INITIATION AND PROPAGATION MECHANISMS OF PROGRESSIVE CRUSHING IN CARBON-EPOXY LAMINATED PLATES

D. Guillon[1], S. Rivallant[1], J.-J. Barrau[2], C. Petiot[3], P. Thévenet[3] and N. Pechnik[4]

[1] *Université de Toulouse / ISAE / DMSM 10 av. E.Belin - 31055 Toulouse Cedex, France*
[2] *Université de Toulouse / UPS / LGMT 118 Rte de Narbonne, Bât 3R1 - 31062 Toulouse Cedex, France*
[3] *EADS IW / Mechanical Modelling / 12, rue Pasteur - BP 76 - 92152 Suresnes Cedex, France*
[4] *AIRBUS France / EDSAZ / 316 route de Bayonne - 31060 Toulouse, France*

ABSTRACT

This article presents original experiments that enhance the understanding of the mechanisms that drive the progressive crushing of fiber-reinforced laminated composite materials and their energy absorption capability. An innovative experimental fixture has been created in order to obtain detailed monitoring of quasi-static and dynamic crushing of laminated plates. The fixture enables the development of a regular crushing front through the whole width of the plate, without parasite rupture modes, and the real-time observation of this front with a high speed camera. Results of experimental works on fabric and unidirectional Carbon-Epoxy laminated composite plates are exposed. The obtained crushing modes are analysed, their stability and energy-absorbing capability are discussed.

1. INTRODUCTION

The use of laminated composite in vehicle structure requires a good understanding of their crash behaviour. But the range of crushing mode is very wide and strongly depends on numerous factors. Despite extensive experimental works, it is still very hard to predict the crash response of a complex structure.

The aim of this study is to obtain experimental results providing a better understanding of the progressive crushing mechanisms and a databank for the validation of advanced numerical methods. The identification of the contribution in energy absorption of each crush mechanism is experimentally unattainable. The experimental objective of this work is to perform crushing tests that exhibit elementary crush modes in order to study separately the energy absorption capacity of each mechanisms. Thanks to the fixture, crushing under highly controlled conditions may be studied . This leads sometimes to poor crushing characteristic but allows to observe fundamental phenomena.

The initiation and the propagation of a stable crushing front is necessary to absorb energy with composite structure. Hull [1] and Farley [2] have classified the crush process in two primary modes : the splaying mode in which bundle of bending delaminated lamina splay on both sides of a main crack, and the fragmentation mode in which the plies sustain multiple short length fractures due to pure compression, transverse shearing or sharp bending. Crushing of most of composite structures is a combination of these two modes.

Structural crushing is a very complex problem [3], due to a great number of parameters such as geometry, laminate sequences, mechanical properties, contact and friction…

Authors [4] [5] have tried to experimentally optimize material properties and structure geometries to maximize energy absorption. Tubular elements achieve good results with high stability of the crushing front, but the crushing modes are complex and hard to observe. Open profiles must be design carefully to be crush progressively and present complex behaviour as well. Therefore these tests fail to highlight the influence of each elementary damage mechanism in the energy absorption. And their results are limited to specific domains of validity. Numerical simulations [6] [7] have been proposed but are too simplified or too specific to be predictive on complex structures. Improving understanding of elementary crush mechanisms is thus necessary to better understand structures crash behaviour.

2. EXPERIMENTS

2.1 Fixture design

Plate specimens were chosen for this study to avoid complex crushing damages. Various crushing modes will be obtained thanks to variations in material and laminate sequences, triggers and fixture adjustment.

Plate crushing offers several advantages like simplest theory and easy manufacturing, but requires stabilising fixtures. A recent article [8] reviews the fixture found in the literacy. The Lavoie Fixture [9] and the Hogg fixture [10] use lateral supports from top to bottom that promote longitudinal tearing of the plate at the front vicinity. Engenuity Ltd, a private firm, developed a crush fixture where lateral and out–of plane movement of the plate specimen are fully constrained, except for a “spacer height” from the base-plate, where the specimen is unsupported, allowing it to deform freely. Friction is reduced thanks to delrin sliders. The crushing mode obtained are simpler, but depend on the “spacer height”. This fixture is used for industrial material characterization, and it seems to be impossible to observe crush front. The US Department Of Energy has developed a test fixture dedicated to splaying mode energy absorption characterization. Plate specimens are pushed on a curved contact profile. Contact radii and degrees of constraint in the vicinity of the profile are the key factor. In his current works, P.Feraboli [8] developed a fixture based on the Lavoie’s one modified to accommodate for an unsupported height.

The original fixture (figure 1.) created for this study enables to introduce unchanged limit conditions through the whole width of the crushing front. As a result, the visible edges of the plate is representative of the crush phenomenon under way through the whole width. Real-time visualisation of the front geometry enables to follow the initiation and propagation of damages and to link them to the load vs. stroke curve evolutions, both for static and dynamic tests. This ensures a better observation of the crush mechanisms, compared to post-mortem analysis. A high speed camera is used for the real-time observation of the crushing front : the side of the plate is filmed through a hole in the upright. The acquisition speed for dynamic test is set to 20000 frames/sec, with a 512*256 pixels resolution.

Buckling stabilisation of the laminate is obtained thanks to two pair of vertical guides on each side of the laminate. Two horizontal guides, underneath the vertical ones, ensure that the boundary conditions are the same along the plate width, and avoid tearing of the plate. The height between base plate and the horizontal guide is the unsupported height where the crush front can form freely. Many parameters are adjustable on the fixture. The thickness of the specimen can vary from 0 to 10mm. The unsupported height can vary from 0 to 40 mm. At last, the base plate can be changed to include specific triggers.

The fixture is used both for quasi-static test on a screw-driven universal testing machine and for dynamic tests on a drop tower apparatus. The load is introduced through the top of the specimen with a steel cylinder. At the bottom of this cylinder, a piezoelectric sensor measures the crushing load. The small distance between the specimen and the sensor limits the mechanical filtering of the signal.

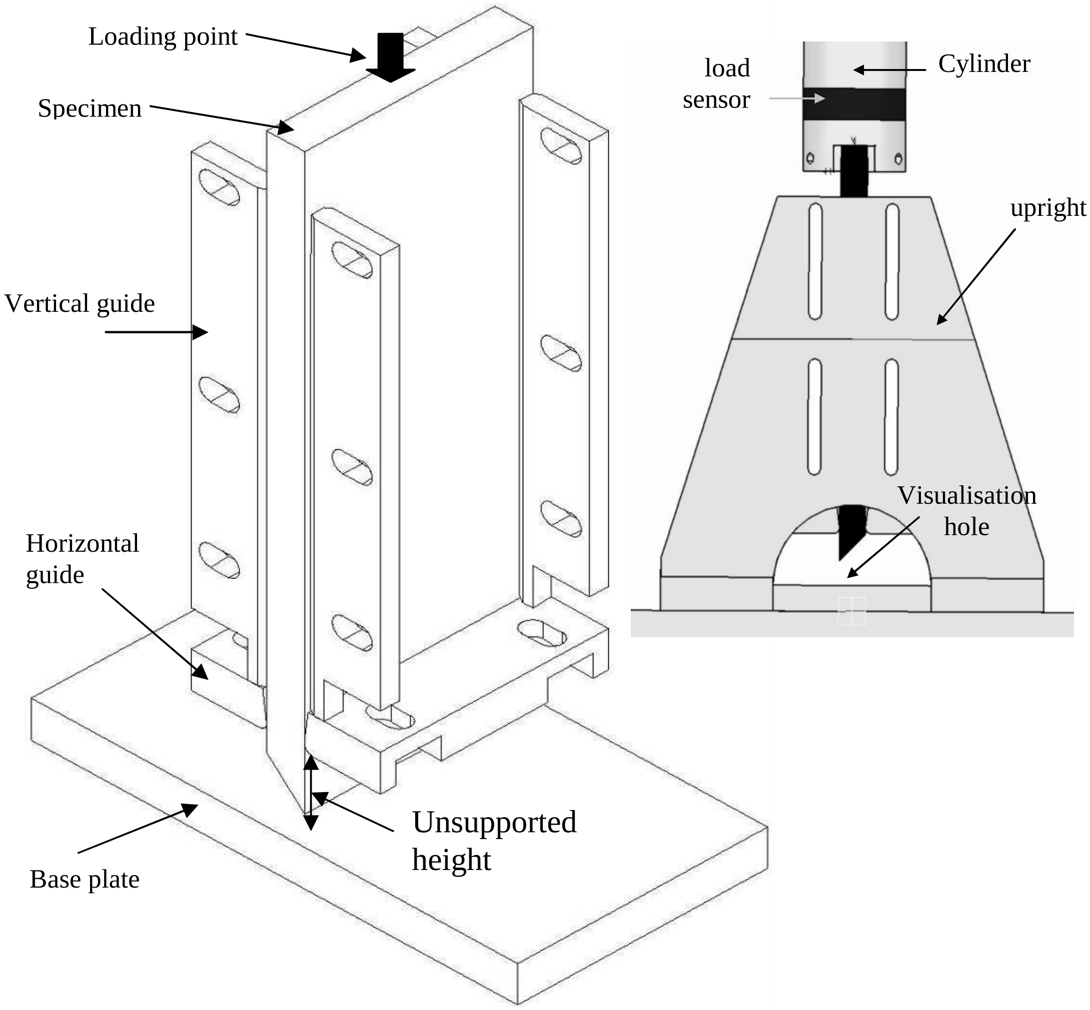


Figure 1 : Design of the fixture, with (on left) and without (on right) upright

This fixture presents the advantage, like the engenuity's and the new Feraboli's, to have unsupported height to allow free development of the crush front. The horizontal guides guarantee unchanged limit conditions through the width of the specimen. Furthermore, this fixture is specially design to give, even in dynamic test, high quality pictures of the crush front. The maximum stroke (up to 100 mm) is longer than in other fixture.

2.2 Design of experiment

Specimens are 160*60 mm flat plates. White graduations are drawn on the edge of the specimen each 5 mm. Three carbon-epoxy prepreg material are used : a balanced 5H-satin fabric and two unidirectional (UD) tape of same material with different fibre mass. The material configurations are :

- FAB-CP : cross-ply fabrics $[(0^\circ,90^\circ)]_{8,s}$ thickness = 5mm

- FAB-QI : Quasi-isotropic fabrics : $[(0°,90°) / (\pm 45°)]_{4,s}$ thickness = 5mm
- UD 1 : 20 plies of UD, with fibres on the 4 principal direction, thickness = 5.2mm
- UD-AP : angle-ply UD laminates : $[+45° / -45°]_{8,s}$ thickness= 3.9mm

The trigger mechanisms are (figure 2) :

- CH : a 45° chamfer machined at the bottom end of the plate,
- ST : a 140° steeple machined at the bottom end of the plate
- BL : a metallic blade machined in the base plate.

Two test speeds are used :

- QS : quasi-static at 20 mm/min
- DYNA : the velocity of the falling weight at impact is 5.2 m/s.

Lay-up	**Crush speed**	**Trigger**		
		ST	**CH**	**BL**
FAB-QI	QS	1	2	4
	DYNA	0	2	3
FAB-CP	QS	2	2	2
	DYNA	1	1	1
UD 1	QS	2	5	1
	DYNA	0	3	1
UD-AP	QS	0	2	0
	DYNA	0	0	0

Table 1 : summary of tested configurations

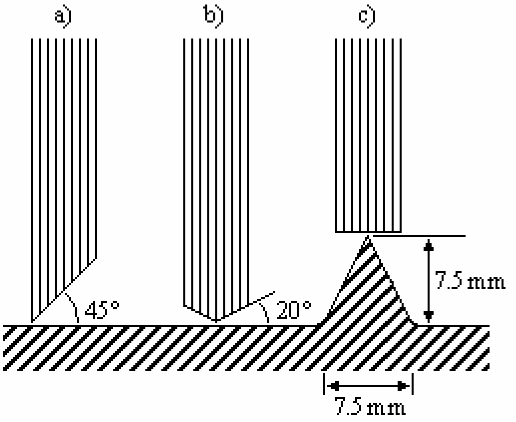


Figure 2 : Trigger definition
a) Chamfer - b) Steeple - c) metallic blade

The unsupported height is set to 20 mm for all tests, except for the UD-AP that use a 10 mm unsupported heigth, better adapted to its higher flexibility. Effects of change of unsupported height for a given test is not studied. The blade trigger prevents contact at right angle between laminate and base plate. The plies bend on the blade, and are therefore directed to a splaying crushing mode. Comparison between chamfer and steeple (which apex angle is large in order to favour fragmentation) trigger allows to observe the stabilization of the progressive crushing mechanisms after a differenced initiation.

Progressive crushing involves short scale mechanisms. Use of fabric and various UD lay-up will create different crushing modes. Dynamic tests are representatives of crash events. But quasi-static tests are helpful to observe precisely the crushing mechanisms, and are often similar to dynamic tests. These choices enable to study a satisfactory variety of crushing mode.

3. DETAILLED ANALYSIS OF PROGRESSIVE CRUSHING MECHANISMS

Figure 3. shows some examples of load-stroke curves obtained from the tests. Each curve may be divided in three phases : the initiation phase, the transition phase and the stable crushing phase on which the specific energy absorption (SEA) is calculated as :

$$SEA = \frac{F_{mean}}{\rho * A} \text{ kJ/kg}$$

F_{mean}	mean load during the crushing phase
ρ	specimen density
A	surface of the cross-section

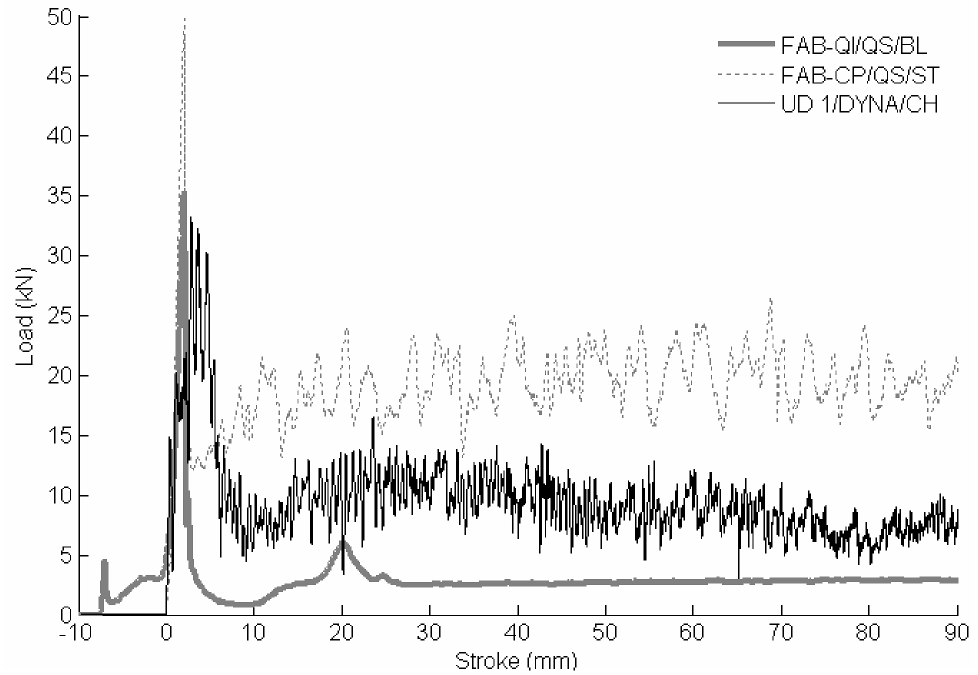


Figure 3 : some examples of load-stroke behaviour

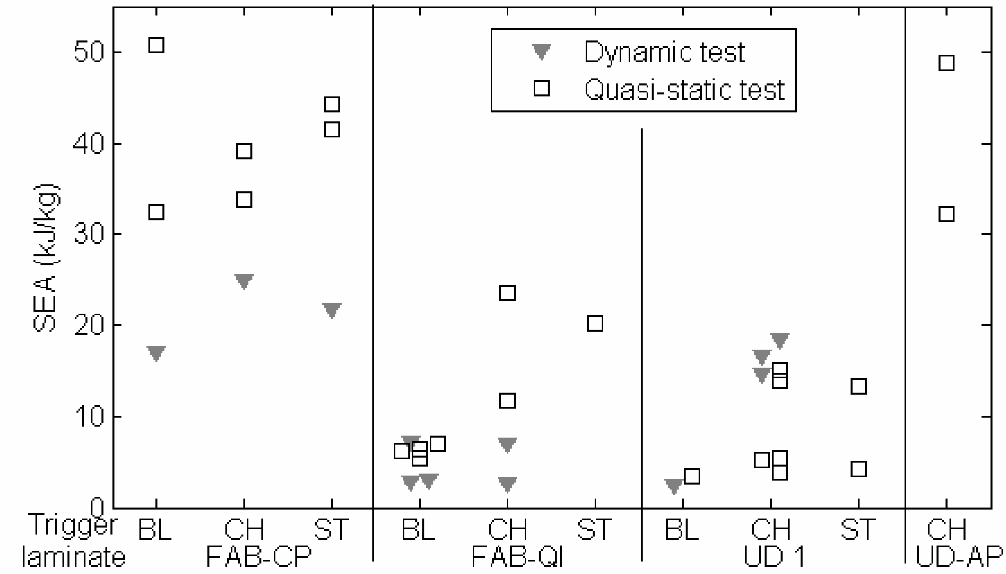


Figure 4 : Results of crushing test

Results presented figure 4 show a wide range of energy absorption capabilities. This heterogeneity may be summarized with three crushing modes of homogeneous trends :

- The splaying mode has been observed on tests whose SEA are under 7.5 kJ/kg
- The mixed mode has been observed on tests whose SEA are between 9.5 and 24 kJ/kg, except FAB-CP/DYNA tests.
- The fragmentation mode has been observed on all FAB-CP and UD-AP tests and give SEA larger than 30 kJ/kg for quasi-static test.

3.1 Observation of each crushing mode

- **Splaying mode**

In splaying crush mode, plies bend and are evacuate on each side without intralaminar failure. Bending create both mode II interlaminar stress and longitudinal intralaminar stress. If delamination propagate before ply fail, bending longitudinal stress falls and (half-)laminate can curve furthermore, until it reaches a curvature radius allowing its evacuation. Without blade trigger, a debris wedge made of debris issued of the initiation process or of fractured central plies can appear, stabilizing the splaying mode by forcing central plies to bend.

Front geometry depends on ratio between longitudinal modulus and delamination criterion. With easy delamination, all ply will be isolated and will therefore suffer a sharp bending radius. On the contrary, if plies remain grouped, they will impose a smooth bending radius. When a geometry is stabilized, delamination propagate at the crush speed. Various fronts geometries may be obtain for a given test. Figure 5 show a FAB-QI/BL/DYNA test at two different states.

Energy absorption, very small in this mode, is made through three distinct mechanisms :

- Interlaminar delamination. Simplified calculation (delaminated surface times energy release rate) estimate this part at a third of the total absorbed energy.
- Friction between the platen, debris and plies.
- Intralaminar damage. Bended plies present residual deformation that prove that matrix yielding or sliding at the fibre/matrix interface occurs (no cracks are visible).

Surprisingly, easy delamination increases energy absorption in splaying mode because it multiplies the delaminated interface and allows sharper bending radius that increases intralaminar damage. Figure 4, the load sustain at state A is 56% higher than at state B. This conclusion is valid only if delamination criterion is not high enough to cause intralaminar failure, then changing the splaying mode in fragmentation mode.

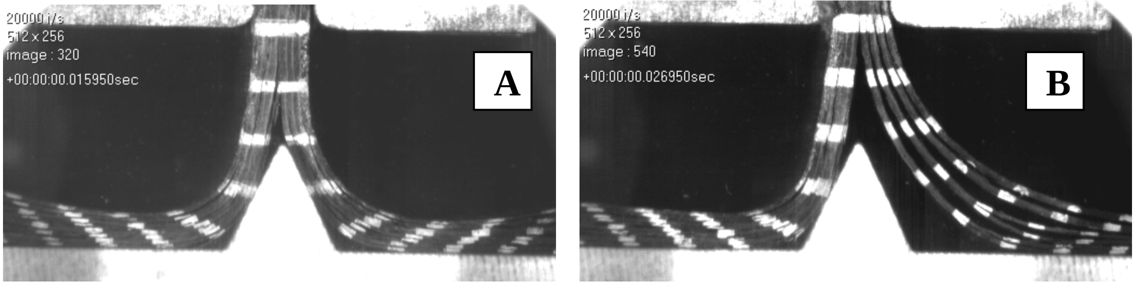


Figure 5 : pictures of FAB-QI/BL/DYNA test at 50 mm (A) and 95 mm (B) strokes

- **Fragmentation mode**

In fragmentation mode, plies have to fracture to be evacuated. This lead to much higher energy absorption. Three distinct processes of fragmentation have been observed :

- The “fractured splaying” appears when a blade trigger or a debris wedge force the plies to bend, if the plies fail before they reach the curvature radius allowing their evacuation. The failure spring out from the exterior of the laminate, where compressive stresses are maximum, and propagate toward the central plies. Broken fragments are regularly created. Figure 6 shows a FAB-CP/QS/CH specimen after the crushing. Regular failure are visible.

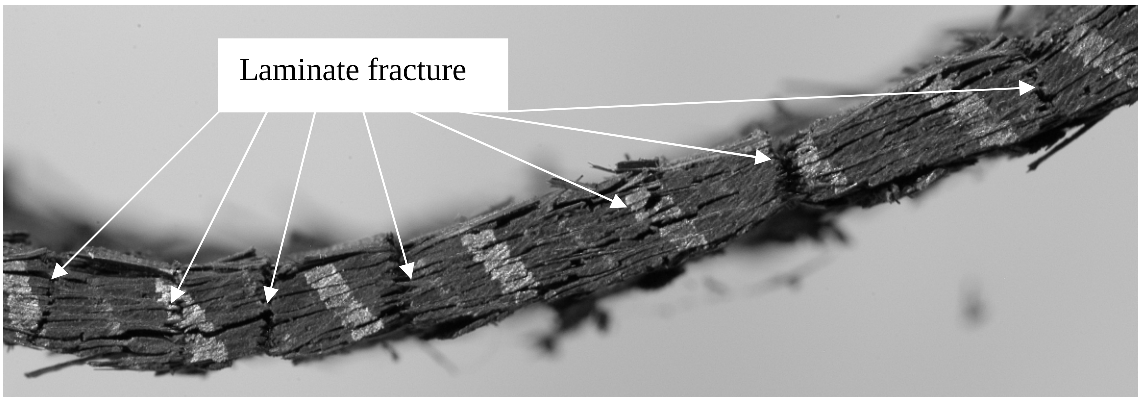
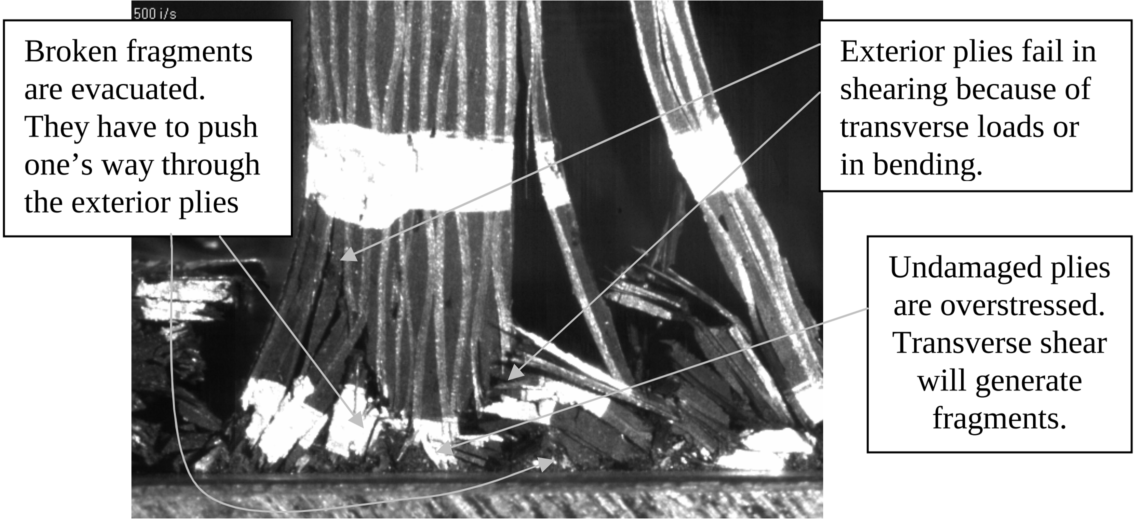


Figure 6 : Post-mortem picture of a FAB-CP/QS/CH half-laminate crushed on "fractured splaying" mode

A study of the frequencies making up the load vs. stroke curve of all FAB-CP tests shows a particular amplitude of events with 1.4 mm repetition, corresponding to the fabric's yarns wide. It can be conclude that fibre's undulation favour regular fracture.

- The "transverse shearing fragmentation" appears when plies bundles contact the base plate at right angle. Initiation process has created a serrated face, therefore compression pressure create localized overstresses that lead to transverse shear fracture. Newly created debris will break adjacent plies as they evacuate. Figure 7 comments a typical transverse shearing fragmentation front.



Broken fragments are evacuated. They have to push one's way through the exterior plies

Exterior plies fail in shearing because of transverse loads or in bending.

Undamaged plies are overstressed. Transverse shear will generate fragments.

Figure 7 : Commented picture of a FAB-CP/QS/ST laminate crushed on "transverse shearing fragmentation" mode

- The "shear damaged splaying" appears during UD-AP tests because the high flexibility of ±45° plies allows very sharp curvature radius (figure 8). Plies sustain severe intralaminar shear damage without fracture. This generalized damaged splaying is possible only if there is no rigid plies in the laminate. Otherwise, the less flexible plies fix the curvature radius, preventing flexible one from severe damage.

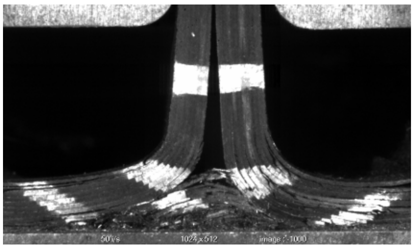


Figure 8 : Picture of shear damaged splaying crush front of a UD-AP test

- **Mixed mode**

In mixed crush mode, exterior plies on both side bend and are evacuate in splaying crush mode. The proportion of plies that bend on each side is variable. The remaining proportion of central plies (not necessary in the middle) can’t bend because they are constrained by splaying plies. They contact the base plate at right angle, and therefore sustain severe damage (figure 9.) The energy absorbed through this damage cause the increase of SEA observed for mixed mode test compared to corresponding splaying mode test. Damage on central plies depends on the fibre’s orientation. 90°’s plies suffer brittle fracturing, ±45°’s plies suffer large strain due to sharp bending. 0°’s plies suffer extensive matrix damage and spaced fibre fracturing.

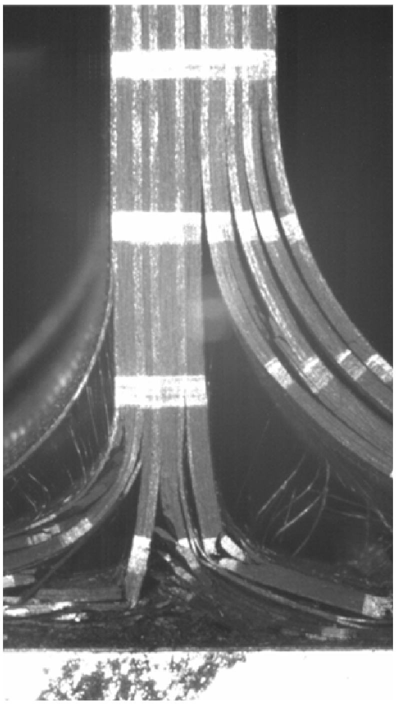


Figure 9 : Picture of mixed mode crush front of a UD 1 test

3.2 Stability of the crushing modes

- **Initiation process**

The initiation process depends on the trigger, but similar trends appear. With blade and steeple trigger, laminates are first split by a deep central crack. Each arm bend and load increase strongly. With chamfer trigger, load increases smoothly as the proportion of plies in contact with the base increases. First plies crush but don’t slide, thus the laminate bends. With either trigger, laminate is therefore loaded by a combination of bending and asymmetrical (only a part of the plies contact the base) compression. This creates high transverse shear stress which leads to multiple delaminations. With chamfer trigger, delaminations appear at the limit of the crushed zone (figure 10) and are staggered as crush zone move forward, causing multiple load drop. With steeple or blade trigger, multiple delaminations appear suddenly, allowing each arm to bend more (figure 10).

Crush front may evolve during still several tens of millimetres before to reach a stabilised geometry. Initiation process are highly dependant on experimental defects, but influence is generally limited in duration, because crush front tends to join its fundamental mode. However, specially in fragmentation mode, initiation consequences like presence and size of the debris wedge may be long-standing.

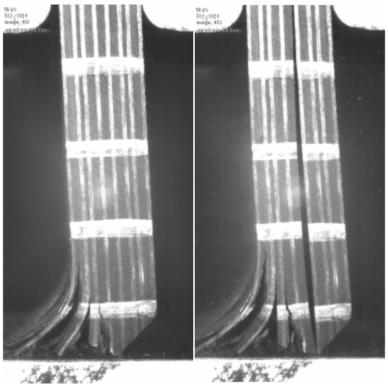
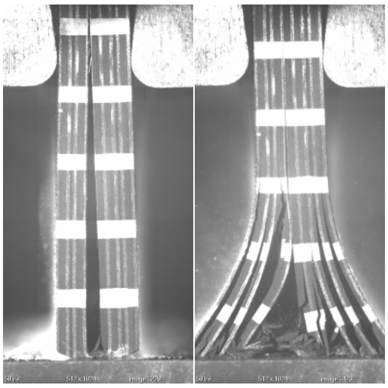


Figure 10 : Pictures from the initiation phase of an UD 1/QS/CH (top) and ST (bottom) test



- **Crushing phase**

The long stroke of crush allows to show evolutions during the “stable” crushing. Evolutions may be permanent, when they lead to a different stable crush front, or transient, if the same stable crush front come back after a perturbation.

Splaying mode may show permanent evolution when, like figure 5, delamination distribution changes and installs a more easily crushing front. Mixed mode is particularly subject to permanent evolution. If a central ply bend and don’t fail, it will join the splaying plies. This occurs often with UD tapes. A comparison of the crush load between the initial and final 10 mm of the stable crush stroke shows a mean drop of 22% for the 6 “mixed mode” UD 1 test. It can be conclude that the mixed crushing mode is not really stable, and may systematically tend to a splaying mode. That’s why FAB-QI and UD 1 plies crush either in splaying mode or in mixed mode. Test speed seems to have few influence in those modes : same front geometry absorbs same energy.

On the contrary, FAB-CP and UD-AP specimens crush systematically in fragmentation mode. Permanent evolution are rare and restrict to change between “fractured splaying” and “transverse shearing” mode, but perturbations are frequent. The debris wedge is specially unstable. If it is feed continuously with new debris, it grows up and bends exterior plies until they break This happens 3 times out of 6 on FAB-CP/CH and ST tests. This causes a large drop in load curve, during the evacuation of the broken arm. Figure 11 shows pictures of the crushing of the FAB-CP/ST/DYNA specimen, and the corresponding load vs. stroke curve.

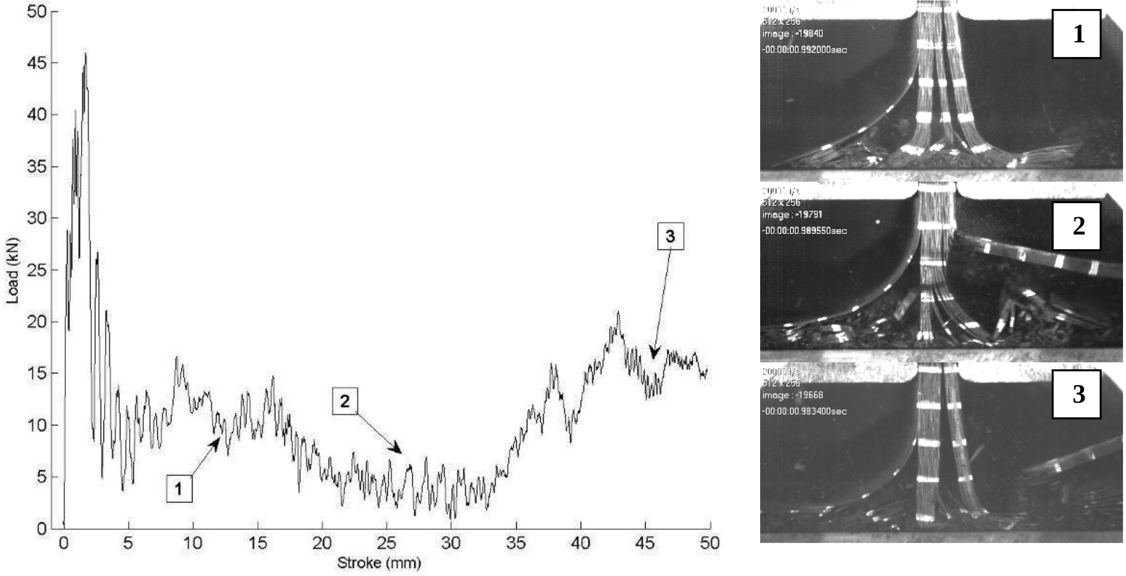


Figure 11 : Load vs. stroke curve of FAB-CP/DYNA/ST test and selected pictures of the crushing front

Dynamic tests on FAB-CP test show significantly lower value of SEA than corresponding QS tests. Firstly because perturbation are greater in these tests, secondly because “fractured splaying” create more spaced failure.

4. CONCLUSIONS

An innovative experimental fixture has been created for the static and dynamic crushing of plate coupons. It enables a wide range of investigations by allowing changes in test configuration to favour specific types of crushing modes and has proven their ability to link the damage phenomenology and the global load vs. stroke curves. From a numerical modelling point of view, these tests give essential information. Real-time visualisations provide pertinent information concerning deformations of the structure and front aspect to correlate numerical simulations. Specific tests concerning specific damage modes can be done to focus on a limited number of parameters, which enable a step-by-step approach of modelling by introducing modes separately. Computer simulations of each elementary mode are in progress at ISAE, with a model representing delamination and damage on each ply.

Tests has been made to go further in the understanding of brittle laminated composite crush modes. Detailed descriptions of the splaying mode and of several type of fragmentation modes have been proposed. The low energy absorption capability of the splaying mode and the utility of fabrics to favour fragmentation modes is highlighted. Mixed mode crushing have to be avoided, because any perturbation may degenerate them into inefficient splaying mode crushing. Therefore, designers of energy absorber have first to check that their structure adopt consistently a stable and efficient crushing mode. Curved geometry may allow to combined stabilized “flat” fragmentation with complex damages dues to hoop constraints, but dynamic effects have to be studied carefully. Parametric studies are reliable only if they are done for a given crushing mode.

REFERENCES

1- Hull D. “A unified approach to progressive crushing of fibre-reinforced composite tubes”, *Composites science and technology* 1991;40:377-421.
2- Farley G.L., Jones M.R. “Crushing characteristics of continuous fibber-reinforced composites tubes”, *Journal of composites materials* 1992;26:37-50.
3- Mamalis A.G., Robinson M., Manolakos D.E., Demosthenous G.A., Ioannidis M.B., Carruthers J. “Crashworthy capability of composite material structures”, *Composite structures* 1997; 37:109-134.
4- Ramakrishna S. “Microstructural design of composite materials for crashworthy structural applications”, *Materials & Design* 1997;18:167-173.
5- Karbhari V.M., Haller J. “Effect of preform structure on progressive crush characteristics of flange-stiffened tubular elements”, *Composite Structure* 1997; 37:81-96.
6- Fleming D.C. “Finite element simulation of delamination with application to crashworthy design”, *AHS 62nd annual forum*, Phoenix, May 2006.
7- Pinho S.T., Camanho P.P., de Moura M.F. “Numerical simulation of the crushing process of composite materials “, *International journal of Crash 2004;* 9:263-276.
8- Feraboli P., Deleo F., Garattoni F., “Efforts in the standardization of composite materials crashworthiness energy absorption”, *22nd American Society for Composites Technical Conference*, Seattle, September 2007.
9- Lavoie J.A., Kellas S. “Dynamic crush tests of energy absorbing laminated composites plates”, *Composites: Part A* 1996;27:467-475.
10- Daniel L., Hogg P.J., Curtis P.T. “The crush behaviour of carbon fibre angle-ply reinforcement and the effect of interlaminar shear strength on energy absorption capability” *Composites: Part B* 2000;31:435-440.