Effect of Mechanical Loading on the Delamination of Stratified Composite in Mode I

H. Achache, Y. Madani, A. Benzerdjeb

Abstract—The present study is based on the three-dimensional digital analysis by the finite elements method of the mechanical loading effect on the delamination of unidirectional and multidirectional stratified composites. The aim of this work is the determination of the release energy rate G in mode I and the Von Mises equivalent constraint distribution along the damaged area under the influence of several parameters such as the applied load and the delamination size. The results obtained in this study show that the unidirectional composite laminates have better mechanical resistance one the loading line than the multidirectional composite laminates.

Keywords—Delamination, release energy rate, stratified composite, finite element method and ply.

I. INTRODUCTION

THERMOSET composites reinforced with different types of fibers are used in the transport sector, including aerospace and automotive. They are widely used in applications where weight reduction is critical. More, the use of a material is enlarged more probability of possible failure is increased. The ability to characterize ruptures, for example in terms of identifying failure modes, characteristic parameters or rupture critical values, is essential to ensure the integrity of parts and services for the design of future products. The main aspect of this failure is the crack, which provides the location and progression of the fracture. The study of an existing crack and its stability is of great importance. In reality, the propagation of a crack can lead to rupture of a component that may lead to the total collapse of the structure. The fracture mechanics is the right tool to analyze this situation based on the fracture characteristics of the material that are the critical stress intensity factor (Kc) and the critical energy release rate (Gc) also called tenacity. This composite degradation has been studied by several authors.

Experimentally, it has been observed that the different mechanisms of damage in the transverse cross-laminates are cracking, delamination crack tip and the longitudinal or interlaminar cracking [1]. The order and sequence of occurrence of such damage depends mainly on the following parameters: nature of the fiber constituents/matrix architecture of the laminated plate, and the manufacturing process of

Habib Achache is with the Department of Material Engineering, University DrYahia Fares Medea, Algeria (corresponding author, phone: 00 213 660652545; e-mail: achachehabib@ yahoo.fr).
Youcef Madani is with the Department of Mechanical Engineering, University USTO Oran, Algeria (e-mail: mdysifo@hotmail.com).
Dr. Abdelouahab Benzerdjebis with the University of Sciences and Technology M.B of Oran, Algeria (e-mail: abdoubenzerdjeb@yahoo.com).

shaping and different types of loads. The final collapse of the composite is the result of the spread and accumulation of these three types of damages. In the literature, these damages have generally been studied separately: studies focus either on crack propagation by either an analytical or numerical method [2] or an analytical model of delamination [8]. Reference [3] has carried out finite element analysis to analyze the delamination effect on composite structures with two models. Reference [9] determined the angle of crack propagation and found to be more with the mode I contribution 55% and decrease slightly above this value. A survey was conducted again by [13]. Using the model and mode II ENF (End Notched Flexure) composite glass-fibre/vinyl ester [12]. It was concluded that in the loading of the crack growth, in mode II, is a function of fiber / matrix interface properties. However, some authors studied the role of transverse cracks in the initiation of delamination between layers based on properties. For example, [14] study the best stack (0°, 45°, 90°) to reduce the stress concentration at the crack tip and the interface shear stress in mode II. Reference [10] studied the effect of cap and wrap-around on reducing the stress concentration at the crack which leads to suggest the propagation of cracks. It presented a finite element study micro-macro - mechanical growth of interlaminar crack array fiberglass / epoxy DCB specimens for mode I [13]. Due to the heterogeneity of the composite material, probabilistic studies have also been carried out by two approaches: some [5] use a probabilistic criterion for the distribution of critical stress while [4] use a criterion of the randomized critical energy release rate. Reference [11] has shown that the interface shear stress contributes significantly only to the mode-II energy release rate. Reference [7] has located a semi analytical model of energy release rate for delamination analysis of composites. Reference [15] has used the energy deformation refund rate for the characterization of fatigue delamination.

Our study is about the determination of the release energy rate G in mode I and the distribution of Von Mises equivalent stress along the damaged area. Different parameters were considered: - Effect of the applied loading. - Effect of the delamination size. The results show clearly better mechanical resistance on the loading line fort the unidirectional stratified composites than for the multidirectional stratified composites.

II. GEOMETRIC MODEL

The composite laminate studied is a carbon/epoxy, it is composed of 20 plies, each with a thickness of 0.13 mm, with a symmetrical fiber; the first 8 plies are oriented at 0° and the other adjacent plies at 90°. Our analysis goal is to show the

effect of several parameters such as the applied load and the delamination length on mode opening (modeI) for a test composite material with a length of 150 mm, width of 20 mm and a thickness of 2.6 mm.

The unsticking of layers was observed for a constant static load from 10 N to 60 N applied to the half-width of the specimen. For a distance of 5 mm, of his free end.

The delamination is created according to the width of the composite material, and is located between the ten and the eleven layer of the stratified. The composite material is manufactured such as the initial length of the delamination area is 35 mm.

The stratified composite material uses in this study is a carbon\epoxy, its mechanical characteristic are presented in Table I.
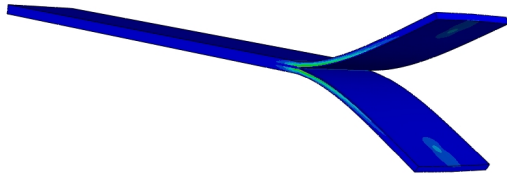

Fig. 1 Schematic representation of the geometrical model

III. MODELING

The adopted approach in this analysis is to use a reasonable modeling with a good refinement of the critical area [6].

In this digital analysis by the finite elements method, the specimen is modeled by quadrilaterals mesh elements of eight nodes, isoparametric type.

TABLE I
ORTHOTROPIC PROPRIETIES OF UNIDIRECTIONAL CARBON\EPOXY LAYER.

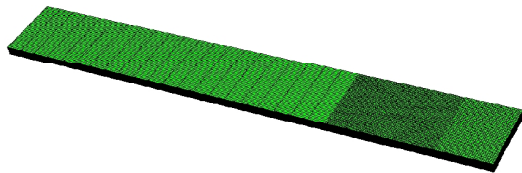| Symbol	Designation	Quantity
E_1	Longitudinal Young's modulus	140GPa
E_2	Transverse Young's modulus,	10GPa
E_3	Transverse Young's modulus	10GPa
v_{12}	Longitudinal Poison ratio	0.3
v_{23}	Transverse Poison ratio	0.3
v_{21}	Transverse Poison ratio	0.0214
G_{12}	Longitudinal shear modulus	5GPa
G_{23}	Transverse shear modulus	3.85GPa
G_{31}	Transverse shear modulus	5GPa

Fig. 2 Schematic representation of the geometrical model with modeling

IV. RESULTS

A. Effect of Applied Load

1. Delamination Length of 35 mm

We represent, in Fig. 3, the variation of the equivalent release energy rate G in function off the length of delamination line (width of the specimen), for different load, we remark the increasing of G parameter with accretion of load.

The minimal values of G parameter where observed in the free edge of the specimen, and begin to increase until a maximal value in the middle of his width. The style of the curve is almost a parabolic curve. For the low loads the release energy rate G is almost constant along the width of the specimen.

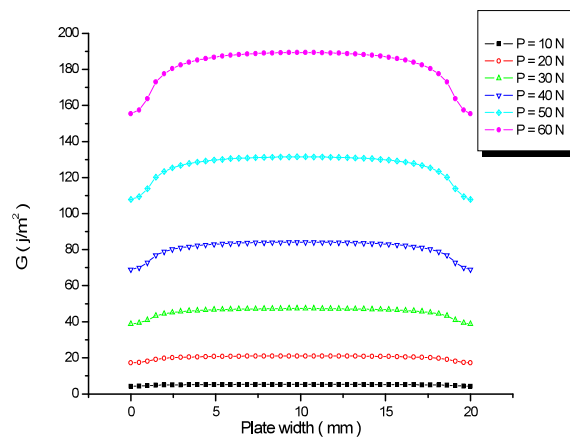The increasing rate of the failure parameter G is accented when in accordance with the applied load accretion.

Fig. 3 Energy release rate distribution versus plate width for delamination length of 35 mm

2. Delamination Length of 45 mm

We observe the same behavior like the precedent figure, but in this time we remark that an increasing rate of G parameter most marked is as the one of the precedent case.

With the same load of 40 N; we remark that the maximum value of G parameter gives a rise of 77% as the precedent case.

- 20 N increasing of 70%
- 30 N increasing of 75%

The release energy rate G reached his critical value for applied loads breaking the 40 N barriers.

3. Delamination Length of 55 mm

We registered an important increasing of the release energy rate G in relation to the precedent case, defined by s:

- 20 N increasing of 50%
- 30 N increasing of 53%
- 40 N increasing of 55%

The increasing rate of G parameter is more intense. Fig. 5 shows that for loads inferior of 40 N, there is no damage for the composite material.
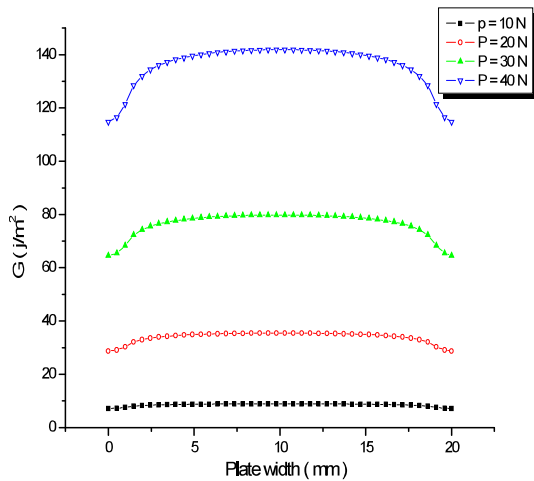
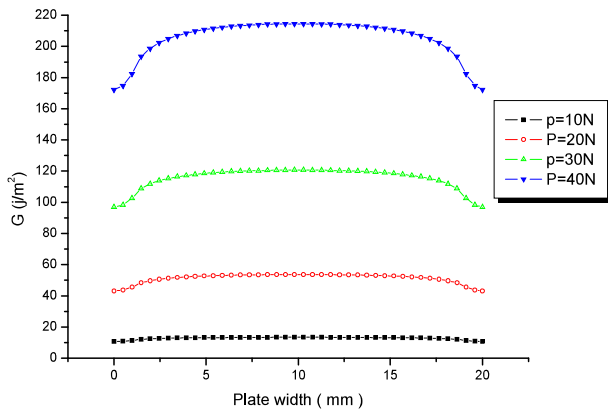Fig. 4 Energy release rate distribution versus plate width for delamination length of 45 mm

Fig. 5 Energy release rate distribution versus plate width for delamination length of 55 mm

4. Delamination length of 65 mm

Fig. 6 shows that the length of delamination has a big influent on the G parameter. However, relatively to the length delamination of Fig. 5, this one present a significant values of G parameter with those percentages:

- 20 N increasing of 35%
- 30 N increasing of 39%

Fig. 7 shows the variation of G equivalent for the two positions P_1 and P_2. The difference between the two values of G parameter are due principally to the increasing of applied load, and reach his maximal value for a delamination length of 65 mm.

Comparatively to Fig. 3, we mark an important difference of G equivalent for the two positions P_1 and P_2 for a load near of an average equal to 20 N. this difference increase with the accretion of load, and it reach the 16% for a load of 30 N, for wish the G parameter approach the critical value in the position P_2.
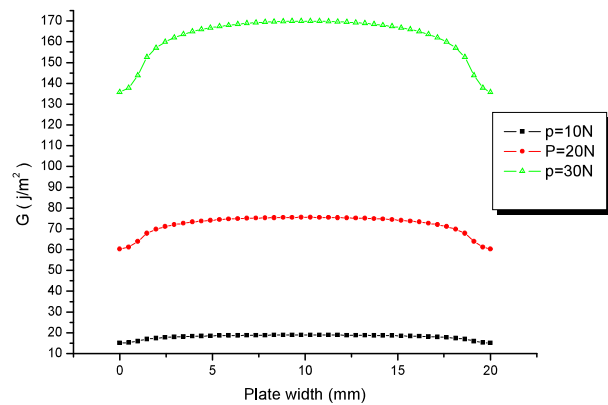

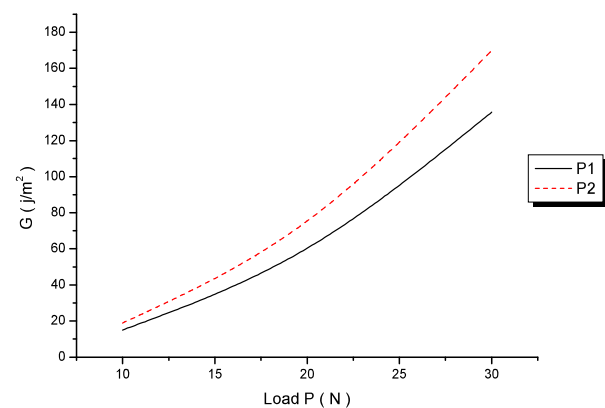Fig. 6 Energy release rate distribution versus plate width for delamination length of 65 mm

Fig. 7 Evolution of G parameter with applied loads for the two positions P_1 and P_2

B. Comparison between the Unidirectional and Multidirectional Stratified

Fig. 8 represents the distribution of release energy rate G in function with the applied loads for a unidirectional stratified composite with a delamination length of 35 mm.

We remark from a part, that whatever the stratified composite material, the release energy rate G proportionally varied with the applied load, other part, from the digital results obtained, we observe that the multidirectional stratified composite (Fig. 3), present a most marked level of release energy rate G equivalent as the unidirectional stratified composite. This attenuation of G parameter is due principally to the mechanical resistance of unidirectional fibers on opened mode in the delamination area.

C. Stress Distribution

We represent the variation of Von Mises stress equivalent intensity and distribution on the requested zone defined by the both position P1 and P2. We recall that the mesh was refined at the level of this zone to obtain accurate results.

The stresses are determined in the various layers of the laminated composite according to the inter distance going from the undamaged zone to the one where the load is applied.
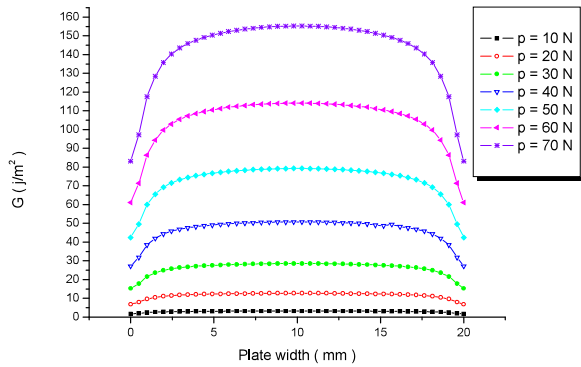
Fig. 8 Energy release rate distribution versus plate width for delamination length of 35 mm

Through the line of delamination, whatever the two positions P1 and P2, the stresses growing in from the undamaged area, reaching a maximum value at the delaminated line and decrease proportionally away from the latter, towards the point of load application.
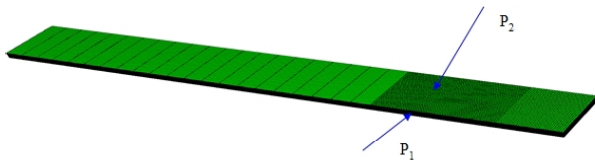

Fig. 9 Mesh model and representation of the positions P_1 and P_2

1. Position P_1

a. Laminated Unidirectional

We observe that the stress field is localized at the level of the line gouged (between ply 10 and its symmetrical, ply 11) for the composite unidirectional. Constraints decrease to another ply away the for which is a concentration of constraints.
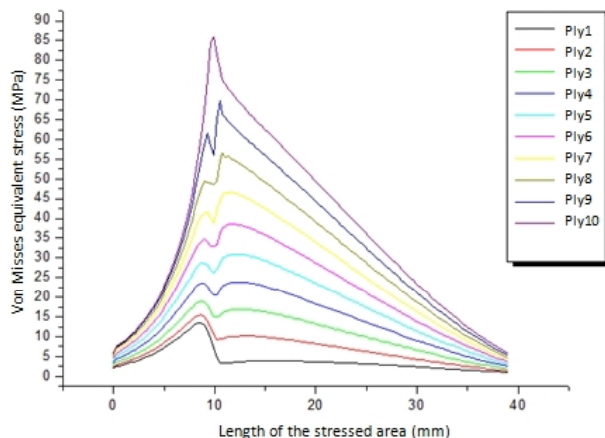

Fig. 10 Distribution of G versus plate width for P_1 position (UL)

b. Cross Laminated

There is a considerable fall of the stress field at the level of ply 9 and 10 oriented to 90° and constraints in the other folds are more intense than those of the composite laminate one-way. The plies 9 and 10 oriented 90° have a low resistance to the opening of the composite and therefore constraints are transferred to the other folds facing 0°.
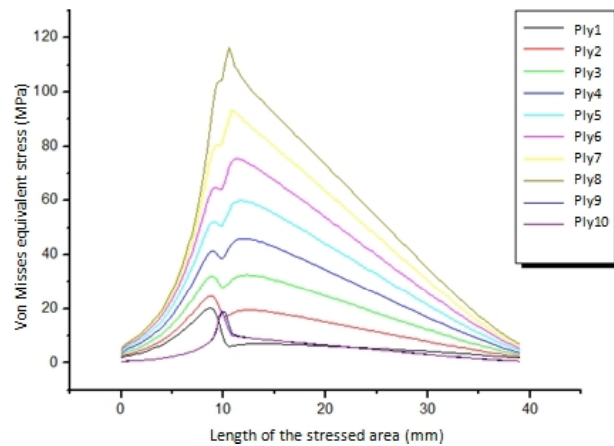

Fig. 11 Distribution of G versus plate width for the P_1 position (CL)

V. CONCLUSION

This numerical study, can draw the following conclusions:

- The delamination of composite laminate in mode I depends on the intensity of the applied load and the surface of the damaged area.
- The rate of refund of energy values are maximum in the middle of the width of the plate composite laminate and they are minimum two free ends of the laminated composite material, specifically at the level of the line of delamination.
- Compared to the cross laminate composite, composite unidirectional presents a good mechanical strength, because oriented at 0° ply better resist the imposed load those oriented at 90°.
- Under the effect of the same loading type and the presence of an identical defect, it is noted that the high level of the equivalent von Mises stress of the cross laminate composite in the ply close to the defect is due to the transfers of constraints following the non-solicitation of adjacent fibers that are oriented at 90 ° and that have a low von Mises equivalent stress; but that of the unidirectional composite increases gradually from the first ply to the one that is at the closest vicinity of the delamination line.

REFERENCES

[1] Bai, T. and Pollard, D.D., "Spacing of fractures in a multilayer at fracture saturation", *International Journal of Fracture*, 1999, 100(4), pp. 23–24.
[2] Berthelot, J.-M. and Le Corre, J.-F., "Statistical analysis of the progression of transverse cracking and delamination in cross-ply laminates", *Composites Science and Technology*, 2000, 60(3), pp. 2659–2669.
[3] Haneef, M., R M S. A. & Ali, M. M., "Studies on Delaminating Effects on Stress Development in Composite Structures", *Proceedings of the World Congress on Engineering* Vol. III WCE, July 6 - 8, London, U.K. 2011.

[4] Katerelos, D.T.G., Kashtalyan, M., Soutis, C. and Galiotis, C., "Matrix cracking in polymeric composites laminates Modeling and experiments", *Composites Science and Technology*, 2008, pp. 2310-2317.

[5] Manders, P.W., CHOU, T.-W., Jones, F. R. and Rock, J. W., "Statistical analysis of multiple fracture in 0/90/0 glass fiber/epoxy laminates". *J Mater Sci*18,1983, pp. 2876-2889.

[6] Product Dassault Systèmes Simulia Corp, ABAQUS Standard Version 6.10, Providence, RI, USA. 2010.

[7] Qing n, G.H., Liu, Y. H. and Li, D.H., "A semi-analytical model for the energy release rate analyses of composite laminates with a delamination". *Finite Elements in Analysis and Design,* 2011,47, pp. 1017–1024.

[8] Rebière, J.-L, Maâtallah, M.-N and Gamby, D., "Analysis of damage mode transition in a cross-ply laminate under uniaxial loading", *Composites structures,* 2002, 55, pp. 115-126.

[9] Smith B. W., "Fractography for continuous fiber composites", in "Engineered materials handbook", volume 1: composite, Ohio, USA, ASM International, 1993, pp: 786-793, ISBN 0871702797 (v.1).

[10] Dasa, Subhankar, Choudhurya, Pannalal, Haldera, Sudipta and Sriramb, P. "Stress and free edge delamination analyses of delaminated composite structure using ANSYS", *Procedia Engineering*, 2013, 64 1364 – 1373

[11] Szekrényes, András, "Interlaminar stresses and energy release rates in delaminated orthotropic composite plates. *International Journal of Solids and Structures*, 2012,49 2460–2470.

[12] Todo, M., JAR, P. Y. B. and Takahashi, K., "Initiation of a Mode-II Interlaminar Crack from an Insert Film in End-Notched Flexure Composite Specimen", *Composites Science and Technology*, 2000, 60, pp. 263–272.

[13] Todo, M., Jar, P. Y. B., "Study of Mode-I Interlaminar Crack Growth in DCB Specimens of Fibre-Reinforced Composites", *Composites Science and Technology*, 1998,58, pp. 105–118.

[14] Wang, J. and Karihaloo, B. L., "Matrix crack-induced delamination in composite laminates under transverse loading", *Composites structures,*1997, 38, 661-666.

[15] Yao, Liaojun, Alderliesten, R.C., Zhao, Meiying and Benedictus, R., "Discussion on the use of the strain energy release rate for fatigue delamination characterization". *Composites: Part A,*2014, 66 65–72.