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Structural Optimization of an Offshore Wind Turbines Transition Pieces for Bucket Foundations

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Abstract

Traditionally, offshore constructions are made of steel. The focus of this paper is optimization of a transition piece (TP) connecting the offshore wind turbine column with a suction bucket foundation. Suction caissons, typically used for shallow water depths, have been proved to be adequate in residual soil conditions for depths up to approximately 40 m. The existing design practice is limited to the use of steel-flange-reinforced shear panels. Desirable outcome is proposal of an alternative material which does not require extensive welding work. Compact reinforced composite (CRC) is suggested as an alternative to steel. CRC has an excellent durability and higher compressive strength compared to traditional concrete. This material has also an increased ductility owing to integration of large contents of short, strong and stiff steel fibres. At present, application of high-tension concrete is limited offshore, mainly, to making a grouting connection of a transition piece to a monopile. Lack of standards and norms puts additional restriction on application of CRC.

In the earlier work, the structural performance of transition pieces with a conical shape was compared for a 5 MW offshore wind turbine. Three construction materials were proposed: CRC with main reinforcement, composite CRC–steel shell elements and steel sheets (reference case). The conical shape of the TP structure has been found to provide the smooth transition of forces from the wind turbine tower down to the bucket skirt. Doubly curved segments have been introduced between the conical part and the tubular parts of the structure. While the minimum amount of steel and concrete was required for the composite CRC–steel shell model, the pure CRC model appeared to be the least sensitive to geometrical imperfections, corresponding to deviation of the middle surface from the perfect ideal shape of the shell structure, and was assumed for further investigation. The steel model showed the highest sensitivity to geometrical and loading imperfections.

This paper presents optimization of the CRC TP structure to lower manufacturing costs without compromising its strength and stiffness. Several models with variously positioned cutaways are presented and compared to find the one providing the better force distribution, preventing buckling and stress concentration and reducing the amount of material used. Minimization of the material consumption is based on assumed current cost of construction materials. Further investigation includes casting scaled concrete samples of the CRC to monitor the direction of flow and the possibility of mass.

Objectives and preliminary design

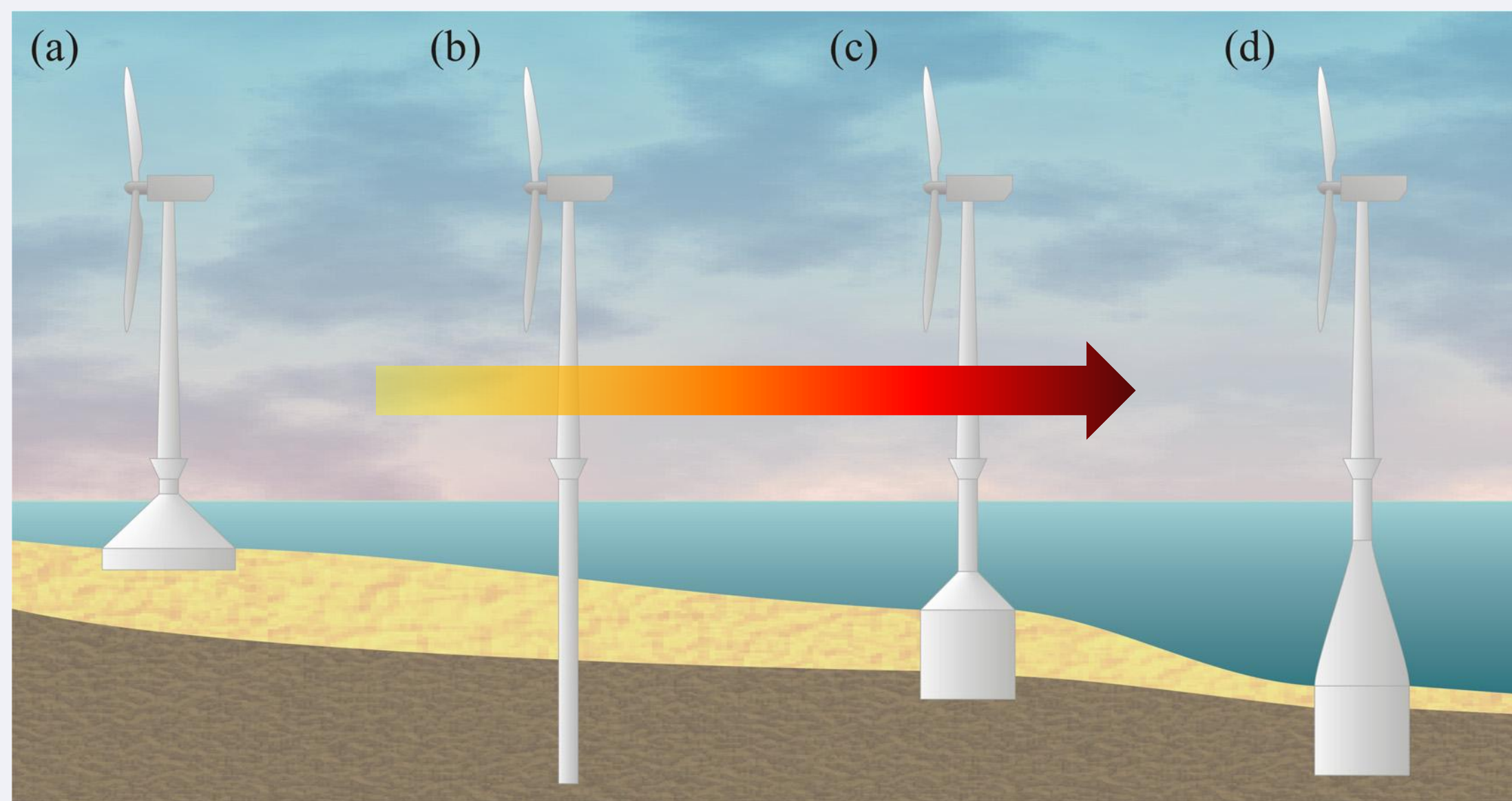


Figure 1: Different types of foundations for offshore wind turbines: a) Gravitational footing; b) monopile; c) suction bucket with traditional transition piece; d) suction bucket with shell transition piece

Use of steel-flange-reinforced shear panels for the production of the TP structure requires a lot of welding at the joints, is labor-intensive, expensive and time-consuming. As an alternative to steel, use of high-performance-fibre-reinforced compact reinforced composite (CRC) invented at Aalborg Portland, Denmark, in 1986 is suggested.

Local optimization of the TP cross section is performed to minimize the material consumption based on the assumed current costs of construction materials. It was found earlier [1,2] that TP of the conical shape (Figs.1 (d) ,2.2) could significantly minimize the wave action on the substructure by providing a smooth transition of the wave and wind loads to the bucket foundation. On the other hand, in their research Whitehouse et al. [3,4] observed that TP of this shape caused significant scour (erosion of the seabed) compared to the traditionally used steel girder top (Figs.1 (c) , 2.1). Scour is known to be one of the critical factors in design of the foundations for the offshore structures affecting the stability of the whole wind turbine and potentially causing its failure.

The wind load is found to be dangerous due to a high moment contribution. Hydraulic pressure produced by the waves appears not to be critical for the TP structure, although the total horizontal load from the waves is several times higher than that of the wind load. Yet, it is desirable to minimize large wave forces acting on the TP structure by making it a shorter and more compact structure. Desired outcome of this paper is developing a procedure for the design and optimization of the transition piece.

Five models of the TP are chosen for further investigation (Fig.2). The radii of the convex, concave, the height from the seabed and variously positioned cutaways for a conical shape TP are chosen as variable geometry parameters.

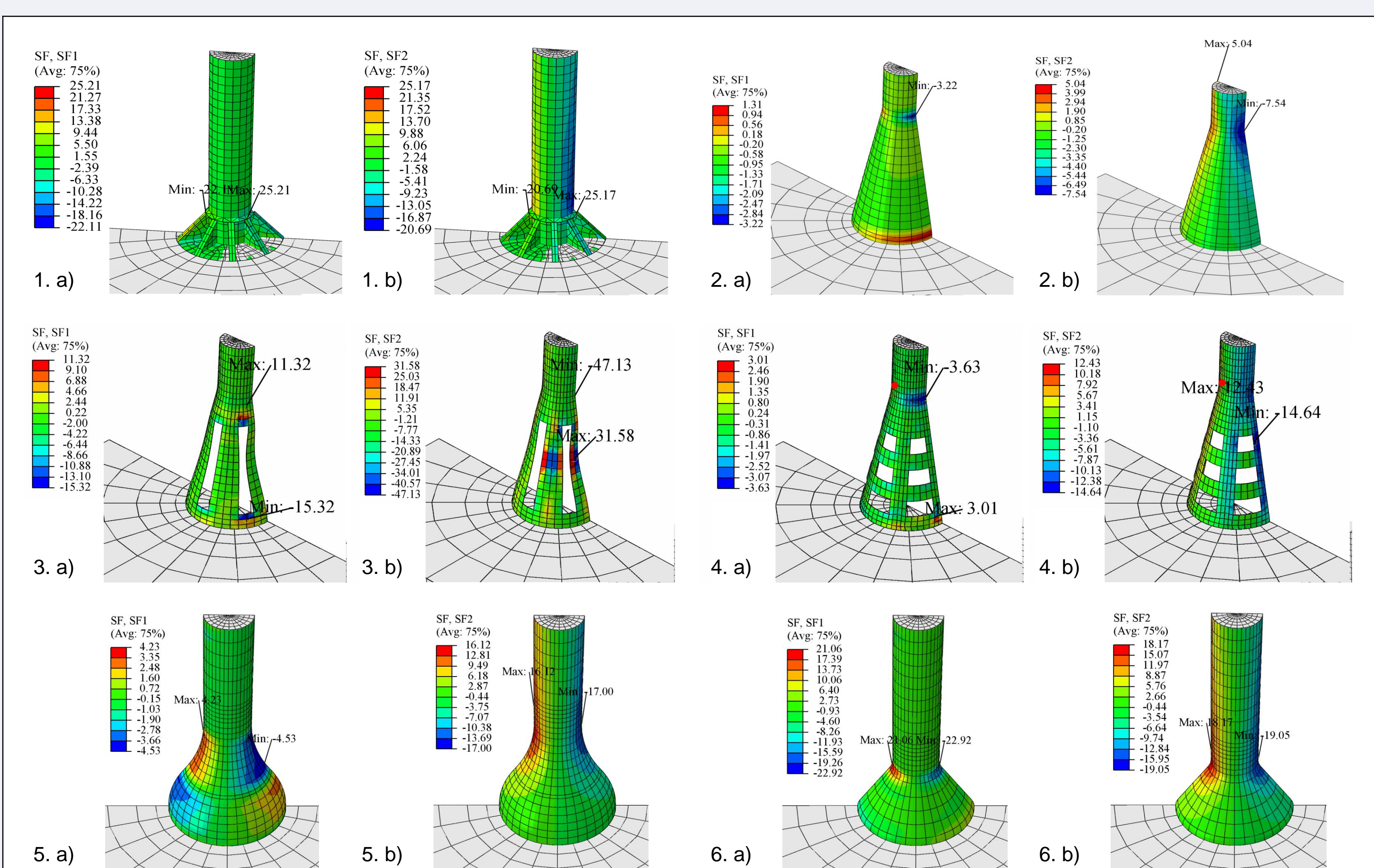


Figure 2. Section forces in the substructure (elastic calculations) : 1. Traditional TP with steel flanges; 2. Conical shape TP; 3-4. Conical shape TP with variously positioned cutaways; 5. Bottleneck shape TP; 6. Conical shape TP with a smaller height from the seabed level.

a) SF1 - Circumferential section forces, MN; b) SF2 - Meridional section forces, MN.

Structure and loads

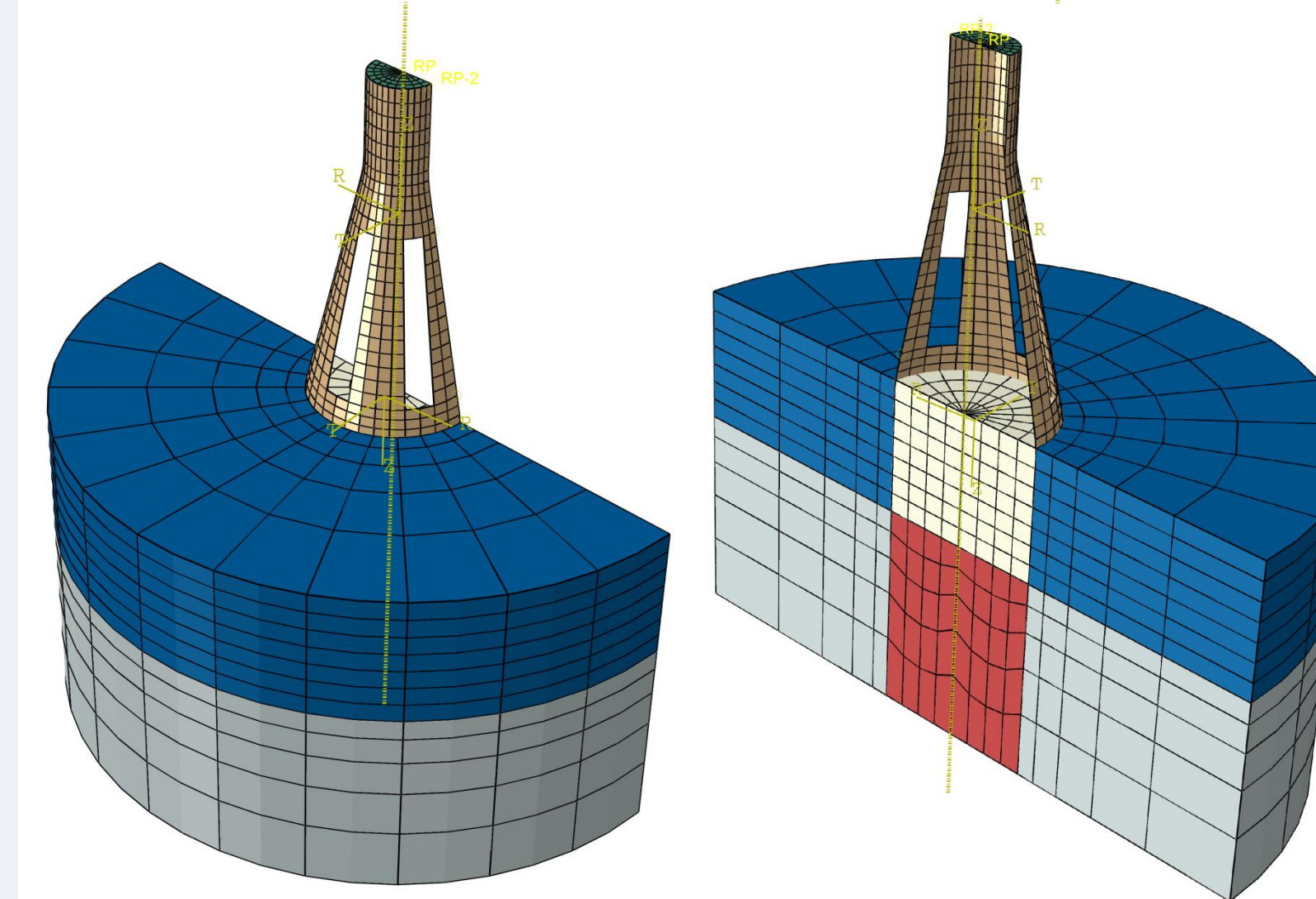


Figure 3: Finite element model and mesh applied for the transition piece, bucket foundation and surrounding soil. The parts indicate different parts of the model

- ✓ FE calculations are performed stepwise in four steps (gravity, pre-buckling analysis, wave and wind loads);
- ✓ The wave load action is simplified using a linear wave theory.

- ✓ 5 MW offshore wind turbine installed at 35 m water depth;
- ✓ rotor diameter - 126 m;
- ✓ hub height above the foundation interface - 91 m;
- ✓ diameter of the tubular support structure - 7 m at the connection to the transition piece;
- ✓ diameter of the bucket foundation - 18 m, skirt length - 14 m made of steel sheets 30 mm thick.
- ✓ support-structure–tower interface level is equivalent to the water depth (35 m);
- ✓ part of the support structure above the sea level is not included in the model.
- ✓ extreme wind load of $H = 2$ MN is applied as an equivalent quasi-static force at 91 m above the sea level.
- ✓ the Fatigue Limit State (FLS) is not considered
- ✓ weight of the wind turbine from all the structures above the water level (nacelle, blades, boat landing, tower etc.) is applied as a single vertical concentrated force of $V = 7.5$ MN on top of the modeled substructure.

Material model

Compared to traditional concrete, CRC has excellent durability, higher compressive strength (150–400 MPa) and increased ductility due to integration of large content of short, strong and stiff steel fibres (usually 2–12 % by vol.) see e.g. Bache [5]. Moreover, CRC allows utilizing 5-10 times more reinforcement than conventional concrete due to a thin (5-15 mm) cover layer and small spacing between the individual reinforcement bars compared to their diameter. This results in a very high compressive and tensile strength of the composite material.

The results of the analysis indicate that the amount of ductile steel in the form of reinforcement, carrying majority of the tensile stresses, is likely to dictate design of the TP [1,2]. Therefore, a strong CRC matrix with steel fibres should be considered as a material providing stabilization and corrosion protection for the main reinforcement. Having a matrix with high compressive strength is possible by using binders with an extremely high resistance to mechanical destruction. Based on the technical data provided by Contec ApS, compressive strengths of 180-240 MPa can be reached for the CRC matrix for 2% amount of steel fibres in the mixture and using bauxite as an aggregate. Reduction of the cost of the CRC matrix can be achieved by using cheaper natural aggregates such as gravel with a fraction of 2-5 mm and silica sand (0,1-1,5 mm fraction). However, this may significantly decrease the compressive strength of the material.

Based on the laboratory experiments carried out at Aalborg University in spring 2011, a mean strength of 115 MPa was achieved for the cylinders tested after 28 days, when using natural aggregates. Consequently, the strength of the CRC matrix decreased approximately to one half compared to the matrix with stronger aggregates.

This research addresses two concrete models, the compressive/tensile stress strain behaviour of which is shown in Fig. 4. The first model utilizes stronger aggregates, such as bauxite of 0-1 and 3-6 mm fraction, and it has a high compressive-tensile strength of 200-20 MPa. For the second one, a cheaper binder is used which decreases its strength twice (100-10 MPa correspondingly). Both models have 2 % steel fibres (0.4 × 12 mm) by volume. Making a final decision regarding the choice of the aggregates is a compromise solution, as one opts between the current price of the materials on the market and the desirable strength of the TP structure.

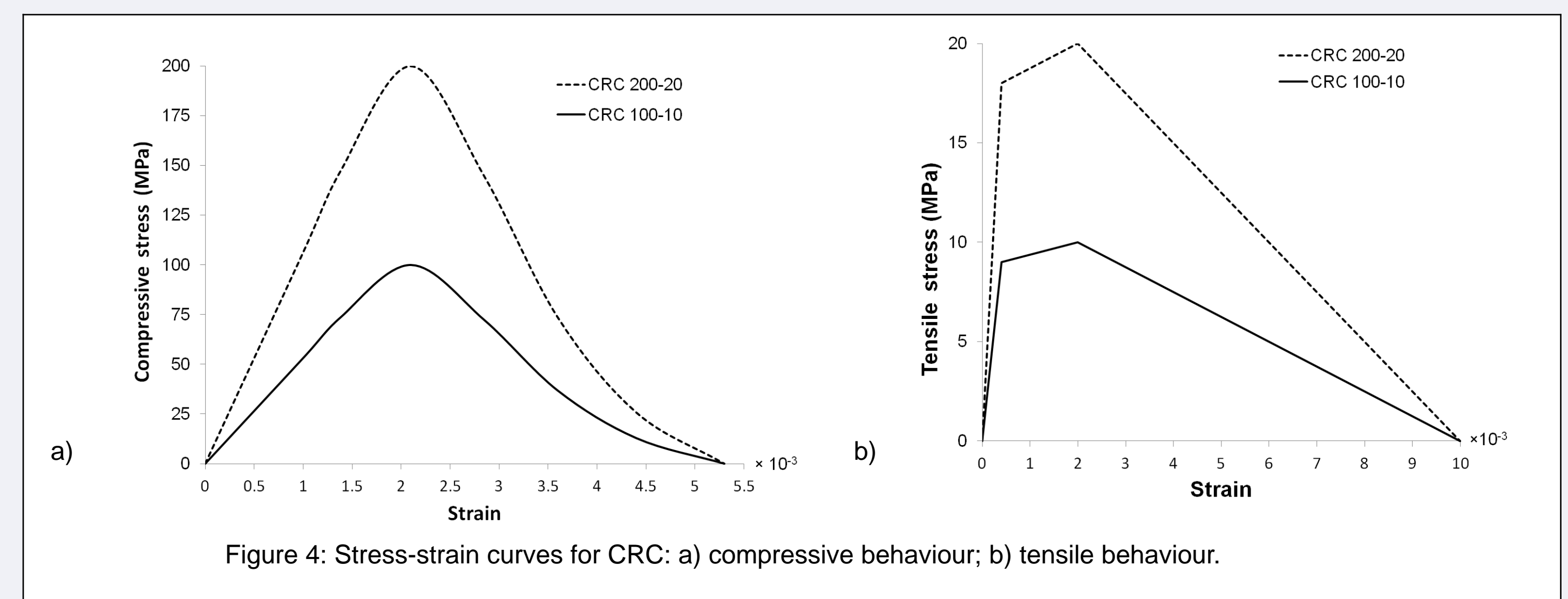


Figure 4: Stress-strain curves for CRC: a) compressive behaviour; b) tensile behaviour.

Results

The Concrete Damaged Plasticity model is applied for the non-linear analysis as the one recommended for analysis of structures subjected to cyclic excitation. The required amount of reinforcement for each model is calculated based on the maximum section force distribution. As shown in Fig. 2 the highest tensile stress concentrations can be found in the concave and convex parts where the substructure has two transition regions. The concave region of Model 6 has a particularly high tensile force in the circumferential direction SF1 (Fig. 2.6a) due to a linear transition with acute angles. A possible way of solving this problem can be for example by adding additional reinforcement and, therefore, by increasing the overall thickness of the TP in the required parts of Models 5 and 6 based on the distribution of the section forces SF1 and SF2. Three parts of the transition piece (top, middle and bottom) are proposed for further optimization. Alternatively, there is another possibility of optimization of the TP. Removing some parts of the material in the regions with the low tensile stresses and creating cutaways of various shapes (Fig.2, Models 3-4) can possibly create additional turbulence around the substructure and, potentially, minimize the scour. An additional advantage of removing some material will be reduction of the weight of the substructure.

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