Dynamic delamination in curved composite laminates under quasi-static loading

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Abstract. In the wind energy industry, new advances in composite manufacturing technology and high demand for lightweight structures are fostering the use of composite laminates in a wide variety of shapes as primary load carrying elements. However, once a moderately thick laminate takes highly curved shape, such as an L-shape, Interlaminar Normal Stresses (ILNS) are induced together with typical Interlaminar Shear Stresses (ILSS) on the interfaces between the laminas. The development of ILNS promotes mode-I type of delamination propagation in the curved part of the L-shaped structure, which is a problem that has recently raised to the forefront in in-service new composite wind turbines. Delamination propagation in L-shaped laminates can be highly dynamic even though the loading is quasi-static. An experimental study to investigate dynamic delamination under quasi-static loading is carried out using a million fps high speed camera. Simulations of the experiments are conducted with a bilinear cohesive zone model implemented in user subroutine of the commercial FEA code ABAQUS/explicit. The experiments were conducted on a 12-layered woven L-shaped CFRP laminates subjected to shear loading perpendicular to the arm of the specimen with a free-sliding fixture to match the boundary conditions used in the FEA. A single delamination is found to initiate at the 5th interface during a single drop in the load. The delamination is then observed to propagate to the arms at intersonic speed of 2200m/s. The results obtained using cohesive zone models in the numerical simulations were found to be in good agreement with experimental results in terms of load displacement behavior and delamination history.

1. Introduction

Composite structures play an important role in the wind turbine industry due to their low weight and high stiffness values especially in load carrying members of large scale wind turbine blades. One of the critical parts is the radius region of composite brackets in the main spar of the turbine blades (L-shaped connector structures). Understanding failure process of these members becomes a significant issue in the design process of the blades. When the external loads on a turbine blade are analyzed, they can be reduced to three simple loading cases namely, axial load which is parallel to the arm (P), shear load which is perpendicular to the arm (V), and the moment load (M). These external loads all lead to
generation of Interlaminar Normal Stresses (ILNS) together with typical Interlaminar Shear Stresses (ILSS) on the interfaces between the laminas.

The delamination failure in L-shaped composite laminates under perpendicular loading to the arm was investigated. In the 1990s, Martin et. al.[1], [2] determined numerically the location of highest radial stress in curved region where delamination is assumed to initiate. They showed that delamination propagates in to the arms of the laminate predominantly in opening mode using energy release rate analysis. In their experimental analysis, delamination growth was found to be unstable but the growth of delamination was not captured. In 2000s, Wimmer et. al. [3] studied the same problem. Their computational models using VCCT showed unstable crack growth for the case without any initial crack and a stable crack growth for a 3-mm pre-crack. In their experimental analysis, they showed the instantaneous load drop in load displacement curve occurred during crack propagation. Feih and Shercliff (2005) [4] also investigated the failure of L-shaped composite laminates positioned between a composite base and vertical rib for perpendicular to the arm loading case. The finite element model is carried out on ABAQUS with UMAT subroutines combined with Hashin's failure criteria for matrix and fiber cracking and with Tong-Norris delamination onset criterion. In numerical results, they showed the failure sequence and failure types with locations and validated by strain gage results in experiments. Gozluklu and Coker (2012) [5] carried out explicit finite element analysis with cohesive elements to model delamination in composite L-beams subjected to parallel loading instead of perpendicular loading. In their simulations, they observed dynamic crack growth and the crack tip speed reaches the shear wave speed of the laminate.

This paper contains experimental and numerical investigation of delamination which is the dominating fracture mode of L-shaped composite beams. Experiments were carried out in which load displacement behavior is recorded and delamination initiation and propagation process is captured with a high speed camera. FEM studies are conducted with cohesive element method and load displacement, stress state, delamination process is investigated.

2. Experimental method and material

2.1. Material and specimen geometry

The specimen was chosen as a simplified version of a typical stacking and material used in the applications of the wind turbine industry. The L-shaped geometry is representative of the corners of the wind turbine spars. The L-shaped composite specimen geometry used in the experiments with dimensions and the coordinate axes are shown in Fig. 1(a). The lengths of the lower and upper arms are 90 mm and 150 mm, respectively. The inner radius at the corner is 10 mm and the width is 30 mm.

The specimen is made of 12 layers of HexPly® AS4/8552-5HS plain weave fabric plies with a lay-up of [0/90]s. The specimens were manufactured by hand lay-up technique where the pre-pregs with a cured thickness of 0.28 mm were laid up on a right angled male tool. After the curing, thickness of the laminate is measured to be uniformly 3.36 mm. The longitudinal and transverse moduli of the composite laminate are 55.7 GPa and 8.5 GPa, respectively and the Poisson's ratio, \( v_{12} \), is 0.05 [6]. In order to obtain micrographs, the specimens were cut through plane A and plane B in Fig. 1a using a diamond saw cutter and were stabilized in an epoxy mount for microscopic inspection. Optical micrographs show the cross sectional views of the plain weave fabric in planes A and B in Fig. 1b-c, respectively where the distribution of the 0° fibers and 90° fibers in the woven plies are shown. In the micrographs 7 plies can be seen. The specimen is assumed to be transversely isotropic considering the fiber architecture of the plies. By using the transversely isotropic assumption, the shear wave speed, \( c_s \), and the Rayleigh wave speed, \( c_R \), are calculated using the reduced stiffness matrix are given by [7],

\[
c_s = \left( \frac{c_{66}}{\rho} \right)^{1/2},
\]

(1)
where $c_{ij}$ are the reduced stiffness matrix coefficients, $\rho$ is the density, $v$ is the speed of the surface wave. The shear wave speed for this laminate is calculated as 1636 m/s from Equation 1 and the Rayleigh wave speed is calculated from the real root of Equation 2 as 1572 m/s [7].

\[
\left(\frac{c_{11} c_{12}^2 - c_{12}^2}{c_{12}^2 c_{66}} \right) \left[ \frac{c_{12}^2}{c_{11}} \left( 1 - \frac{\rho v^2}{c_{12}^2} \right) \right]^{1/2} - \frac{\rho v^2}{c_{66}} \left( 1 - \frac{\rho v^2}{c_{11}} \right)^{1/2} = 0. \tag{2}
\]

Figure 1. (a) Specimen geometry and dimensions and (b-c) optical micrographs of cross-sections taken from Planes A and B, respectively.

2.2. Experimental setup

The L-shaped composite beam is subjected to quasi-static shear loading perpendicular to the horizontal arm. The schematic of the experimental fixture that illustrates the loading condition for the L-shaped composite is shown in Fig. 2(a) together with a photograph of the system in Fig. 2(b). The vertical arm of the L-shaped specimen is clamped and bolted to the lower fixture. The fixture is mounted on a linear motion bearing system which is free to move along the x-axis. The sliding part of the fixture gives a smooth precision motion along the x-axis in order to avoid any reaction force along the x-axis to the upper arm [14]. The horizontal arm of the specimen is bolted to a pivot pin bearing system in order to fix the arm with respect to the corner of the specimen which is free to rotate around the z-axis. The load-displacement data during the experiment is recorded and an ultra-high speed camera system is used to capture the images of the delamination initiation and propagation. The experimental setup showing the fixture, loading and high speed camera system is shown in Fig. 3.

A Shimadzu Autograph AGS-J series with 10 kN capability screw-driven displacement controlled tensile-compression testing machine was used. All tests were conducted at a cross-head speed of 3 mm/min for quasi-static loading. Photron FASTCAM SA-5 high-speed camera system which records the images with frame rates of 7500 fps at full resolution of 1 MP and at 1,000,000 fps at reduced resolution were used. Since the delamination process had been expected to occur at least at the speed of the Rayleigh wave speed, the frame rates of 372,000 and 500,000 fps were chosen. A field of view of 17.5 mm x 15.7 mm is recorded using a 50 mm lens with 12.5 mm extension tubes during the
experiment. Aerosol-Art Ral 9010 white color was used to paint the side face of the specimen to create a contrast for better visualization of the delamination. The images are recorded continuously about 4-5 seconds (2,000,000 frames at 120x64 pixels) that is saved when the record button is triggered manually at the first crackling sound (2 seconds pre-trigger and 2 second post-trigger). The time interval between two pictures is either 2.7 μs or 1.9 μs, where the complete delamination process lasts less than 20 μs in the camera records. The focused area can be captured by 64x120 pixels at the high frame rates.

3. Experimental results

The load displacement curves of the L-shaped composite laminates are shown in Fig. 4. The results for experiments F1, F2 (from 1st batch) and F6 (from 2nd batch) are presented in which the load increases with displacement in the linear elastic region before a sudden load drop is observed at the point of delamination. Both experiments F1 and F2 yielded similar stiffness values and maximum load values of 38.8 N/m and 743 N, respectively, with a 20% variation. The result of F6 was slightly different than F1-F2 since it was from a different batch. Maximum load and stiffness values were
calculated as 931 N and 43.7 N/m, respectively. The sudden load drop is associated with delamination initiation and propagation. It should be noted that, during the loading, low level crackling sound is heard at 60-70% of the maximum load which is attributed to matrix cracking, however, no effect on the load-displacement curves is observed. At the instance of the load drop, a sudden high level breaking sound is heard in real time.

Figure 4. Load-Displacement Curves for experiments F1, F2, F6 and simulation.

After crack propagation ended, single or multiple delaminations were seen on the specimen starting at the curved part and continuing to the arms. After the load drop, load carrying capacity of the specimen decreased substantially to almost 30% of the maximum load after which the experiment was stopped.

During the load drop, images of the delamination initiation and propagation process were captured with a high speed camera system. Figure 5 shows the high speed images of the curved region during initiation and propagation of delamination. The time step between two frames is 1.9 μs. The crack initiates between 5th and 6th plies at 12° left of the center of the curved region and then grows into both arms (Fig. 5b). During the crack formation, some fiber bridging can be observed at the crack surface (Fig. 5e). The delamination then propagates rapidly in both directions into the arms, leaving the field of view in 10 μs (5 frames). As the delamination grows, the separated plies are seen to oscillate and are damped after 4 cycles. The oscillation frequency was calculated from high speed images as 33.3 kHz. After a time interval of 510 μs, a second crack nucleates at the right arm between 10th and 11th plies (Fig. 5g). The first seven pictures in Fig. 5 belong to experiment F2 where the camera was focused on the curved region. On the other hand, the last two pictures belong to experiment F6 which were captured by the camera focused on the lower arm of the specimen.

The crack lengths are measured from the images until the crack leaves the field of view. The crack tip locations measured from the crack nucleation point as a function of time are shown in Fig. 6. Both right and left crack tips in the curved region for F2, right crack tip in the curved region for F1 before 10 μs show that crack growth is similar to each other reaching 8-10 mm crack lengths before the cracks leave the field of view. The first crack length measured is around 3 mm. In the following two frames, the crack growth continues in both directions at a decreasing rate. In the last picture just before leaving the field of view in the curved region at 8 μs, the crack growth has an upward trend for both experiments and crack tips, with crack length difference changing from 2 mm to 6 mm between two frames. For time greater than 10 μs, the results of F6 is superposed in the plot where the camera is focused on the left vertical arm. The crack growth increases in this part, compared to that of the curved region with the crack length difference between two successive images increasing up to 9 mm at this part.
Figure 5. (a-g) High speed camera images of the curved region with a field of view of 15.7 mm by 17.5 mm (experiment F2) at 1.9µs time interval showing delamination nucleation and propagation, (h-i) high speed camera images of the vertical arm with a field of view of 32.01 mm by 16.36 mm (experiment F6) with 2.7µs time interval showing delamination propagation.

The crack tip speeds are calculated from the crack length data using backward difference method. The crack tip speeds as a function of time are given in Fig. 7 for the right and left crack tips. For experiment F1, both crack tips initiate at 1200 m/s; on the other hand, experiment F2 initiates at 600m/s. In both experiments, the crack tip speeds accelerate approximately to the Rayleigh wave speed at the end of the curved region. In the third experiment (Exp. F6), crack enters the field of view in the vertical arm at 2200 m/s and goes up to 3200 m/s before slowing down to 500 m/s before arresting. This is the first experimental observation of intersonic delamination in composite materials.
4. Finite Element Method and Results

Finite element analysis with cohesive zone model is used to simulate the experiments. The cohesive zone model (CZM) used in this study is Bilinear CZM that has been proposed by Mi et al. [8]. The constitutive law of the CZM is based on surface tractions (T) and relative displacements in mode-I ($\delta_I$), mode-II ($\delta_{II}$) and mixed mode ($\delta$). The constitutive law shows a triangular profile formed by initiation and propagation criteria as shown in Fig 8. The initiation criterion is taken from Chang and Springer [9] that provides a quadratic function based on pure-mode maximum tractions. The propagation criterion is Benzegagh and Kenane [10] (B-K criterion) which is based on curve fitting of mixed-mode fracture experiments. The derivation can be found in Camanho and Davila [11]; hence, it is not provided here. In the Bilinear Model, six parameters are required. The first two are the cohesive strengths in mode-I (maximum normal traction) and mode-II (maximum shear traction) which are found to be 40 MPa and 53 MPa, respectively, using 4-Point Bending and Short-Beam Flexure tests, respectively. The fracture toughness in mode-I ($G_{IC}$) and mode-II ($G_{IIC}$) are experimentally obtained as 375.3 N/m and 1467.1 N/m, respectively. The experiments for obtaining $G_{IC}$ and $G_{IIC}$ are Double Cantilever Beam (DCB) and End-Notch Fracture (ENF) tests, respectively. Finally, the curve fitting parameter of B-K criterion and undamaged stiffness of the cohesive model which are found to be 40 MPa and 53 MPa, respectively, using 4-Point Bending and Short-Beam Flexure tests, respectively. The fracture toughness in mode-I ($G_{IC}$) and mode-II ($G_{IIC}$) are experimentally obtained as 375.3 N/m and 1467.1 N/m, respectively. The experiments for obtaining $G_{IC}$ and $G_{IIC}$ are Double Cantilever Beam (DCB) and End-Notch Fracture (ENF) tests, respectively. Finally, the curve fitting parameter of B-K criterion and undamaged stiffness of the cohesive model are taken as 2.25 [5] and $10^{14}$ N/m², respectively. The model has been implemented into ABAQUS/Explicit via user-subroutine. The interface element uses Newton-Cotes integration scheme as suggested by Schellekens and de Borst [12].

The mesh of the L-shaped composite laminate is shown in Fig 9. The length of the arms is 40 mm that represent the region free to deform. The morphology of the mesh is uniform. The width of the
elements is 125 μm and the high of the element is 70 μm that are found after a rigorous mesh sensitivity study. The tips of the arms are inhibited for delamination propagation since they are clamped in the experimental setup. The tip of the lower arm is clamped, whereas the tip of the right arm is loaded by displacement input with a smooth profile. The interface elements are located at all interfaces. The type of the body elements is made of “CPE4R” elements which is quadrilateral plane strain element with single integration point at the centroid [13].

![Figure 8 Mixed-mode constitutive law of Bilinear CZM.](image)

The stress contours before delamination and at the end of delamination propagation is shown in figure 10. The normal ($S_{33}$), shear ($S_{13}$) and longitudinal ($S_{11}$) stress contours prior to the initiation is shown in Fig 10-top. The initiation is observed at the 5th interface with the angular location of 13° counterclockwise from the center of the curved region where the maximum normal stress reaches 40 MPa. The arms are under compressive stress together with non-zero shear stress distribution. This favors pure mode-II loading condition in the arms. The longitudinal stress profile reveals a typical view of a beam under bending. At that instant, the load reaches to maximum of 750 N as shown in figure 4 with a perfect agreement to experiment F1. At the final view, the delamination at the 5th interface has propagated to the ends of the arms during the load-drop (Fig 10-bottom). The propagation occurs during the load drop in figure 4. None of the stresses reaches interfacial strength of the laminate that would initiate another delamination at the arms.

The crack tip speeds as a function of time for the left crack tip calculated from the finite element model is shown in Fig. 11. For the simulation, it can be seen that the initiation takes place intersonically in about 2 μs. The crack propagates in sub-Rayleigh wave speeds for 4 μs after the initiation. Next, the crack propagates at sustained intersonic speeds of 3500 m/s for about 8 μs. The crack tip speeds obtained by the experiment F2 are in good agreement. The results of F6 experiment are in agreement for the intersonic crack propagation. Noting that the delamination in F6 occurs in the 4th interface whereas F2 shows the delamination at the 5th interface that is the same with the
simulation. Moreover, the occurrence of vibrations is also observed where the frequency is calculated around 33 kHz in the simulations.

Figure 10 Normal ($S_{33}$), shear ($S_{13}$) and longitudinal ($S_{11}$) stress distributions of the L-shaped composite laminate prior to the initiation (top) and at the final view (bottom).

Figure 11 Crack tip speed as a function of time curves of simulation and the experiments for the left crack tip.

5. Conclusions

Dynamic delamination of L-shaped composite brackets with [0/90]$_6s$ woven fabric layup were investigated. Experiments were conducted in which L-shaped brackets were subjected to quasi-static shear loading and subsequent dynamic delamination was captured with a million fps high speed camera. In addition, load displacement curves were also recorded. Numerical analysis was performed using cohesive zone method to further investigate the delamination propagation in terms of having stress field and continuous curves of crack tip speeds. The following conclusions were drawn:

- High speed camera images shows that crack initiates between 5th and 6th plies at 12° left of the center of the curved region and then grows to both arms. The same initiation location is predicted by the simulation which shows that the maximum normal strength is attained at the initiation point.
• The experiments and the simulations are consistent in delamination growth starting at sub-Rayleigh speeds and reaching intersonic speeds as the crack propagates from curved region to the arms. This behavior is attributed to crack initiating under pure mode-I condition (where crack tip theoretically cannot exceed Rayleigh wave speed [7]) and propagating to the arms changing to pure mode-II loading condition where intersonic crack growth is shown to be theoretically possible [7].

• Vibrations initiated by delamination are observed in both experiments and simulations. The vibrations are associated with sudden release of strain energy dominantly attributed to radial opening stresses. The strain energy is transformed into fracture and kinetic energy observed in the form of vibrations [15].

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