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Residual stress measurements in offshore wind monopile weldments using neutron diffraction technique and contour method

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ABSTRACT

Reliable assessment of the fatigue life of offshore wind monopiles operating in harsh offshore environments relies on quantifying the level of residual stresses locked-in at circumferential weld regions. This study presents, for the first time, residual stress characterisation, using the contour method, on a large structural welded mock-up, typical of the weldment used in offshore wind monopiles. The contour method and neutron diffraction measurements were also conducted on a compact tension specimen extracted from the large mock-up. The extracted compact tension sample, typically used for fracture and fatigue crack growth tests, showed notably significant remnant residual stresses that could impact fracture and fatigue test results. In addition the measured 2D map of transverse residual stresses, acting normal to the crack plane, playing a key role in fatigue crack opening/closure, exhibited variations through the thickness of the compact tension sample. The key conclusion was that the residual stresses in small laboratory samples extracted from large scale weldments should be carefully characterised and taken into account in structural integrity tests. Besides, the measurement results on the welded mock-up showed that the level of damaging tensile residual stress in large-scale mock-ups and hence real size structural welded monopiles is considerably larger than residual stresses in extracted laboratory samples; hence will have more significant influence on structural integrity of offshore wind assets.

1. Introduction

Renewable energy resources play a key role to mitigate greenhouse gas emissions, global temperature rises and provide energy security. Among renewable energy resources, wind energy is increasingly becoming one of the preferred sources of energy, particularly in Europe, with the potential for larger scale applications expanding rapidly. One of the important challenges in the offshore wind industry is the assessment of structural integrity of wind turbine foundations, which are becoming one of the largest engineering structures currently used in the energy sector.

Among the different types of existing offshore wind turbine support structures, monopile is the most popular foundation type which is widely used in shallow water offshore wind farms. Typical dimensions for the offshore wind turbine monopile range from 50 m to 70 m in length, 3 m to 10 m in diameter and 40 mm to 150 mm in wall thickness [1–3]. The primary function of a monopile is to support the offshore wind turbine structure. Monopiles are installed by driving them into the seabed; hence the structure should withstand the hammering loads during installation which vary from site to site depending on the soil conditions. During operation in harsh offshore environment, monopiles are subjected to wind, wave and sea current cyclic loads; hence they have to be designed for a certain fatigue life with suitable safety margins against failure. Moreover, they have to be designed to withstand the horizontal and vertical loads acting on the entire assembly including the transition piece, tower and wind turbine blades. Further details on the loading conditions and fatigue analysis of offshore wind monopiles can be found in the literature [4,5]. Monopiles are made of thick hot-rolled structural steel plates subjected to cold-rolling and bending followed by welding in the longitudinal direction to form "cans". The individual cans are subsequently welded circumferentially to fabricate a full-length monopile.

It has been demonstrated by many researchers that welding residual stresses notably influence fatigue crack growth (FCG) behaviour of engineering materials. For example Lawrence et al. [6] have developed an analytical model to predict the influence of residual stress and stress

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Nomenclature

hkl	miller indices defining the lattice planes
λ	wavelength of the characteristic rays
d_{hkl}	lattice interplanar spacing of the crystal
$d_{0,hkl}$	lattice interplanar spacing of the strain-free sample
θ	incidence angle (Bragg's angle)
ε_{hkl}	residual strain corresponding to the *hkl* plane
ε_{err}	error in the strain measurements
d_{err}	error in the d-spacing measurements
σ_{err}	error in the residual stress measurements corresponding to ε_{err}
σ_{BM}	base metal yield stress
σ_{WM}	weld metal yield stress
E_{hkl}	Young's modulus of the *hkl* plane
ν_{hkl}	Poisson's ratio of the *hkl* plane
ΔK_{eff}	effective stress intensity factor range
ΔK_{th}	threshold stress intensity factor range
B	specimen thickness
M	mismatch ratio
N	number of cycles
W	specimen width
BM	base metal
WM	weld metal
C(T)	compact tension specimen geometry
HAZ	heat affected zone
PWHT	post-weld heat treatment
FCG	fatigue crack growth
RS	residual stress
TOF	time-of-flight
SCF	stress concentration factor

ratio on the fatigue life of a welded section. The main drawback of their model is that it is limited to crack initiation, and cannot account for welding residual stress effects on crack propagation behaviour of the material [6]. Moreover, the effects of compressive and tensile residual stresses on Mode I fatigue crack growth are discussed in [7] where residual stresses were introduced in the test specimens through shot peening. It has been demonstrated in references [7,8] that locked-in residual stresses alter the mean stress and also stress ratio under cyclic loading conditions and subsequently influence fatigue behaviour. Residual stresses particularly have more pronounced effects in near threshold region during FCG process and as the crack advances residual stresses redistribute and eventually vanish towards the end of the fatigue test [6–11]. It has been shown that the fatigue crack initiation and growth in monopile weldments occur primarily at circumferential welds due to the cyclic loads from wind and wave that offshore wind turbines are subjected to [12]. A significant effort has been made in the SLIC JIP (Structural Lifecycle Industry Collaboration Joint Industry Project) to characterise the FCG behaviour of these welded structures in air as well as in seawater in order to better estimate the remaining life of monopiles based on laboratory scale FCG tests on base metal (BM) and weldments (i.e. weld metal (WM) and heat affected zone (HAZ)) [9,10]. The SLIC project has successfully developed FCG curves to investigate the fatigue behaviour of offshore wind welded steel foundations. However, due to the lack of data available at the time, the effect of residual stress on FCG particularly in the near threshold region was not considered in the analysis and therefore was proposed as an important future work.

There is a significant research gap in reliable characterisation of the state of residual stress in monopile structures upon fabrication, after pile drilling, during service operation and indeed the effect of welding sequence on residual stresses in monopiles [11–17]. In addition, the weld quality itself plays a significant role in the fatigue life of welded components [18]. There is currently high level of uncertainty and conservatism in the existing codes and standards for the design process or lifetime and structural integrity assessment of monopiles due to the lack of consideration of residual stress effects. This is particularly crucial due to the fact that unlike many other industries such as nuclear no post weld heat treatment is performed on monopiles because of the size and cost issues. Moreover, it is quite well known that residual stress measurement results from laboratory scale specimens are not easily transferable to components, due to the size effects and therefore different constraint levels, which subsequently result in different residual stress states. Hence, it is recommended to test samples at quite high stress ratios (i.e. $R = 0.5$) to imply comparably high tensile residual stresses and supply a conservative transfer of laboratory scale test specimen results to welded components and structures.

In order to remove the uncertainty and conservatism in the structural design and integrity assessment of monopiles, welding residual stresses need to be reliably characterised at the fabrication, installation and operation stages leading to reliable estimate of fatigue crack initiation and propagation in monopiles particularly at circumferential weld regions in which the cracks are often first created.

In this paper, for the first time, we present residual stress characterisation using the contour method on a large welded mock-up, in the form of a plate, typical of offshore wind monopile weldment. We also conducted neutron diffraction and contour method measurements on a compact tension, C(T), specimen extracted from the large welded mock-up. C(T) fracture mechanics test specimens are typically used in characterising FCG behaviour of engineering materials in lab environments. The following sections explain the details of the test specimens and the residual stress measurement techniques performed in this work. The results from these measurements are presented and discussed in terms of the effect of residual stress on fatigue crack growth behaviour of monopile weldments in small-scale laboratory samples and real-size scale structures.

2. Specimens

2.1. A large welded mock-up

The material used for the large mock-up is EN-10225:09 S355 G10+M, which is widely used in the fabrication of offshore structures including offshore wind turbine monopiles [19]. The chemical composition of the base metal used in this work, which has the Carbon

Table 1
Chemical composition of the base metal.

Element, wt%										
C	Si	Mn	P	S	N	Cu	Mo	Ni	Cr	
0.061	0.280	1.58	0.013	0.0007	0.0041	0.254	0.006	0.342	0.034	
V	Nb	As	Sn	Ti	Pb	B	Sb	Ca	Bi	Al-T
0.001	0.022	0.003	0.001	0.003	0.00	0.0003	0.001	0.0028	0.0001	0.032