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STRAIN RATE EFFECTS ON THE MODE I INTERLAMINAR FRACTURE OF E GLASS/POLYESTER COMPOSITES

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SUMMARY: When they are submitted to an impact, glass/polyester composite materials used in naval industry, damage mainly by delamination. The mode of most critical solicitation is the mode I for the delamination and can be characterized by Double Cantilever Beam test (DCB). We have developed a particular setting allowing to load the DCB specimen in a large range of speed (from quasistatic to 3 m/s) and determine the energy release rate, for a perpendicular solicitation with the plan of the laminate. We show that energy release rate of propagation is insensible at the opening rate of the sample.

KEYWORDS: Delamination, initiation and crack propagation, strain energy release rate, strain rate effects, E glass/polyester composites

INTRODUCTION

Naval structures, manufactured in glass/polyester composite material, can undergo large range of strain rate during the shock of waves or underwater explosions for military ships. The shock of laminates entails often interlaminar fracture. Indeed, anterior studies (F. Décobert, [1]) have shown that the most critical phenomenon is the delamination. The mode of solicitation the most penalizing for the delamination is the mode I (opening) because the fracture energy measured for this mode ($G_{IC} \approx 550$ J/m²) are more weak that the others. It is therefore very interesting to measure, among others parameters, the fracture toughness of E glass/polyester composites under high speeds when the mode I is tested. The Double Cantilever Beam (DCB) is well adapted to characterize the evolution of the strain energy release rate. Its simplified geometry allows indeed applying, some first approaches, principles of the beams theory that describe the behaviour of "structure" of the sample under a dynamic solicitation. The slenderness of the specimen allows furthermore the application of the compliance method with a succession of loadings, propagations of cracks, and unloadings of the specimen.

The fracture toughness is an intrinsic characteristic of the material whose rate effects have been studied on thermoset matrix composites by some authors (Smiley [2], Roy [3] for example). Nowadays, it does not exist a consensus on the rate effects on the mode I strain energy release rate. This study has for goal, at first to develop a reliable test Double Cantilever Beam (DCB) on a large range of velocity and secondly to measure the mode I strain energy release rate versus the opening rate of the specimen.

MATERIAL AND DEVELOPMENT OF THE DCB TEST IN " DYNAMIC "

Material and test procedure

The studied material is a quasi-unidirectional E glass/polyester composite whose fibre volume fraction is approximately 60%. This composite is manufactured by manual stratification before a cure cycle to finish the reticulation of the resin. So as to insure the bond of the woven of fibre-glasses, 5% of fibres all in all are in the sense of the weft (fig. 1 - a).

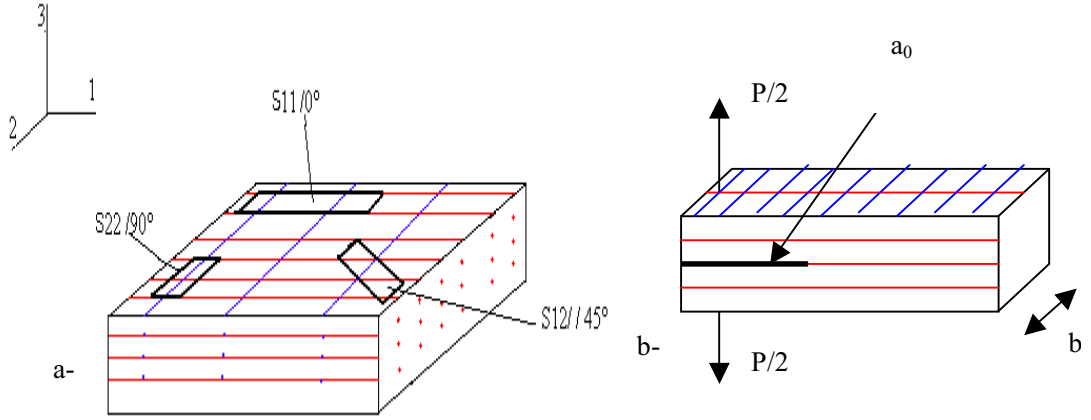

Fig. 1a and 1b Presentation of quasi-unidirectional E glass/polyester composite in laminate (a) and DCB specimen (b)

DCB specimens (fig. 1-b) are constituted of 28 plies; their dimensions are 20 mm large and 135 mm long. An anti-adherent film (P.E.T.) 50 mm length allows to obtain in a mid-plan a pre-crack of the specimen (called a_0). Quantities recorded during the test are the load, the opening of the specimen, and the crack length. The load is measured by strain gauges on arms in aluminium on either side of the specimen that load the specimen. An optical extensometer (Zimmer™) allows to follow precisely the displacement of the internal edge of the specimen and therefore knowing its opening. Finally, cracking gauges are installed on either side of the sample allowing to follow the crack propagation during the test.

Improvements brought to the DCB test, allow a measure of the strain rate energy release rate, from quasistatic to the high opening rates for a same geometry of sample. A first correction consists to add a damping foam PVC between the piston and the setting, so as to absorb the shock wave. More, the test configuration and the sample loading are symmetrical, optimised by finite elements at high opening rates (Joannic, [4]).

Determination of the strain energy release rate

The mode I strain energy release rate, GI is defined by the energy due to the fracture growth a + Δa arising from the changes in external work and internal energy in mode I. It expresses for a crack growth in quasistatic load conditions :

$$G_I = \frac{1}{b}\frac{\partial W_p}{\partial a} = \frac{1}{b}\left(\frac{\partial W_e}{\partial a} - \frac{\partial W}{\partial a}\right) \quad (1)$$

where b is the width of the sample, Wp is the potential energy, We the external work and W the strain energy. The analysis of the DCB test is based on the variation of the compliance. An extension of the crack from a to (a + Δa) entails a variation of the compliance linked to a loss of strain energy. The compliance method is therefore used for the determination of the critical strain energy release rate GIC :

$$G_{Ic} = \frac{P_c^2}{2b}\frac{dC}{da} \quad (2)$$

where Pc is the critical external load (beginning of the crack propagation), C, the compliance, b the width of the sample.
Wilkins and al. [5] propose to write the phenomenological expression of the compliance $C = ka^n$. Coefficients k and n are determined experimentally with variable crack lengths in DCB specimen. The compliance C measured at weak openings of sample is given in a graph log-log such that :

log C = n log a + log k (4)

The expression of Gc is evaluated :

$$G_{Ic} = \frac{nP_c\delta_c}{2ab} \quad (4)$$

This is the relation that we used to determine the mode I strain energy release rate.

Preceding expressions are valid in quasistatic ; a complete energetic analysis at high velocity, takes into account total kinetic energy. Smiley and al. [2] determine the kinetic energy from the beams theory. According to our material and test conditions, the part of kinetic energy versus the strain energy release rate is negligible (2.6%). We can therefore apply the compliance method for high velocities without taking into account kinetic energy.

The increase of Gc is well described by a graphical representation of the strain energy release rate versus crack advance a - a represents the total length of the crack, including the pre-crack a_0. It is called resistance curve or R curve (fig. 2). It characterizes the response of the material during the propagation of the delamination. The determination of R curve is easy from the compliance method. This curve presents two characteristic values. The strain energy release rate on initiation is the minimal value of G for a weak crack growth. Physically, this value represents the energy necessary to begin cracking the material, in the rich zone of resin that is found before the pre-crack. For higher values of a, the strain energy release rate reaches a constant that called the strain energy release rate of propagation which is an intrinsic characteristic of the material.

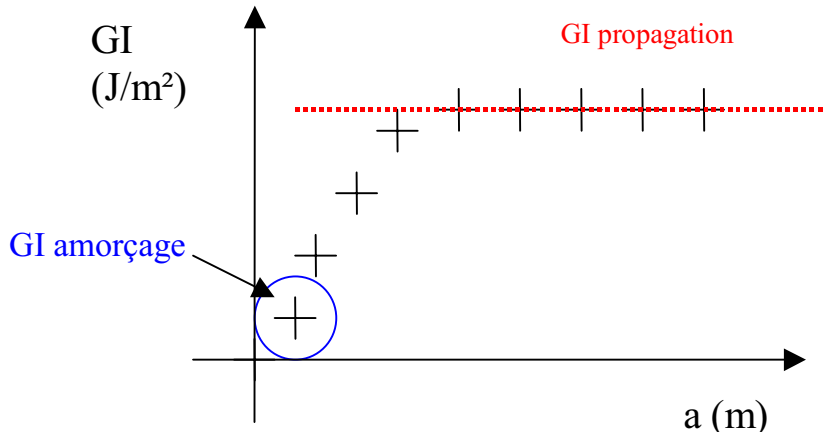

Fig. 2 R curve schematic of the glass/polyester composite

INTERRUPTED DCB TEST RESULTS : RATE EFFECTS ON INITIATION AND PROPAGATION STRAIN ENERGY RELEASE RATES

Interrupted DCB tests have been realized for 5 specimens in the same range of velocity (from quasistatic to 3 m/s). Curves load/opening are measured for a succession of loads, crack propagations and unloads on a same specimen (fig. 3a to 3d). These curves are necessary to determine the strain energy release rate from the compliance method.

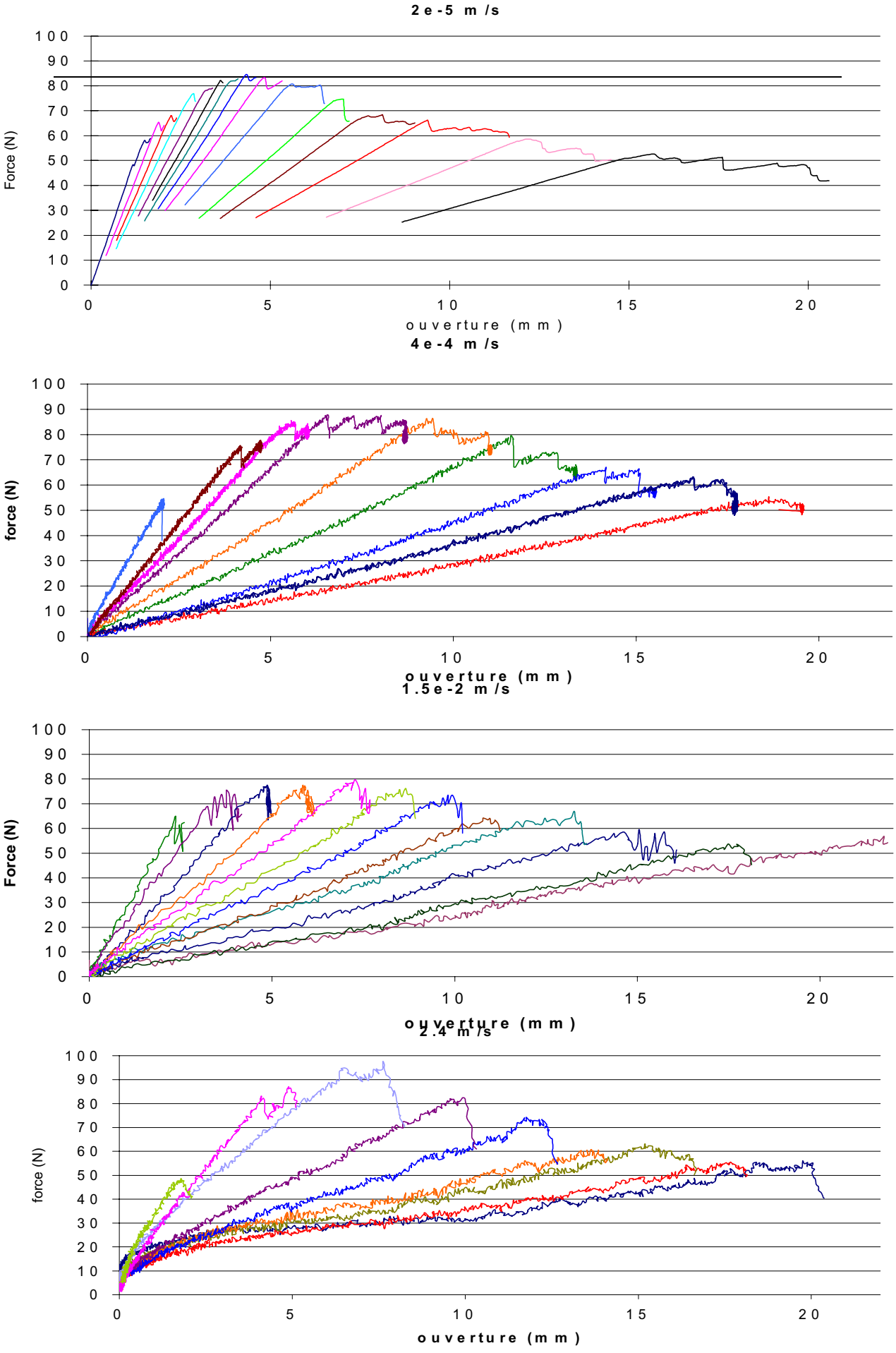

Fig. 3a, 3b, 3c and 3d Curves of interrupted loading at 4 opening rates (2 10^{-5}, 4 10^{-4}, 1.5 10^{-2} and 2.4 m/s)

We can quantify the strain energy release rate by the compliance method (paragraph 2.1). In the linear part of the loading, we measure the compliance and determine the constant n. For the two extreme velocities of our study, we obtain very close values : 2.7 approximately ; n does not evolve with the opening rate. Values of the fracture toughness are determined for the crack initiation and the crack growth from quasistatic to 3 m/s. R curve is not really clear to observe the rate effects, the strain energy release rate can be expressed versus other parameter.
Kusaka and al. [6] introduce a "loading rate" defined as the derivative of the strain energy release rate $\dot{G}_{I\,c}$. We have adopted this analysis to express the rate effects on the fracture energy. Indeed, from this relation, one estimates the loading rate in a DCB test as follows :

$$\dot{G_I} = \frac{2G_I\dot{\delta}}{\delta}$$

with $\dot{\delta}$, the opening rate of the sample, G_I, the mode I strain energy release rate and δ, the opening of the specimen.
On the fig. 4, are presented average values and standard deviation of the strain energy release rate of crack initiation versus the loading rate. Similarly, the energy of propagation is given versus $\dot{G}_I$ on the fig. 5.

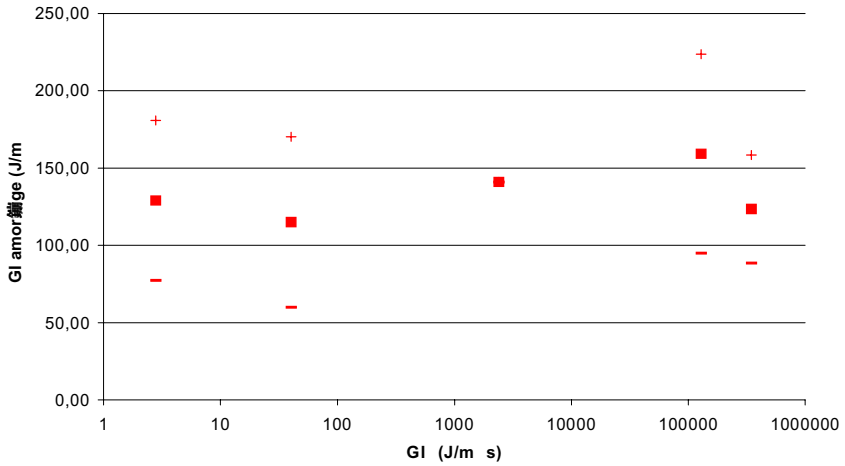

Fig. 4 Rate effects on the strain energy release rate of initiation for the E glass/polyester composite

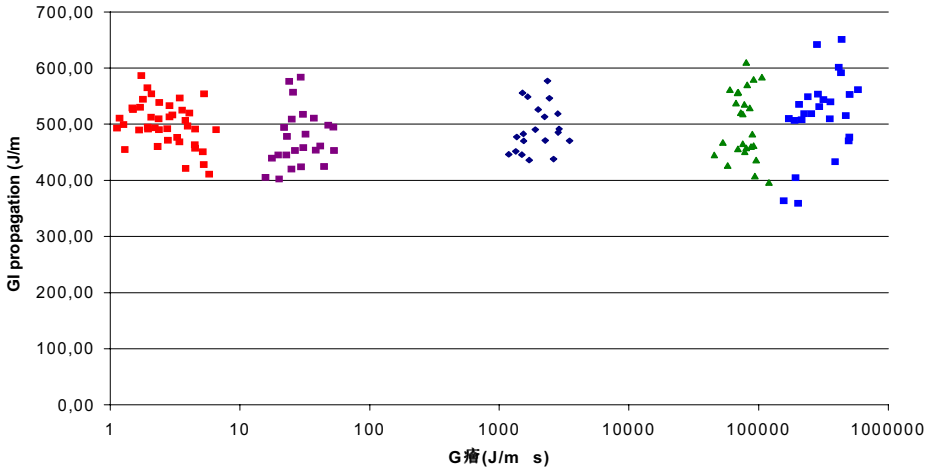

Fig. 5 Rate effects on the strain energy release rate of propagation for the E glass/polyester composite

We note that the opening rate has no effect on initiation or propagation fracture energy values. Their average is 133 +/-50 J/m² for the initiation energy and 500 +/-100 J/m² for the propagation energy. The fracture toughness is independent of the loading rate in these conditions. These results agree with those obtained by A. Roy [3] on a glass/polyester composite in the range of velocity from 10^{-4} to 10^{-1} m/s.

The mode I fracture toughness of an unidirectional composite is governed by mechanical characteristics of resin. Indeed, we have observed near the crack tip an accumulation of resin of some micrometers thick. Fracture energy of initiation is the energy necessary to start a crack in the resin. Elsewhere the value of the strain energy release rate of initiation for the composite is very close to that of the polyester resin (respectively 133 J/ m² and 110 J/ m²). Similarly, for this kind of solicitation, the strain energy release rate of propagation depends on the resin and on the fibre/resin interface. We have shown in anterior works (Pardo [7]) that the behaviour of the polyester resin is elastic, brittle and evolves weakly with the strain rate. This behaviour would explain the fact that there are no rate effects on fracture energies of the glass/polyester composite.

CONCLUSION

We have developed a setting allowing to test the mode I of opening on specimens of typical double cantilever beam (DCB) from quasistatic to 3 m/s. We have measured the strain energy release rates of initiation and propagation for an E glass/polyester composite in this range of velocity. We show that properties of delamination of this material are insensible to the velocity. That means that for a glass/polyester composite structure whose critical mode is the delamination in mode I, the fracture toughness will be equivalent at quasistatic and at very fast solicitations.

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