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Numerical simulation of delamination under mixed mode loading of woven fabric reinforced composites through cohesive zone elements

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***Abstract*— Numerical model for prediction of progressive delamination in woven fabric reinforced composite is proposed in this paper. An orthotropic model is used in which the interface is modeled as bilinear cohesive zone elements subjected to mixed mode loadings. The mixed mode loading is applied through displacements. Mesh insensitive model is obtained at a converged mesh. Mass scaling is used to run the model at high mesh density and the results are accurately found. Effect of displacement rate is studied. Load displacements graphs are obtained, and they agreed with the experimental load displacements graphs.**

Keywords—mixed mode; composite; woven fabric; cohesive zone; laminates

I. INTRODUCTION

Delamination is one of the most common type of damage in composite laminates due to their week interfacial strength. Delamination in composites is studied extensively in the past few years. Woven fabric reinforced composites exhibit complex failure mechanisms such as fiber cracking, matrix cracking and interface damage modes predominantly delamination. Woven fabric reinforced composites are used extensively in aerospace, automobile and wind turbine blades etc. Delamination can occur in different modes. Practically delamination occurs in mixed mode. For Accurate prediction of delamination in composite laminates, numerical model is required. A detailed orthotropic model with an interface modeled as cohesive zone elements is used in this paper for prediction of progressive damage in woven fabric composite laminates.

For prediction of delamination as a main concern, several modeling techniques have been suggested in literature which can be used to model the interface for predicting damage initiation and damage progression [1, 2, 3, 4]. Most analyses of delamination apply a Virtual crack closure technique approach to model the interface, which require crack front development by complex meshing, Other analyses use fracture mechanics technique for evaluation of fracture energy through J-integral [1, 2]. A more advanced and appealing approach to overcome all the complexities is cohesive zone approach. Cohesive zone modeling was first proposed by Dugdale [4], later Barenblatt [5] and Hillerborg et al [6] improve the model. Since then many researchers have worked on cohesive zone approach [7, 8, 9].

For better performance of composite laminates, woven fabric reinforced composites are preferred than unidirectional laminates. In recent years mixed mode loading behavior of different unidirectional and multidirectional laminates has been the focus of many researchers [10, 11, 12, 13, 14, 15]. The performance of composite laminates depends on stacking sequence, Fiber orientation, fiber matrix bonding and fracture toughness of the specimen. Enhanced properties have been proven experimentally with different fiber orientation [11, 14].

This paper focuses on numerical modeling of mixed mode woven fabric reinforced composite. The model is validated with experimental results. Detailed numerical model incorporating all the mixed mode ratios, predicting progressive delamination and how to run mixed mode with high mesh densities have not been studied yet. Mixed mode experimental tests have been conducted with various mode ratios to obtain the load-displacement curves according to Astm standard [16]. Numerical model is suggested using built-in composite layup model for plies, for prediction of progressive damage of the interface cohesive zone model has been used.

II. EXPERIMENTAL SETUP

A. Test specimen

Specimens for experimental tests were prepared using Primco-SL246/40, which is glass fiber/phenolic pre-preg. (8-harness stin weave glass fabric pre-impregnated with a modified phenolic resin mix to a nominal 40% resin content). Quickstep method was used to manufacture these specimens. The layup consists of 12 layers of prepreg $(0/0_f)$. A polymer film with thickness between 5-7μm was used as delamination insert after laying up six plies. The delamination insert length was approximately 65mm (to have approximately 50mm of delamination after cutting the edges). The final approximate dimension of the specimens was, span length 110mm, width 20mm, thickness 30mm and delamination length 30mm.

B. *Experimental procedure*

Reeder and Crews [17, 18] first proposed mixed mode bending test. This standard after improvements and redesign has been adopted by American Society for Testing Materials as ASTM D6671/D6671 M-03 [16]. This standard is followed for experimental work. This test method is commonly referred as Mixed Mode Bending (MMB) test, standard test fixture required for these tests was supplied by Wyoming Test Fixtures, Inc. The MMB test fixture used in one of the test with key components labeled is shown in figure 1.

Initiation and progressive damage of delamination in composite laminates take place under combined effect of normal and shear mode. The MMB loading is combination of simple mode 1 (Normal) and mode 2 (Shear). Figure 1 shows the picture of the actual test, the load P applied and the loading lever in terms of load P. The loading position c in figure 2 determines the mode mix that is applied. The details of specimen are shown in figure 3.

Experimental tests were performed according to the standard [20]. Tests were performed for mode mix ratios of (20%, 30%, 50%,75% and 100%). Five specimens were tested for each mode mix ratio. Table 1 shows the different mode mix ratios and their corresponding loading lever position. Mode mix ratio can be changed by changing the load position c. Pure mode 2 can be achieved by applying the load on the mid position of the specimen and pure mode 1 can be attained by removing the lever and directly applying load on the hinge.

Table 1 Mode mix ratio and loading lever

Mode mix	**20%**	**30%**	**50%**	**75%**	**100%**
Loading lever c	112mm	67mm	39mm	29mm	21mm

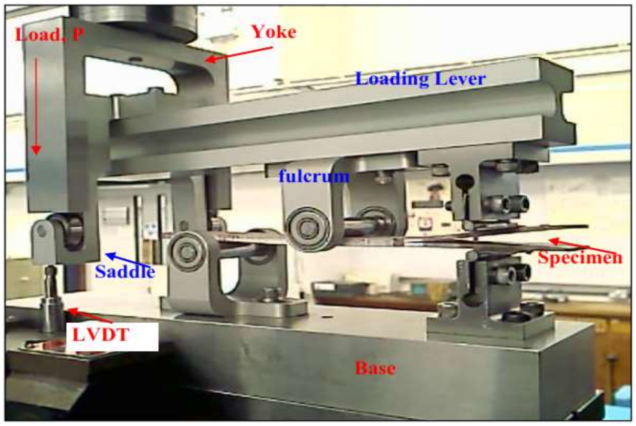

Fig. 1 The mixed mode bending test jig and specimen during a test

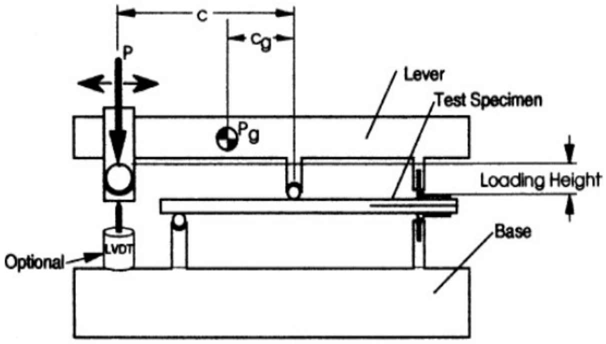

Fig. 2 The schematic of MMB apparatus from [20]

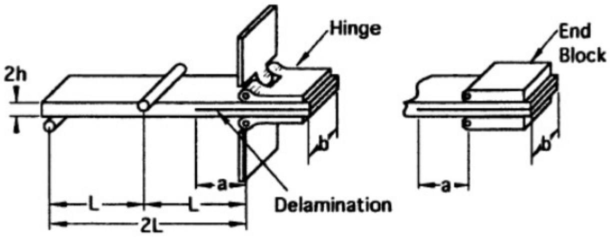

Fig. 3 The schematic of MMB test specimen and variables from [20]

III. NUMERICAL SIMULATION

Numerically simulated model was created in ABAQUS 6.14, consisting of 12 individual plies and an interface modelled as cohesive zone elements with a pre-crack in the middle.

A. *Modelling of geometry and boundary condition*

Figure 4 shows model dimension and boundary conditions. The dimensions of the numerical model are same as the experimental model with span length of 110mm, width 20mm

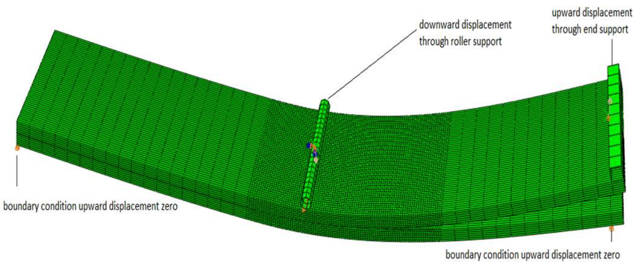

Fig. 4 Schematic of numerical model

and thickness 4mm. FE simulations are carried out for all the mode mix ratios given in table 1. On the lower side of the specimen displacement in z axis is zero at two ends of the specimen as shown in figure 4. The end support on upper side which is the hinge in experimental specimen is modeled as discrete rigid and the roller is also model as discrete rigid. The end support is linked with specimen as tie constraint and the roller is placed on the specimen with general contact interaction defined and all degree of freedom except z axis is placed zero for the roller as shown in figure 4. To achieve different mode mix, G_{11}/G_t ratio, displacement boundary condition is applied according to (1), where U is the applied on the load point as displacement which is applied here through mid-point on roller support as U_u downward and on hinge point as U_u upward. Equation (1) was validated by discrete rigid link in one simulation and by comparing the results of the two different mode mix ratios with the experimental results.

$$U = (c + L)/L \times U_d + c/L \times U_u \qquad (1)$$

B. Mesh details

Plies of the specimen are modeled through built-in composite layup of 12 layers and elements used are continuum shell elements with reduced integration (SC8R), interface is modeled as cohesive zone elements (COH3D8). The cohesive zone is generated through offset mesh. The initial delamination length is obtained by deleting mesh of the cohesive zone elements in mid plane of the specimen where required.

C. Material model

Material type Lamina which is built-in transversely isotropic plane stress material model (orthotropic) is used for the plies. The properties are given in table 2. For the cohesive zone, traction separation elastic model is used, for initiation of damage Quadratic damage initiation model is used as shown:

$$\left(\frac{\tau_n}{\tau_n^0}\right)^2 + \left(\frac{\tau_s}{\tau_s^0}\right)^2 + \left(\frac{\tau_t}{\tau_t^0}\right)^2 = 1 \qquad (1)$$

Table 2 Properties of material for individual plies in numerical simulation [19]

ρ	Composite density	1566.3 kg **m**
E_1	Modulus of tensile in first direction	24.2 GPa
E_2	Modulus of tensile in second direction	23.1 GPa
υ_{12}	Poison’s ratio	0.2
G_{12}	In-plane shear modulus	3.85 Gpa
E_3	Out of plane section modulus	7.71Gpa
K_{11}=K_{22}	Transverse shear stiffness of shell section in 13 and 23 planes	0.482 MPa

Table 3 Properties of material for cohesive zone in numerical simulation [19]

ρ	Resin density	1085 kg m
$K_{nn}=K_I^0$	Mode I penalty stiffness	44400 GPa
$K_{ss}=K_{II}^0$	Mode II penalty stiffness	22200 GPa
$K_{nn}=K_{III}^0$	Mode III penalty stiffness	22200 GPa
T_I^c	Inter-laminar tensile strength	44.4 MPa
$T_{II}^c=T_{III}^c$	Inter-laminar shear strength	22.2 MPa
G_{Ic}	Fracture Toughness in mode I	425 J m^{-2}
G_{Ic}	Fracture Toughness in mode II	905 J m^{-2}
η	Neta for progressive damage	4.8
	Softening	Linear

τ_n, τ_s, and τ_t are normal and shear elastic limits for the interface. For propagation of damage B-K criteria is used. Table 3 shows the properties of interface cohesive zone.

IV. RESULTS AND CONCLUSIONS

Validation of numerically simulated model is done with experimental results. Load versus displacement plots are obtained from numerical simulation of the model and are compared with the experimental graphs for all mode mix ratios (20%, 30%, 50%, 75% and 100%). Figure 5 to 9 shows the graphs of all mode mix ratios.

Load displacement graphs from simulations are compared with linear portion of experimental graphs. Numerical graphs show good agreement with experimental graphs. Graphs overlap each other to the point of initiation of progressive damage, beyond the point of initiation of progressive damage percent difference is high. This difference is due to the mode mix measured from experimental fracture toughness and numerically from progressive B-K criteria.

With the increase of mode mix ratio from 20% to 100%, load P increases, since interlaminar shear toughness is greater than normal out of plane toughness in mode II. With increase of load, load point displacement decreases for high mode mixity.

Simulation with different displacement rates showed that it is independent of displacement rates at normal rates. The solution was found in good agreement with experimental results at 3mm/s.

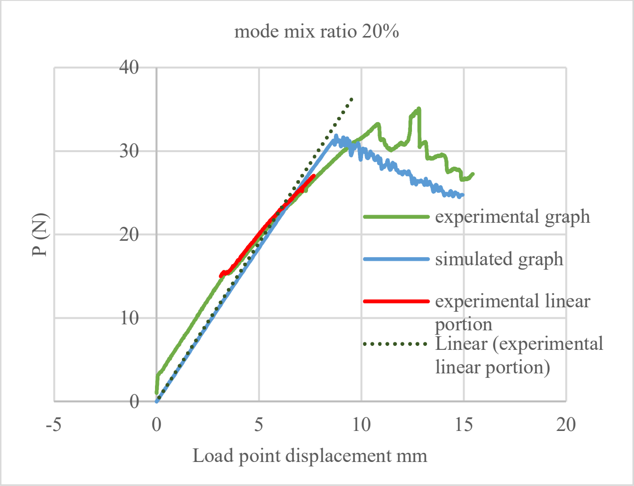

Fig. 5 Load vs displacement graph of 20% mode mix

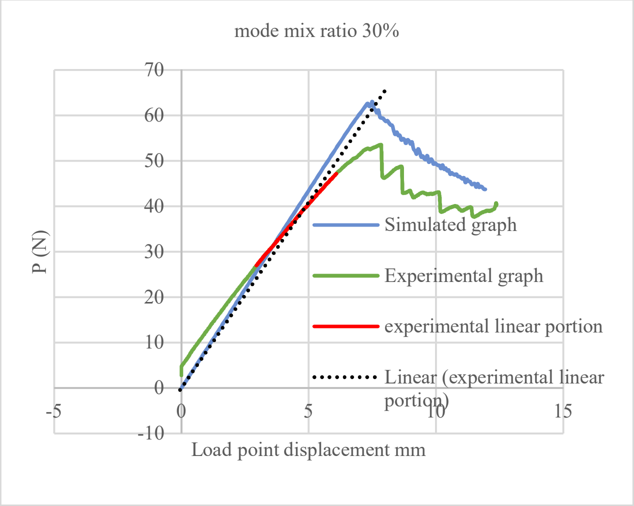

Fig. 6 Load vs displacement graph of 30% mode mix

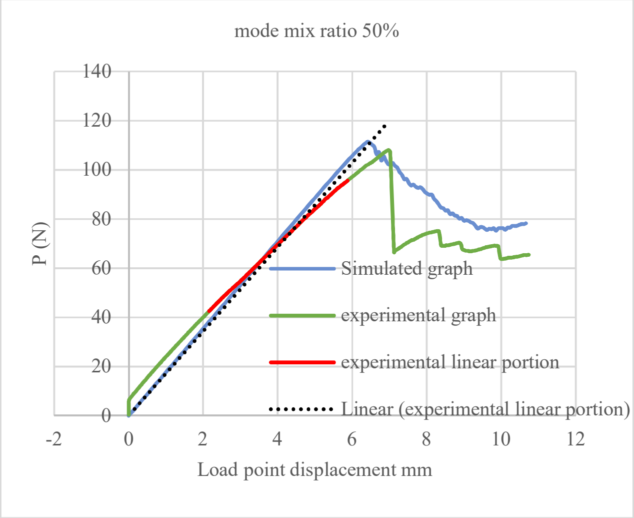

Fig. 7 Load vs displacement graph of 50% mode mix

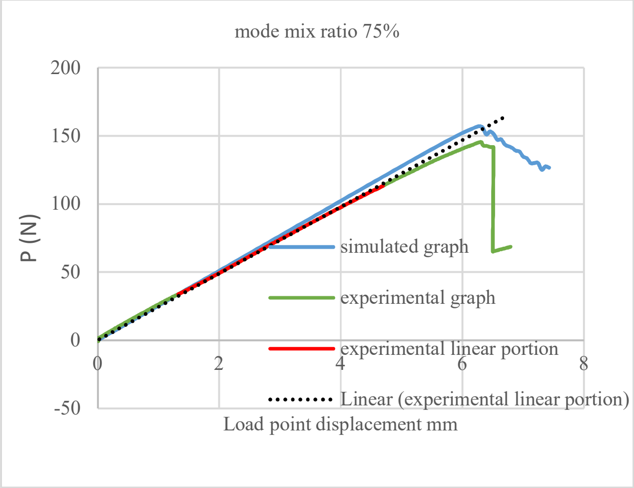

Fig. 8 Load vs displacement graph of 75% mode mix

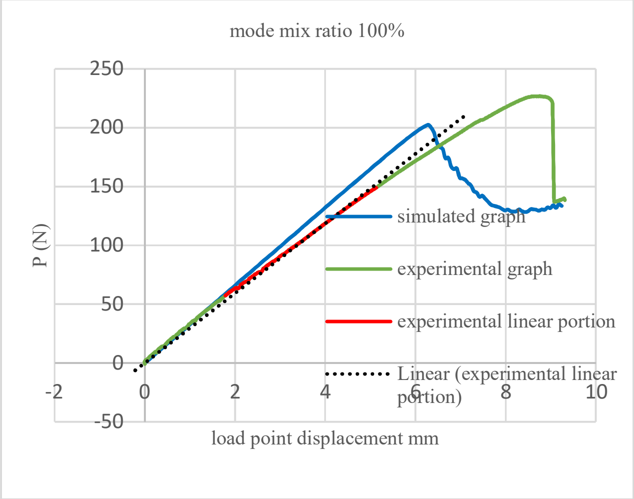

Fig. 9 Load vs displacement graph of 100% mode mix

Simulations with mass scaling to speed up the simulation showed that mass scaling to up to 1×10^{-6} and lower values give results in good agreement, mass scaling higher than this value gives ripples in the solution.

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