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Influence of the stacking sequence and crack velocity on fracture toughness of woven composite laminates in mode I

P. Navarro [a], J. Aubry [a], F. Pascal [a], S. Marguet [a], J.F. Ferrero [a,*], O. Dorival [b]

[a] Université de Toulouse; INSA, UPS, Mines Albi, ISAE; ICA (Institut Clément Ader), 10 Avenue Edouard Belin, BP54032, 31055 Toulouse Cedex 4, France
[b] LMT-Cachan (ENS Cachan/CNRS/PRES Univ Sud Paris), 61 av; President Wilson, Cachan 94235, France

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ABSTRACT

Woven composites are well-known for their good transverse properties and for their high fracture toughness. The damage mechanisms leading to delamination in woven composites are identified in mode I. The influence of several parameters, including the draping sequence and the fiber/matrix interface on the fracture toughness of woven composite laminates is studied. Pure mode I tests are carried out on several carbon/epoxy and glass/epoxy woven composites configurations and the differences observed are discussed from a fractographic point of view. A novel experimental method is designed to perform dynamic pure mode I tests. The study illustrates the high fracture toughness of the composites made of woven fabrics as well as the influence of the orientation of the plies, the nature of the fibers and the addition of an adhesive film on the fracture toughness in mode I. The dynamic tests prove that, on the configurations tested and for crack velocities up to 100 m/s, the crack propagation velocity has a limited effect on the value of G_{Ic}.

1. Introduction

The laminate structure of composites makes delamination a critical damage mechanism at the interfaces between plies. Delamination may reduce the in-plane strength and stiffness and can lead to the failure of the composite structure [1]. Study of the fracture toughness of composite is thus fundamental for the characterization of composites.

In laminates made from unidirectional plies, cracks can propagate between plies and cross a ply through the matrix [2].

Woven fabrics can be used to block the intra-ply crack propagation. Indeed, the entanglement of the warp and weft tows prevents the crack from crossing the plies. Generally, woven composites show higher fracture toughness compared with unidirectional composites as shown by early studies of Funk and Deaton [3]. The authors have quantified the greater values of G_{Ic} for carbon/epoxy woven fabrics compared to carbon/epoxy unidirectional tape. Values of 300–500 J m^{-2} were recorded for the woven fabrics, to be compared with the critical energy release rate of 100 J m^{-2} for the unidirectional composite.

This difference is also explained by the intrinsic roughness of woven fabrics that increases the surface to be separated [4]. Kim and Sham [5] also explain the greater toughness by the alternation of warp and weft tows. When the crack propagates in the warp direction, the fibers parallel to the crack propagation tend to speed up the crack, whereas for the weft tows, the fibers are perpendicular to the crack propagation and tend to slow down the crack [6]. This effect is also found in unidirectional laminates where delamination off the axis of the fibers requires more energy [7].

* Corresponding author.

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Nomenclature

P	load
δ	opening
B	width of the specimen
a	crack length
Δa	corrective term
F	corrective term
N	corrective term
G_{Ic}	energy release rate

Woven fabrics are not affected by fiber bridging the same way unidirectional laminates are. The entanglement of the tows generally prevents the fibers from being torn off from the composite surface [4]. However Alif et al. [8] have shown that fiber bridging in woven fabrics can still play an important role in dissipating energy. For this type of composites, fibers from the warp direction can break between two tows in the weft direction and be torn of the composite surface. This phenomenon is particularly predominant in twill and satin weave pattern compared to plain weave pattern, where the distance between two weft tows prevents fibers to be pulled out [8].

Dynamic crack propagation has been mainly investigated on unidirectional composites. Experimental set-ups include modified wedge tests on Hopkinson bars [9,10], specific rigs for high-speed hydraulic machines [11] or drop weight towers [12]. All of these studies have established that measuring a dynamic fracture toughness in mode I is complex, either for measurements problems considering the velocity of the phenomena, or because the inertia of the specific rigs makes it impossible to reach a steady crack propagation state before the complete failure of the specimen. Guo and Sun [13] have worked on a modified experiment that consists in placing an adhesive film right after the pre-crack. This allows charging the specimen before the crack propagates and produces crack velocities up to 200 m s^{-1}, with close to quasistatic loading rates.

Damage mechanisms during delamination of woven fabrics are thus known up to a certain point. However most articles study the delamination of woven fabrics in the warp or weft directions. In this paper, we present an experimental study in pure mode I of the influence of the orientation of the woven fabric plies, of the material nature and of crack propagation speed. A fractographic study is carried out on each configuration to bring to light the damage mechanisms leading to delamination and to relate the delaminated surfaces obtained with the value of the fracture toughness of the composite.

2. Experimental procedure

2.1. Materials and specimen manufacture

Hexcel 913/45%/7781 satin weave glass fabrics and *Hexcel 913/45%/G963* satin weave carbon fabrics are used to manufacture the specimens. Both fabrics are 0.3 mm thick pre-impregnated plies. The adhesive used in this study is a 0.1 mm thick *Hysol EA 9686* unreinforced epoxy film.

For each configuration tested, a 12 plies-thick panel is manufactured using a hydraulic heating press. A 40 μm thick PTFE film is placed at mid-thickness to initiate the delamination. The stacking sequence of each configuration is chosen so that the stiffness of the two arms of the specimen is equal and so that the bending of the arms does not produce torsion, as advised by several papers [14,15]. Each panel is cut using a diamond saw into specimens of length 170 mm and width 20 mm.

The stacking sequences for each configuration are given in Table 1 where C stands for a ply of carbon woven fabric, G for a ply of glass woven fabric and *adh.* stands for a ply of adhesive. For each interface, the numbers given in subscript indicates the angle between the warp direction and the crack propagation direction. Four specimens are tested for each configuration to account for statistic distribution.

Table 1
Stacking sequence of the configurations tested.

Influence tested	Studied interface	Stacking sequence
Stacking sequence	$C_0//C_0$	$(C_0)_6//(C_0)_6$
	$C_0//C_{45}$	$(C_0)_4\ C_{45}\ C_0//C_{45}\ (C_0)_5$
	$C_{45}//C_{45}$	$(C_0)_5\ C_{45}//C_{45}\ (C_0)_5$
Material nature	$G_0//G_0$	$(C_0)_5\ G_0//G_0\ (C_0)_5$
	$C_0//G_0$	$(C_0)_2\ (G_0)_3\ C_0//G_0\ (C_0)_5$
	$C_{45}//G_0$	$(C_0)_4\ G_0\ C_{45}//G_0\ (C_0)_5$
Adhesive film	$C_0/adh./C_0$	$(C_0)_6/adh./(C_0)_6$
	$C_0/adh./C_{45}$	$(C_0)_4\ C_{45}\ C_0/adh./C_{45}\ (C_0)_5$