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Design of Ultra High Performance Fiber Reinforced Concrete shells

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Summary. The paper treats the redesign of the float structure of the Wavestar waver energy converter. Previously it was designed as a glass fiber structure, but due to cost reduction requirements a redesign has been initiated. The new float structure will be designed as a double curved Ultra High Performance Fiber Reinforced Concrete shell. The major challenge in the design phase has been securing sufficient stiffness of the structure while keeping the weight at a minimum. The weight/stiffness issue has been investigated by means of the finite element method, to optimize the structure regarding overall deformation and buckling resistance.

Key words: UHPFRC, Ultra-thin double curved shell, Linear buckling analysis.

Main ideas

The basic idea of the Wave star wave energy concept is to generate power by the motion of the waves, letting a float structure follow the wave elevations. This displaces the floats up and down. The floats are connected to an arm structure, which are mounted on a hull structure, see figure 1. The float displaces the arm position vertically and as the arm moves vertically it drives a hydraulic cylinder which is attach to the top surface of the arm structure. Inside the hydraulic cylinder a piston follows the displacement of the arm. The piston pumps hydraulic oil into a common manifold system, collecting the oil pressure from each hydraulic pump mounted on each arm. The manifold creates an even flow of high oil pressure into a hydraulic motor that drives an electric motor directly. The concept behind the Wavestar WEC was formulated back in 2000 by Niels and Kjeld Hansen and has since proved its feasibility at open sea. Thus a redesign of the

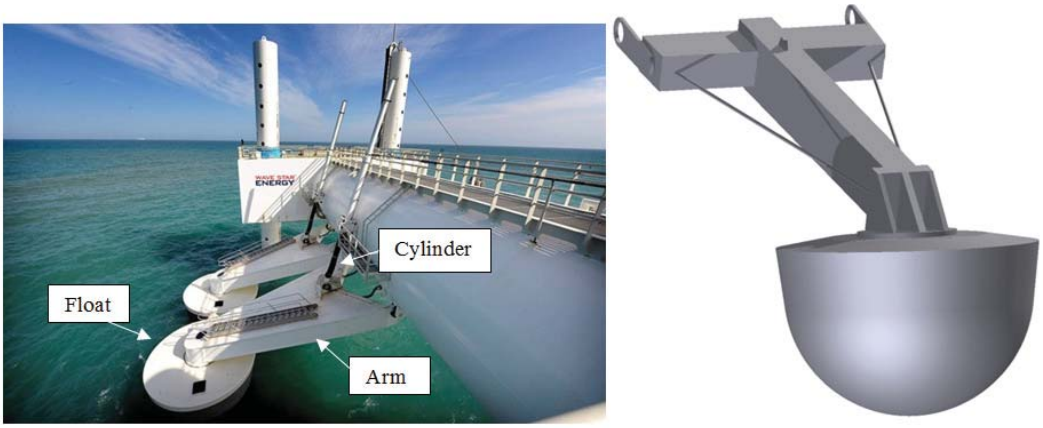

Figure 1. Right - The current WSE prototype of steel arm and glass fiber float. Left - UHPFRC design.

arm and float is initiated, see figure 1, to improve the structure and avoid the problems made evident on the first prototype. The major concern is how to lower the overall cost and increase the durability of the float structure. In the current design of the structure several problems has been recognized during manufacturing and installation[1]. The current design of the Wavestar float is a complex glass fibre structure. The structural design can be seen in figure 2 and it consists of an outer double curved 5 meter in diameter shell hemisphere which is connected to the top cap. Inside the float a complex system of thin bracing walls secures the rigidity of the structure. The complexity in manufacturing the glass fibre floats has been a major issue for the

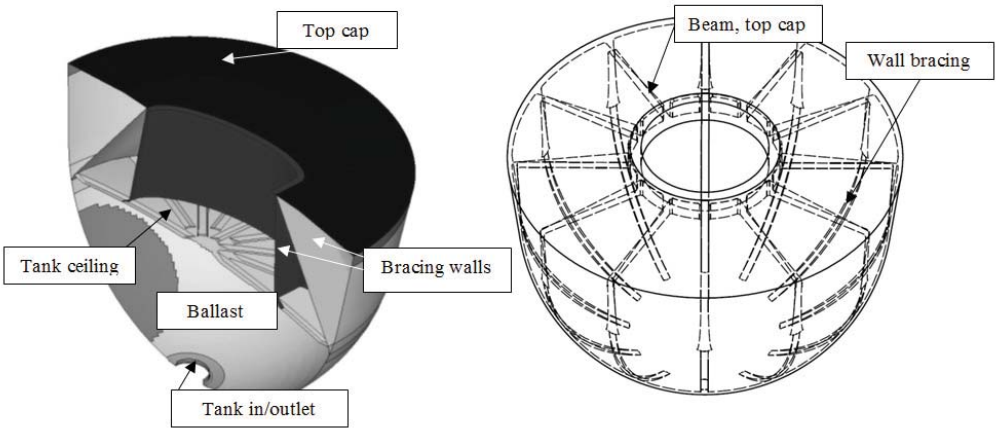

Figure 2. Left - Existing glass fiber float, Right - Ultra High Performance Fiber Reinforced concrete float.

Wave Star project, because a full scale Wave Star wave energy converter will consist of 20 floats. Thus a series production is a necessity to reduce the overall cost. This requirement has initiated a structural optimization where the current material configuration of the float has been changed from glass fibre to an Ultra High Performance Fibre Reinforced Concrete structure.

New Design Material

Choosing the UHPFRC as the main material makes it possible to accommodate the need for series production and increase the durability [2]. The float will be cast in two parts, one hemisphere and one top cap. The composition of the UHPFRC utilized in the project is a mortar with quartz sand, and steel fibre contents up to 6 vol. % straight steel fibres of 12 mm in length and 0.4 mm in diameter. Generally the UHPFRC matrix has compression capacities above 120 MPa. Increasing the compressive strength of concrete causes highly brittle failure modes. This is abbreviated by means of the fibre addition. The fibres increase the overall ductility and the ultimate tensile strength capacity, which is approximately 1/10 of the compressive strength. In figure 3 the material behavior is illustrated by means of direct tensile tests. When the first micro crack opens, the fibers inside the crack prevents further crack opening, because less energy is needed to open another micro crack. The development of multiple micro cracks causes strain hardening which is a very desirable material property in the design of civil engineering structures.

Design principles of the UHPFRC float

The basic idea is to create a UHPFRC float as seen in figure 2 where the outer geometry is adopted from the existing float. While the outer geometry is kept, the entire load carrying system inside the float is changed. In the new design no ballast tank is necessary, due to the increased weight of the structure. This means that no secondary support structure has to be

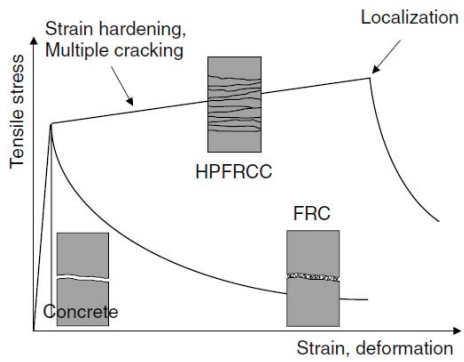

Figure 3. Strain hardening effect of the UHPFRC materials [3].

provided inside the float. Consequently a more efficient load carrying system can be achieved. In the new design, the internal forces are carried in the bracing system situated in the walls, see figure 2. The external forces at the shell or the top cap will be transferred to the cap beams. The beams are connected to the inner ring, which connects the float to the transition piece and arm. This gives an effective load carrying system, where the external forces on the shell structure is transferred directly into the inner ring as normal forces and bending moment in the top cap beams. Here the cap shell also contributes in carrying the normal forces, by membrane effect. Bending of the cap will be carried by the beams. One of the major concerns of the new design has been the weight/stiffness ratio. To investigate the design linear buckling analysis was carried out, to secure that the final design has sufficient buckling stiffness, which is of great importance in thin shell structures.

Computational issues

The structural analysis of the float is carried out in ANSYS Workbench 14.5. The first finite element model is designed to reveal which load conditions that will govern the design regarding weight and stiffness. In figure 4 the float model can be seen and it is initially analysed as a linear elastic structure discretised by ANSYS SOLID186 which is a 20 node element. The model is furthermore discretised by means of adaptive meshing, which has revealed geometrical spots with high stress gradients. This has been of special concern due to the geometrical design of both the internal bracing and the hatch in the top cap, see figure 4 right. In the design of the

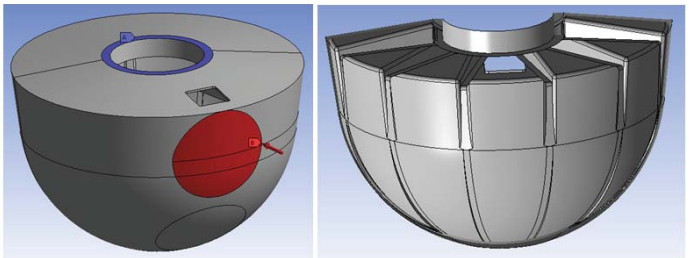

Figure 4. Left - (Blue) Boundary condition, (Red) Pressure load, Right - Internal bracing.

float, great effort has been directed to estimate the governing load conditions and how they can be applied to the model. In figure 4 the red area illustrates the pressure load, which simulates the slamming wave load on the top part of the double curved shell. Several load conditions has been investigated, but the case sketched in figure 4 cause the most critical condition regarding buckling [4]. In the structural investigation the pressure load is situated between two internal bracings. The resulting span between the two bracings in combination with the hole cut out for

the hatch make this section sensitive to a significant compressive stress field in the membrane plane. The design optimization of the internal geometry of the float, concerns primarily the number of bracings. The number of bracings has to be kept at a minimum to secure minimum weight. The final number of bracings was achieved by means of a linear elastic buckling analysis,

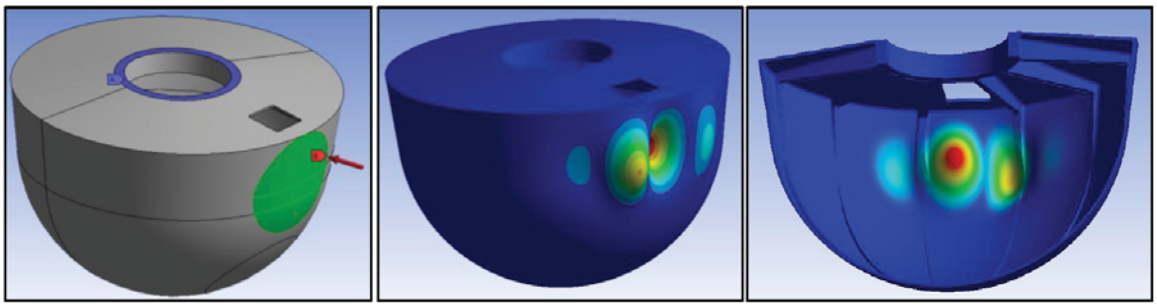

Figure 5. Left - Boundary condition, Right - Pressure load.

treated as an eigenvalue problem in ANSYS Workbench. For the most critical load case a load factor of 14 was achieved and clearly depicts the high buckling resistance of the structure. The float design has converged to an initial design with a weight of 9.7 tons, where 1.5 tons is the bracing in the double curved shell and in the top cap.

Result

The float structure has initially been investigated by means of linear elastic analysis, where the overall deformations of the UHPFRC structure have been considered. It has to be emphasized that the current float model does not take eventual rebar reinforcement into account and relies solely on the elastic properties of the UHPFRC material. The new design has a very desirable load carry system, where the loads primarily is obtained in the thin shell and translated into normal forces and flexure of the beams in the top cap. The arrangement of the internal bracing gives high rigidity against buckling, as can be seen in figure 5.

Conclusion

The redesign of Wavestar float has been investigated and a more efficient load carrying system has been achieved. The design has shown high rigidity to the environmental loadings, where especially the slamming loading is a governing condition. The number of internal bracings is optimized regarding stiffness and weight, and it can be concluded that 12 bracings are sufficient to cope with the overall deformation criterion and the buckling resistance.

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