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Design of a reinforced concrete wave energy converter in extreme wave conditions

Costanza Anerdi[1] [0000-0002-2322-9743] and Bruno Paduano[2][0000-0002-0598-9853]
and Pietro Casalone[3][0000-0001-8757-7619] and Giuliana Mattiazzo[4][0000-0002-7212-2299] and
Luca Giordano[5][0000-0003-2006-9438]

Politecnico di Torino, Turin 10128, Italy
[1]costanza.anerdi@polito.it
[2]bruno.paduano@polito.it
[3]pietro.casalone@polito.it
[4]giuliana.mattiazzo@polito.it
[5]luca.giordano@polito.it

Abstract. In the last decades, the growth of renewable energies showed to be more cost competitive, although traditional fossil fuels are still more affordable. Among the renewable energies, one of the most promising is wave energy, thanks to the high energy density stored in the waves. However, this precious resource requires further development, in particular to identify convenient and reliable production processes for conversion devices, known as Wave Energy Converters (WECs), and a view toward future changes and improvements of the existing prototypes. An interesting method to reduce the technological costs of energy and its environmental footprint could be found in the use of concrete structures, as opposed to traditional steel ones. This paper investigates the use of reinforced concrete for PeWEC, a floating wave energy converter, which converts wave energy into electrical energy thanks to its pitch motion. A preliminary design is carried out; pressure and mooring forces are evaluated and their structural effects are calculated by means of a finite element analysis. The design of reinforcements in a concrete shell is then reviewed. The general procedure is applicable to the case of a shell subjected to both bending and membrane stresses.

Keywords: SDG7, renewable energy, WEC, PeWEC, concrete, FEM, LCOE.

1 Introduction

Pollution, CO_2 emissions, and world temperature increase push the international community to intensify the application of renewable energy to satisfy human consumption: achieving the 60% of the energy from renewable sources by 2050 [1] is one of the most important goals in terms of sustainability.

Marine energy shows a great potential within renewable energies despite the fact that it is relatively new compared to the other more mature technologies. At the moment, technologies capable to extract energy from the sea are in full development. Some of the most common technologies use waves and sea current as driving forces or work through the exploitation of chemical or thermal potential of the environment. In a nutshell, the energy of the sea can be divided into the following sources: waves, tides, sea currents, temperature gradients, and salinity. In particular, the wave energy field has grown enormously [2] thanks to its power density [3] which is higher than other renewables sources. Nevertheless, these very young energy fields cannot be compared in terms of Levelised Cost Of Energy (LCOE) to traditional energy production methods [4,6]. Hence, the necessity to minimize energy cost becomes every day more important. From the analysis of the different components of a technology, it seems clear that one of the main cost drivers is the capital expenditure for the external structure, so it is interesting to consider alternative solutions and materials. Moreover, concrete is more environment sustainable than steel [5], thanks to a lower carbon embodiment. For this reason, the use of concrete for wave energy converters [7] shows some advantages: it could decrease the LCOE by reducing the capital costs while also reducing the manufacturing carbon footprint, making the renewable energy technology more affordable and economically viable, and ultimately contributing to reaching global Sustainable Development Goals (SDGs), in particular SDG-7 “Affordable and Clean Energy”. [8]. As previously mentioned, wave energy converters represent a new technology, compared to other marine structures or devices (naval, offshore structures, etc.) and dedicated standards or best practices are quite rare and incomplete. On the other side, adapting an offshore standard structure to the design process of Wave Energy Converter (WEC) could lead to oversizing, reducing the benefits in terms of costs optimization.

1.1 PeWEC

PeWEC is a floating offshore device that takes advantage from pitch motion produced by incoming waves and transforming it into electricity [11]. The hull is a reinforced concrete shell structure with a semi-cylindrical shape. The inertial properties able to guarantee the hydrodynamic performances are ensured by internal sand ballasts (located on the stern, bow, and keel). The internal pendulum is an oscillating steel mass that is supported by a trellis (attached to the hull) and connected to a PTO (Power Take-Off).

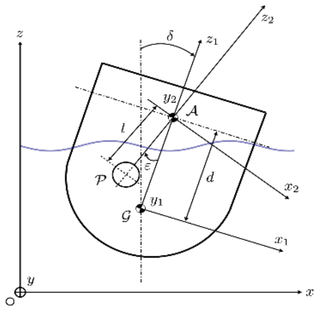

Fig. 1. PeWEC scheme.

The device is moored to the seabed through 4 catenary lines. Each line is formed by a chain with two attachments:

- a jumper that unloads the device from the vertical loads.

- a clump-weight that ensures a correct restoring force on the device.

This paper presents a preliminary analysis for the load assessment and structural design of the concrete structure; therefore, only major loads are considered (static and dynamic wave pressure field, viscosity, turbulence, mooring loads), while secondary or less impactful loads (splash, slam, spray, stress concentration) are neglected.

2 Advantages of concrete compared to steel

In pursuing the SDGs, concrete industry has an important role [10]. The World Business Council for Sustainable Development (WBCSD) identifies a series of recommendations to keep the contribution of the concrete structures sustainable [8]. According to WBSCD [9], CO2 emissions per tonne of cementitious material correlated to cement and concrete industry has been decreased by 19.2% since 1990. This represents one of the most important goals achieved in terms of sustainability, considering the extensive use of the material all over the world. In addition, raw materials constituting the cementitious materials are widely available on the territory allowing a reduction on the carbon footprint from transport unlike steel. Concrete is a traditional and reliable construction material, and is well suited to the marine environment. It has numerous advantages both from an economic and performance points of view. In fact, reinforced concrete guarantees excellent durability (intended as maintenance of the performance and functional characteristics over time), especially when compared to steel, provided that the characteristics of the marine environment are appropriately considered. This feature significantly reduces the need for systematic maintenance with a relative reduction in operating costs. At the same time, the low unit cost of concrete ensure a significant drop in the capital cost. In addition, reinforced concrete has good fatigue resistance, which is essential in a dynamically stressed structure such as PeWEC. Concrete structures are generally heavier than steel ones, reducing the need for additional ballast. In this context, structural concrete can present an efficient solution by directly using the weight of the structure. A fundamental aspect to investigate is the mix design for offshore reinforced concrete stuctures which must be carefully considered following laboratory tests and developing durability models. Typically, marine concrete has a low water / cement ratio (W / C <0.45) and involves the use of additives to facilitate its workability and protect the reinforcements from corrosion.

3 Load definition

In the growth of renewable energies, international standards [11] are starting to take into account the related technologies in the certification process. Pressure field evaluation in extreme sea states could be achieved according to standards [12,13] following semi-empirical formulations or simplified models or also developing hydrodynamic models.

For the hydrodynamic modeling of wave energy converters, there are different approaches with increasing accuracy and computational cost [15,16]: starting from linear models that perform analysis in the frequency domain, through simplified time-domain analysis, to arrive, gradually removing all the simplifying hypotheses, to the application of Navier-Stokes equations in Computational Fluid Dynamic (CFD) codes. Low and medium-fidelity models, when applied appropriately, can provide reasonable results in terms of load assessment, at a fraction of the computational expense of CFDs. However, for extreme sea states and higher-order effects not included in the potential model [14,15,17,18], linear results show significant errors compared to the CFD-based results and become an unsuitable tool for design. Considering that a statistical approach based on the governing response [19] of the device could not be used in the CFD environment for its computational time, several paths can be chosen to find short design waves [22,23]. Such methodologies can be used for CFD simulations because they do not require a long time to reach regime condition. Detailed analysis on the wave choice lies outside this paper's purpose, but further details can be find in [20,21,22,23]. For the sake of clarity, CFD simulation has been performed considering an extreme regular wave [22] starting from an environmental contour (long-term probability distribution [23]) with 100 years of returning period with data from [25] for “Mazara del Vallo” site, in Southern Italy.

4 Numerical simulation

4.1 CFD model

A full 3D model has been created to consider frontal and not-frontal waves and use mesh techniques more efficiently, and the mooring effect has been included thanks to a coupling between STAR CCM+ [27] and Moordyn© software. The inclusion of mooring forces in CFD software is essential to have a realistic hull motion. The pressure field is extracted when a maximum of one of the kinematic degrees of freedom is reached and in correspondence with the maxima of local pressures recorded on the hull;to monitor the pressure trend over time in various points of the hull, point probes have been included in the model. The total fluid forces are instead obtained by integrating pressure and shear stresses on the whole hull. After the critical load conditions have been identified, these will be projected into the structural mesh that is different from the fluid dynamic mesh, since different physical phenomena require a different discretization of the continuum. In our case, the fluid dynamic mesh is a polyhedral mesh of smaller dimensions compared to the structural mesh, which is a quadrilateral mesh (Fig. 2). When pressure forces have been transferred from the fluid dynamic mesh to the structural mesh, it is necessary to ensure that the two load systems are equivalent from an energetic point of view, i.e. that no work has been created or eliminated by transferring the forces from one mesh to another. This is guaranteed by the mapping algorithm implemented in STAR CCM+ which, through a least-squares approximation, ensures a reliable mapping between the two meshes.

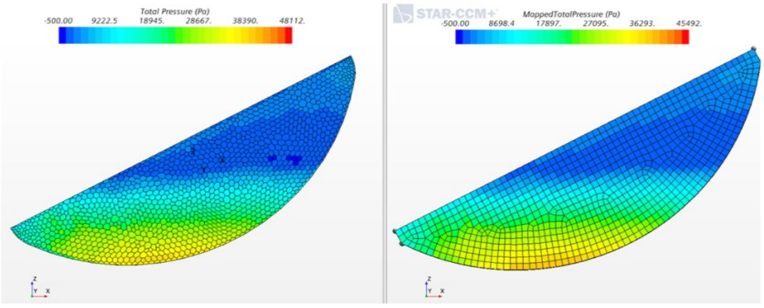

Fig. 2. Pressure mapping. On the left STAR-CCM+ mesh, on right the FEM mesh in ADINA.

Thanks to the use of MoorDyn software, the mooring loads acting on the device can be considered and included on fairleads position.

4.2 Finite Element Model

ADINA Version 9.5, a general purpose finite element code has been selected as the basic platform for this study [29]. Structural analysis has been conducted based on the results obtained through a 3D numerical model of the device performing a linear elastic analysis. The numerical model is realized through bi-dimensional elements (Shell). A shell element is defined as a surface element with in-plane stiffness and out-of-plane bending stiffness with constant thickness. The reinforced concrete slabs have been modeled with quadrilateral 300 x 300 mm shell elements. The software can provide response information at the nodes and element stresses at the integration points within the element. Boundary conditions that represent structural supports specify values of displacement and rotation variables at appropriate nodes. The evaluation of the boundary conditions for PeWEC device, able to ensure a stable equilibrium of the structure, have been a challenging process that have led to the development of a two-step procedure:

- ***MODEL 1***: the node corresponding with the center of mass of the structure has been fully restrained in order to obtain the resultant forces and moments of the water pressure and mooring force. The center of mass has been temporarily connected with the structure, to transfer actions, by rigid frames. The material corresponding to those elements has been set to a null mass material, in order to not increase the mass of the hull.

- ***MODEL 2***: definition and application of an equivalent acceleration system (linear accelerations + angular accelerations) (Eq. 1, 2) that, togheter with water pressure and mooring forces, equilibrates the structure. The fixed boundary has been set to a generic node, and the rigid connections to the centroid have been removed.

$$\begin{Bmatrix} A_X \\ A_Y \\ A_Z \end{Bmatrix} = \begin{Bmatrix} R_X \\ R_Y \\ R_Z \end{Bmatrix} \cdot \{mass\}^{-1} \qquad \text{(Eq. 1)}$$

$$\begin{Bmatrix} \alpha_X \\ \alpha_Y \\ \alpha_Z \end{Bmatrix} = \begin{Bmatrix} M_X \\ M_Y \\ M_Z \end{Bmatrix} \cdot \begin{bmatrix} I_{XX} & -I_{XY} & -I_{XZ} \\ -I_{XY} & I_{YY} & -I_{YZ} \\ -I_{XY} & -I_{XY} & I_{ZZ} \end{bmatrix}^{-1} \qquad \text{(Eq. 2)}$$

Ax, Ay, Az are the linear accelerations along x, y and z; Rx, Ry, Rz are the constraint reactions on the center of mass. Ax, Ay, Az . Similarly, $\alpha x, \alpha y, \alpha z$ are the angular accelerations around the three axis divided by the inertial matrix [I]. This procedure is necessary to switch from a CFD dynamic model and the corresponding loads to a structural static model, avoiding unlikely reactions on arbitrary nodes. Once the internal actions are defined through the Finite Element Analysis (FEA) for each element, the design of reinforcement for concrete shells is based on the provisions in [28].Generally, slab elements are subjected to eight stress resultants: three membrane force components (n_x, n_y and n_{xy}), two flexural moment components (m_x and m_y), the twisting moment (m_{xy}), and the two transverse shear force components (v_x and v_y), as represented in Fig. 5. For the purpose of design, the slab is conceived as comprising two outer layers centred on the mid-planes of the outer reinforcement layers and an intermediate core. This is sometimes referred to as a "sandwich model". The covers of the sandwich model (i.e., the outer layers) are assumed to carry moments and membrane forces while internal layer carries the out-of-plane shear components and should be designed in accordance with the beam approach by using the principal shear v_0 (Eq. 3) [30].

$$v_0 = \sqrt{{v_x}^2 + {v_y}^2} \qquad \text{(Eq. 3)}$$

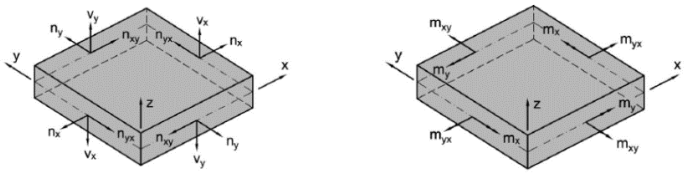

Fig. 3. Multiaxial state on shell elements

The design forces are calculated and are converted into reinforcement intensities (i.e., rebar area per unit width) using appropriate steel stress from the material properties assigned to the shell element. Finally, the concrete compressive forces are obtained and used to compute the compressive stresses to top and bottom layers. The amount of reinforcements in top, bottom and intermediate layers are calculatedelement by element. Then, an envelope representing the maximum amount of reinforcement for each extreme condition considered is used to assess the layout of steel reinforcements that have to be placed.

Results and conclusions

This study was undertaken to assess the application of a well known technology, as reinforced concrete to a novel field. Given the lack of standards and the innovative nature of the project, the hull design has undergone a process of direct design through a Finite Element analysis and a previous definition of the loads by means of a CFD analysis. The results obtained, in terms of quantity of concrete and steel for the reinforcement, are typical for traditional reinforced concrete shell structures. Given the low unit cost of concrete and referring to a price-list for public works [31], a significant reduction of the capital cost is resumed.

$$\frac{Concrete\ hull\ cost\ *}{Steel\ hull\ cost} = 0.42$$

The cost reduction has been estimated considering also [32]. It is important to note that all the formworks considered are reusable and represent a cost that is amortised over time considering a large scale production. This suggest that the use of reinforced concrete for PeWEC hull could be a promising alternative, giving to a realistic reduction of LCoE.

*** average cost over 50 hulls, considering an initial expense for the formwork.**

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