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Damage mechanics based design methodology for tidal current turbine composite blades

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ABSTRACT

A material model based on the Puck phenomenological failure criteria for fibre and inter-fibre failure of glass-fibre and carbon-fibre reinforced polymer composites is presented. The model is applied through a user-defined material subroutine for 3D shell elements. Sub-modelling is used for detailed analysis of the highest stressed regions in the blades. The material model is incorporated into a methodology for the design and analysis of composite tidal current turbine blades. The methodology employs an iterative design process with respect to a number of failure criteria to ensure optimal structural and material performance of the blade. The methodology is automated using the Python programming language to enable efficient variation of model parameters for various design conditions. The forces acting on the blades are determined from blade element momentum theory for a number of turbine operating conditions. The results of a design case study for a typical horizontal axis device are presented to demonstrate the methodology.

1. Introduction

Tidal current turbines take advantage of highly predictable tidal cycles, without the issue of intermittency faced by other forms of renewable energy capture devices [1]. Ireland's coasts have good potential for consistent tidal energy. Tidal turbines can achieve significantly higher power output than wind turbines for a similar blade length, due to the higher density of water, leading, however, to considerably higher loads. The increased root bending moments on a blade become prohibitive with respect to material structural capacity as blade length increases. Existing tidal energy devices, therefore, are typically limited to tidal velocities of between 2 and 3 m/s. Composite materials are a candidate design solution [2] due to their high specific stiffness, specific strength and fatigue performance. Glass-fibre reinforced polymer (GFRP) composites, such as glass-fibre epoxy or glass-fibre with vinyl ester, are often used as the material of choice in wind turbine blade design due to their relatively low cost, with carbon-fibre (CFRP) being used for larger blades. The increased stiffness required for large-scale horizontal axis tidal turbines is likely to necessitate a combination of these materials [3].

Damage in fibre reinforced composite materials is characterised by gradual stiffness and strength degradation due to the accumulation of micro-damage in the matrix and fibres. This includes such damage as matrix cracking, fibre fractures, and fibre debonding (see, for example [4–6]). Composites exhibit extensive and distributed damage throughout the stressed region before eventual ply failure [4]. Most cyclically-stressed composite structures experience early-stage damage; this damage does not always reduce strength, but generally decreases stiffness [7]. Phenomenological approaches to damage modelling utilising residual stiffness and residual strength models have been developed by a number of authors (for example [7–11]). The model applied in this work is based on the fibre failure and inter-fibre failure criteria defined by Alfred Puck [12]. The stiffness degradation models of Knops and Bogle [7] and Puck and Mannigel [13] are used to predict the damage in the laminates before and after inter-fibre failure (matrix cracking) occurs. The results of the World Wide Failure Exercise (WWFE) [14] indicate that this is a valid method for prediction of static failure of composites, as applied by a number of

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Nomenclature

UMAT	user material sub-routine in Abaqus
BEMT	blade element momentum theory
FE	finite element
FRP	fibre reinforced polymer (glass or carbon)
WWFE	World Wide Failure Exercise
TSR	tip speed ratio
δ_{tip}	blade tip deflection
$\delta_{tip,\ allow}$	maximum allowable blade tip deflection
C_p	power coefficient
C_t	thrust coefficient
FF	fibre failure
IFF	inter-fibre failure
XFOIL	2D panel method code for determining airfoil performance
U	incoming tidal current velocity
ω	blade angular velocity
V_{rel}	relative velocity on blade section
a, a'	axial and tangential load induction factors
φ	flow angle
α	angle of attack
β	twist angle
c	chord length
L, D	lift and drag forces
F_T, F_N	in-plane and out-of-plane forces
$\partial\Delta\sigma/\partial\Delta\varepsilon$	material Jacobian matrix
σ_1, σ_2, τ_{12}	in-plane lamina oriented longitudinal, transverse and shear stresses
ε_1, ε_2, γ_{12}	in-plane lamina oriented longitudinal, transverse and shear strains
ν_{12}, ν_{21}	major and minor Poisson's ratios
E_1	fibre direction (longitudinal) modulus
E_2	transverse modulus
G_{12}	in-plane shear modulus
ρ	density
D_1, D_2, D_{12}	longitudinal, transverse, and shear moduli damage variables
f_E	stress exposure or risk of failure
$f_E(FF)^+$, $f_E(FF)^-$	tensile and compressive FF stress exposure
$f_E(IFF)_A$, $f_E(IFF)_B$, $f_E(IFF)_C$	Mode A, Mode B, and Mode C IFF stress exposure
X_T	longitudinal tensile strength
X_C	longitudinal compressive strength
S_{12}	in-plane shear strength
Y_T	transverse tensile strength
Y_C	transverse compressive strength
ε_{1T}	longitudinal tensile failure strain
ε_{1C}	longitudinal compressive failure strain
ε_{2T}	transverse tensile failure strain
ε_{2C}	transverse compressive failure strain
γ_{12}	in-plane shear failure strain
$m_{\sigma f}$	mean stress magnification factor for the fibres
$p_{\parallel\perp}^{(+)}$, $p_{\perp\parallel}^{(-)}$, $p_{\perp\perp}^{(+)}$, $p_{\perp\perp}^{(-)}$	shape parameters for IFF failure envelopes
$n^{(\sigma_2)}$, $n^{(\tau_{12})}$	exponents in stiffness degradation equations
$C^{(\sigma_2)}$, $C^{(\tau_{12})}$	coefficients in stiffness degradation equations
η_E, η_G	factors in stiffness degradation equations
C_E, C_G	coefficients in stiffness degradation equations
ξ_E, ξ_G	exponents in stiffness degradation equations
$f_{E\ thr}^{(\tau_{21})}$, $f_{E\ thr}^{(\sigma_2)}$	threshold stress exposures for shear and transverse stresses
E_{2s}, G_{12s}	secant transverse and shear moduli

authors (for example [15–18]).

For a typical 20-year operating life of a tidal turbine, the eventual failure in the blades is most likely to be caused by (i) structural damage to the blade resulting in loss of functionality, or (ii) stiffness degradation leading to inefficiency [19,20]. Predictive modelling methods can help to reduce the potential costs by improving the structural design and analysis of the blades. In this paper, the forces acting on the blades are determined using a hydrodynamic model based on blade element momentum theory (BEMT), finite element models of the blade designs are generated using Python coding, and a stress-strain and failure analysis is performed using a user-defined material sub-routine and sub-modelling methods within Abaqus. The automation steps were implemented with the Python open source programming language, which Abaqus has built-in functionality to support. This enables efficient variation of model parameters such as the forces acting on the blade, the thickness of the laminates at each section and the pitch angle of the blade. The methodology is applied to a case study for the design of a horizontal axis device. The conditions were determined for a turbine situated in 30–40 m water depth. O'Rourke et al. [21] indicate that the Irish resource is highest in this depth range. Some key novel features of the presented research are as follows:

1. Computationally efficient automated processes for the development of shell element models of composite blades within a finite element framework.
2. A novel methodology for the structural design and analysis of tidal turbine blades.
3. A new efficient shell-element damage mechanics material model for glass-fibre and carbon-fibre reinforced composites.

2. Methodology

The blade design and analysis methodology presented here is outlined in the flowchart of Fig. 1. A hydrodynamic analysis using a blade element momentum theory (BEMT) model is used to define the forces on the blade, while finite element models in Abaqus determine the structural response. The structural analysis includes a user-defined material subroutine for modelling the damage in fibre-reinforced composite materials. Additionally, a check of the highest risk regions of the blade is performed using sub-modelling within Abaqus with a higher resolution mesh.

2.1. Hydrodynamic analysis

In order to accurately determine the validity of a potential blade design, a hydrodynamic analysis of the turbine is first performed. BEMT is often used in the design and analysis of the loads on wind turbines. It is applied here to the tidal turbine case where the increased density of water compared to air is the main difference between the two. In a BEMT model the rotor area is split into a number of concentric annular streamtubes which are radially independent and experience purely 2D flow. Fig. 2 [22] shows the incident velocity (V_{rel}) and its component axial (U) and tangential (ωr) velocity vectors on a single blade element. The axial and tangential flow induction factors, a and a' respectively, are modifications to the incoming flow velocities of the blade section. An iterative process is used to solve for the two induction factors. When the induction factors have been determined the lift and drag forces (L and D in Fig. 2 respectively) are computed and are resolved into the in-plane (F_T) and out-of-plane (F_N) forces for each blade