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A SUBSTRUCTURE TEST SPECIMEN FOR FATIGUE DELAMINATION CRACK GROWTH INITIATING AT PLY DROPS

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Abstract

In this work, we propose a substructure test specimen to explore the predictability of delamination fatigue crack growth driven by cyclic loadings. The design procedure to create a substructure test specimen out of a full blade is presented. The focus of this work is on the design challenges of the specimens. An analytical ply drop model is used to determine the dimensions of the specimen. The present substructure test specimen is designed for cyclic tension-tension loading. Practical considerations related to the design are presented. This includes in-field investigation on a decommissioned blade to determine the cutting locations and dimensions in order to obtain consistent interfaces over a long length for substructure specimens. The locations and dimensions of blade segments to be cut out for manufacturing the specimens are carefully planned to avoid damages that had developed in the commissioned time.

1. Introduction

Laminated composite structures e.g. helicopter rotor blades and wind turbine rotor blades are designed to meet specific requirements e.g. aerodynamic efficiency and low weight. This means that their geometrical configurations are not always the same along the dimensions. Thickness tapering is a common design strategy employed in laminated composite structures to tailor the geometrical configurations. The tapering of the laminate thickness is achieved by introducing ply drops at specific locations where geometry modifications are needed [1,2,3]. Ply drops refer to the termination or reduction of plies along the length of laminates. By doing so, a gradual change in the thickness of the structure can be made without altering the entire laminate. When the structure is subjected to cyclic loading, there will be stress concentrations at the locations of the ply drops, due to the discontinuities in the material and geometry. Such stress concentrations can lead to initiation and growth of delamination cracks [4,5,6]. The growth of the delamination cracks reduces the load carrying capacity of the composite structures and eventually leads to catastrophic failures of the structures. From the perspective of structural damage tolerance, the predictability of the growth rate of fatigue delamination crack becomes critical. A high damage tolerance means damage or crack grows in a stable manner over a long distance, and under static loading the load carrying capability can be predicted, and under cyclic loading the damage or crack growth rate and remaining number of cycles to failure can be predicted over a large size in a structure [7]. For example, a delamination crack can develop at ply drops of main spars of wind turbine blades and the crack can grow a long distance along the length of the main spar. It can be a significant mode of failure while might not be visibly detectable in operating blades since there are paints and coatings on the blade surface to protect the blade from corrosion and erosion.

In this work, we propose a substructure test specimen specifically designed for exploring the predictability of delamination fatigue crack growth driven by cyclic loadings. The design procedure to create substructure test specimens out of a full blade is presented.

2. Specimen design

We design a relatively long substructure test specimen in order to allow a delamination crack to grow a long distance. This is to ensure that there is enough size to identify whether the crack behaves a stable growth over a long distance. An analytical ply drop model [8] is used to determine the design parameters of the substructure test specimen, i.e., the ply thickness, the thickness of the underlying layers, and the load levels. The specimens will be cut from the main spars of a decommissioned blade made by Siemens Gamesa.

2.1. Ply drop damage model

An analytical model by [8] based on J integral to calculate the energy release rate at the tip of the delamination crack initiating from a ply drop is used to determine the thickness and loads to be applied on the substructure test specimen. The J integral equation is presented for a symmetric tri-layer model consisting of a central layer with thickness, $2H$, and two surface layers each with thickness, h_1 as shown in Figure 1.

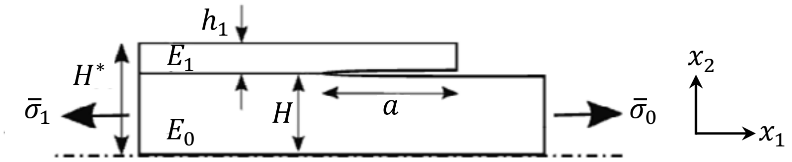


Figure 1. A tri-layer specimen undergoing delamination from a ply drop with a crack length, a. Due to symmetry only half of the specimen is shown. The dashed line indicates the symmetry plane.

When the crack grows sufficiently long i.e., crack length a exceeds two times the ply thickness [9], the energy release rate at the crack front attains a steady-state value. Under such conditions, the steady-state energy release rate is equal to the J integral evaluated along the external boundaries [8]. For a plane stress condition, the J integral equation is given by [8]

$$J_{\text{ext}} = \frac{\bar{\sigma}_0^2 H}{E_0}\left(\frac{\Sigma\eta}{1 + 2\Sigma\eta}\right) \tag{1}$$

Where $\bar{\sigma}_0 = \bar{\sigma}_1$, $\Sigma = E_1/E_0$, and $\eta = h_1/2H$. The layers are assumed to be orthotropic linear elastic with Young's modulus in the x_1- direction denoted E_0 for the central layer and E_1 for the surface layers.

2.2. Design methodology

The procedure for determining the dimensions of the substructure test specimen are described below:

- Step 1: The length of the specimen is designed as 1200 mm. This is determined based on the capability of the test machine, i.e., the maximum allowable distance between the grips of the test machine.

- Step 2: The width w of the specimen is designed as 40 mm. We estimate the total thickness of the substructure specimen under the assumption that the maximum applied strain ε is 0.3 %. The Young's modulus of the composite laminate is taken to be 38 GPa, corresponding to a unidirectional glass fibre composite. We obtain the maximum total thickness as $H^*_{\max} = F_{\max}/(wE_0\varepsilon)$, where $F_{\max}$ is the maximum load capacity of the test machine used for the fatigue testing, and $F_{\max}$ = 250 kN, then $H^*_{\max}$ = 55 mm.

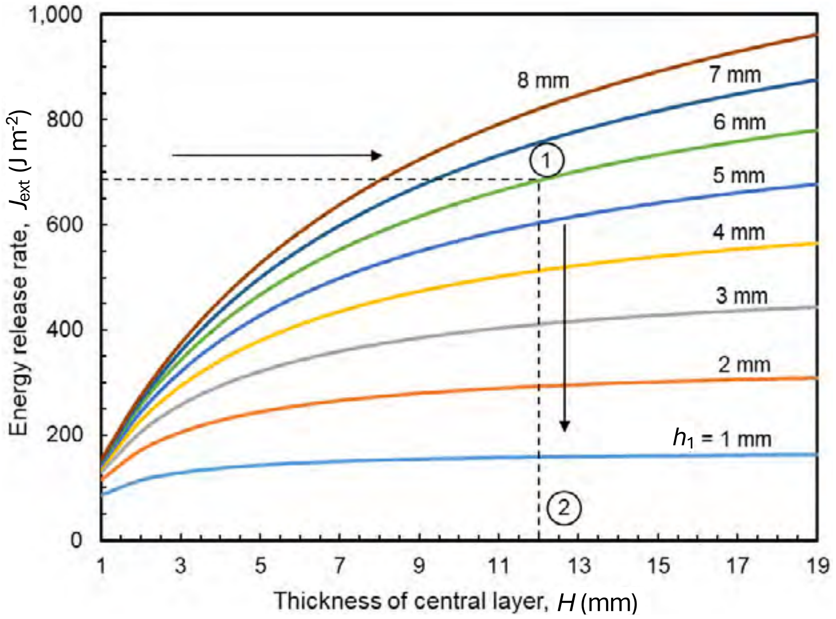


Figure 2. Values of the J integral, calculated from Eq. (1), are shown as a function of ply drop thickness for different central layer thicknesses. The steps for determining H and h_1 for $J_{\max}$ = 700 J m^{-2} are indicated with the dashed lines.

- Step 3: We design the specimen for the crack growth rate where $(\mathrm{d}a/\mathrm{d}N)_{\max} = 2 \times 10^{-3}$ mm cycle^{-1}. From Figure 9 of [10], we find for a glass-epoxy composite laminate loaded in mixed mode configuration with a mode mixty value of 53 %, that the crack growth rate of $(\mathrm{d}a/\mathrm{d}N)_{\max} = 2 \times 10^{-3}$ mm cycle^{-1} corresponds to a maximum J integral value of approx. $J_{\max}$ = 700 J m^{-2}.
- Step 4: From Figure 2, we obtain the combination of H and h_1 as 12 mm and 6 mm, respectively, that yields J = 684 J m^{-2} which is close to the chosen $J_{\max}$ value. As a result, the total thickness is H^* = 18 mm which fulfills the criterion $H^* < H^*_{\max}$ (step 2).
- Step 5: We set the initial pre-crack length as a = 30 mm as shown in Figure 3, so that $a >> h_1$.

2.3. Geometrical details of the specimen

Figure 3 shows the dimensions of the specimen. The specimen is 1200 mm in length, 40 mm in width, and 18 mm in thickness. It is designed with an external ply drop [6], and the height of the dropped plies is 6 mm. A 30 mm long pre-crack is placed at the ply drop. The thickness of the specimen is determined also based on the dimensions of the main spar of the decommissioned blade. It should be noted that in wind turbine blades, the ply drops are situated on the inner side.

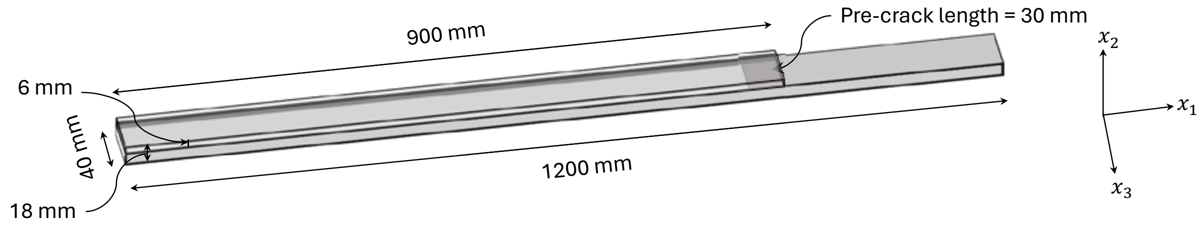


Figure 3. Dimensions of the substructure test specimen and details of the ply drop.

3. Specimen preparation

The substructure test specimens were cut out from a decommissioned blade from Siemens Gamesa. An in-field investigation on the blade was conducted to determine the cutting locations and dimensions in order to obtain consistent interfaces over the length of substructure specimens. Figure 4 shows the cutting sketch of the decommissioned blade after the in-field investigation. The cutting steps to obtain the main spar segments from the blade are the following:

- Step 1: Mark the blade parts to be cut out with a part name and an arrow to indicate the direction towards the blade tip. (Figure 4(a))
- Step 2: Cut out three blade parts according to the marked locations and sizes.
- Step 3: Cut out main spar segments from the blade parts (Figure 4(b)).

In total, six main spar segments with a length of approx. 2400 mm of each were obtained (Figure 4(c)). The locations and dimensions of the main spar segments to be cut out for manufacturing the specimens were carefully planned to avoid damages that had developed in the commissioned time. For the convenience of manufacturing, each main spar segment was further cut into four smaller pieces with approx. 1240 mm in length. The segment is made of unidirectional glass fibre composites.

As shown in Figure 3, we aim to manufacture 1200 mm long test specimens with ply drop at $x_1 = 900$ mm. Figure 5 shows the cutting arrangement of main spar segment HZHAAA-02. We can see that there are three types of specimens planned to be cut out: samples for fibre orientation, fibre volume fraction, and substructure test specimens, respectively. The fibre orientation and fibre volume fraction tests are conducted to examine the properties of the laminate and provide knowledge for understanding the failure behaviour of substructure test specimens.

As illustrated in Figure 5, three substructure test specimens were cut into 1200 mm length and 40 mm width, and machined to achieve 18 mm thickness. Figure 6 shows the first three specimens prepared for tests, placed at the same location where they were cut from. The ply drop was made with a 30 mm long pre-crack to initiate the crack propagation. The pre-crack was made by clamping the specimen in crack tip area and initiating the crack by gently hammering a sharp chisel directly in ply drop transition layer.

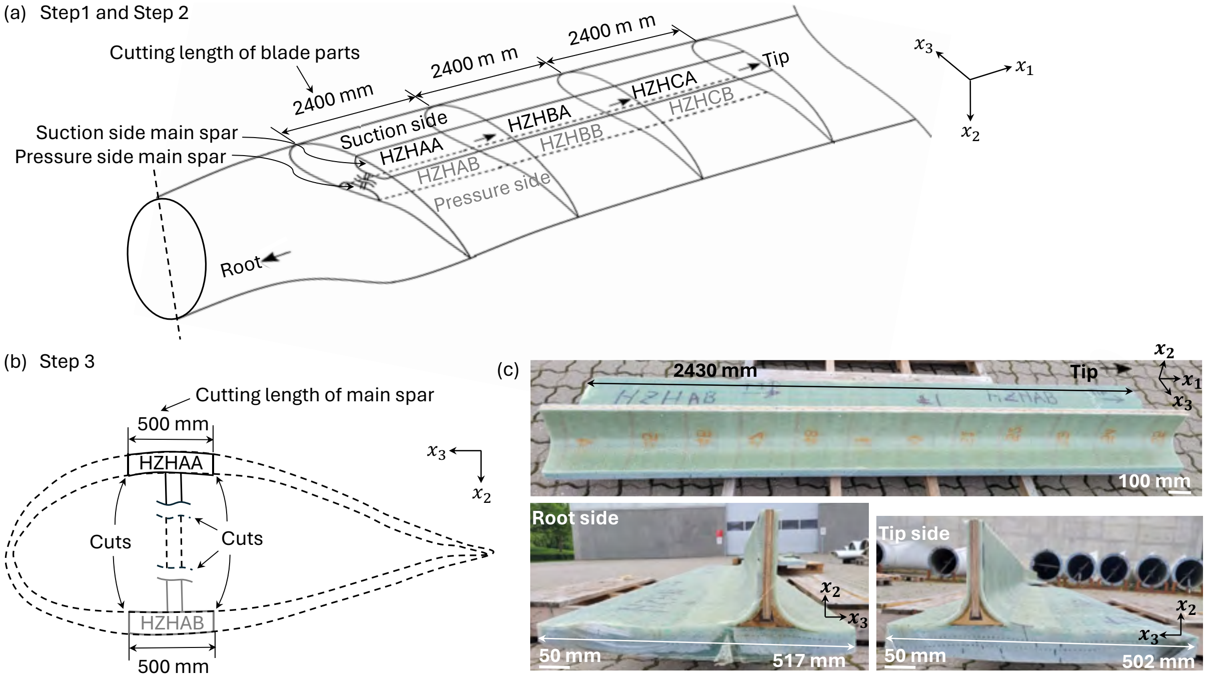


Figure 4. Cutting sketch of the decommissioned blade after in-field investigation. (a) Marked cutting dimensions and locations of three blade parts. (b) Marked cutting dimensions and locations of main spars. Dashed lines represent original blade cross section. (c) Images of cutout blade part HZHAB.

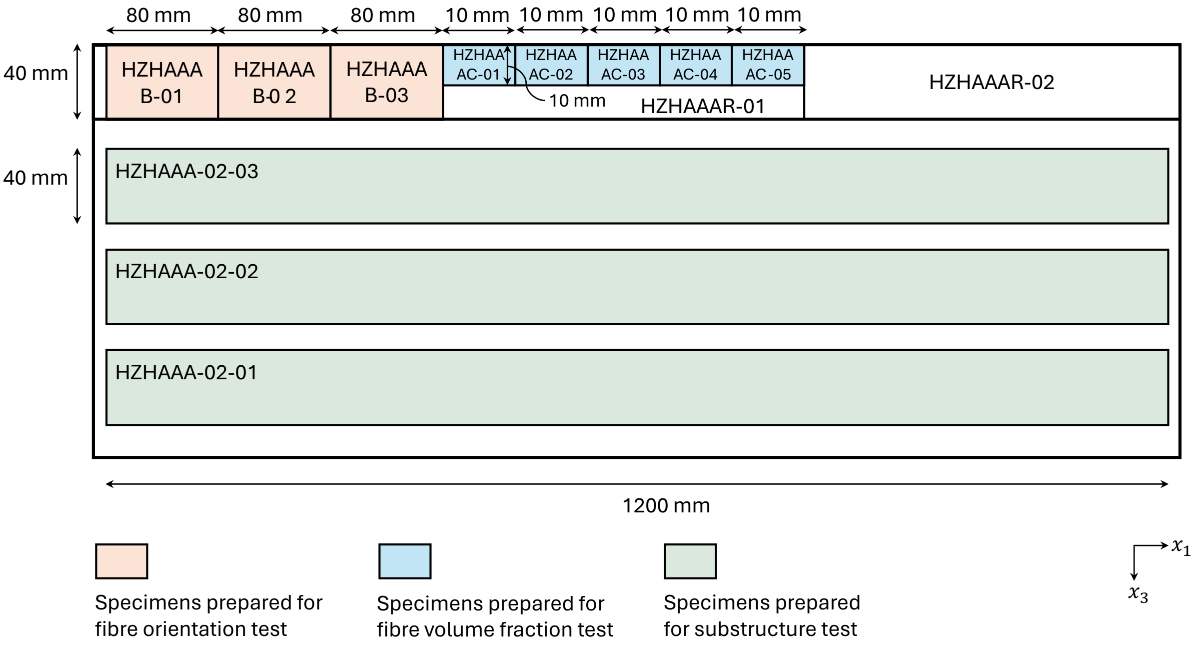
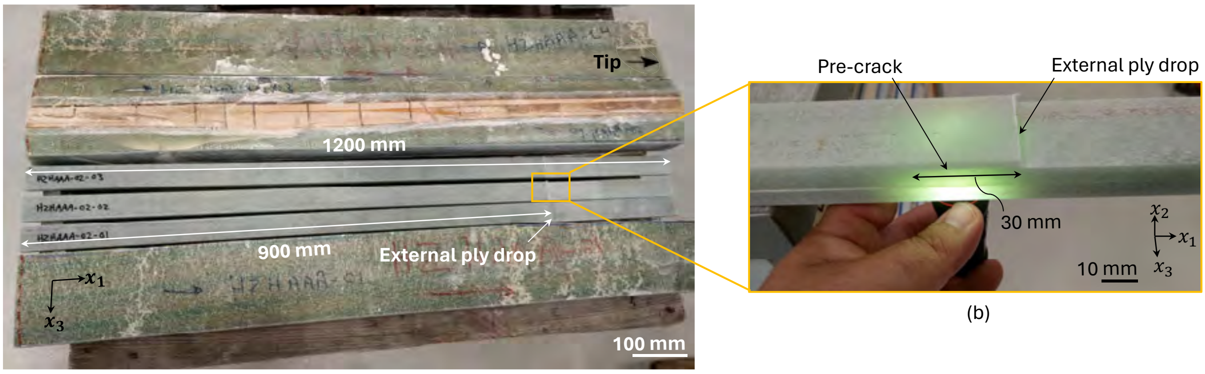


Figure 5. Cutting arrangement of main spar piece HZHAAA-02 to prepare samples for fibre volume fraction, fibre orientation, and substructure test specimens.



(a)

(b)

Figure 6. Substructure test specimens. (a) Locations of three specimens in main spar HZHAA. Ply drop is located at 900 mm. (b) Pre-crack made at the ply drop.

4. Summary

In this work, we present a design procedure for a substructure test specimen under cyclic tension-tension loading. The specimen is designed to study the predictability of the growth rate of fatigue delamination crack initiating at ply drops. The proposed design procedure provides a reference for manufacturing test specimens out of practical full blades. By testing specimens cut directly from decommissioned wind turbine blades, the practical fatigue delamination cracking behaviour in the main spars of the blades could be examined.

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References

[1] F. Mortensen and O. T. Thomsen. A simple approach for the analysis of embedded ply drops in composite and sandwich laminates. *Composites Science and Technology*, 59(8):1213–1226, 1999.
[2] D. Cairns, J. Mandell, M. Scott, and J. Maccagnano. Design and manufacturing considerations for ply drops in composite structures. *Composites Part B: Engineering*, 30(5):523–534, 1999.
[3] S. Obata, K. Takahashi, and K. Inaba. Laminate design for a tapered frp structure with ply drop-off based on yielding of resin pockets. *Composite Structures*, 253:112787, 2020.
[4] D. Samborsky, D. Avery, P. Agastra, and J. Mandell. Delamination and failure at ply drops in carbon fiber laminates under static and fatigue loading. In *44th AIAA Aerospace Sciences Meeting and Exhibit*, 1195, 2006.
[5] J. Wang, K. Potter, and J. Etches. Experimental investigation and characterisation techniques of compressive fatigue failure of composites with fibre waviness at ply drops. *Composite Structures*, 100:398–403, 2013.
[6] S. Goutianos and B. F. Sørensen. Fatigue crack growth rate at material and geometry transitions in glass-epoxy composites. *Composites Structures*, 275:114445, 2021.
[7] M. McGugan, M. Pereira, B. F. Sørensen, H. Toftegaard, and K. Branner. Damage tolerance and structural monitoring for wind turbine blades. *Philosophical Transactions A*, 373:20140077, 2015.

[8] B. F. Sørensen. Microscale testing and modelling for damage tolerant composite materials and structures. In *IOP Conference Series: Materials Science and Engineering*, 942(1):012004, 2020.
[9] T. Nakamura and S. M. Kamath. Three-dimensional effects in thin film fracture mechanics. *Mechanics of Materials*, 13(1):67-77, 1992.
[10] M. Kenane, S. Benmedakhene, and Z. Azari. Fracture and fatigue study of unidirectional glass/epoxy laminate under different mode of loading. *Fatigue & Fracture of Engineering Materials & Structures*, 33(5):284-293, 2010.