EXPERIMENTAL TEST TO IDENTIFY THE MEAN CRUSHING STRESS OF 0° AND 90° UNIDIRECTIONAL PLIES INSIDE A LAMINATE

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Keywords: Fragmentation, Crushing, CFRP Laminate, Least Mean Square

Abstract
Quasi-static crushing tests were performed for different configurations of unidirectional (UD) CFRP laminates to determine the mean crushing stress of plies alone and inside a laminate. This study shows there is a linear relationship between crushing load and the contact surface of the plies being crushed which enables actually to define a mean crushing stress for a ply inside a laminate. The calculation method to estimate this value is presented in this paper. Tests show that for the UD material, the mean crushing stress in 0° and 90° direction are close to each other.

1 Introduction
A challenge today in crashworthiness simulation is to be able to predict the crush damage modes, their evolution during crushing, and the energy absorption in any structure from elementary material characterisation data. Based on this point, a mesoscopic scale numerical model of crushing of carbon fiber reinforced plastic (CFRP) plate has been developed by the authors, based on elementary material mechanical characteristics [1]. This model gives a good correlation on the crash initiation but the localized crushing of plies at the extremity of the plate (local fragmentation mode), in contact with a metallic base, is not well represented. Consequently, the global crushing mode in simulation evolves not in the same way as in experiments. One of the reasons is the absence of specific law to accurately represent this fragmentation mode which basically relate to the global behavior of one ply in pure local crushing.

Since 1980's, many studies have been done on different perspectives [2-6] concerning the energy absorption capability of composite structures during crash for example the effect of laminate design [3], specimen geometry [4], etc. However, very few discussions [7-8] concerning the mean crushing stress have been done in the past. To the author's knowledge, there is no specific study concerning the local mean crushing stress of plies inside a laminate reported in the literature and there are no standards or appropriate test methods to determine the local mean crushing stress.

Therefore, in this paper an experimental methodology is introduced to determine the mean crushing stress and global behavior of carbon-epoxy plies in pure compressive crushing mode that could be used for the simulation of fracture mechanisms at meso-scale. The conclusions of these observations could lead to the implementation of specific laws in numerical models.

2 Experimental Setup

2.1 Specimen

Small specimens with short length (from 30 to 35mm) and small width (from 8 to 10.5mm) were used in this study. They are made from carbon epoxy unidirectional (UD) prepreg T700/M21.There are three different specimens, the first two are UD laminate made of 8 plies that are used to determine the mean crushing stress of plies alone in pure longitudinal direction [(0°)8] (specimen T-0) and pure transverse direction [(90°)8] (specimen T-90). While, the third specimen (T-0/90) is a 16 plies laminate with stacking sequence [(0°/90°)*4]sym used to study the mean crushing stress of plies inside a laminate. Besides that, one end of the specimens was cut to form a chamfering-type trigger with two different angles as shown in figure 1.

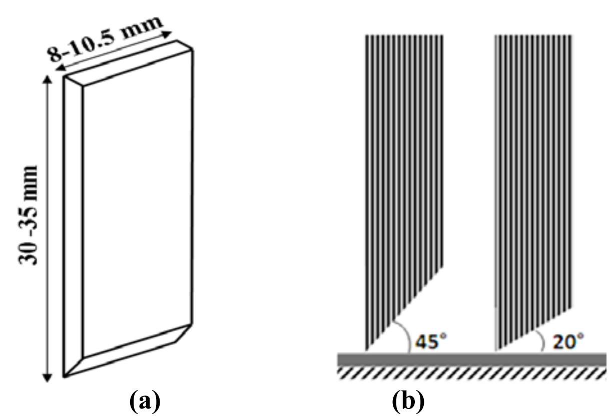

Figure 1 : Specimen description: (a) geometry (b) chamfer angles

There are only a few in number of specimens, but one must see that each crushing test provides a wide range of force/surface contact configurations (as much as the number of images taken during tests). All specimen geometry configurations are listed in table 1. (*Note: The designation of specimens was based on the code [M-S-C°-n] where; M: Material, S: Stacking sequence, C°: Chamfering angle, n: number of specimen.)*

Specimen	Thickness (mm)	Width (mm)
T-0-20°-n1	2.11	10.23
T-0-45°-n1	2.11	10.22
T-90-20°-n1	2.11	10.16
T-90-45°-n1	2.11	10.13
T-90-45°-n2	2.11	10.13
T-0/90-20°-n1	4,26	8,32
T-0/90-45°-n1	4,26	8,34
T-0/90-45°-n2	4,26	8,30

Table 1: Specimen geometry configurations

2.2 Test Setup

The mechanical tests were performed using a hydraulic testing machine in compression testing mode at a constant loading speed (6mm/min). The specimens were clamped in the moving grip and the metallic base on which specimen are crushed was fixed. Figure 2 shows the test set-up and the location of specimen. The force and displacement were obtained for each of the crush specimens, sampled at a rate of 100Hz. To avoid global buckling and too much bending, the non-clamping length is limited to 30mm for the specimens of T-0/90 and 10mm for the thinner UD specimens. For the T-0/90 specimens, tests were interrupted after 10mm crushing displacement while 6mm displacement for the other specimens, which was considered enough to have both the initiation step and a steady crushing front which gives different configurations of specimen fragmentation in the same test to allow the determination of the mean crushing stress. Two cameras were placed at both sides (front and back respectively) to capture the images of crushing process every 0.1mm of displacement during the experiment in order to calculate contact areas. Image resolution is approximately 100 pixel/mm.

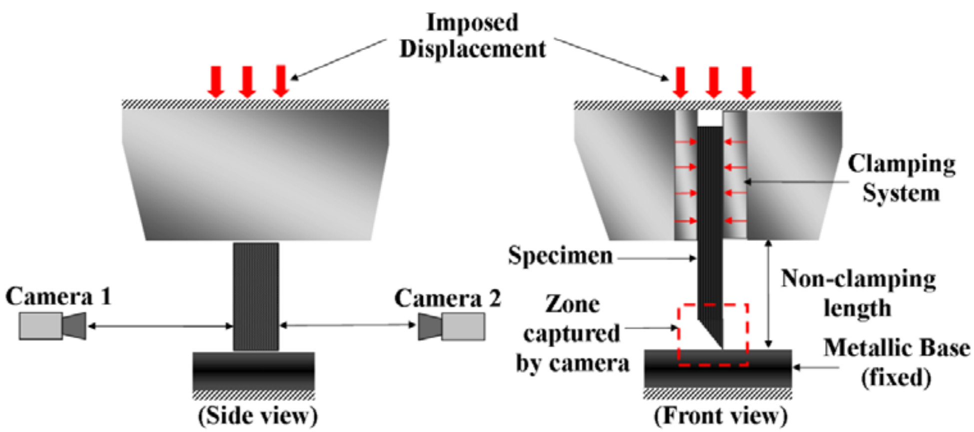

Figure 2: Test set-up

3 Calculation Method

3.1 Contact Length Measurement

Since the specimens have been chamfered at one end of the plate, most of the specimens are experiencing mixed mode crushing morphology except the T-90 specimens. Basically, one can observe five main mechanisms during crushing as shown in figure 3;

a) Splaying (high bending)
b) Fragmentation
c) Debris accumulation
d) "small bending" (short length ply bending), with still fragmentation at tip
e) Rupture (bending or shear)

From the observation of figure 3, the number of plies having direct contact with metallic base seems to be proportional to the force measured during the test. Hence, it can be concluded that only plies in fragmentation and having "small bending" are enable to sustain forces. So, only their contact length at the extremity is measured to estimate the mean crushing stress.

The force sustained by plies in the splaying mode (figure 4a) is considered negligible. These plies generate a very low bending force compared to the mean crush load in pure fragmentation mode [9].

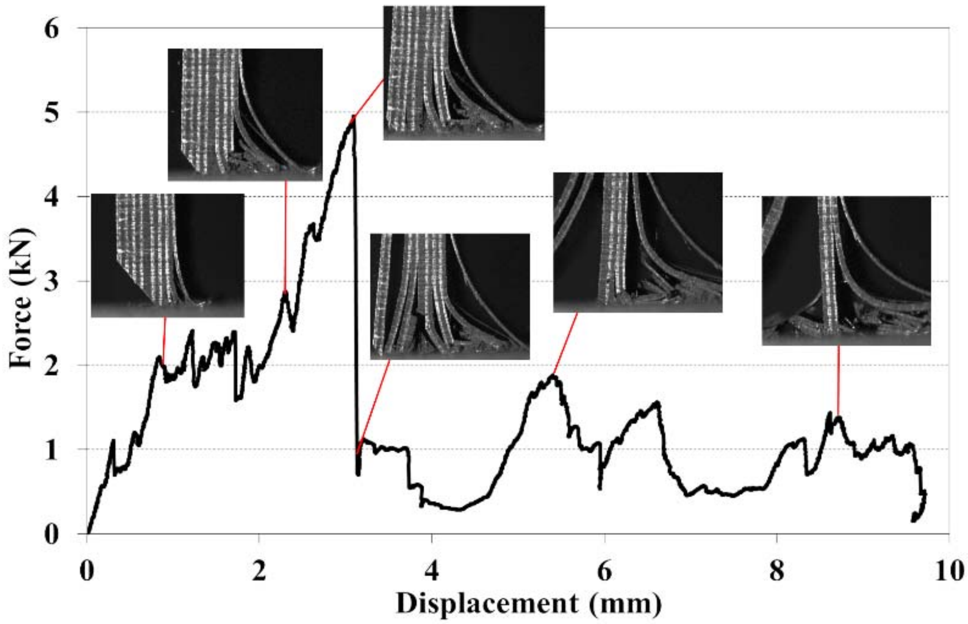

Figure 3: Example of force-displacement curve of T-0/90-45° test and selected pictures of the crushing front.

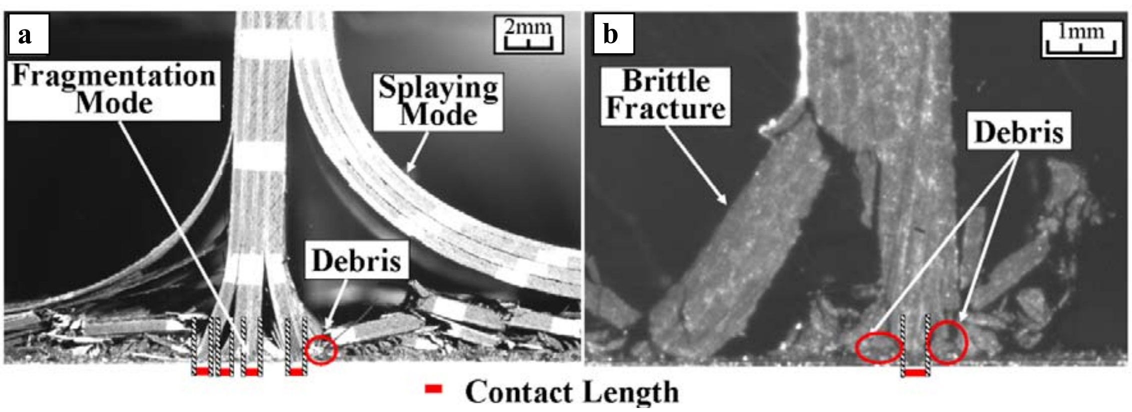

Figure 4: Contact length definition: (a) T-0/90 (b) T-90

For the T-0/90 specimens, the contact length of 0° and 90° plies were measured separately in order to be able to determine the local mean crushing stress for each ply orientation. In addition, the measurement is done on both side images (2 cameras) to ensure that it will give same results, and help in determining the contact area. However, there were some obstacles in measuring the contact length from the images due to the quality of images, for example too much flare in the images, debris blocking the vision, etc. Thus, the measurement was not possible for each image and the unclear images were removed from the analysis of contact length.

Finally, determination of contact length was made entirely independent from the recorded data (force), not to have any bias in the method. The contact length for each specimen is calculated and plotted in function of time together with the experiment measured force as example in figure 5. It shows similarities in the curve shapes. In the case of 0° or 90° UD there is clearly proportionality (example for 0° ply in figure 5a), but in the case of laminate (T-0/90), it is more complex to see due to the two considered parameters: contact length of 0° and 90° plies (figure 5b).

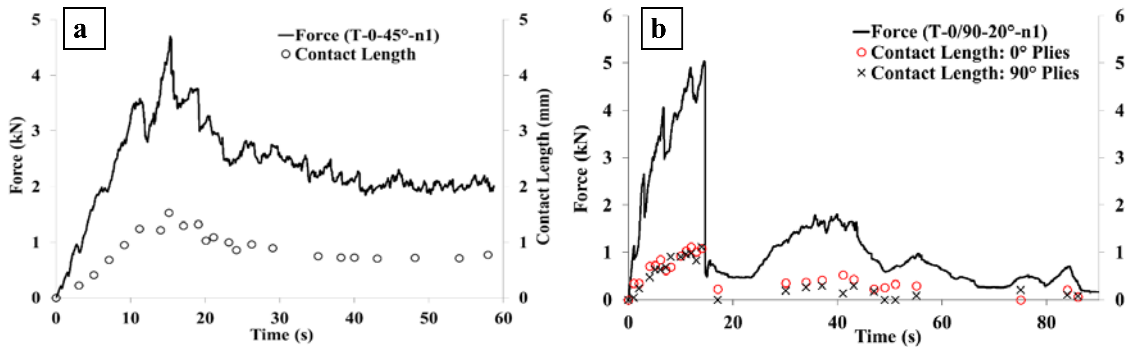

Figure 5: Examples of contact length and force curve: (a) UD T-0 (b) laminate T-0/90

3.2 Estimation Model

From the similarity of curve shapes between force and contact length observed in the figure 5, model A (eq.1) is proposed to estimate the mean crushing stress of ply for the case of T-0 and T-90 specimens.

$$F = \sigma_{0^\circ} S_{0^\circ} \text{ (or } F = \sigma_{90^\circ} S_{90^\circ}) \quad (1)$$

Where F is the force, σ_{0° (σ_{90°) is the mean crushing stress for 0° (90°) plies and S_{0° (S_{90°) is the contact surface of 0° (90°) crushing plies calculated by multiplying the contact length with the width of specimen.

Model B (eq.2) is introduced as an extension from model A for T-0/90 specimens since it has two parameters: crushing surface of 0° and 90° ply. Therefore, the local mean crushing stress of 0° and 90° ply inside laminate can be estimated separately.

$$F = \sigma_{0^\circ} S_{0^\circ} + \sigma_{90^\circ} S_{90^\circ} \quad (2)$$

4 Result Discussion

4.1 Least Mean Square Analysis

The estimation of mean crushing stress is done by using a least mean square (LMS) fitting of the experimental data. All the results of mean crushing stress for each case are presented in table 2 and 3.

Laminate Plate	Specimen	No. of points for LMS calculation	σ_{0° (MPa)	σ_{90° (MPa)	Standard deviation
(0°)8	T-0-20°-n1	25	274	-	4%
	T-0-45°-n1	24	271	-	3%
	All T-0 specimens	**49**	**273**	**-**	**5%**
(90°)8	T-90-20°-n1	37	-	259	2%
	T-90-45°-n1	17	-	253	1%
	T-90-45°-n2	18	-	257	2%
	All T-90 specimens	**72**	**-**	**259**	**2%**

Table 2: Mean crushing stress of 0° and 90° plies for UD specimens (Model A)

Laminate Plate	Specimen	No. of points for LMS calculation	$\sigma_{0°}$ (MPa)	$\sigma_{90°}$ (MPa)	Standard deviation
[(0/90)*4]sym	T-0/90-20°-n1	26	288	252	3%
	T-0/90-45°-n1	24	286	281	5%
	T-0/90-45°-n2	23	280	275	3%
All T-0/90 specimens		**73**	**280**	**269**	**4%**

Table 3: Mean crushing stress of 0° and 90° plies for laminate specimens (Model B)

The calculation of the last row for both parts in table 2 and last row in table 3 corresponds to the results of mean crushing stress for all tests in each type of specimen. It corresponds to a LMS executed on all points i.e. 49 data points (one data point is equivalent to one image taken from the tests) from all T-0 specimens, 72 data points from T-90 specimens and 73 data points from T-0/90 specimens. The maximum error between the experimental force and the calculated force is 14% for UD specimens and 16% for laminate specimens.

By combining all the data points (194 points), the domain of calculation for LMS become relatively wide, as there are pure 0°, pure 90°, mixed 0° and 90° (with different ratio in contact surface), and different levels of contact surface in each case as shown in the figure 6a. All experiment data are well fitted by an interpolating plane which validates the prediction model B is suitable to be used to estimate the mean crushing stress of a ply. Furthermore, figures 6 (b-d) shows the good correlation between estimated forces from prediction models determined by LMS and force from experiment on the different specimens.

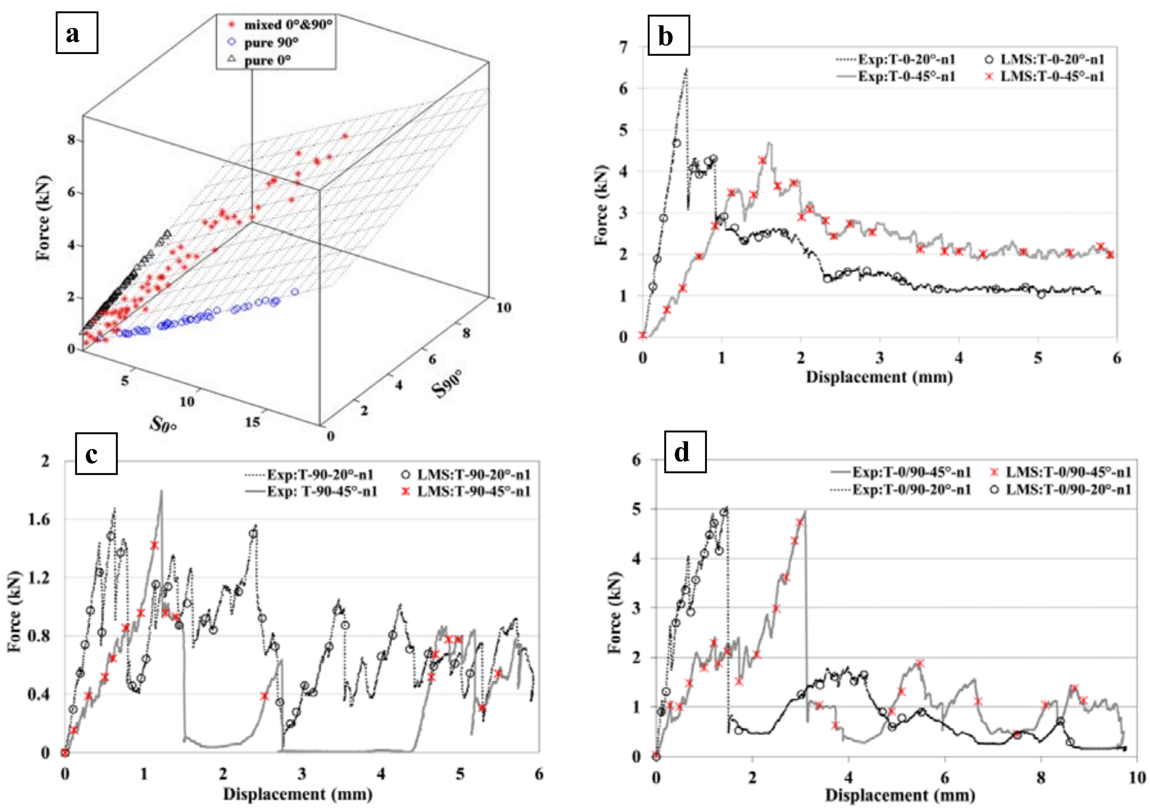

Figure 6: (a) Range of contact length and global correlation. LMS-experimental correlation for (b) T-0 (c) T-90 (d) T-0/90

Whatever the way of calculation: model A on UD specimens, model B on T-0/90 laminates, or model B on all specimens, calculated mean crushing stress for 0° and 90° are very close i.e. 277MPa and 270MPa for all data points LMS fitting (see figure 7). The value for 90° is also very close to the usual compressive strength. But for 0°, the crushing stress is far below the compressive strength (1015MPa). Thus, it seems that energy absorption capability for 0° and 90° plies, in case of pure crushing, are almost the same.

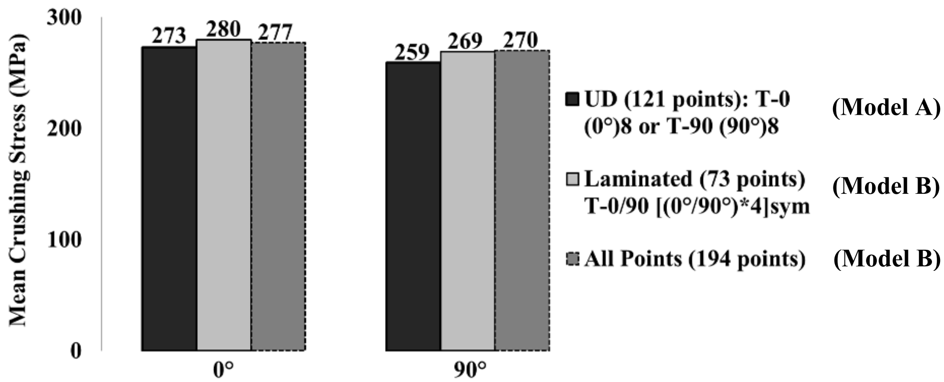

Figure 7: Mean crushing stress for 0° and 90° plies inside the laminate

4.2 Microscopic Observation

Several micrographs were taken from the tested specimens by using scanning electron microscope (SEM) to improve understanding of the crushing surface. These micrographs were taken at the corner of specimens that clearly showed the plies have been suffered a pure compressive crushing mode as shown in figure 8.

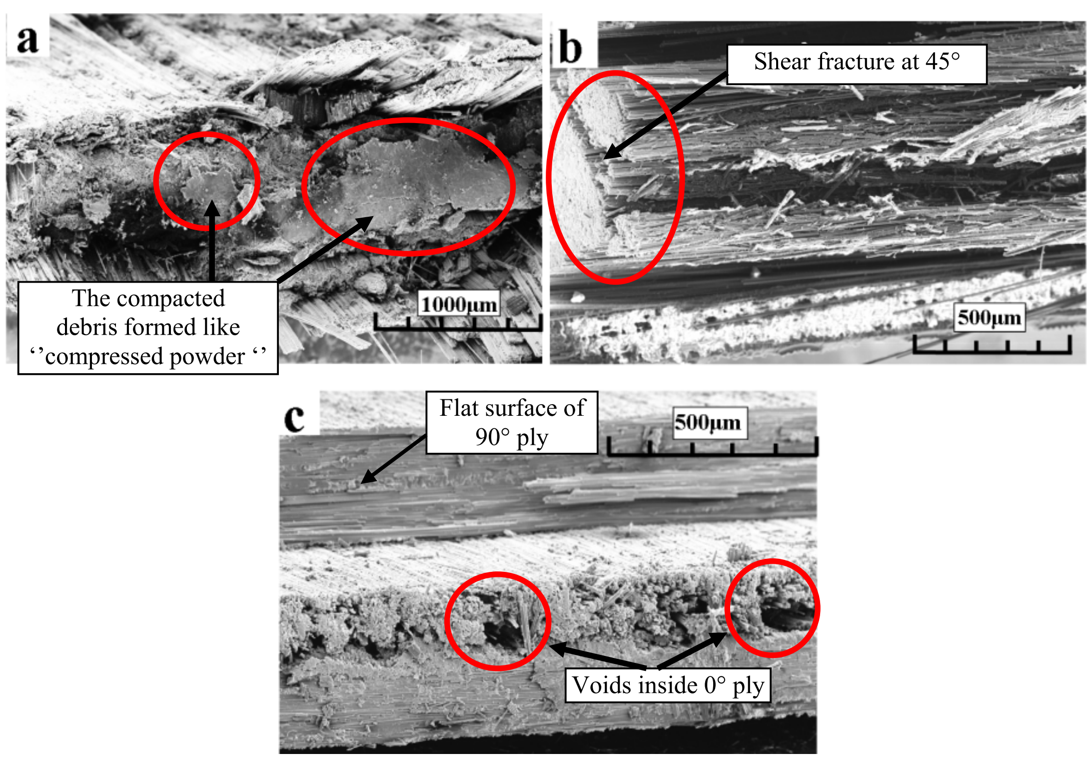

Figure 8: Example micrographs of crushing surface for the selected specimens:
(a) T-0-45°-n1 (b) T-90-45°-n1 (c) T-0/90-45°-n1

From figure 8a, it shows that certain areas have some small debris that stuck at crushing front being compacted together during crushing to form like "compressed powder" (combination of fiber and matrix). As expected, the UD specimen in pure transverse direction (T-90) has undergone shear fracture at 45° as shown in figure 8b. For the specimen T-0/90 (figure 8c), there are some voids along the ply 0° perhaps due some fibers have ruined and then dropped when delamination occurred between 0° and 90° interface. This caused discontinuities of geometry at the extremity of 0° ply. On the other hand, some 90° plies has flat surface as a result of brittle fracture (big fragment) because of bending mode of these 90° plies during the test.

In general, these observations are able to provide some information regarding the crushing surface of plies at the extremity that might be useful for the development of numerical model. However, it could not provide any important explanations to relate with the results of mean crushing stress obtained in the previous section.

5 Conclusion

The proposed method works well in determining the mean crushing stress of plies inside a laminate with a simple methodology. This method is correct since the correlation is done all along the crushing progression and not at specific points of test. From a numerical point of view, this study has delivered essential data regarding the magnitude of the mean crushing stress that may be very valuable for finite element model as 'material input' parameters. On the other hand, the real-time visualizations and SEM observations provide pertinent information concerning deformations of the structure and front aspect of the plies that could be very beneficial when implementing new compressive law inside numerical model.

Acknowledgements

Grateful acknowledge to the Ministry of Higher Education, Malaysia (MOHE) for the sponsorship of this PhD program.

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