Simulation of Delamination Crack Growth in Composite Laminates: Application of Local and Non-Local Interface Damage Models

HASSAN IJAZ*, MUHAMMAD ASAD*, AND BILAL AHMED KHAWAJA**

ABSTRACT

The use of composite laminates is increasing in these days due to higher strength and low density values in comparison of metals. Delamination is a major source of failure in composite laminates. Damage mechanics based theories are employed to simulate the delamination phenomena between composite laminates. These damage models are inherently local and can cause the concentration of stresses around the crack tip. In the present study integral type non-local damage formulation is proposed to avoid the localization problem associated to damage formulation. A comprehensive study is carried out for the selection of different non-local variables. Finite Element simulations based on proposed non-local damage models and classical local damage model are performed and results are compared with available experimental data for UD IMS/924 Carbon/fiber epoxy composite laminate.

Key Words: Laminate; Delamination, Non-Local Modeling, Damage Mechanics, Finite Element Analysis.

1. INTRODUCTION

Composite laminates are used as a major load bearing structural parts in different industries like avionic and automobile. The driving force behind the increasing use of composite materials is high strength to weight ratio and directional properties. The composite laminates consist of different layers of fibers/fabric stacked together and cured with thermosetting resin [1]. Because of their inherent laminate nature, any two adjacent layers of composite laminates can separate due presence of delamination crack and may fail under given loading conditions [2-3].

In order to simulate the delamination crack growth in composite laminates, interface modeling techniques are developed using damage and fracture mechanics failure theories under static and fatigue loadings [4-7]. A lot of work has been carried out at the meso-scale level to understand the delamination failure process. Meso-scale, which lies between micro and macro scale consists of two basic constituents, layers and interfaces. The interlaminar interface, which is a mechanical surface, connects two adjacent layers and depends on the relative orientation of their fibres [8-9].

Localization is a common phenomenon associated to already available classic damage models [10-11]. Localization can cause the concentration of simulated results to certain regions rather a realistic and uniform

* School of Engineering, University of Management and Technology Lahore, Pakistan
* University of Central Punjab, 1-Khayaban-e-Jinnah Road, Johar Town, Lahore, Pakistan

distribution. This phenomenon is more visible in 3D (Three-Dimensional) finite element simulations rather than 2D (Two-Dimensional). One way to avoid localization is to introduce rate dependant damage modeling [12]. Rate dependant models are termed as delay damage models and avoid/limit the localization phenomenon by delaying the numerical computation of damage variable "d", the details of the model can be found in the work of Marguet, et. al. [12]. In recent times much attention is made to integral type non-local damage modeling in order to reduce the localization effects. The use of this type of modeling is effectively discussed for delamination crack growth in composite laminates [13-14].

In the present study a classical damage model proposed by Allix, et. al. [4] is further modified to a non-local damage model [8]. In integral type non-local damage modeling, one variable is chosen for averaging of the results using Gaussian distribution function. For interlaminar interface damage modeling, two different types of variables like damage variable "d" and damage energy release rate "Y_d" are available for non-local damage formulation [14]. Finite element simulations on delamination crack growth with different types of non-local variables are performed and compared with each other and with classical local damage model in the present study. All the mathematical details regarding formulation of non-local modeling is comprehensively discussed and presented in this study.

This paper is organized as follows: Classical local damage model is presented in Section 2. Proposed non-local interface damage modeling is detailed in Section 3. Section 4 covers the finite element simulations of Mode-I delamination crack growth based on classical local and proposed non-local damage models for Carbon/fiber epoxy composite laminate. Finally, some concluding remarks are given in Section 5.

2. LOCAL DAMAGE EVOLUTION LAW

The interface is a 2D surface entity that ensures the transfer of stress and displacement between two adjacent plies [4,8]. This model coupled with the damage mechanics theory can take into account the phenomena of delamination that may occur during mechanical loading of structural parts. The relative displacement of one layer to other layer can be written as [8]:

$$U = U^+ - U^- = U_1 N_1 + U_2 N_2 + U_3 N_3 \tag{1}$$

Here U^+ and U^- are displacement vectors on the top and bottom surfaces. Let the bisectors of the fiber direction be N_1 and N_2. The direction N_3 is normal to the interface, Fig. 1.

The deterioration of the interface is taken into account by three internal damage variables d_1, d_2 and d_3. Here d_3 is associated with the opening mode (or Mode-I) and d_1, d_2 are associated with two shearing modes (Mode-II and Mode-III) of the interface.

The relationship between stress and displacement in orthotropic plane of axis can be expressed as:

$$\begin{pmatrix} \sigma_{13} \\ \sigma_{23} \\ \sigma_{33} \end{pmatrix} = \begin{pmatrix} k_1^0(1-d_1) & 0 & 0 \\ 0 & k_2^0(1-d_2) & 0 \\ 0 & 0 & k_3^0(1-d_3) \end{pmatrix} \begin{pmatrix} U_1 \\ U_2 \\ U_3 \end{pmatrix} \tag{2}$$
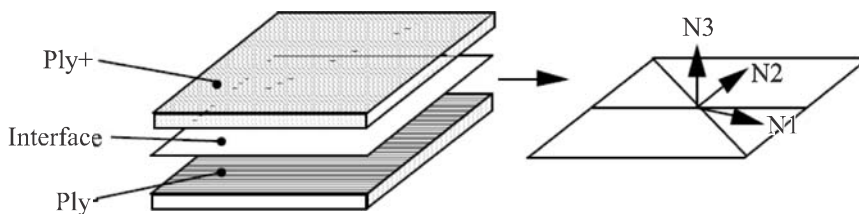

FIG. 1. ORTHOTROPIC DIRECTIONS OF INTERFACE

Where $k^0{}_1$, $k^0{}_2$ and $k^0{}_3$ are interface rigidities associated to damage variables in orthogonal directions. Three different damage variables can be distinguished according to three modes of failure. The thermodynamic forces combined with the variables of damage and associated to the three modes of delamination are [8]:

$$Y_{d_3} = \frac{1}{2} \frac{\langle \sigma_{33} \rangle_+^2}{k_3^0 (1-d_3)^2} \quad Y_{d_1} = \frac{1}{2} \frac{\sigma_{13}^2}{k_1^0 (1-d_1)^2} \quad Y_{d_2} = \frac{1}{2} \frac{\sigma_{32}^2}{k_2^0 (1-d_2)^2} \qquad (3)$$

here $\langle X \rangle_+$ represents the positive part of *X*. The energy dissipated in this model can be written as:

$$\Phi = Y_{d_1} \dot{d}_1 + Y_{d_2} \dot{d}_2 + Y_{d_3} \dot{d}_3 \qquad (\Phi \geq 0) \qquad (4)$$

Three different damage variables corresponding to three modes of failure are strongly coupled and are governed by equivalent single energy release rate function as follows [15]:

$$\underline{Y}(t) = Max\big|_{\tau \leq t} \left(\left((Y_{d_3})^\alpha + (\gamma_1 Y_{d_1})^\alpha + (\gamma_2 Y_{d_2})^\alpha \right)^{1/\alpha} \right) \qquad (5)$$

Where g_1 and g_2 are coupling parameters and a_0 is a material parameter which governs the damage evolution in mixed mode. The local damage evolution law is then defined by the choice of a material function as follows [15]:

$$
\begin{aligned}
&if \quad \left[(d_3 < 1) \, and \, (\underline{Y} < Y_R) \right] \\
&then \\
&\qquad d_1 = d_2 = d_3 = \omega(\underline{Y}) \\
&else \\
&\qquad d_1 = d_2 = d_3 = 1
\end{aligned}
\qquad (6)
$$

The damage function is selected of the form [8,15]:

$$\omega(\underline{Y}) = \left[\frac{n}{n+1} \frac{\langle \underline{Y} - Y_O \rangle_+}{Y_C - Y_O} \right]^n \qquad (7)$$

Where Y_O is threshold damage energy, Y_C is critical damage energy, *n* is Characteristic function of material (higher values of *n* corresponds to brittle interface) and Y_R is energy corresponding to rupture and can be expressed as.

A simple way to identify the propagation parameters (Y_C, g_1, g_2) is to compare the mechanical dissipation yielded by two approaches of Damage Mechanics and LEFM (Linear Elastic Fracture Mechanics). In the case of pure mode situations, when the critical energy release rate reaches its stabilized value at the propagation denoted by G_C, comparison of dissipations between Fracture Mechanics and Damage Mechanics approaches lead to [15]:

$$G_{IC} = Y_C \, ; \, G_{IIC} = \frac{Y_C}{\gamma_1} \, ; \, G_{IIIC} = \frac{Y_C}{\gamma_2} \qquad (8)$$

In order to satisfy the energy balance principle of LEFM, the area under the curve of stress-displacement curve for the whole DP (Debonding Process) obtained through Damage Mechanics formulation is set equal to critical energy release rate G_{iC}, and the following relations for the Mode-I, Mode-II and Mode-III critical energy release rates can be written:

$$G_{IC} = \int_{DP} \sigma_{33} \, dU_3, \quad G_{IIC} = \int_{DP} \sigma_{13} \, dU_1, \quad G_{IIIC} = \int_{DP} \sigma_{23} \, dU_2 \qquad (9)$$

The area under the curve will always equal to critical energy G_C for any mode of delamination as shown in Fig. 2. For mixed-mode loading situation, a standard LEFM model is recovered as [15]:

$$\left(\frac{G_I}{G_{IC}} \right)^\alpha + \left(\frac{G_{II}}{G_{IIC}} \right)^\alpha + \left(\frac{G_{III}}{G_{IIIC}} \right)^\alpha = 1 \qquad (10)$$

3. NON-LOCAL DAMAGE EVOLUTION LAW

Damage models need to describe strain-softening behavior in order to characterize microscopic degradation processes. A phenomenon called "localization" occurs in structural analyses with strain-softening models. Regularization techniques are therefore essential in Damage Mechanics. The goal of using these techniques is to control the localization. In order to control the localization problem some authors proposed rate-dependent [12] and gradient

enhanced [11] damage models. However, in this paper an integral type non-local damage model is proposed. Basically, three different types of non-local models are proposed in this section and their details are given below.

3.1   Averaging the Damage Variable "*d*"

In this type of non-local damage model, the damage variable *d* is made non-local by means of a spatial averaging over the surrounding domain *V* with respect to weight function a_0 [16]:

$$\bar{d}(x) = \frac{1}{V_r(x)} \int_V \alpha_0 \left(\| x - \zeta \| \right) d(\zeta) d\zeta \tag{11}$$

Where

$$V_r(x) = \int_V \alpha_0 \left(\| x - \zeta \| \right) d\zeta \tag{12}$$

Here the damage variable d which is made non-local through above equations is calculated initially from Equation (6). An isotropic function such as Gaussian distribution function is chosen as weight function over the domain *V* [13].

$$\alpha_0(r) = \exp \left(-\frac{r^2}{2l^2} \right) \tag{13}$$

This weight function depends on the distance $r = \| x - \zeta \|$ between points *x* and *z* and on a parameter *l* called the internal length scale. This quantity represents a measure of the non-local averaging. The distribution of a_0 with respect to distance *r*, where, is shown in Fig. 3.
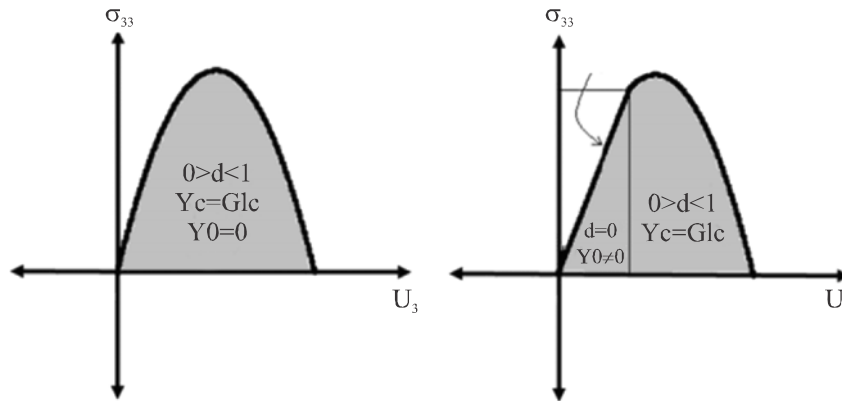

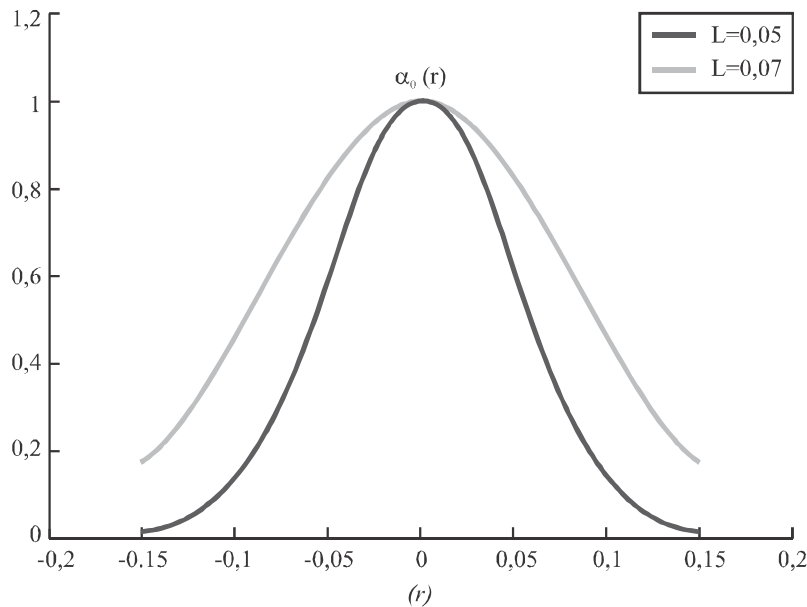FIG. 2. INTERFACIAL STRESS VS DISPLACEMENT CURVE FOR MODE-I

FIG. 3. DISTRIBUTION OF WEIGHT FUNCTION

3.2 Averaging the Damage Energy Release Rate $Y_{di}(i,=1,2,3)$

Now take the damage energy release rates $Y_{di}(i,=1,2,3)$ correspond to three failure modes, Equation (3). Now one can write:

$$\overline{Y_{di}}(x) = \frac{1}{V_r(x)} \int_V \alpha_0 \left(\|x - \zeta\| \right) Y_{di}(\zeta) d\zeta \qquad (14)$$

Now $V_r(x)$ can be calculated using Equation (12). Once the value of is known for three failure modes then non-local damage variable d can be calculated as a function of i.e. . Here Y is the equivalent damage energy release rate. Once the value of equivalent Y is known using non-local variables, one can calculate damage variable d using Equation (6).

4. FINITE ELEMENT SIMULATIONS AND RESULTS

The proposed non-local damage models presented here are implemented in CAST3M (CEA) finite element code. For the study of delamination, a special interface element of zero thickness has been used [17], which is already implemented in finite element software CAST3M [18]. A four node zero thickness interface element "JOI2" available in CAST3M library [18] is used in the finite element analysis. The "JOI2" element has 2dof/node and two Gauss points of integration per element. Implementation of three different non-local damage evolution laws are made in CAST3M via procedure PERSO1 and using subroutine UMAT [18].

Experimental results of Cartié [19] for Mode-I delamination crack growth are used for verification of simulation results. Geometry of the specimen is given in Fig. 4. The mechanical properties of UD laminated composite beam "IMS/924" are given in Table 1 [19]. The interface properties determined through identification procedure explained earlier are given in Table 2. The mesh diagram is shown in Fig. 5. A fine mesh is used around the crack tip. The simulation results of local damage model are shown in Fig. 6 and are compared with experimental results. A good agreement is found between numerical and experimental results.

Fig. 7 shows the result of applied load versus delamination crack opening displacement for "d" based non-local formulations. The effect of internal length parameter l can be observed in the Fig. 8. From figure it can be concluded that non-local damage evolution law

TABLE 1. MECHANICAL PROPERTIES OF IMS/924 [18]

E11 (MPa)	138000
E22 (MPa)	1100
E33 (MPa)	100
12	0.3434
G12 (MPa)	4400

TABLE 2.IDENTIFIED INTERFACE PROPERTIES OF IMS/

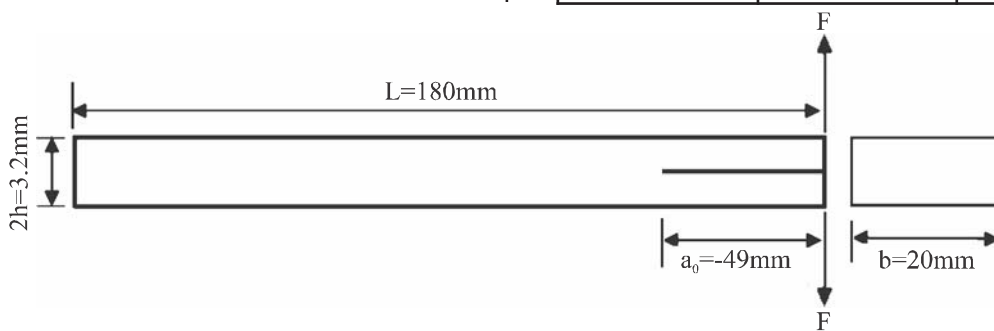| TestMethod	GC (KJ/m2)	Interface Properties
Mode I (DCB)	0.26 + 0.01	N=0.2, YC=0.26 + 0.01 KJ/m2 K30 = 1000 MPa/mm

FIG. 4. GEOMETRY OF DCB SPECIMEN

behaves like local one for small values of l. This is because for small values of l there will be fewer elements available for making the average of damage variable d. The good value of l can be found from experiments by closely observing the delamination crack front because this material length l defines the size of interaction zone of damage localization [20-21].As the value of l increases the crack initiation point moves farther away and then drops after the crack propagation has started but this crack propagation portion of the curve stabilizes a bit higher in comparison to smaller values of l, Figs. 7-8 shows the result of applied load versus delamination crack opening displacement for "Y_{di}" based non-local formulations. From Fig. 8, it is clear that as the value of l increases, the crack initiation point also moves away but the crack propagation portion of the curve is not as stable as in previous case of "d" based non-local formulations. In fact, results can be considered quite erratic for "Y_{di}" based non-local formulations because of ups and downs of curves for different values of internal length parameter l. The unstable crack propagation in the post-peak regime might be due to the fact that energy dissipation rate "Y_{di}" is not a physical parameter.
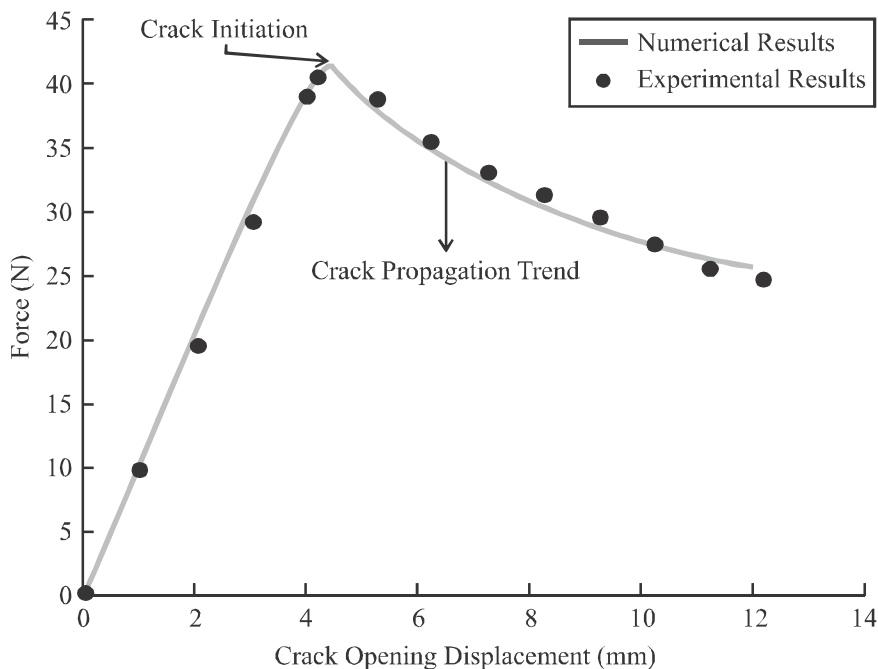

FIG. 5. MESH DIAGRAM OF DCB SPECIMEN

FIG. 6. FORCE VS CRACK OPENING DISPLACEMENT CURVE FOR LOCAL DAMAGE MODEL

Fig. 9 shows the in-plane stresses obtained from finite element analysis of DCB for "*d*" based non-local damage model for different values of internal length parameter *l* during crack propagation process. From Fig. 9, one can observe the higher amount of stresses with increasing values of *l* that is also in accordance with results shown in Fig. 7.
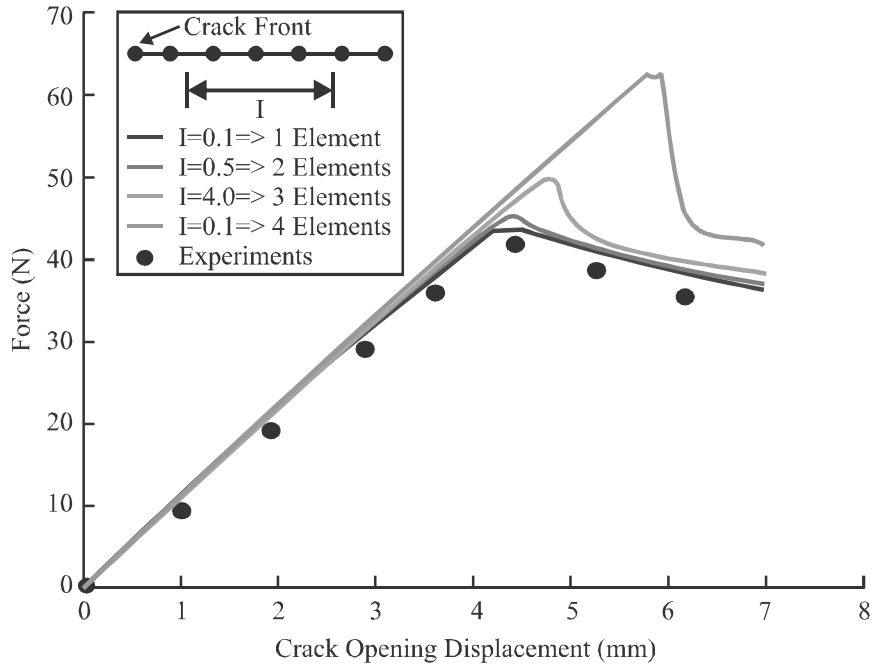

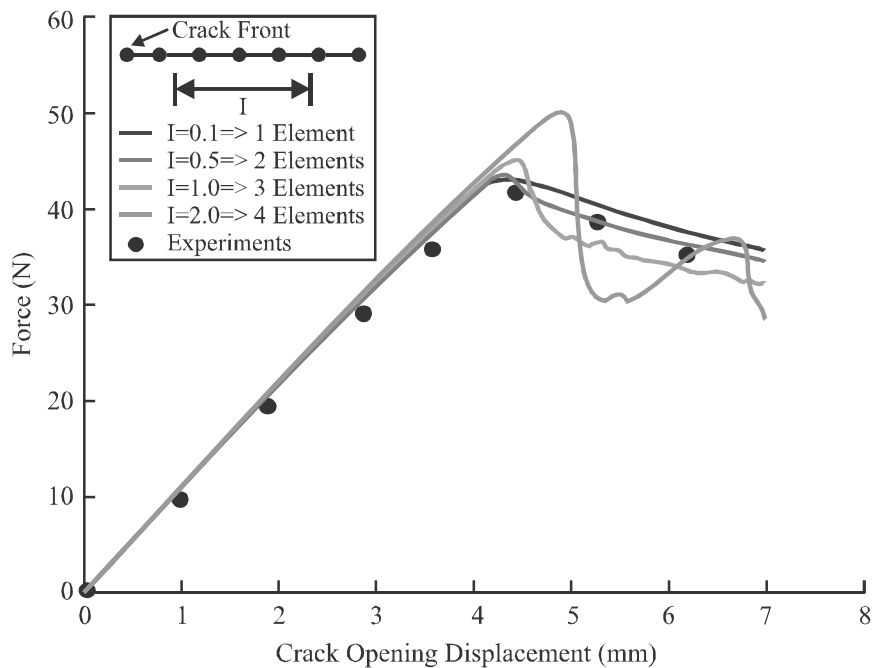FIG. 7. FORCE VS CRACK OPENING DISPLACEMENT CURVE FOR "*d*" BASED NON-LOCAL MODEL

FIG. 8. FORCE VS CRACK OPENING DISPLACEMENT CURVE FOR "Y_{di}" BASED NON-LOCAL MODEL

Similarly Fig. 10 presents the in-plane stresses during crack propagation of DCB specimen for "Y_d" based non-local damage model for different values of internal length parameter l. Contrary to "d" based finite element results,

one can observe decreasing trend of stresses with increasing values of l. Fig. 8 also shows similar trend for "Y_d" based non-local formulation, but Fig. 8 also shows that reaction force varies erratically as value of l increases.
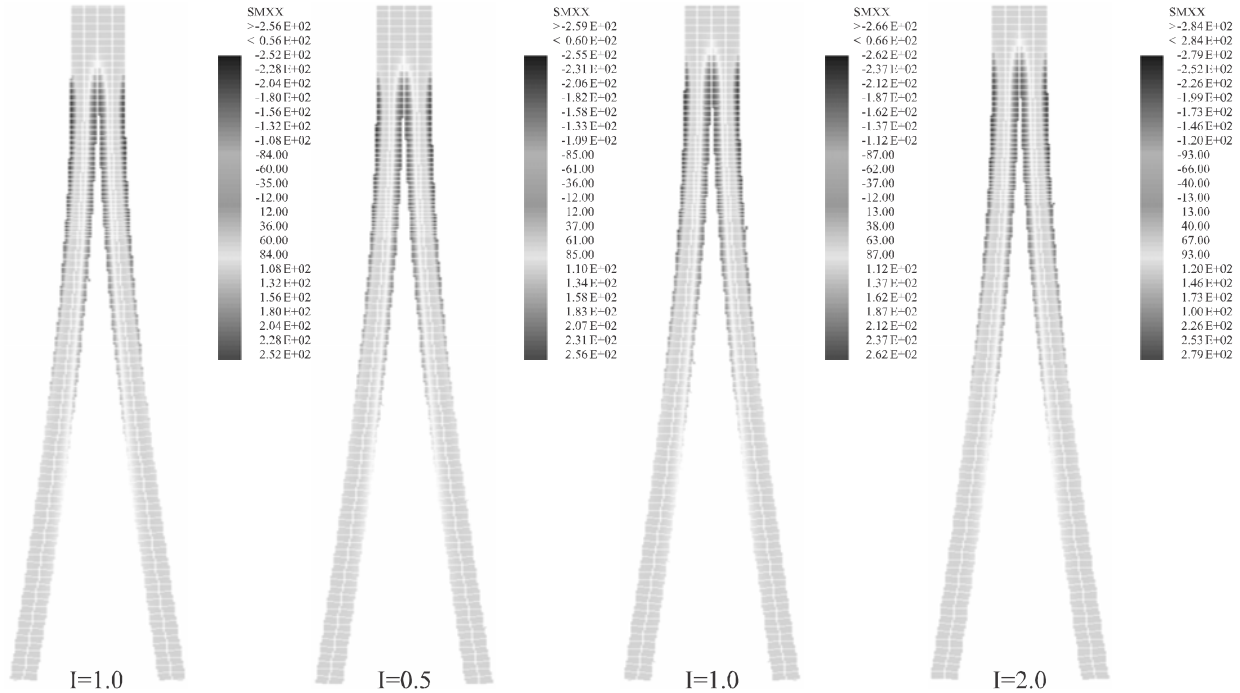

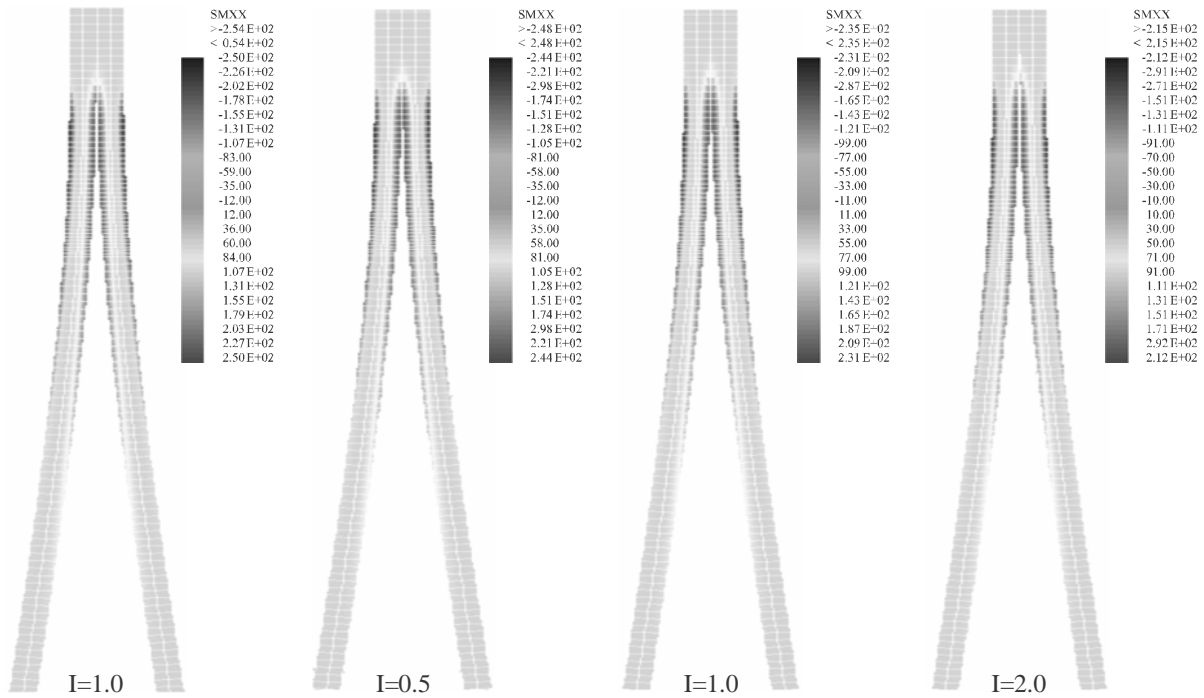FIG. 9. IN-PLANE STRESSES OF DCB SPECIMEN FOR d BASED NON-LOCAL DAMAGE MODEL

FIG. 10. IN-PLANE STRESSES OF DCB SPECIMEN FOR Y_d BASED NON-LOCAL DAMAGE MODEL

5. CONCLUSION

In the present study, a classical local damage model presented by Allix,et. al. is further modified to incorporate the non-local effects. Two different non-local interface damage formulations based on averaging of variables d and Y_d are presented. Finite element simulations of IMS/924 composite laminate for Mode-I delamination crack growth are performed and results are compared with each other. From the finite element simulations it is clear that d based non-local damage model shows much better results in comparison of Y_d based non-local formulation. For Y_d based non-local formulation, reaction force start varying erratically with increasing values of l. From finite element simulations, it is also clear that non-local modeling is strongly influenced by internal length parameter l. For smaller values of l, the results of local and non-local interface modeling are close to each other because few number of elements are available for averaging in non-local modeling with smaller value of l.

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