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The effect of buffer-layer on the steady-state energy release rate of a tunneling crack in a wind turbine blade joint

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ABSTRACT

The effect of a buffer-layer on the steady-state energy release rate of a tunneling crack in the adhesive layer of a wind turbine blade joint, loaded in tension, is investigated using a parametric 2D tri-material finite element model. The idea of embedding a buffer-layer in-between the adhesive and the basis glass fiber laminate to improve the existing joint design is novel, but the implications hereof need to be addressed.

The results show that it is advantageous to embed a buffer-layer near the adhesive with controllable thickness- and stiffness properties in order to improve the joint design against propagation of tunneling cracks. However, for wind turbine blade relevant material combinations it is found more effective to reduce the thickness of the adhesive layer since the stiffness mismatch between the existing laminate and the adhesive is already high. The effect of material orthotropy was found to be relatively small for the blade relevant materials.

1. Introduction

A typical wind turbine blade joint is manufactured of a structural adhesive layer that is bonding two glass fiber laminated shells meaning that the structural adhesive is constrained in-between stiffer laminates. This is exemplified in Fig. 1(A) for a trailing-edge joint in a wind turbine blade. Observations from full scale blade tests of this joint with tensile stresses, $\sigma_{yy,2}$, in the adhesive, show that cracks can initiate at the free-edge and propagate through the adhesive layer as a so-called tunneling crack. The tunneling crack is constrained by the laminates as shown in the sketch in Fig. 1(A) and the photo in Fig. 1(B).

Novel models are desired for establishing design rules for an improved joint design in order to prevent tunneling cracks propagating across the wind turbine blade joint in Fig. 1(A). An improved joint design aims at decreasing the energy release rate for tunneling cracks in the joint and thus enable a reduction in the amount of reinforcement needed in the laminates. This leads to a reduction in blade mass and thus a decrease in the cost of energy since lighter blades are more efficient and can save structural reinforcement in the other wind turbine components e.g. nacelle, hub, tower and foundation [1].

Generally, the process of tunneling crack propagation includes three-dimensional effects. However, when the crack in Fig. 1(A) reaches a certain length from the edge (in z-direction), the energy release rate becomes steady-state meaning that the energy release rate no longer depends on the crack length. The problem of steady-state propagation of a tunneling crack was analysed for an isotropic bi-material model by Ho and Suo [2,3]. Although tunneling cracking is a 3D problem, the steady-state energy release rate, can be determined exact from a 2D solution by [2,3]:

$$\mathcal{G}_{ss} = \frac{1}{2}\frac{\sigma_{yy,2}}{2h_2}\int_{-h_2}^{+h_2}\delta_{cod}(x)dx \tag{1}$$

where $\sigma_{yy,2}$ is the far field stress in the cracked adhesive layer (uniform applied stress) and the adhesive thickness is $2h_2$ according to Fig. 1. $\delta_{cod}(x)$ is the crack opening displacement profile for the plane strain crack far behind the crack front. For the elementary case of a central crack in an infinitely large plate subjected to remote tensile stresses (Griffith crack), the crack opening displacement is [3]:

$$\delta_{cod} = \frac{4\sigma_{yy,2}}{\bar{E}_2}\sqrt{(h_2^2 - x^2)} \tag{2}$$

where $\bar{E}_2$ is the plane strain Young's modulus of the plate. Inserting Eq. (2) into Eq. (1) and evaluating the integral gives [2,3]:

$$\mathcal{G}_{ss} = \frac{\pi}{4}\frac{\sigma_{yy,2}^2 2h_2}{\bar{E}_2} \quad (asymptotic\ limit) \tag{3}$$

This asymptotic limit, established by Ho and Suo [2,3] in Eq. (3), is representing the mode-I steady-state energy release rate of a tunneling crack in a homogenous structure with infinitely thick substrates. Therefore, it is convenient to normalise other energy release rate results

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Nomenclature

E_1	Young's modulus of substrate
E_2	Young's modulus of adhesive
E_3	Young's modulus of buffer-layer
$\overline{E}_1$	plane strain Young's modulus of substrate
$\overline{E}_2$	plane strain Young's modulus of adhesive
$\overline{E}_3$	plane strain Young's modulus of buffer-layer
F	non-dimensional function
$\mathcal{G}_{ss}$	mode-I steady-state energy release rate
G_{xy}	shear modulus
h_1	thickness of substrate
h_2	half thickness of the adhesive layer
h_3	thickness of buffer-layer
x,y,z	coordinates
α_{12}	first Dundurs' parameter (substrate/adhesive)
α_{32}	first Dundurs' parameter (buffer-layer/adhesive)
β_{12}	second Dundurs' parameter (substrate/adhesive)
β_{32}	second Dundurs' parameter (buffer-layer/adhesive)
δ_{cod}	crack opening displacement profile
λ	first orthotropy parameter
ν	Poisson's ratio
ρ	second orthotropy parameter
$\sigma_{yy,2}$	stress in the adhesive (y-direction)
Biax	bi-axial
FE	finite element
UD	uni-directional

with this elementary case i.e. $[(\sigma_{yy,2}^2 2h_2)/(\overline{E}_2)]$.

The tunneling crack models by Ho and Suo [2,3] were extended to account for debonding [4–6], transient effects for short crack lengths [7] (although first demonstrated for thin film [8,9]) and material orthotropy [10,11]. Yang et al. [10] studied the effect of ply angles on the critical stress to propagate a tunneling crack embedded in the central layer of a carbon-epoxy laminate. It was found that the critical stress to propagate the tunneling crack were highest when the uni-directional fibers were oriented perpendicular to the tunneling crack i.e. fibers oriented in the y-direction in Fig. 1. Beom et al. [11] presented results for the case where only the adhesive layer was modelled with material orthotropy i.e. the modelling results were limited to substrates with isotropic material properties of infinitely thickness.

In a wind turbine blade joint the adhesive can be assumed isotropic, but the substrates consist of several layers of different type, typically uni-directional- (UD) and bi-axial (Biax) glass-fiber layers as exemplified in Fig. 1(B, C). The in-plane orthotropy of these materials can be described by two dimensionless parameters [12]:

$$\lambda = \frac{E_{xx}}{E_{yy}}, \qquad \rho = \frac{(E_{xx}E_{yy})^{1/2}}{2G_{xy}} - (\nu_{xy}\nu_{yx})^{1/2} \tag{4}$$

which reduces to $\lambda = \rho = 1$ for an isotropic material [12]. The material directions of the laminate are in accordance with the coordinate system in Fig. 1, where E_{xx} and E_{yy} are the Young's modulus, G_{xy} is the shear modulus, and ν_{xy} and ν_{yx} are the Poisson's ratio.

The substrates, constraining the adhesive, can be modified in order to prevent the propagation of tunneling cracks since the substrates are layered composite materials. Thus, one way of improving the adhesive joint design is to modify the ply-thickness and stiffness of the individual layers of the laminates. However, modification of the original layup might have a negative effect on the existing blade design that is designed such that the joint can withstand the various other load cases e.g. bending, compression and torsion.

Another way to prevent tunneling crack propagation across the adhesive layer of the joint is to add a new layer, called a buffer-layer,

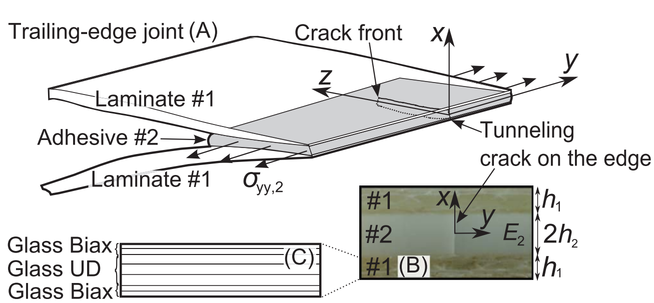

Fig. 1. (A) Trailing-edge joint with a tunneling crack propagating across the adhesive layer in the z-direction. (B) Photo of a tunneling crack in a trailing-edge wind turbine blade joint. (C) Typical layers in a glass fiber laminate used in a wind turbine blade joint.

near the adhesive and control the properties of this layer. The buffer-layer design philosophy is attractive since the original joint design can be maintained and at the same time, by adding the buffer-layer, the joint design can be improved against the propagation of tunneling cracks. Furthermore, it is well known for thin films that it is the thickness and stiffness of the layer closest to the adhesive that has the greatest constraining effect on the crack [13].

The objective of this research is to study the effect of in-plane stiffness, E, and layer-thickness, h, on the steady-state energy release rate, $\mathcal{G}_{ss}$, using finite element (FE) models. More specifically, it is the aim to determine the effect of a buffer-layer on the steady-state energy release rate for an isolated tunneling crack in the adhesive layer of a wind turbine blade joint. This should lead to design rules for an improved bonded joint design. The primary applicability is for wind turbine blade relevant joint design and -material combinations since there is a high demand for novel design rules for adhesive joints in the wind turbine blade industry.

The design idea of a buffer-layer for improvement of a wind turbine blade joint is novel and the implications and effects of this buffer-layer need to be investigated before potential implementation in the future joint design. Therefore, parameter studies with a new symmetric tri-material FE model is used to address the design challenge. Furthermore, the study of steady-state tunnel cracking for a multi-layered sandwich structure with orthotropic substrates has not been addressed in the literature. This includes the applicability on wind turbine blade joints with realistic material combinations.

The paper is organised as follows. In Section 2 the materials and the problem are defined, and in Section 3 the finite element modelling techniques are described. Hereafter, tunneling cracking in a generalised perspective is analysed using first bi-material FE models in Section 4 and tri-material FE models in Section 5 (see Fig. 2). In Section 6, a case study with blade relevant materials demonstrates how a wind turbine blade joint design are influenced by the presence of a buffer-layer including the effect of material orthotropy. Finally, a discussion and conclusion highlights the major findings of the present study.

2. Problem definition

The problem we investigate in the present study is that of an isolated tunneling crack in Fig. 2(A), which is used to clarify the effect of substrate stiffness- and thickness, and used to test the implementation of the numerical models. This model is extended by embedding a buffer-layer, named material #3 in Fig. 2(B), to analyse the effect of buffer-layer thickness and -stiffness on the steady-state energy release rate of a tunneling crack. The model is limited to three layers since more layers complicate the modelling unnecessarily. The effect of material orthotropy of the substrates is investigated in order to test whether it is feasible to model blade relevant materials as isotropic materials.