PHENOMENOLOGICAL STUDY OF CRACK PROPAGATION IN MULTIDIRECTIONAL STRATIFIED SUBJECTED TO MODE (I)

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Abstract : The object of this work is the study of the behaviour of composite multidirectional laminate under opening (mode I) loading. The material used is a composite glass / epoxy. The stacking sequence was selected in the form $\left[\left(+\theta\,/\,\text{-}\theta\right)_2\right]_{2S}$ to minimize the effects of coupling.

The experimental results show that the shape of the head of crack as well as the evolution of the propagation of crack depends on the angle of orientation of the plies. For the weak angle ($\theta \leq 30°$, the fracture is done by délamination on the médian plan. For the great angle ($\theta \,\phi\, 67°$) the fracture takes place by flexure at the head of the precrack. For the intermediate angles, the bifurcation phenomenon leads to a delamination in staircase.

Key-words: Mode I, Multidirectional laminated composites, bifuration, fracture propacation.

1. INTRODUCTION

The characterization of behaviour to delamination under pure mode (I) loading of composite laminate is carried out in the majority of the cases for the unidirectional laminates $(\theta = 0°)$ considered as homogeneous and orthotropic. However, structures in service belong rather to the family of the multidirectional laminates from which the behaviour and damage mechanisms can be basically different from those met on the unidirectional laminates.

The literature concerning the multidirectional laminates, is scarce. It shows that practically all the work carried out is interested only to the effect of the adjacent plies in the plan of precrack and for their purposes on the mode of propagation and the fracture surface. As for the remainder of the plies constituting the sequence, they are approached little.

Hunston & Bascom [1] by examining various multidirectional sequences, found that if there are no plies with $(0°)$ among the median plies, the crack would tend to bifurcate from one of a ply to another. They suggest considering one or more plies $(0°)$ in the adjacent plans to the plan of délamination, to control the propagation of the crack.

Chai [2] showed experimental results on DCB specimens of multidirectional brittle laminate T300/5208 and ductile laminate in graphite/epoxy T300/BP907. The sequence used was [$+45°/0°_2/+45°/0°_2/+45°/0°_2/90°$]. The precrack was selected in the interfaces $0°/0°$, $0°/45°$, $+45°/-45°$ and $0°/90°$. As it was observed in the preceding work, the crack does not remain in the initial plan but tends to change interfaces when it develops.

Laksimi & al.[3] carried out tests of mode I on composite laminate in carbon/epoxy to study the fracture energy on the interfaces 0°/0°, 0°/90° and 90°/90°. They found that the energy of propagation decreases continuously after initiation for the interface 0°/0°. On the other hand, it increases for the interfaces 0°/90° and 90°/90° after fracture initiation. They concluded that the plies 90° make obstacles to the propagation of delamination by obliging it to be divided into two plans of cracking around the ply 90°

An experimental methodology was applied to the different staking sequences. It allows the identification of the starting cracks as well as it permits to follow the evolution of the crack propagation. This methodology consists of :

- using D.C.B. specimen instrumented with strain gauges and a sensor acoustic emission,
- testing the same specimen in several steps, for each staking sequence,
- following each loading step with microscopic observations in order to identify the generated damages.

It should be noted that, if arms of the specimen after the unload are not maintained open, the microscopic cracks can be closed and becom difficult to detect even under the microscope. Thus, to avoid that, a small plastic wedge low thickness is introduced between the arms of the specimen before reducing the load to zero.

2- MATERIAL and EXPERIMENTAL CONDITIONS

2-1- Material

The material used in this study is a glass E/resin composite (Vicotex M10) moulded in an autoclave (1H with 120°, empties 0.85bars, pressure 3bars). The elementary plies are almost uni-directional (5% fiber in the perpendicular direction). The mechanical characteristics of the unidirectional laminate are summarised in table 1. The tseted laminates are draped from preimpregnated plies in a multidirectional manner. The stacking sequence was selected in the forme $[(+\theta\,/\,-\theta)_2]_{2S}$ with four different configurations : $\theta = 15°$, 30°, 45° and 60°. The final fiber volume content was approximately 52%. The specimens used are DCB type, cut out in a plate thickness equal to 5mm containing 16 plies. A precrack (Teflon) is inserted into mid thickness as indicated on figure (1).

Table I: Mechanical *charactéristics of the unidirectiona laminatel.*

E_{xx} (GPa)	E_{yy} (GPa)	G_{xy} (GPa)	ν_{xy}
44,11±3,22	17,98±1,67	6,16±0,24	0,267±0,005

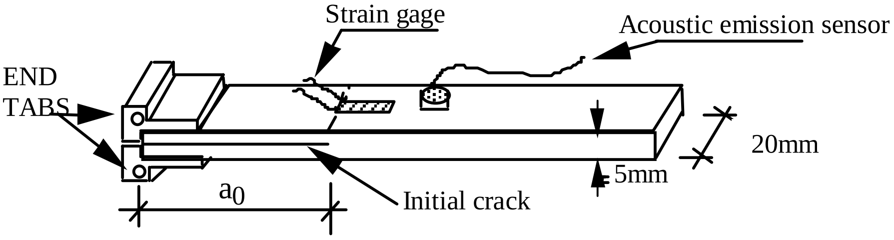


Figure 1*: Specimen DCB instrumented*

2-2- Instrumentation of the specimens

A 5mm strain gauge and sensor of acoustic emission were instumented in each specimen (figure 1). The sensor used is a broad frequency hand from 20KHz to 1 MHz. The specimens were loaded in displacement control at a constant rate of 2mm/mn.

3- STUDY OF THE DELAMINATION PHENOMENA

3-1-Phase of crack initiation

In the literature, among the methods most used to detect the starting of delaminations, in addition to the visual observation, one recommends the method of compliance and especially the sound emission. The standards Structural ESIS(european Integrity Society) and JIS (japanese industrial Standard Group) recommend the value which corresponds to a change of compliance of 5%, while standard ASTM requires the determination of three values NL (not of non-linearity on the curve of load/displacement), 5% (compliance of the elastic phase +5%) and visual (initiation visually located).

In the present study, an experimental methodology applied to the various sequences of stratification made it possible to choose the point NL which corresponds to the beginning of the acoustic emission and a change of the curve of deformation. That consists in loading a specmen of each type of stratification until the starting of the sound emission, then to introduce a smoall plastic wedge low thickness between the arms of the specimen before reducing the load to zero and observing the specimen, on the sides, under the scanning elctronique microscopy (SEM) to confirm or cancel of an unspecified damage. The results of these tests show that all the specimens tested up to point NL present a starting of cracking on the two sides. The crack starting occurs in the median plane. These results show that the crack starting is made in the same manner for all the staking sequences. The example of the sequence ±45° is illustrated by the curves of the figure (2) to which the photographs of figure (3) correspond.

It should be noted that in addition to the phenomenologic study, was carried out to the calculation of the critical energy release rate G_{Ic} on the basis of theory of IRWIN-KIES [5] by applying the method of experimental compliance. The results show that the orientation of angle θ have no influence on the critical energy release rate ($G_{Ic} \approx 185/m^2$). This is explained by the fact why starting occurs in the resin at the head of precrack.

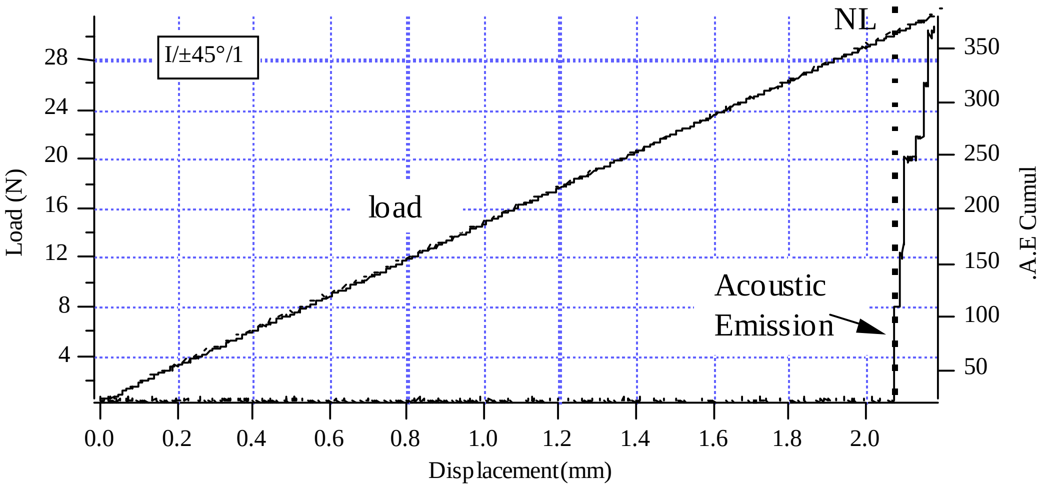


***Figure 2**: curve of load and cumul (AE) vs the displacement of the séquence [(+45°/-45°)2s]s loaded in mode I up to point NL.*

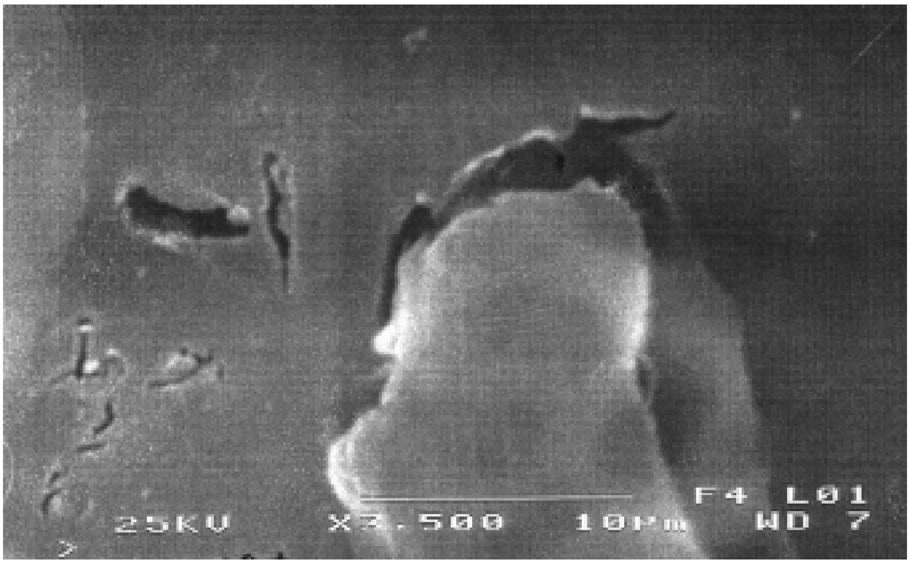


Figure.3: *crack starting (left side)*

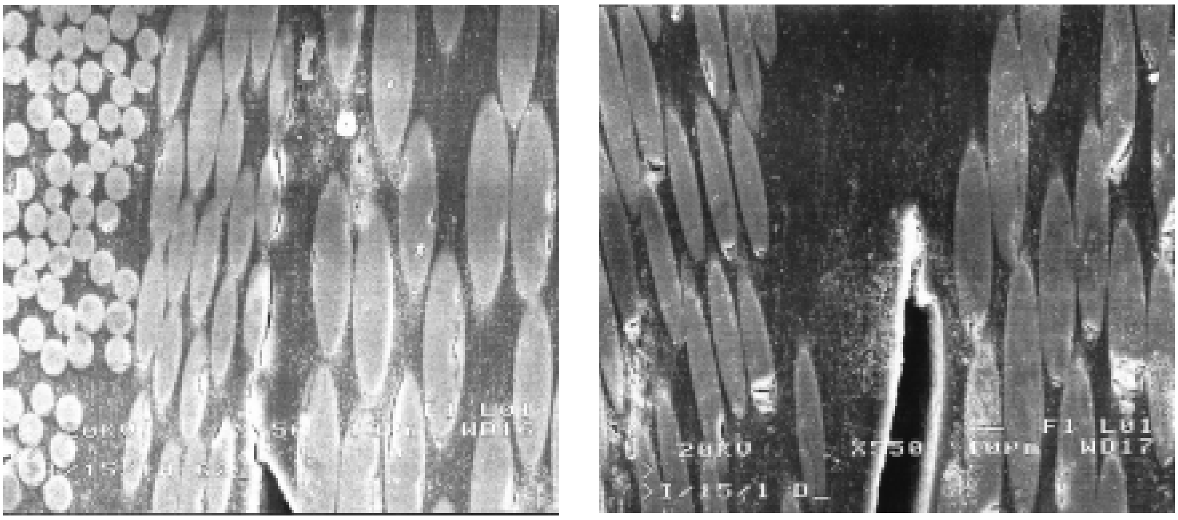
3-2- Phase of propagation

If the starting of delamination, such as it has been just noted in paragraph (2-2), does not depend on the sequence of stratification, can one then expect such a report in the case of the propagation? To this end, experimental methodology quoted above will be continued for the specimen already tested in the phase of crack initiation.

The results of these tests show that, for all the staking sequences. The crack initiation occurs in the median plane on the left side before the right side (figure 4). Thereafter, the right side in starts to fissure in its median plane but this crack is very quickly arrested. Another crack occurs upstream head of the precrack and crosses one of the two adjacent plies in the normal plan of delamination (figure 5), and continuous to be propagated with a ply of the median plane in the case of the sequences ±45° and ±60° (figure 6). For the sequences ±15° and ±30°, the crack returns quickly in the median plane where it continues its propagation (figure 7). In the case of the ±15° and ±30°, the continuation of the propagation is done almost in the median plane by alternation between the two adjacent plies. However, it should be noted that, in the case of the ±30°, the crack passes around a bundle of fibres before returning in the median plane. On the other hand, in the case of the ±45° and ±60°, the propagation is done in a complex way. Indeed, in this case there are no more only one plan of delamination but two. The first, located in the median plane, attenuates gradually and ends after a propagation d_1=Bctgθ (figure 8). The second, located at a ply of the median plane, widens gradually to occupy all the width of the specimen after a propagation d_1. It should be noted that at the time when the propagation reache d_1 the load has a very significant diminution at point B (figures 9, 10). Beyond the propagated distance d_1, delamination continues to advance with a ply of the median plane, i.e. with two arms different thicknesses: one with seven plies and the other nine plies. After a distance d_2 (figure 8), it appears a new crack bifurcation of a ply in the arm with 7 plies on the left side, and a diminution of load less significant than at the end of d_1. There are thus again two plans of delamination: the first with a ply of the median plane and the second with two plies.

The distance d_1 (figure 8) represents the distance at the end of which the crack passes completely to a ply of the median plane. It depends only on the angle θ and the width B of the specimen: d1=B.ctgθ. On the other hand, the distance d_2 of same figure (figure 8) depends on the geometrical and mechanical parameters of the laminate, namely, the width of the specimen, the length of the precrack, the thickness of the arms, and the stifness of material. Finally , for the ±45° and ±60° the total propagation of delamination is done in the form of staircase. A Shematic modeling of the propagation of crack in the multidirectional laminates ±θ loaded in mode I is illustrated by the figure 8. This delamination associated with bifurcations continues to be propagated to succeed, at the end of some bifurcations, with a transverse rupture occurring brutally by inflection at the head of crack.

Just as for the phase of initiation, was carried out to the calculation of the energy of rupture in propagation. The found results show that energy in propagation depends on the nature of stratification, on the width of the specimen and on the length of crack propaged.



a) *left side*

a) b) *right side*

Figure 4: *delay of beginning of propagation on the right side compared to the side left*

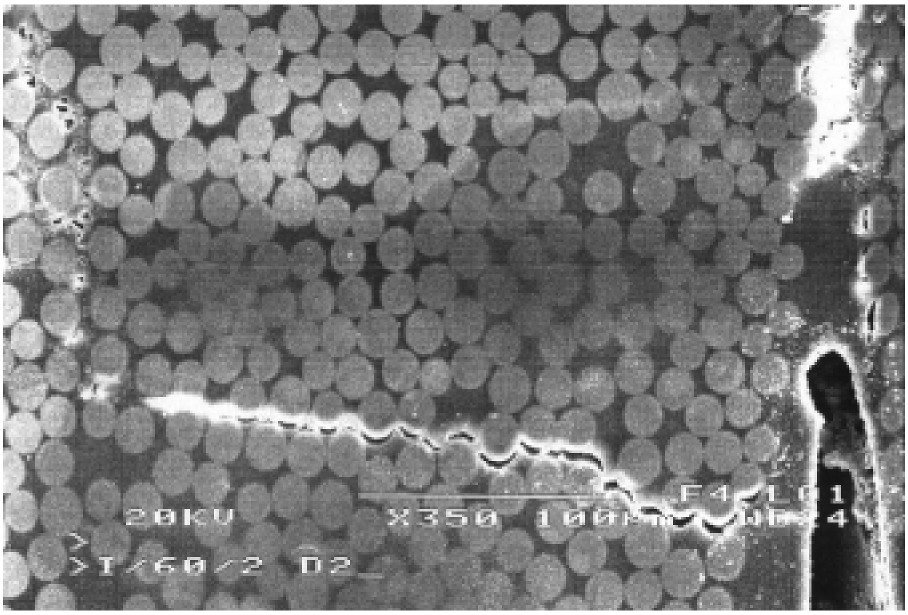


Figure 5*: appearance of a bifurcation of crack on the right side*

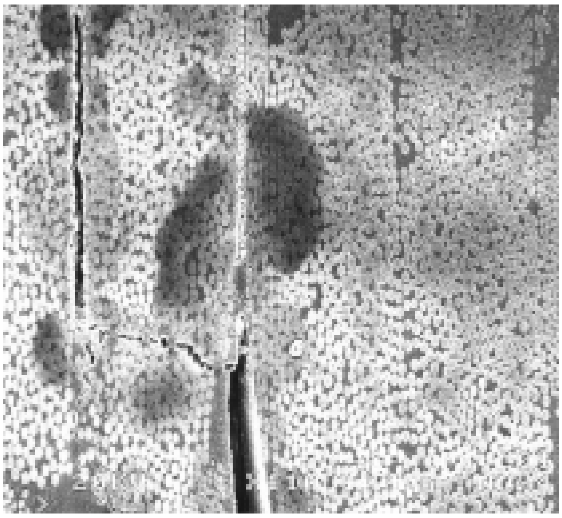


***Figure 6:** for the ±45° and ±60° the crack is propagated with ply of the median plane on the right side*

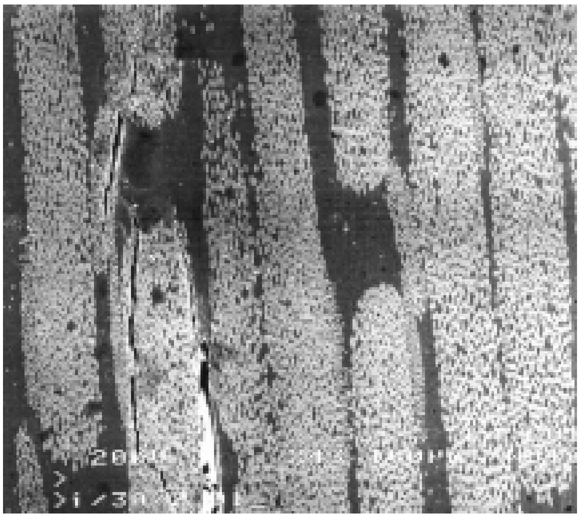


***Figure 7:** return towards the median plane of the crack after bifurcationfor the ±15° and ±30°*

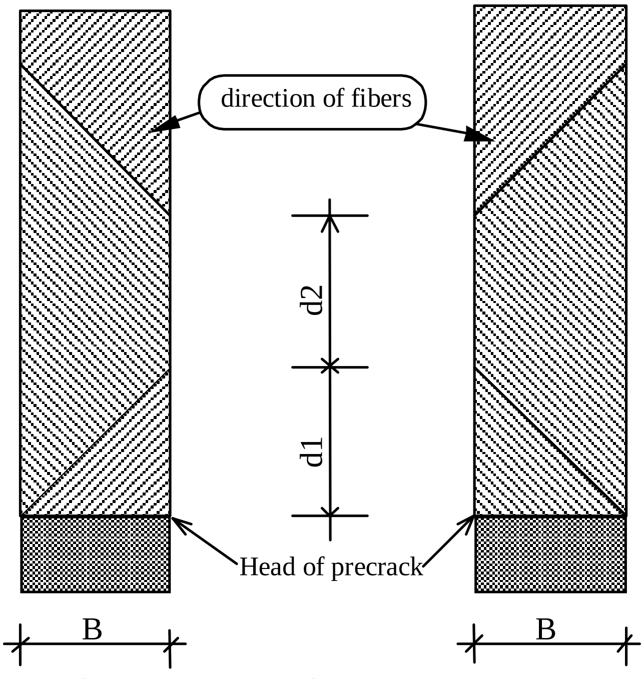


***Figure 8:** fracture scheme of laminate with* 33,5° < θ < 67,5°:

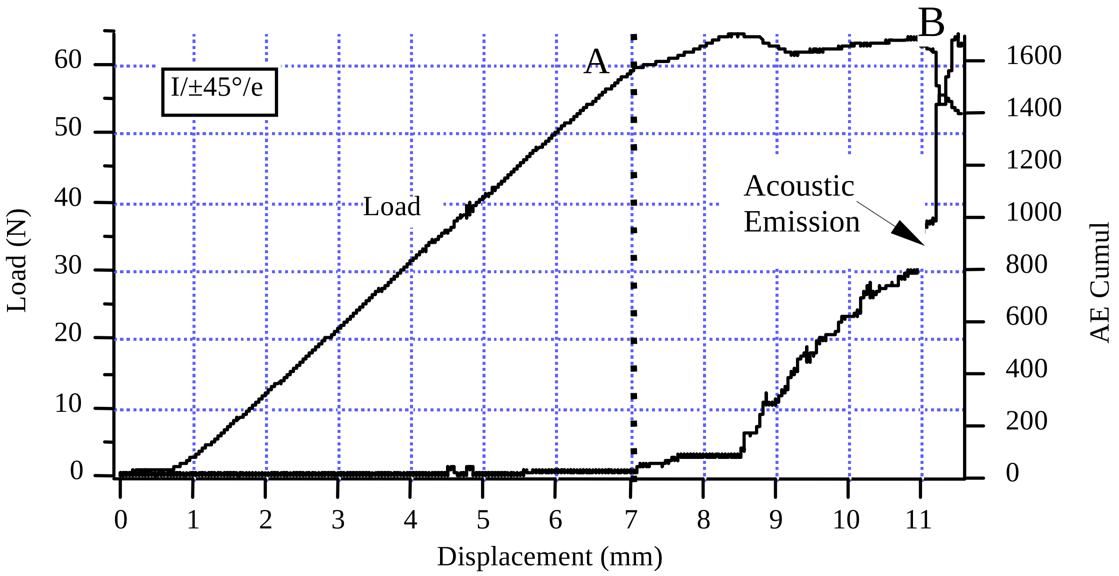


***Figure 9**:. brutal diminution in the load (point B on the load diagram)*

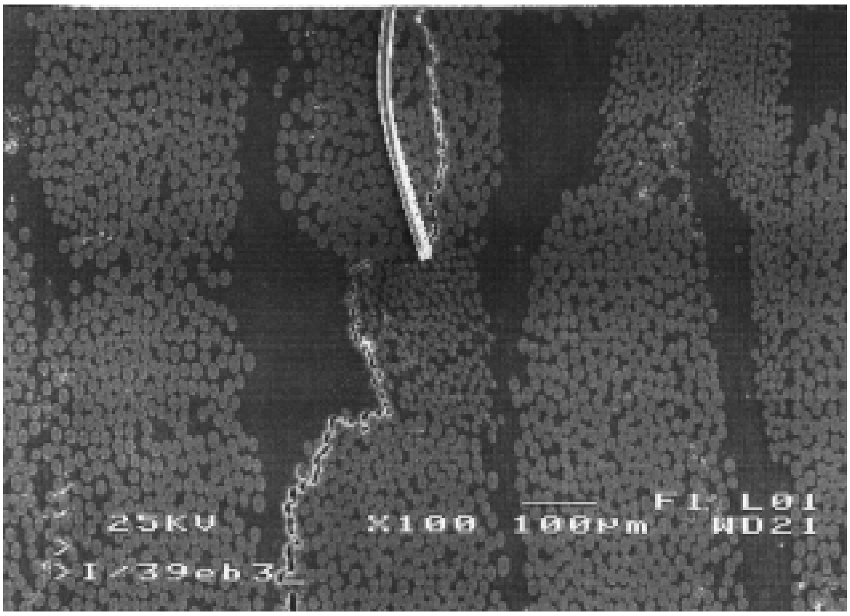


***Figure 10**: photograph on the left side of the specimen corresponding to the loading in figure 9*

4 – DISCUSSION and CONCLUSIONS

The present study underlined two modes of rupture: a delamination in the median plane for the angles ±15° and ±30°; and a rupture illustrated by figure (III-22) for the angles ±45° and ±60° (delamination in staircases). The exploitation of Think-composite software (TSAI) for material of this study loaded in inflection, reveals that the rupture of the first ply in a ±θ passes from the ply more tended for a θ=33,5° towards the ply more compressed for a θ<33,5°. This makes it possible to think that in fact, for the multidirectional laminates of sequence [$(\pm\theta)_{2s}]_{sym}$ with a prédéfaut in the median plane and loaded in mode I, the angle θ is divided into three intervals of which each one corresponds to a type of rupture quite specific. Indeed, one could check in experiments what follows:

1. 0°< θ < 33,5°: delamination in the median plane with a growth of the roughness of the facies as θ increases,
2. 33,5° < θ < 67,5°: the mode of rupture is more complex, figure 8. Delamination on the level of the median plane gradually changes ply at a distance d_1. After a distance d_2, bifurcations of the plans of cracking follow one another thus forming a delamination in staircases. Lastly, the rupture takes place by inflection at the end of some bifurcations (3 to 5 bifurcations),
3. θ> 67,5°: rupture of the one of the two arms by inflection right downstream from the head of the precrack with a small propagation by delamination. When θ = 90°, the rupture of the one of the two arms intervenes at the head of the precrack.

Hence, the cracking mode of multidirectional stratified subject to an opening mode is no longer a delamination of perfect mode I, as the case of unidirectional. If is rather a mixed mode (mode I+II+III) depending on θ angle. The modal separation is then more complexe to carry out and needs a 3D finite elements computations.

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