DEVELOPMENT OF ULTRA HIGH PERFORMANCE FIBER- REINFORCED CONCRETE BARGE FOR WIND TURBINE

By

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Floating offshore wind turbines (FOWT) are considered the economically viable solution for installing wind turbines in waters greater than 60m deep. The barge is one of the floating structures developed for the FOWT. It has the simplest design, fabrication and installation in comparison to other FOWT like the semi-submersibles, Tension Leg Platforms and Spar buoys. In order to reduce the cost of FOWT, concrete has been utilized to reduce the capital and operational expenditure of steel. However, there are limiting factors to the construction of concrete FOWT, which form the basis of this project. Concrete has low tensile strength and susceptible to chemical attack and freezing temperatures. As a result, a larger wall section is required to combat the environmental conditions of the sea which results in higher energy consumption, large volume of construction materials, a weightier structure and more difficulty in massive production.

Hence in this study, ultra high performance fiber reinforced concrete (UHPFRC) is used to develop a barge FOWT to support a 5MW wind turbine for a site at the Atlantic and Northern North Sea region offshore Scotland. According to extensive review of the literature conducted, UHPFRC material has shown better mechanical properties and more resistance to marine conditions in comparison to conventional reinforced cement concrete (RCC). Also, due to high strength of UHPFRC material, the thickness of structural element can be reduced which leads to less material consumption and easy manufacturing. Therefore, UHPFRC barge is developed and investigated in this study to support a FOWT.

The considered Barge is square shaped (40m x 40m) with a moon pool at the center (10m x 10m). Analysis had been conducted using a finite element method to evaluate hydrodynamic motions and structural strength of the UHPFRC barge under different loading conditions and the results were compared to a conventional reinforced cement concrete barge. Also, experimental tests were performed to measure the stability of the

UHPFRC barge small sized prototype subjected to water waves in the wave flume and compared with RCC barge small sized prototype.

The hydrodynamic analysis results from the finite element analysis showed less pitch motions in the UHPFRC barge than the RCC barge in 7 out of the 12 design load cases (DLCs) considered. The roll motions were less than 5^0 in both barges with insignificant difference between them and the UHPFRC barge experienced 10% to 20% less heave motions than the RCC barge in all 12 DLCs. In the structural analysis, the UHPFRC barge experienced a maximum deformation of 14mm under the applied loads. From the experimental tests conducted on the UHPFRC and RCC barge small sized prototypes, the RCC barge had lower heel compared to the UHPFRC barge with a percentage difference of 10% - 70%. However, the RCC barge experienced severe green water load which could cause it to capsize. In overall, the UHPFRC barge proved to be more effective in achieving better hydrodynamic motions and stability for the barge FOWT in comparison to the RCC barge and should be considered as alternative to the RCC material.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PEMBANGUNAN KONKRIT BERTETULANG GENTIAN BERPRESTASI ULTRA TINGGI UNTUK TURBIN ANGIN

Oleh

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Turbin angin luar pesisir terapung (FOWT) dianggap sebagai penyelesaian yang berdaya maju dari segi ekonomi untuk situasi memasang turbin angin di perairan yang lebih dalam daripada 60 meter. Tongkang adalah salah satu struktur terapung yang dibangunkan untuk FOWT. Ia mempunyai reka bentuk, fabrikasi dan pemasangan yang paling mudah berbanding dengan FOWT yang lain seperti FOWT jenis separa tenggelam, jenis Pelantar Kaki Ketegangan dan jenis Spar buoys. Bagi mengurangkan kos FOWT, konkrit telah digunakan untuk mengurangkan modal dan perbelanjaan keluli. Walau bagaimanapun, terdapat beberapa faktor yang mengehadkan pembinaan FOWT konkrit. Faktor-faktor tersebut adalah asas projek ini. Konkrit mempunyai kekuatan tegangan yang rendah dan terdedah kepada ancaman serangan kimia dan suhu beku. Akibatnya, dinding yang lebih besar diperlukan untuk menghadapi persekitaran laut. Hal ini meningkatkan penggunaan tenaga, menambahkan jumlah bahan binaan, menghasilkan struktur yang lebih berat dan menyukarkan pengeluaran secara besar-besaran.

Oleh itu, dalam kajian ini, konkrit bertetulang gentian berprestasi ultra tinggi (UHPFRC) digunakan untuk menghasilkan baj FOWT untuk menyokong satu turbin angin 5MW yang berada di rantau Atlantik dan utara kepada Laut Utara luar pesisir Scotland. Menurut tinjauan literatur yang dijalankans secara meluas, bahan UHPFRC telah menunjukkan sifat mekanikal yang lebih baik dan lebih tahan terhadap keadaan laut berbanding dengan konkrit bertetulang simen konvensional (RCC). Selain itu, disebabkan kekuatan bahan UHPFRC yang tinggi, ketebalan elemen struktur boleh dikurangkan. Hal ini akan mengurangkan penggunaan bahan dan memudahkan pembuatan bahan. Oleh itu, tongkang UHPFRC dibangunkan dan disiasat dalam kajian ini untuk menyokong FOWT.

Baj yang dipertimbangkan adalah berbentuk empat segi (40m x 40m) dengan satu kolam bulan di tengah (10m x 10m). Analisis telah dijalankan menggunakan kaedah

unsur terhingga untuk menilai gerakan hidrodinamik dan kekuatan struktur baj UHPFRC di bawah keadaan pemuatan yang berbeza dan datanya dibandingkan dengan baj RCC. Selain daripada itu, ujian eksperimen telah dilakukan untuk mengukur kestabilan prototaip baj UHPFRC bersaiz kecil yang tertakluk kepada gelombang air dalam flum gelombang dan dibandingkan dengan prototaip bersaiz kecil tongkang RCC.

Hasil analisis hidrodinamik daripada analisis unsur terhingga menunjukkan kurang prestasi pic dalam baj UHPFRC berbanding dengan baj RCC dalam 7 daripada 12 kes beban reka bentuk (DLC) yang dipertimbangkan. Pergerakan guling adalah kurang daripada 5º dalam kedua-dua baj dengan perbezaan yang tidak ketara antara mereka dan baj UHPFRC mengalami 10% hingga 20% kurang gerakan limbung berbanding baj RCC dalam kesemua 12 DLC. Dalam analisis struktur, baj UHPFRC mengalami ubah bentuk maksimum 14mm di bawah beban yang dikenakan. Daripada ujian eksperimen yang dijalankan ke atas UHPFRC dan atas prototaip baj RCC bersaiz kecil, baj RCC mempunyai tumit yang lebih rendah berbanding baj UHPFRC dengan perbezaan peratusan 10% - 70%. Bagaimanapun, baj RCC mengalami beban "green water load" yang teruk yang boleh menyebabkannya terbalik. Secara keseluruhan, baj UHPFRC terbukti lebih berkesan untul mencapai pergerakan hidrodinamik dan mempunyai kestabilan yang lebih tinggi untuk baj FOWT berbanding dengan baj RCC dan boleh dianggap sebagai satu alternatif kepada bahan RCC.

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LIST OF ABBREVIATIONS

deg	degrees
DLC	Design loading conditions
FEM	Finite element method
kg	kilogram
m	meters
N	Newtons
No.	Number
RCC	Reinforced cement concrete
UHPFRC	Ultra high performance fiber reinforced concrete
UPM	Universiti Putra Malaysia

CHAPTER 1

INTRODUCTION

1.1 Introduction

Floating Offshore Wind Turbines (FOWT) are wind turbines which are mounted on floating structures that allows the turbine to generate electricity in water depths not feasible for fixed- foundation turbines. They are considered the economically viable solution for installing wind turbine in waters greater than 60m deep. The average water depth and distance from shore for installing offshore wind turbines have been on the increase over time. The increase in distance from the shore correspond to higher mean speed and increased capacity factors ((Rodrigues et al., 2015).

Several floating structures have been developed to support the FOWT. These include semi-submersibles, spar buoys, Tension Leg Platforms (TLP), tri- floaters, barges and hybrid platforms (combination of two or more of the floating structure concepts mentioned). The Barge is one of the floating structures developed for the FOWT. It has the simplest design, fabrication and installation in comparison to other floating platforms like the semi-submersibles, Tension Leg Platforms and Spar buoys (Jonkman and Buhl, 2007). It is generally square shaped with a square moon pool at the center which has several functions including, extracting wave energy from the sea, providing damping for the barge and reducing its heave motions. It is ballasted in order to achieve a reasonable draft and to avoid wave slamming (Vijay et al., 2016). Stability of the barge is achieved through distributed buoyancy and the weighted water plane area for righting moment.

Figure 1.1 : FLOATGEN damping pool®
(Source : Ideol, 2016)

1.2 Background and Earlier Work

Offshore wind turbines (fixed-bottom turbines in shallow waters and FOWT) are rapidly growing in Europe with more than 8GW already installed (Nuno and Margarida, 2019). The UK offshore wind is the front runner with over 20.8TWh installed in 2017 which supplied 6.2% of the UK's total estimated electricity generation (The Crown Estate, 2017). Yibo et al. (2021) highlighted that this development has reduced the UK's CO_2 generation to 8.6 million tonnes. The European Wind Energy Association suggested that 150GW capacity be achieved by 2030 to meet 14% of the EU's final electricity consumption (EWEA, 2018). In Asia, China and Japan have already installed over 1.5GW and 50MW respectively, while Korea and Taiwan have capacity targets for the coming years (Nuno and Margarida 2019).

The average water depth and distance from shore for installing offshore wind turbines have been on the increase over time. The farther the distance from the shore, the higher the mean speeds and capacity factors (Rodrigues et al., 2015). FOWT makes it possible to install offshore wind turbines at long distances from shore to harvest the vast wind resources in those regions. However, increasing the distance from shore increases the foundation and installation costs as well as the operational and maintenance costs. The strong wind and waves experienced by FOWT makes them more fragile and increases their rate of failure as well as the severity of failure consequences (He et al., 2021). Preliminary analysis by Beiter et al. (2016) suggested that FOWT have the potential of achieving lower cost of energy (LCOE) than fixed-bottom turbines. However, Hundleby et al. (2017) performed a detailed modelling which showed that long term cost reduction is most likely to come from a combination of complimentary innovations rather than a single breakthrough innovation.

A concrete floating structure has been proposed by researchers as one of means of reducing the cost of FOWT. Doman (2014) designed a concrete tri floater semisubmersible and compared the cost to a steel Hywind Float. The comparison showed a cost reduction of about $2 million by using concrete. There is also a cost saving on the concrete structure over its service life due to reduction in maintenance requirements. However, there are limiting factors to the construction of concrete FOWT floating structures, which form the basis of this project. Concrete has low tensile strength and susceptible to chemical attack and freezing temperatures. Also, a larger wall section is often required to combat the environmental conditions of the sea which then results in higher energy consumption, large volume of construction materials and a weightier structure (Butterfield et al., 2005; Denis et al., 2017).

Ultra high performance fiber reinforced concrete (UHPFRC) is a new and commercially available concrete unique for its high strength, ductile behaviour and high stability (Richard & Cheyrezy, 1995). Its unique properties include faster concrete production, less curing waiting time, reduced construction costs, early completion of projects, less maintenance and increased service life. Its application has mainly been in constructing bridges, building components such as sunshades, cladding and roof components and repair/rehabilitation of existing concrete structures (Voo, 2017).

Different studies have been performed to investigate the characteristics of UHPFRC in marine environments. Abbas et al., (2015); Elfmarkova et al., (2015); Pyo et al., (2017) investigated the chloride diffusion of UHPFRC matrix and compared it with conventional normal strength concrete (NSC). The results showed a far less diffusion of (1 - 10) x 10^{-14} m^2/s in the UHPFRC and (1 - 10) x 10^{-12} m^2/s in the NSC. Abbas et al. (2015) experimented on a 10cm thick UHPFRC concrete member immersed in 10% NaCl solution for six months and then evaluated for compressive and flexural behavior. Although the surface fibers corroded due to the presence of the chloride ion, the mechanical properties of the concrete remained intact. In the case of a collision, UHPFRC has displayed superior qualities in absorbing impact energy. Fan et al. (2018) studied a novel steel- UHPFRC composite fender for a bridge protection in vessel collisions by testing it in a drop hammer impact system. The proposed fender demonstrated capability of effectively decreasing impact forces and responses on the bridge and impact vessel. Fan et al. (2020) investigated the dynamic response of bridge piers strengthened with UHPFRC, under barge impact. Three different configurations were considered and the columns with two ends strengthened with UHPFRC jackets were found to be superior in terms of costs-benefit ratio.

1.3 Problem Statement

A disincentive for the adoption of a concrete FOWT barge is its size and weight, which requires sufficient dry dock facilities and giant cranes for its construction. Ioannou et al., (2018) highlighted that, although concrete-based floating structures appear to be cheaper than the steel based structures, they tend to be larger and there are problems with their massive production.

A second disincentive for a concrete FOWT barge is its permeability and surface cracks from various sources of loading which promotes chlorine diffusion. Chlorine induced diffusion has been found to be the primary cause of premature deterioration of reinforced concrete exposed to marine environment (Nabavi et al., 2012). Post-tensioning has been used to increase concrete structures' ability to resist cracking (Doman, 2014), which also reduces the size of the structure. However, the structure is still large and requires greater reduction in size and weight to make massive production more effective.

According to extensive review of the literature conducted, UHPFRC material has shown better mechanical properties and more resistance to marine conditions in comparison to conventional reinforced concrete. Also, due to high strength of UHPFRC material, the thickness of structural element can be reduced which leads to less material consumption and easy manufacturing. Therefore, UHPFRC barge is designed and investigated in this study to overcome the challenges experienced by concrete FOWT barge.

1.4 Objectives of Study

The following are the objectives of this study:

1. To develop an appropriate design for an UHPFRC barge to support an NREL 5MW reference wind turbine. The design is deemed appropriate based on compliance to set guidance/regulations for the FOWT.

2. To assess the hydrostatic, hydrodynamic and structural behaviour of the UHPFRC barge using a FEM software.

3. To evaluate the performance of the proposed UHPFRC barge and an RCC barge by constructing scaled models and conducting experimental test to measure their stability at different sea states in a wave flume.

1.5 Scope and Limitation of Work

This project work focuses on the design and evaluation of the hydrostatic, hydrodynamic and structural behaviour of a UHPFRC barge in wind and wave conditions. The effect of the vibrations from the wind turbine on the barge structure during operation was not evaluated due to limited simulation tools available. Also, the analysis of the mooring lines for sea keeping was not covered in this project.

1.6 Layout of the Project/ Thesis

Chapter 1 introduces the research topic and a background study on the topic is outlined. The problem statement and objectives for the study are also presented therein. Chapter 2 presents the review of literature related to floating offshore wind turbines, the barge and ultra high performance fiber reinforced concrete. The procedure employed to design the UHPFRC barge is outlined in chapter 3. The analysis procedure used are also clearly shown. The materials, equipment and procedure used in carrying out the experimental tests are presented. Chapter 4 contains the results obtained from the FEM analysis and experimental tests. Discussions and comparisons of the obtained results are presented with the aid of graphs, figures and tables. In chapter 5, a summary of the project is presented, conclusions are drawn based on the objectives of the study and recommendations are made for future study.

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