Ocean Engineering 160 (2018) 264–275

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

New shape function solutions for fracture mechanics analysis of offshore wind turbine monopile foundations

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ARTICLE INFO

Keywords:
Stress intensity factor
Shape function
Fatigue crack growth
Inspection
Monopile
Offshore wind turbine

ABSTRACT

Offshore wind turbines are considered one of the most promising solutions to provide sustainable energy. The dominant majority of all installed offshore wind turbines are fixed to the seabed using monopile foundations. To predict the lifetime of these structures, reliable values for shape function and stress intensity factor are needed. In this study, a new equation is developed through finite element simulations which have been performed for a wide range of monopile geometries with different dimensions, crack lengths and depths, to evaluate shape function and stress intensity factor solutions for monopiles. The new solutions have been verified through comparison with the existing solutions provided by Newman & Raju for small hollow cylinders. The empirical shape function solutions developed in this study are employed in a case study and the results have been compared with the existing shape function solutions. It is found that the old solutions provide inaccurate estimations of fatigue crack growth in monopiles and they underestimate or overestimate the fatigue life depending on the shape function solution employed in the structural integrity assessment. The use of the new solution will result in more accurate monopile designs as well as life predictions of existing monopile structures.

1. Introduction

The offshore wind industry has grown exponentially in recent years due to the global energy demand and targets set by the European Union to fulfil at least 20% of its total energy needs with renewables by 2020 (National Renewable Energy Action Plan for the United Kingdom, 2009, Electricity Generation Costs, 2013). With large capital costs through the manufacture and installation of offshore wind farms, the levelised cost of energy (LCoE) is high, making it difficult for wind energy to be price-competitive in the energy market. The UK's Department for Business, Energy & Industrial Strategy (BEIS) (formerly known as Department of Energy and Climate Change (DECC)) have set a challenge for offshore wind to achieve a levelised cost of electricity, which is a measure of the overall competitiveness of different generating technologies, of £100/MWh by 2020 (Electricity Generation Costs, 2013). Surprising LCoE reductions in 2016, to as low as €49.9/MWh for the Kriegers Flak and other similar projects in Europe have resulted in exceeding the initial targets and making offshore wind energy prices competitive with onshore wind and alternative sources of energy (The Global Wind Energy Council's (GWEC), 2016). Therefore, due to reduction in prices as well as availability of more spaces for installation, better wind flows, and less noise it is expected that the development of offshore wind farms will exponentially increase in the coming years. In 2016, 12.5 GW of new wind energy capacity was installed in the European Union, of which 1.6 GW were installed offshore, increasing the total installed offshore wind energy capacity to 12.6 GW (Europe, 2016). Currently wind energy accounts for 17% of Europe's total installed power generation capacity, overtaking coal as the largest form of power generation (Europe, 2016).

With the growing interest in expansion of offshore wind energy in Europe and worldwide, an important area that needs to be considered is the structural design and integrity enhancement of offshore wind turbines, which can contribute to further reduction of the levelised cost of offshore wind energy. Knowing that fatigue and corrosion-fatigue are the dominant failure mechanisms in offshore structures due to the constant exertion of cyclic loading from wind and wave, the uncertainties involved in fracture mechanics analysis of fatigue crack growth, particularly for foundations which are at a higher risk of failure, must be minimised. Support structures make up around 35% of the total cost of an offshore wind project (Esteban et al., 2015) and monopile foundations in particular have been used for around 75% of offshore wind turbine installations, making them an important area for research and development. Design standards for offshore monopiles, which are a suitable

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https://doi.org/10.1016/j.oceaneng.2018.04.073
Received 16 January 2018; Received in revised form 17 April 2018; Accepted 18 April 2018

Nomenclature

a	Crack depth
b	Half width (in a plate)
c	Half crack length (in a semi-elliptical crack)
D	Pipe or monopile Diameter
E	Elastic Young's modulus
F	Normalised stress intensity factor in Newman & Raju solution
h	Pipe height
I_z	Second moment of area along the z axis
K	Stress intensity factor
M_Z	Bending moment along the z axis
Q	Non-dimensional shape factor
R_{in}	Inner radius
R_{out}	Outer radius
t	Thickness
y	Distance from the neutral axis
Y	Shape function
σ	Applied stress
σ_b	Bending stress
σ_t	Tensile stress
σ_{max}	Maximum bending stress
ν	Poisson's ratio
Φ	Circular crack tip angle
BM	Based Metal
FE	Finite Element
FP	Finite Plate
HAZ	Heat Affected Zone
HC	Hollow Cylinder
LEFM	Linear Elastic Fracture Mechanics
MP	MonoPile
N&R	Newman & Raju Shape Function Solution
OPEX	OPerational EXpenditure
SIF	Stress Intensity Factor

foundation type for water depth of up to 40 m (Li et al., 2013), have been developed from the oil and gas industry as this is the only sector with experience of similar offshore structures. The structures used in the oil and gas industry however are much smaller than wind turbine monopile foundations, which are generally 3–7 m in diameter. These standards have been derived from the testing of piles of up to 1.22 m in diameter (Doherty and Gavin, 2011), the results of which have been used to scale up the designs, bringing with them uncertainties in the structural behaviour as well as creating the possibility of over-engineering and different failure modes. The thickness and diameter of monopiles depend on various parameters such as the water depth, soil composition and characteristics, size of the wind turbine and environmental conditions. The diameter and thickness of some of the current monopiles in various offshore wind farms across Europe have been reported by Laszlo Arany et al. (2017) and this data is summarised in Fig. 1.

Offshore wind turbine monopiles are fabricated by rolling, and then, welding relatively thick structural steel plates in a longitudinal direction to produce "cans" and subsequently welding these cans in a circumferential direction. Characterisation of the surface flaws, which often occur in the form of semi-elliptical shaped cracks initiating at the outer surface of the circumferential weld region and propagating in through-thickness direction, need to be carefully considered in the design and inspection of offshore wind turbine monopile foundations. Accurate characterisation of fatigue crack initiation and growth in monopiles can significantly improve the fracture mechanics-based inspection of the current assets, reduce maintenance efforts, reduce the Operational expenditure (OPEX) and optimise the design of future generation of monopiles. A key parameter which is used in fracture mechanics analysis of monopiles is the shape function which is used to calculate the stress intensity factor (SIF) and subsequently characterise the fatigue crack growth behaviour of the material and build fracture-mechanics based inspection plans accordingly. The shape function and stress intensity factor solutions for various elliptical and semi-elliptical cracks in infinite, finite and semi-infinite bodies have been investigated by many researchers. For example Irwin provided solutions for an elliptical crack in an infinite body in (Irwin, 1962) using the solution of Sneddon and Green (1946) and Wigglesworth (1957). Smith et al. (Smith et al., 1967; Smith and Alavi, 1971), Shah and Kobayashi (1973) made similar attempts to obtain stress intensity factor solutions for circular, semi-circular and elliptical cracks in a semi-infinite body. Moreover, Miyamoto and Miyoshi (1971) and Tan and Fenner (1980) investigated stress intensity factor solutions for a semi-elliptical crack in a finite plate using the finite element method and in pressurised cylinders using boundary integral equation method, respectively. Although various researchers have experimentally investigated the fatigue crack growth behaviour in hollow cylindrical structures with circumferential semi-elliptical cracks at the outer surface (Shahani et al., 2010; Brighenti and Carpinteri, 2013; Paffumi et al., 2015; Sahu et al., 2017), the only relevant fracture mechanics shape function and SIF solutions available to analyse experimental data for such geometry are those proposed by J.C. Newman & I.S. Raju (N&R) in 1986 (Raju and Newman, 1986). However, the range of normalised dimensions given in (Raju and Newman, 1986) is way below those in monopiles (see Fig. 1). The current practice to estimate SIFs in monopiles is to employ the solutions available for finite plate under tension in another publication by N&R (Newman and Raju, 1979), but the accuracy of this simplified assumption to use finite plate solutions for cylindrical monopiles has been never examined. Hence, the aim of this study is to investigate and propose new accurate shape function and stress intensity factor solutions for offshore wind turbine monopile geometries through finite element (FE) modelling, by considering their actual dimensions. The procedure to develop the new solutions are described in this paper and the results are compared with the old solutions proposed by N&R.

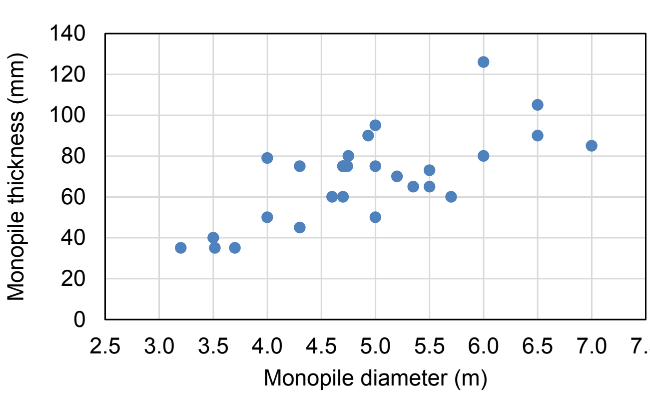

Fig. 1. The thickness and diameter variation in some of the existing offshore wind turbine monopiles.

2. Existing stress intensity factor solutions for semi-elliptical cracked geometries

The stress intensity factor, K, is the linear elastic fracture mechanics (LEFM) parameter used to describe the stress distribution ahead of the crack tip when the deformation at the crack tip region is dominantly elastic. In 1961, Paris showed that this fracture mechanics parameter can