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Advanced numerical modelling techniques for the structural design of composite tidal turbine blades

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ABSTRACT

Tidal stream turbine blades must withstand both extreme one-off loads and severe fatigue loads during their 20–25 year required lifetimes in harsh marine environments. This necessitates the use of high-strength fibre reinforced composite materials to provide the required stiffness, strength and fatigue life, as well as resistance to corrosion, whilst minimising the mass of material required for blade construction and allowing its geometric form to provide the required hydrodynamic performance. Although composites provide superior performance to metals, potential failure mechanisms are more complicated and difficult to predict. A dominant failure mechanism is interfacial failure (delamination) between the composite layers (plies). This paper demonstrates how the development of numerical techniques for modelling the growth of interfacial cracks can aid the design process, allowing the effects on crack growth from potential manufacturing defects and the effect of stacking sequence of composite plies to be analysed. This can ultimately lead to reduced design safety margins and a reduction in the mass of material required for blade manufacture, essential for reducing lifecycle costs. Although the examples provided in this article are specific to tidal turbine blades, the analysis techniques are applicable to all composite structures where fatigue delamination is a primary failure concern.

1. Introduction

Although estimates of the global resource vary, tidal stream devices could potentially extract significant quantities of energy from a variety of regions where there are fast flowing tidal currents, such as the Pentland Firth, Bay of Fundy, Skagerrak–Kattegat, the Gulf of Mexico and the Gulf of St Lawrence, rivers such as the Amazon and the Straits of Magellan and Messina (Charlier, 2003). The UK has one of the world's richest resources and recent estimates suggest that tidal stream energy devices could provide approximately 21 TWh/yr of UK electricity (Black & Veatch, 2011), which is equivalent to around 5% of total supply.

There is currently a wide range of tidal stream devices under development, but those closest to commercial deployment are generally open-bladed horizontal axis turbines, such as Marine Current Turbine Ltd.'s SeaGen, Tidal Generation Ltd.'s DeepGen and Andritz Hydro Hammerfest's HS1000 (RenewableUK, 2012). Similar to wind turbines, the design lifetime of tidal stream devices will be 20–25 years but there is an even greater incentive for low maintenance requirements due to the harsh, inaccessible, marine environments where they will operate. This makes it vital to fully understand the loads that tidal turbines will experience and to design against potential failure mechanisms.

The cyclic loads experienced by tidal turbine blades are significantly different to those acting on wind turbine blades. Water has a density 832 times that of air and as a result, flapwise bending loads dominate for tidal turbine blades, wheareas for wind turbine blades, centripetal loads dominate due to the low density of air and their relatively high rotational speeds (Fraenkel, 2004). Although tidal turbines are subjected to a predictable tidal current, which varies between two maximum speeds of typically 3–4 m/s in opposite directions over a 12 hour period, short-term variations in load are imposed by wave action and turbulence (e.g. due to sea-bed roughness and temperature effects). This means that in addition to extreme one-off load cases, such as a 50-year extreme wave event, material degradation under cyclic loads (fatigue) is a highly important design consideration (McCann, 2007). The severity of fatigue loads experienced by tidal turbines is both design and site-specific, depending on factors such as the depth of installation, the proximity of the sea-bed and the wave environment (McCann et al., 2008). The acquisition of appropriate experimental data to gain an improved understanding of fatigue loading has received much attention at sites such as the European Marine Energy Centre in Orkney (Droniou and Norris, 2007; Lawrence et al., 2009).

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Nomenclature

Interface element properties

G_C	critical strain energy release rate
K	interface element stiffness prior to damage initiation
σ	interface element stress
σ_{max}	maximum interfacial stress
δ	interface element relative displacement
δ_e	interface element relative displacement at damage initiation
δ_f	Interface element relative displacement at final failure subscripts I, II and m are used to denote properties under mode I, mode II and mixed mode loading respectively

Laminate properties

E_{11}, E_{22}, E_{33}	Young's Moduli
G_{12}, G_{13}, G_{23}	Shear Moduli
ν_{12}, ν_{13}, ν_{23}	Poisson's ratios where subscripts 1–3 denote the principal material axes

Miscellaneous

G_T	total strain energy release rate (subscripts I and II are used to denote mode I and mode II components)
P	load
t	time
a	crack length
N	number of fatigue cycles
C	Paris law constant
m	Paris law exponent

The structure of a typical tidal turbine blade is shown in Fig. 1 and consists of a main spar running along the length of the blade, enclosed by a skin to give the blade its hydrodynamic shape. Carbon and glass fibre reinforced composites are currently the favoured materials for these components (Marsh, 2004) due to their high stiffness, strength, and fatigue/corrosion resistance. During manufacture, layers known as plies, which consist of straight, continuous fibres, pre-impregnated with resin, are stacked on top of one another. The resulting stack of plies, known as a laminate, is then heated and cooled in a controlled manner so that the resin forms strong chemical bonds with the fibres and sets to form a rigid structure. The thickness of the blade is tapered from root to tip by incrementally terminating plies along the length of the blade, forming features known as ply drops. The combination of very strong fibres surrounded by a lightweight plastic matrix enables a greater strength and stiffness to weight ratio than is possible using metallic materials. Compared to metals, composites offer the additional advantages of an ability to be moulded into complex shapes and resistance to corrosion. Although the fatigue performance of composites is also generally better than metals, fatigue remains a significant design consideration and is a highly complex failure regime to predict due to the many types of damage mechanism that can occur in fibre reinforced composites. These include cracks developing both within the individual plies of the laminate (intralaminar damage) and often more significantly, along the interfaces between plies (interlaminar damage) (Jones, 1999; Harris, 2003).

Although guidelines and standards for the certification of tidal turbine devices have been issued (Germanischer Lloyd (GL), 2005; Det Norske Veritas (DNV), 2008), efforts to develop and refine the associated design processes remain ongoing. The structural design process for tidal turbine blades can be divided into three main stages, as shown in Fig. 2:

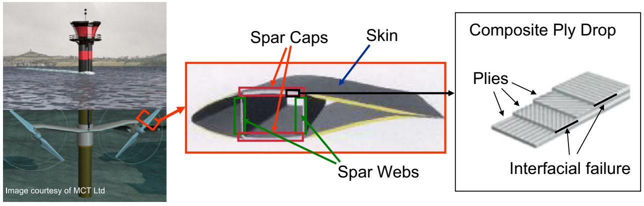

Fig. 1. A typical tidal turbine blade structure.

1. Modelling the actual load time series that a tidal turbine blade will be subjected to during its 20–25 year lifetime (Gant and Stallard, 2008). This relies on having reliable data for both the range of mean current speeds and level of flow turbulence at a given site. Specialist software tools such as DNV GL's 'Tidal Bladed' (Bossanyi, 2007) and NREL's 'TurbSim' (Jonkman and Kelley, 2007) have been developed which can model both the hydrodynamic performance and the fatigue load time series, based on empirical turbulence data from sites such as the European Marine Energy Centre. Fig. 2 (1. Extraction of time series data for blade loads from model simulation) shows a typical time series output from a Tidal Bladed model, where the temporal variation of the bending moment at the blade root consists of both a sinusoidal periodic component due to the harmonic tidal cycle and random short-term variations due to turbulence.
2. Converting this complex load time series to a sequence of constant amplitude, constant frequency, sinusoidal fatigue loads (equivalent fatigue loads) that cause an equivalent level of material degradation over the turbine lifetime and can be used for design and experimental certification purposes. Fig. 2 (2. Generation of simplified load time series) shows sets of constant amplitude, sinusoidal fatigue loads that can be used within a numerical simulation to represent the cyclic components of the actual load time series. Although this will not account for any variations in damage accumulation due to the sequence in which cyclic loads are applied, modelling the actual load time series within an explicit finite element simulation, as performed in the present study, is not currently feasible (see Section 2.1).
3. The application of design and analysis techniques to ensure that the simplified load time series, along with any extreme loads that need to be considered, will not result in structural failure within the required design lifetime. This is the focus of the current paper and the methods being applied to address this challenge are now discussed in more detail.

For wind turbine blades, extensive experimental studies have been conducted to investigate the effect of cyclic loading on composite material degradation (McGowan et al., 2007) and