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Stress and free edge delamination analyses of delaminated composite structure using ANSYS

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Abstract

Laminated polymer composite structures manufactured using conventional layup technique, are prone to edge delamination, which can be suppressed by wrap-around technique. Present study is in regard to understanding of the interlaminar normal stress distribution ahead of the delamination front with respect to delamination suppression. An initial delamination of symmetric composite laminates with and without wrap-around is considered for performing static analysis of these laminated composites structures using finite element analyses. Understanding of delamination parameter was further extended in terms of strain energy release rate utilizing modified crack closure integral technique for various virtual crack extension sizes.

Key words: composites, laminates, delamination, finite element analysis, strain energy releace rate, modified crack closoure integral ;

1. Main text

Delamination or interlaminar fracture of polymeric based structural composites is generally caused by high inter laminar stresses, that arises due to mismatch in elastic properties between plies and at free edge. Laminated composite structures manufactured by conventional lay-up technique are prone to edge delamination. The presence and growth of delamination in composite laminates may lead to severe reliability and safety problems, such as reduction of stiffness, strength and fatigue life, disintegration of the material etc. Therefore, understanding the

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behaviour of stress and delamination is of critical importance in the assessment of structural integrity of composite materials and structures. Numerous investigators have studied free edge effects in finite width delaminated composite laminates subjected to uniaxial load because of the adverse effect of delamination on the structural integrity. Pagano et al. [1] and Pagano et al. [2] postulated that through the thickness stress or the interlaminar normal stress (ILNS) is the main cause of delamination for polymeric material based structural composites. The basis of this postulation is a combination of experiments and stress analyses for laminates with different stacking sequences. Sarvestani [3] have established an analytical method to exactly obtain the interlaminar stresses near the free edges of generally laminated composite plates under the extension and bending. Harikumar et al. [4] have studied the stress field ahead of the delamination tip and the strain-energy release rate (SERR) in symmetric composite laminates with mid-plane delamination subjected to mechanical and thermal strains with the aid of a modified form of the Whitney-Sun theory. The delamination is found to be sensitive to fiber orientation, laminate stacking sequence, and ply thickness as suggested by Herakovich [5], Herakovich [6], Rodin [7], and Kim [8]. For the prevention of edge delamination, several techniques have been proposed, such as free-edge cap reinforcement as suggested by Heyliger [9], free-edge stitching as suggested by Mignery [10] and Dransfield [11], hybridization as suggested by Kim [12], stacking method in balanced symmetrical laminates as suggested by Kim [13], wrap-around technique as suggested by Rao [14], Choudhury et al. [15] and adhesive-layer reinforcement as suggested by Soni [16]. Raju [17] has obtained SERR for edge-delaminated composite laminates using quasi three-dimensional finite element analysis and studied the problem of edge-delamination at the -35/90 interfaces of an eight ply [0/±35/90]s, composite laminate subjected to uniform axial strain. Ye [18] has presented a representative model for delamination growth in composite laminates and a simple energy release rate model for delamination growth is established. Krueger [19] has presented an overview of the virtual crack closure technique. Schellekens et al. [20] have simulated free edge delamination of uniaxially stressed layered specimens using nonlinear finite element analysis. Venkatesha et al. [21] have proposed a generalized modified crack closure integral (GMCCI) algorithm for four and eight-noded isoparametric quadrilateral elements, which can estimate the SERR components for several sizes of virtual crack extension through a single finite element analysis. Haneef et al. [22] have carried out finite element analysis to analyze the delamination effect on composite structures with two models.

In view of above, it is clear that excellent studies have been made on free edge effects and their suppression for uncapped and capped composite laminates. However, problems encountered with already delaminated composite structures (containing delamination at free edge) were not addressed properly. An understanding therefore is required to be developed on the behaviour of delaminated composite structures with and without wrap-around since the existing delamination could be critical to the laminated composite structure's final failure. The present study is motivated by a requirement to develop an understanding on the above mentioned behavioural aspect. The present work aims at the studies of the effect of cap and wrap-around on reduction of stress concentration at crack tip which leads to the crack propagation. ANSYS has been used to develop models for laminates (+22/-22/90)s and perform Finite Element (FE) analyses. Although no formulation has been attempted for this study, an understanding on behavioural aspect of the delaminated composite structures is developed here.

Nomenclature

2B	ply width
L	ply length
B_e	element thickness
E_{11}	longitudinal young modulus
E_{22}	transverse young modulus
F	element nodal force
U	relative displacements between points on the crack faces
F_z	nodal force in Z-direction
F_x	nodal force in X-direction

F_y	nodal force in Y-direction
G_{12}	longitudinal shear modulus
G_{23}	transverse shear modulus
G	stain energy release rate
G_I	strain energy release rate corresponding to mode-I failure
G_{II}	strain energy release rate corresponding to mode-II failure
G_{III}	strain energy release rate corresponding to mode-III failure
G_T	total strain energy release rate
U_z	nodal displacement in Z-direction
U_x	nodal displacement in X-direction
U_y	nodal displacement in Y-direction
h	ply thickness
a	length of delamination
Δa	crack front extension
μ_{12}	Poisson's ratio
ε_{xx}	axial stain in X-direction

2. Theoretical background

SERR is a material characteristic, which is often used for determination of resistance to delamination growth in terms of fracture toughness and elastic modulus. SERR is the energy dissipated during fracture per unit of newly created fracture surface area. SERR can be determined according to three particular modes of crack action *viz*. Mode-I or opening mode, Mode-II or shearing mode and Mode-III or tearing mode as shown in Fig. 1. In the present study, for determination of SERR following assumptions were considered, (a) the material in the lamina comprising the laminate is homogeneous and orthotropic even though the lamina material is usually a fibre reinforced system, (b) +22 and -22 fibres woven layer separated out as two different layers and (c) delamination propagates in a self similar manner

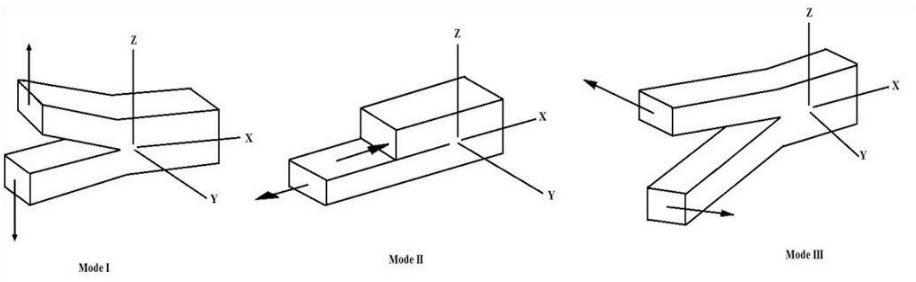

Fig. 1. Basic modes of delamination

A practical computational procedure uses the definition of SERR in terms of the crack closure integral as described by Rybicki & Kanninen [24] according to which, for linear materials, crack closure integral results from fact that if a crack extends by a small amount Δa, the energy release rate can be defined in terms of the work required to close the crack to its original length. Moreover, modified crack closure integral (MCCI) technique based on Irwin's virtual crack closure integral (VCCI) concept, developed by Rybicki & Kanninen [24] was utilized in the past to estimate the SERR components for several sizes of virtual crack extension through a single

FE analysis. This scheme however, does not require a special singular element or knowledge of a stress singularity in the solution. In the present study the simple expressions developed by Rybicki & Kanninen [24] for 2D element has been modified for 3D solid element. Evaluation of SERR can be facilitated by using finite elements with nodal forces and expressing the work to close the crack extension in a form consistent with nodal forces and nodal displacements of the elements. The expression for Mode-I, Mode-II and Mode-III strain energy release rates are modified in the following equations:

$$G_I=[\ (F_z)_c(U_z)_{oj} + (F_z)_d(U_z)_{pk} + (F_z)_e(U_z)_{ql} + (F_z)_f(U_z)_{rm}]/\ [2B_e\Delta a] \quad (1)$$

$$G_{II}=[\ (F_x)_c(U_x)_{oj} + (F_x)_d(U_x)_{pk} + (F_x)_e(U_x)_{ql} + (F_x)_b(U_x)_{ni} + (F_x)_f(U_x)_{rm}]/\ [2B_e\Delta a] \quad (2)$$

$$G_{III}=[\ (F_y)_c(U_y)_{oj} + (F_y)_d(Uy)_{pk} + (F_y)_e(U_y)_{ql} + (F_y)_b(U_y)_{ni} + (F_y)_f(U_y)_{rm}]/\ [2B_e\Delta a] \quad (3)$$

Where *G* is the strain energy release rate, *F* is the element nodal force, *U* is the relative displacements between points on the crack faces, Δa is the crack front extension and B_e is the element thickness. The Illustration of finite element interface nodes near crack front is shown in Fig. 2.

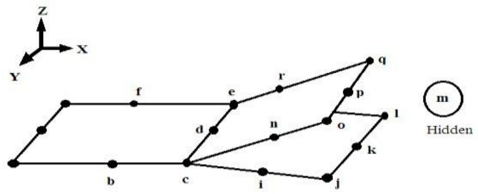

Fig. 2. Illustration of finite element interface nodes near crack front

3. Results and Discussion

3.1. Finite Element Representation and Analyses in ANSYS

Two delaminated models (with and without wrap-around) have been developed to study the effectiveness of wrap-around on delaminated composite laminates. Considering initial finite size of delamination at the critical interface (-22/90), FE models were represented for the composite laminates having the following lay-up specification and material specification by simulating tension test coupons which were experimentally studied by Rao [14]. Edge delaminations in the delaminated models with and without wrap-around are shown in Fig. 3(a, b) Lay-up specification (+22/-22/90)s (a) Orthotropic material Model: E_{11}=142.20x10^9 Pa, E_{22}= 7.27x10^9 Pa, G_{12}=3.43x10^9 Pa, G_{23} = 2.85x10^9 Pa; μ_{12}= 0.246 . The other specifications of laminates are that has been considered are, ply thickness (h) = 0.00014 m, width (2B) =140 h, axial strain (ε_{xx}) = 1%, length of delamination (a) = 6h. The decency of the models with wrap-around is that no extra material layer is provided for wrap-around. Outer two plies of +22^0 and -22^0 fibre orientation run around the inner 90^0 plies. U-shaped delaminations are seen at the interface between -22^0 and 90^0 layers of the delaminated models with wrap-around as shown in Fig. 3(b).

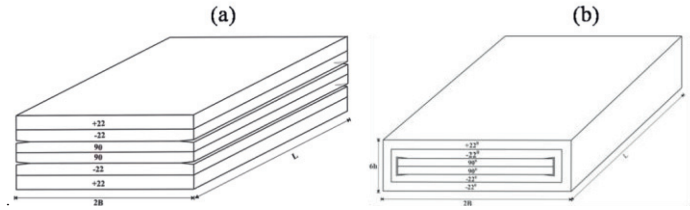

Fig. 3. (a) Delaminated model without wrap-around and (b) Delaminated model with wrap-around

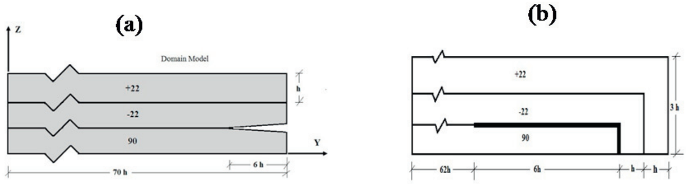

Fig. 4. (a) One fourth model without wrap-around and (b) One fourth model with wrap around

Symmetric condition has been considered in the direction of thickness (z direction) and width (y direction) as shown in Fig. 4 for the models. The runs accordingly are done by imposing uniform displacement boundary conditions, to the extent of zero on one end plane and a finite displacement of $L\varepsilon_{xx}$ on the other.

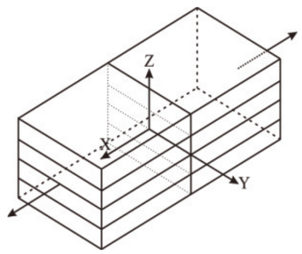

Fig. 5. Laminate geometry and loading

The finite element analysis was performed on the delaminated models with and without wrap-around are basically modeled using Mechanical Ansys Parametric Design Language (APDL). Finite element meshing of the models is done with three dimensional 20 noded isoperametric brick element (ANSYS element solid 95). Considering the symmetry, only one fourth of the laminate cross-section was analyzed. Each lamina was represented with more than one row of elements so that stress variation within the lamina can be captured. Since the use of many elements in the model may severely reduce the computational efficiency therefore, the number of elements was selected to achieve both the geometric and computational efficiency. Since singularity is expected only at the delamination front, the number of elements per unit width of the laminate is large in the vicinity. Thus, the mesh distribution system selected consists of three zones (Zone 1, Zone 2 and Zone 3 respectively) as shown in

Fig. 6. Zone 1 having elements with a 1:1 aspect ratio (Width to thickness ratio) near the delamination front, zone 2 having 5:4 ratios adjacent to the delamination front and zone 3 having 25:8 ratios. A maximum of 8:1 ratio is taken to decide on the number of elements in the length direction. The total number of elements used for the models are given in Table 1. The different mesh distribution system for all both the models after meshing is shown in Figs 7(a) and (b), where (a) represents without wrap-around and (b) represents with wrap-around.

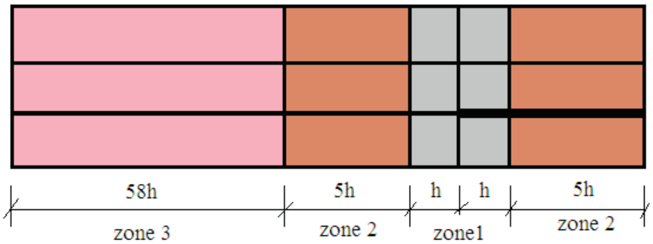

Fig. 6. Zone distribution of one fourth delaminated model

Table 1. Depicting total numbers of element for both models

Models	No of elements
Delaminated Model without wrap-around	10248
Delaminated Model with wrap-around	10017

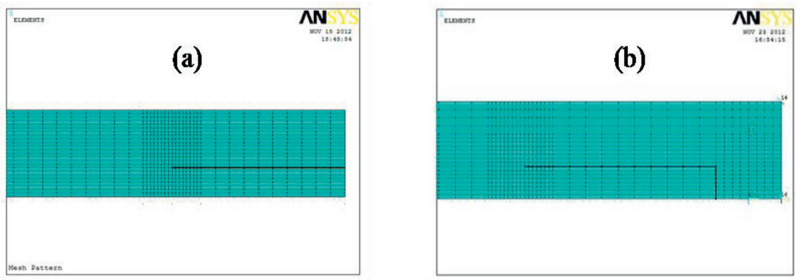

Fig. 7. Finite element representation of (a) without wrap-around laminates and (b) wrap-around laminate

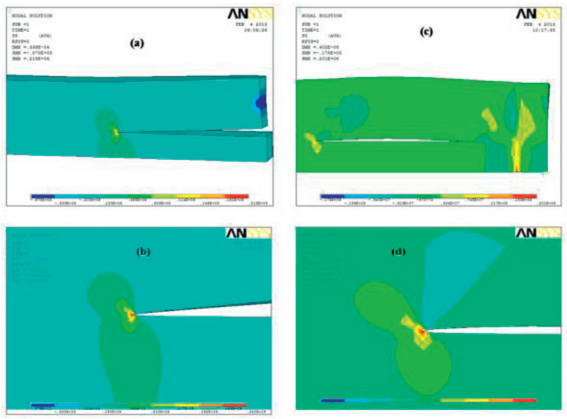

Fig. 8. (a) Contour of inter laminar normal stress distribution in without wrap around model, (b) Enlarged view of normal stress variation around the crack tip (c) Contour of inter laminar normal stress distribution in wrap around model and (d) Enlarged view of normal stress variation around the crack tip

3.2. *Stress analysis of composite laminates:*

Since the length of ply (L) is very large (approx 725h), it is difficult to carry out the entire numerical analyses (3D) with this length. To minimize the computational time and memory required for obtaining the numerical solution, length of the laminate models (simulating the tension test coupons) is decided as 7h since laminate length of 7h serves the purpose of analyses without sacrificing the accuracy of results. Delaminated model with and without wrap-around subjected to uniaxial strain is considered for the present study to see the effect of ILNS around the crack tip. Uniaxial strain of 1 % was applied in both the models. The contour plots of laminates with and without wrap-around are shown in Fig. 8 (a, b, c and d). In Figs.8 b & d represents the enlarged contour plot near the crack tip.

From Fig. 8 shows stress contour around the crack tip. The maximum stress of 1.97×10^{8} Pa was observed at the crack tip which leads to the propagation of delamination**,** Pagano [1-2]. In Fig. 8(b) red contour represent the maximum stress location and cyan represent the minimum stress location. Fig. 8(c) shows the contour of normal stress in delaminated model with wrap-around where Fig 8 (d) represents the enlarged view of stress contour around the crack tip. It was interestingly observed that by using wrap-around technique the interlaminar normal stress at delamination front is reduced drastically. The magnitude of stress at the crack tip for wrap-around model was observed as 0.13309 Pa which was phenomenal when compared to wrapped laminate (+22/-22/90) laminate. The comparison of ILNS along the width ahead of the delamination front for these two models is shown in Fig. 10. It was found that change in ILNS gradient was steep ahead of the crack tip. However this behaviour was observed to be suppressed in the case where wrap around is considered. The values of ILNS and interlaminar shear stress at the crack tip are also shown in Table 2.

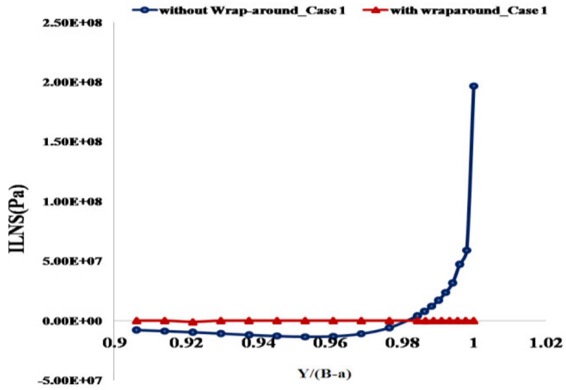

Fig. 9. Distribution of the ILNS ahead of the crack

Table 2. Showing interlaminar normal Stress and interlaminar shear stress at the crack tip

Model Name	Interlaminar Normal Stress (Pa)	Interlaminar Shear Stress (Pa)
Delaminated Model without wrap-around	$1.97\text{E}\times10^{8}$	-1.105×10^{7}
Delaminated Model with wrap-around	0.13309	-2.66×10^{7}

3.3. Delamination Analysis

The composite laminates having width (2B), length (L), thickness (t) was subjected to a uniaxial extension by the application of a constant longitudinal strain ($\boldsymbol{\varepsilon}_{xx}$). Delamination analysis which involves calculation of strain energy release rate use MCCI approach. The SERR components G_I, G_{II} and G_{III} of delaminated model with and without wrap-around have been calculated for various virtual crack extensions using single finite element analysis. The finite element mesh used had a crack front element size equal to 0.0000175a (highest refinement) and $\Delta a/a$ was varied from 0.0000175 to 0.00007 for MCCI procedure. All these were used to study the convergence aspects of G components. With increase in number of elements (1 2 3 & 4) around the crack tip, both G_I and G_{II} values are converged to a stable values whereas G_{III} remains unchanged as shown in Fig. 10 (a, b). Fig. 11(a) shows the comparison values of G_I, G_{II}, G_{III} and G_T (summation of all the SERR components) between both the models (without wrap around and with wrap around). From the Fig. 11(a) it is clear that G_I and G_{II} are the dominant modes of failure where G_{III} has minimal effect on delamination in composite structures. A significant reduction in SERR components are observed with wrap-around laminates compared to unwrapped laminates as shown in Fig. 11(a). This behavior highlights the importance of wrap around technique on the suppression of free edge delamination in polymer composite laminates. Fig. 11(b) shows the magnitude of percentage reduction in G_I, G_{II} and G_T. percentage reduction G_{III} is not shown in Fig. 11 (b) since Mode-III has negligible effects on delamination.

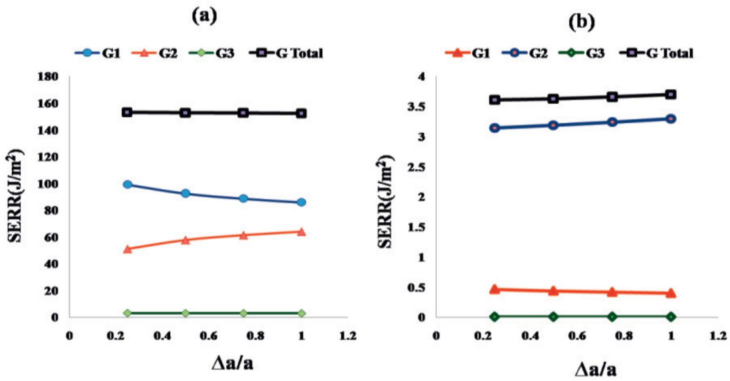

Fig. 10. (a) Convergence study of SEER components of without wrap-around model and (b) Convergence study of SEER components of wrap-around model

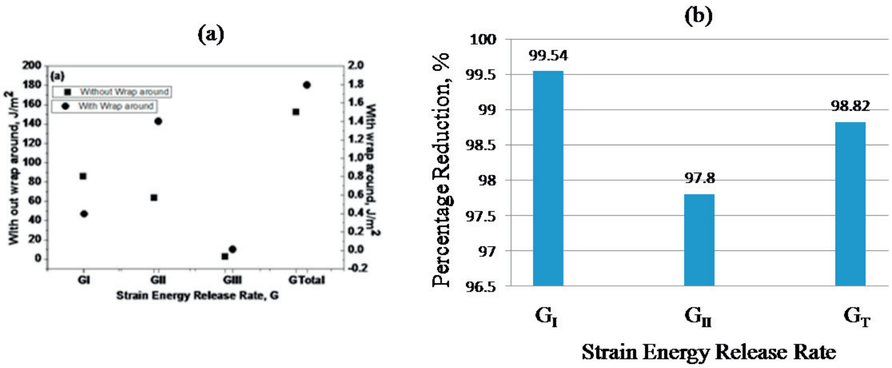

Fig. 11. (a) Strain Energy Release Rate for both models and (b) Percentage of reduction of Strain Energy Release Rate with wrap-around model.

4. Conclusion:

FE representation of laminates with and without wrap around in laminated composites has been devloped in ANSYS. ILNS and interlaminar shear stress were analysed for both the models. It was found that by wrap around technique the stress around crack tip was significantly suppressed. The SERR for both the laminates are computed using FE analysis. Mixed mode delamination analysis was carried out by evaluating SERR, used as the delamination parameter. MCCI technique was utilized to estimate the SERR components for several sizes of virtual crack extension through a single FE analysis. A significant reduction of percentage in SERR components were observed when wrap-around is used. This behaviour highlights the importance of wrap around technique on the suppression of free edge delamination of polymer composite laminates. However, this is a part of an ongoing work towards the development of an approach to the design of wrap around for delamination suppression.

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