NUMERICAL INVESTIGATION OF DELAMINATION IN L-SHAPED CROSS-PLY COMPOSITE BRACKET

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Abstract

Interlaminar normal stresses are induced with interlaminar shear stresses leading to mixed-mode delamination (MMD) in curved cross-ply composite laminates. Dynamic mixed-mode delamination is studied using explicit finite element method and Cohesive Zone Modelling. Dynamic response of the specimen is compared with the experiments.

1. Introduction

Composite materials are highly advantageous compared to metallic materials due to their high specific strength. Although having been used in aerospace structures for more than 40 years, they recently made their way to be extensively used in commercial airplanes with B787, and A350 programs. The full potential of composite materials is being exploited incrementally and slowly, due to its complex structure.

L shaped composite materials are used in the areas where load transfer is needed to form a torque box by connecting two structural members. The spars and ribs of a wing structure are joined to the panels with the help of L-shaped composite materials. Under loading, interlaminar stresses occur between the laminas in the curved region. These stresses impose Mode-I, Mode-II, and Mode-III type of fractures which are shown in Figure 1. While it has been proven that Mode-I stresses are the source of most critical failure mode "delamination" in these type of structures, they occur simply because of the highly curved shape of the radius.

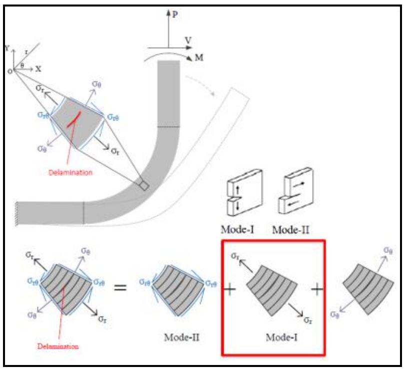

Figure 1. Interlaminar stresses inside a curved laminate under normal load [1]

Gozluklu and Coker [1] carried out explicit finite element analysis with cohesive elements to model delamination in composite uni-directionally stacked 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. The results of this study were correlated with test performed by Uyar and Arca et al. [2] showing crack location. Uyar and Arca et al. [2] also performed cross-ply [0/90] stacking configurations tests as shown in Figure 2, which were not derived with numerical studies previously.

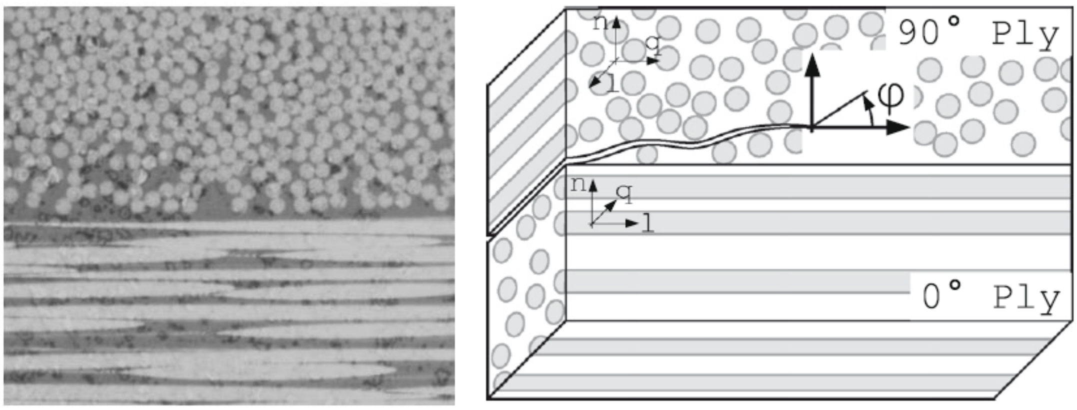

Figure 2. Optical micrographs of a cross-ply composite specimen showing cross sectional distribution of fibers and epoxy matrix [2]

In this paper, an L shaped composite laminate bracket with 17 layers of cross-ply stacking under normal loading is dynamically simulated with ABAQUS, using cohesive zone modeling. The numerical outputs of the simulation will be compared with the test results.

2. Geometry / FEM

2.1. Geometry

The test specimen manufactured for the tests performed is shown in Figure 3. The laminate is manufactured by hand lay-up technique. HexPly® AS4 / 8552 UD carbon pre-pregs having 0.18 mm cured thicknesses are laid up using right angled male tool. The width of the bracket is 30 mm wide. The stacking is in a 17 layer, cross-ply $[0/90]_{17}$ configuration. The dimensions are tabulated in Table 1. In the test, the force is applied to the specimen trough a displacement controlled testing machine creating V (perpendicular load), and M (bending moment) on the structure. The fixture includes a free to rotate pivot-pin system, which enables to keep the load perpendicular since the clamped part is connected to a rail. The test system and tested specimen dimensions are also shown in Figure 3.

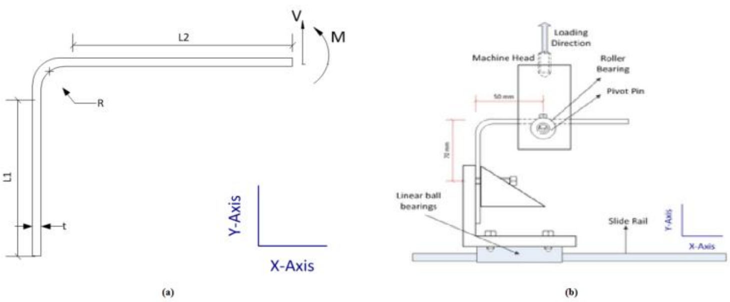

Figure 3. (a) Geometry and dimensions of the manufactured laminate [2] **(b)** L bracket test setup [2]

w [mm]	L_1 [mm]	L_2 [mm]	R [mm]	t [mm]
30	90	150	10	3.13

Table 1. Geometrical properties of the manufactured laminate

2.2. Finite Element Model

The finite element model is assembled to reflect the test setup as much as possible. The load applied, and fixed nodes have roller type BC's defined in the analysis while the dimensions used are representing the test part of the specimen.

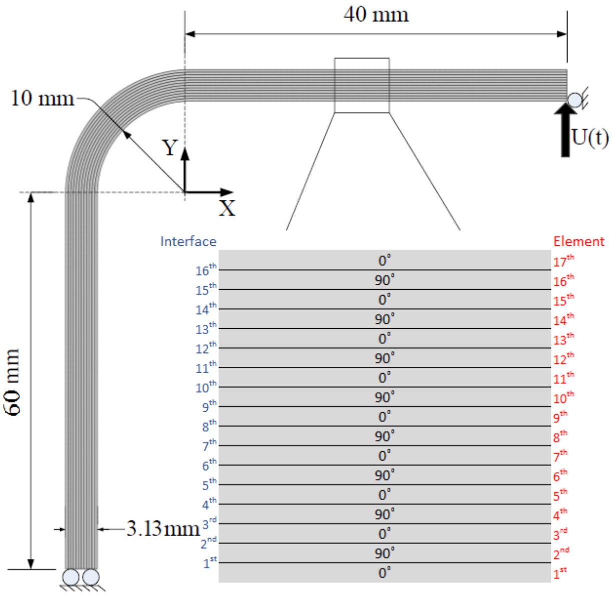

Figure 4. Finite element model sketch showing geometry, boundary conditions, and interfaces

ABAQUS is used for the simulation of the test. Each ply is modeled with CPE4R solid element, whereas COH2D is used to model interface elements laying in each interface. The loading is applied dynamically over a period of 0.01 seconds.

The AS4/8552 laminate mechanical properties used in the study are taken from [5] and tabulated in Table 2.

E_1 [GPa]	$E_2 = E_3$ [GPa]	$G_{12} = G_{13}$ [GPa]	v	Ply thickness [mm]	Density [gr/cm^3]
135	8.5	4.2	0.29	0.184	1.59

Table 2. Mechanical properties of AS4/8552 laminate.

3. Cohesive zone modeling methodology

The formulation of the cohesive element is based on the Cohesive Zone Model (CZM) approach for modeling complex fracture mechanisms at the crack tip. The cohesive zone approach models an extended cohesive zone, or process zone, ahead of the crack-tip using traction-separation laws that relate the opening displacements in the process zone to the resisting tractions. The traction separation laws are defined in each fracture mode by an initial elastic stiffness, the peak traction, or interfacial strength, and the area under the traction-separation law that is equal to the critical energy release rate. An illustration of a CZM is shown in Figure 5.

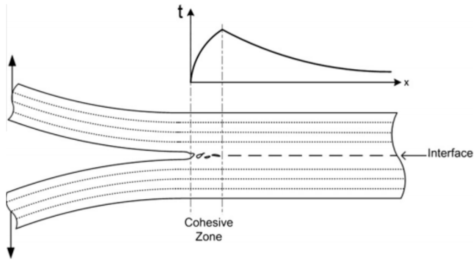

Figure 5. Cohesive zone region illustration

Bilinear (BL) is one of the most popular CZMs in the composite literature for simulating the initiation of delamination with its ability to correctly represent composite laminate interfaces. Its relation is given by;

$$t = \begin{cases} E_0\delta, & \delta < \delta_0 \\ (1-d)E_0\delta, & \delta_0 \leqslant \delta \leqslant \delta_c \\ 0, & \delta > \delta_c \end{cases} \tag{1}$$

Where E_0 is the initial (penalty) stiffness, d is the damage term, and δ is the displacement. δ_0 represents the delamination initiation at the interface, while δ_c represents a wholly damaged interface. The bilinear relation is shown in Figure 6.

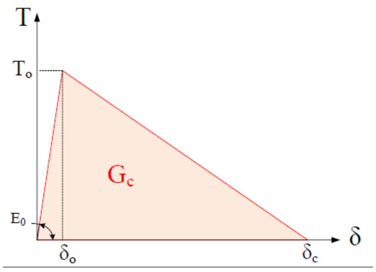

Figure 6. Bilinear cohesive zone model traction displacement chart.

There are two steps to the whole delamination process which can be separated as initiation and propagation.

3.1. Initiation

Chang and Springer [3] proposed a quadratic function to guess delamination initiation based on the excession of critical interlaminar tractions in mixed mode. The function is given by,

$$\left(\frac{T_I}{T_{o,I}}\right)^2 + \left(\frac{T_{II}}{T_{o,II}}\right)^2 = 1 \tag{2}$$

The delamination initiates when the applied tractions are outside of the formed elliptical surface by this quadratic function.

3.2. Propagation

A mixed-mode fracture toughness criterion suggested by Benzeggagh and Kenane [4] can be used in mixed mode cases for the proparagation fracture toughness. The criterion is a curve fitting approach performed for various mode-mixities determined by double cantilever beam (DCB), mixed-mode bending (MMB) and end notch fracture (ENF) tests. The mixed mode fracture tougness is given by,

$$G_c = G_{IIc} - G_{Ic}\left(\frac{G_{II}}{G_I + G_{II}}\right)^{\eta} \tag{3}$$

where G_{Ic} and G_{IIc} are the fracture toughness values in mode-I and mode-II, respectively. The parameter (η) is the curve fitting value for fracture toughness test. A rate-independent cohesive law using static fracture toughness values are assumed for dynamic crack growth which are tabulated in Table 2.

G_{Ic} [J/m^2]	G_{IIc} [J/m^2]	$T_{o,I}$ [MPa]	$T_{o,II}$ [MPa]	B-K criterion
375.3	1467.1	40	53	2.25

Table 2. Interface properties of AS4/8552

4. Results

4.1. Cross-Ply vs unidirectional stacking results

A unidirectional finite element model was created simply by modifying the directional mechanical properties of the 90˚ plies. The delamination initiates from the center of the thickness of the laminate, closer to the lower half of the radius. Delamination initiation plots are shown in Figure 7.

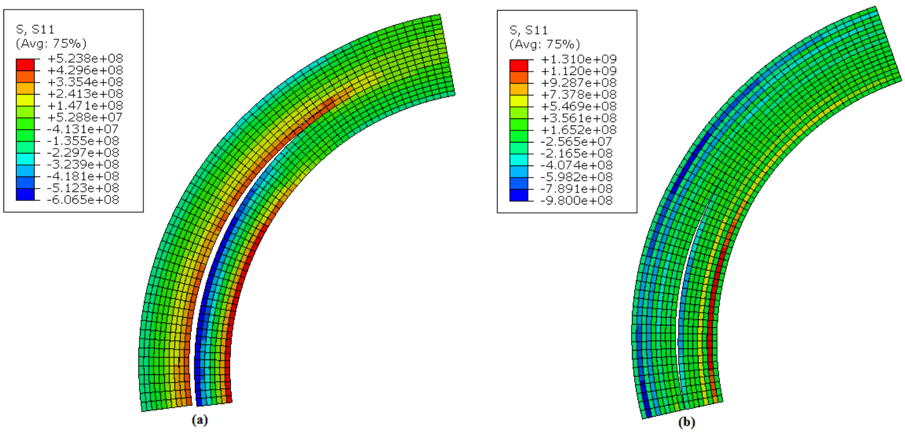

Figure 7. Delamination initiation for (a) UD layered bracket (b) Cross-ply layered bracket

The first delamination force is calculated around 900 N for both of the stacking configurations. There was not a difference regarding that the two specimens are differently stacked.

4.2. Cross-ply vs Test results

The delamination initiation observed in the test is shown in Figure 8. It can be noted that, the failure occurs at the ply interface near the radius. This failure location is specific to the cross-ply stacking configuration, and was not observed in laminates with unidirectional stacking configuration.

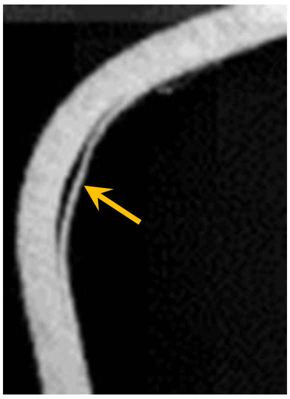

Figure 8. Delamination initiation location for a 17 cross-ply laminate [2]

The delamination initiation in Figure 7b predicts the delamination initiation near the center interface. Boundary conditions, mesh sensitivity, cross-ply interface behavior, cohesive zone models may be the source of inaccurate simulation.

5. Conclusion

A 17 layer cross ply laminated composite bracket under normal loading was investigated. The simulation results did not match well with the test results, by not being able to predict the failure location. It was shown that, the methods that is able to correctly simulate a UD stacking delamination, fails to predict cross-ply stacking configurations in the same way. A great deal of effort is being made to understand and correctly simulate the effect of stacking configurations on the failure characteristics of the laminate in METU Aerospace Engineering department. Other cohesive zone models, such as Xu-Needleman [6] will be used to correctly simulate cross-ply stacking delamination initiation and propagation behavior.

References

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