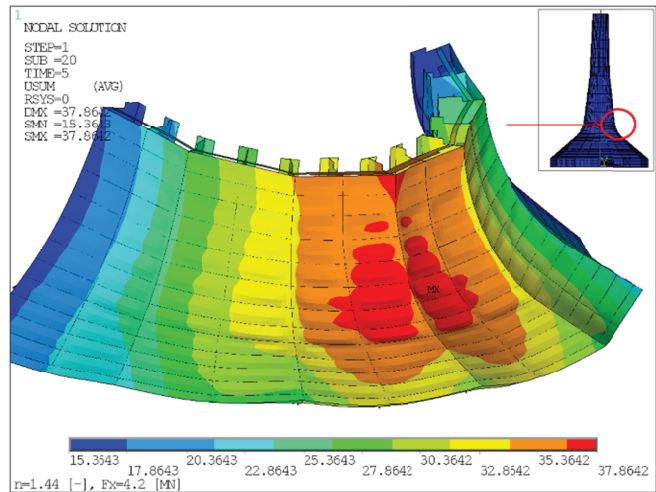

Fig. 11. Local plating deformations for the critical force which initiates buckling
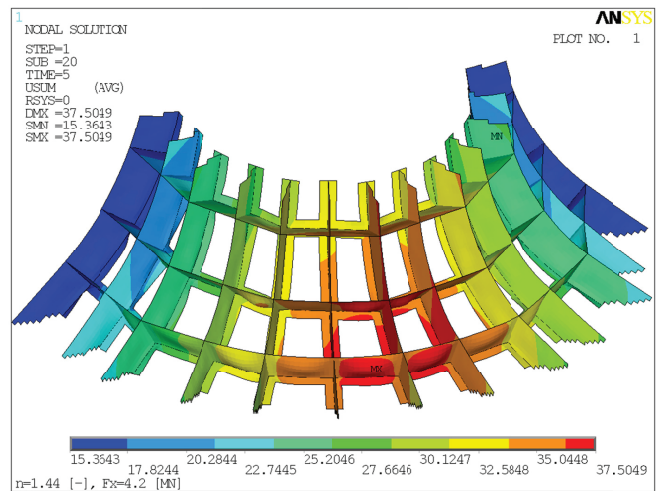
Fig. 12. Maximal truss web deformations for the critical force which initiates buckling

Fig. 10. Maximal turbine node displacement u_x vs. turbine load amplification factor n[-]

3.5 GEOMETRICAL SHAPE EVOLUTION OF THE MOST HEAVILY LOADED REGION OF SUPPORT STRUCTURE

The starting point for developing the concept of the untypical supporting structure for an offshore wind turbine were structural solutions used in modern merchant vessels. These structures consisted of plating stiffened with one-directional low stiffeners, which were in turn supported by trusses. After preliminary verification calculations, the column deflection level and the local stress distribution in the support were modified. The elements loaded with excessive stresses were reinforced, while those revealing poor cooperation were removed, at the same time preserving smooth characteristic of the longitudinal stiffness of the column. Five calculation variants were analysed for the self-mass change limit equal to 10%. The final effect of the design work performed with the aid of the FEM model based simulation was reducing the maximal total deflections by

11% and the maximal reduced Huber-Mises stresses by 71%. The total mass of the structure was reduced by 9%. The geometry change introduced to the most important bottom truss region is shown in Fig.13. The plating thickness in the bottom region was 20 mm. The thicknesses of bottom truss webs and flanges were equal to, respectively, 15mm and 25 mm. Profiles HP430x17 were applied as plating stiffeners. General arrangement of elements in the final version of the structure is shown in Fig.14.
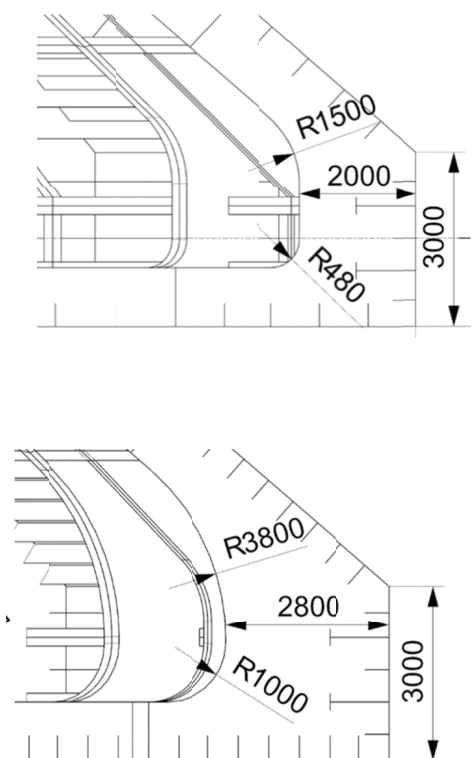

Fig. 13. Geometry changes in the bottom truss region: initial version (upper) and final version (bottom)
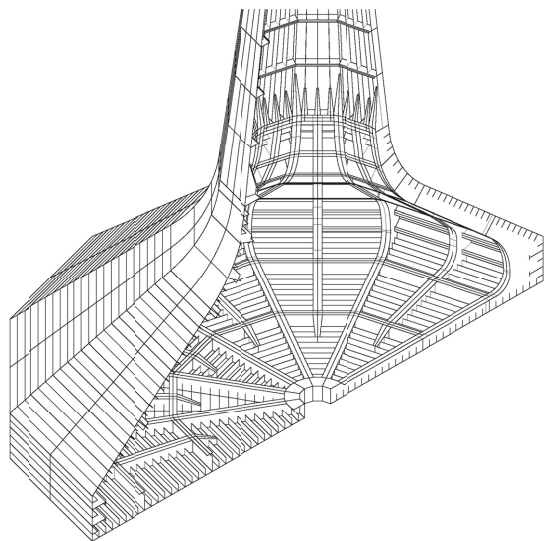

Fig. 14. Explanatory figure of the offshore wind turbine supporting structure (hidden geometry half)

CONCLUSIONS

The offshore wind power industry is a rapidly developing sector which already plays an important role in electric energy production from renewable sources. However, further technological development of this sector is required to meet market demands concerning reduction of energy production costs. What is essentially needed in this area is working out technical solutions which will provide opportunities for installation of large-power wind turbines, of 10 MW and more, arranged in wind farms situated at a large distance from the seashore and, consequently, on relatively deep waters. A key issue here is turbine immobilisation with respect to the seabed, which can be solved in many ways. There are numerous concepts of supporting structures, including various types of floating platforms, partially submerged platforms, TLP type columns, etc. A possible and potentially favourable solution here can also be a gravitational support. The article presents a concept of a large-size supporting structure of gravitational type which has the form of a steel container. The support can be towed to the place of operation and then submerged by filling ballast tanks with the mixture of sand and water taken from the seabed. The main part of the article is the container structure strength analysis, performed in accordance with the standard DNVGL-ST-0126 [46]. The required numerical calculations were conducted using the Finite Element Method. The obtained results reveal that the structure meets basic strength requirements for the given strength limit. The critical force, which is the load carrying capacity limit for the structure, was assessed. Then the structure design was modified. The introduced modifications allowed to reduce the maximal stress level by 71%, the maximal column deflection by 11%, and the total mass of the structure by 9%. A design modification introduced to the most important bottom region of the structure is presented. After this modification, the mass of the structure was 1250 tonnes. The estimated support production cost is approximately equal to 4 million euro (for the euro/kg-of-structure coefficient equal to 3.2). It is noteworthy that further structural optimisation is possible, making use of the fact that the loads coming from sea waves and wind turbine are very directional, and not circularly-symmetric as was assumed in the preliminary support concept. In research tests of supports intended for deeper water regions, of high importance is high directionality of maximal design loads. This factor gains even more in importance when we consider enormous dimensions and mass of the structure. Hence, when designing the supporting structure, it is economically profitable to include in the analysis the direction of action of maximal environmental loads, assessed based on statistical hydro-meteorological data for the given water region. This will remarkably reduce the self-mass of the supporting structure and, consequently, costs of its production, transport, installation, and disassembly.

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