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A Study of the Dynamic Behavior for Low Velocity Impact on Thin Composite Laminates

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Abstract: During the last two decades, research on the development of structural components with high crashworthiness has been carried out by the automobile, aeronautics, naval, trains and elevators industries. Many kinds of components have been made using composite materials, because these materials can absorb high amount impact energy and can guarantee the survival of the passengers. However, the dynamic behavior of composite laminates is very complex because there are many concurrently phenomena during composite laminate failure under impact load. Fiber breakage, delaminations, matrix cracking, plastic deformations due contact and large displacements are some effects which should be considered when a structure made from composite material is impacted by a foreign object. Thus, an investigation of the low velocity impact on thin composite laminates of epoxy resin reinforced by carbon fiber is presented. The study shows the technology to manufacture the specimens and the set-ups of equipments to make dynamic experimental tests using a drop-tower instrumented. Afterwards, non-destructive evaluation (NDE) using ultrasonic C-Scan was carried out in order to determine the main kind of failure. The influence of stacking sequence and energy impact were investigated using load-time histories, displacement-time histories and energy-time histories as well as images from NDE. Finally, indentation tests were developed and the quasi-static results were compared to dynamic results, verifying the inertia effects when thin composite laminate were impacted by foreign object with low velocity.

Keywords: impact, experimental tests, NDE, composite laminates

NOMENCLATURE

E = energy, J
m = impact mass, kg
v = velocity, m/s
t = time, s
h = impact height, m

Subscripts

o relative to initial velocity
i relative to impacter
exp relative to experimental tests

INTRODUCTION

During the last years, criteria of automobile and aircraft projects have been more and more rigorous for component developed in order to absorb impact energy. Research on the development of structural components with high crashworthiness has been carried out not only by the automobile and aeronautics industries, but also, by naval, trains and elevators industries. The project concept for structural components with high crashworthiness depends on the crash resistance concept described by Kindervater and Georgi (1993). The crash resistance concept is based on the energy absorption capacity and structural integrity. For developing a project that reaches those requirements, it should change the material and/or architecture of the component. However, changes on the architecture can cause increase of costs and/or of weights, reducing the performance of the structure. The weight increase is not attractive for the aircraft development, because it reduces the aircraft performance; so, it's more interesting change the material. Nowadays, many kinds of components have been made using composite materials, because these materials can absorb high amount impact energy and can guarantee the survival of the passengers. However, the dynamic behavior of composite laminates is very complex, because there are many concurrently phenomena during composite laminate failure under impact load. Fiber breakage, delaminations, matrix cracking, plastic deformations due to the contact and large displacements are some effects which should be considered when a structure made from composite material is impacted by a foreign object. Therefore, it's very common to find research works about this issue at the literature, for example: Levy Neto and Al-Quereshi (1986); Oñate et al. (1991); Cairns and Lagace (1992); Farley and Jones (1992); Haug and De Rouvray (1993); Belingardi, Gugliota and Vadori (1998); Collombet, Lalbin and Lataillade (1998); Gottesman and Girshovich (1998); Vicente, Béltran and Martínez (2000); Kindervater et al. (2000); Tita and Carvalho (2001); Kostopoulos et al. (2002); Lopresto and Caprino (2002).

Thus, this work is other scientific contribution that shows an experimental investigation of the low velocity impact on thin composite laminates plates of epoxy resin reinforced (matrix) by carbon fiber (reinforcement). This study describes the technology to manufacture the specimens and the set-ups of equipments to make dynamic experimental tests (using a drop-tower instrumented) and to realize non-destructive evaluation (NDE) (using ultrasonic C-Scan). Afterwards, it is shown discussions about:

- Experimental results as load-time, displacement-time and energy-time histories of the laminate plate impacted under low velocity, considering different stacking sequence and different impact energies;
- Experimental results as images from NDE of laminate damaged after impact test, using non-destructive evaluation (NDE) by ultrasonic C-Scan technique;
- Experimental results as load-displacement of the laminate under indentation test (quasi-static loading), considering the same stacking sequence used during impact test and the same maximum force level reached at impact tests;
- Comparison between experimental results from impact and indentation tests.

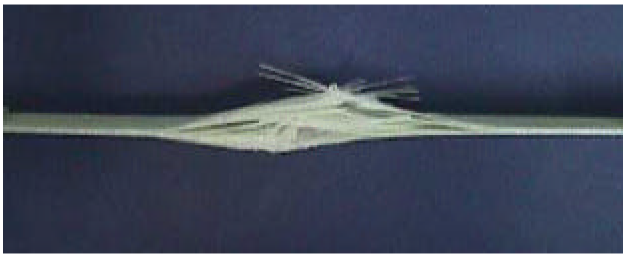
IMPACT ON COMPOSITE STRUCTURES

First, it is shown the failure mechanics of composite laminate during an impact loading and how these mechanics can absorb impact energy. Second, it is shown how the impact and absorbed energy can be measured during the impact event, using experimental test results.

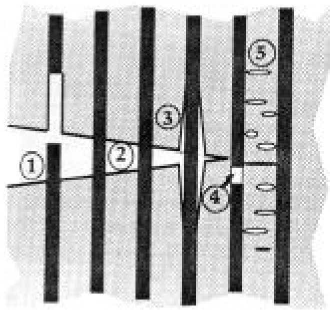
Composite failure mechanics

Composite laminate structures were made from the stacking of plies, which contains a polymeric matrix reinforced by fibers. Therefore, composite laminate shows two failure modes (Fig. 1(a)):

1. Intra-ply failure mode: damages at fibers, polymeric matrix and/or interface between fibers and matrix.
2. Inter-ply failure mode: delaminations between plies.



(a)



(b)

Figure 1 – (a) Composite failure mechanics: intra-ply and inter-ply failures;(b) Intra-ply damages(Anderson, 1995)

The intra-ply damage at fibers is showed by mechanic 4 (Fig. 1(b)) that is the fiber rupture. However, the fiber failure mode depends on the type of loading, because, compression loads can induce micro-buckling, but, tensile loads can induce rupture of fibers. The intra-ply damages at matrix depend on the ductility of the polymer, as well as, the in service temperature. Thus, the polymeric matrix can present a fragile or a plastic behavior (mechanic 5). There are other intra-ply failure mechanics showed by Fig. 1(b). The mechanic 1 is called “Pull-Out” and occurs when the interface between fiber and matrix is weak. So, the fiber is pulled out of the matrix after the debonding mechanic (mechanic 3) occurs. If the interface between fiber and matrix is strong, the fiber isn’t pulled out of the matrix and the mechanics 2 called “Fiber Bridging” occurs.

The inter-ply failure called delamination occurs, in many cases, after intra-ply damages, i.e., the evolution of intra-ply damages propitiates the delaminations, because, the regions damaged at the ply propagates when the load increases and the cracks at two adjacent plies (with different orientation angle) join for creating a discrete failure between them. In that moment, the interlaminar shears increases strongly and the delamination process initiates. This failure mechanics is very common to occur during impact events. According to Abrate (1998), there is a characteristic shape for the plate thickness when the laminate suffers impact loading (Fig. 2). For thick laminates, the damages occur at the outer plies, which contact to the impacter, because, the structure is less flexible. The damages at those plies occur due to the high contact stress values and propagate to the inner plies, promoting delaminations. The delaminations increase the flexibility of the structure and new intra-ply damages occur close to the delaminations. The intra-ply damages evolution increase the interlaminar shears that promotes new discrete damages between adjacent plies, forming a “pine tree” shape at the plate thickness (Fig.2(a)). This progressive failure process stops when the impact energy isn’t more enough to activate any failure mechanic. For thin laminates, the damages occur at the opposite plies that contact to the impacter, because, the structure is more flexible. The damages at those plies occur due to the high flexural stress values and propagate to the inner plies, promoting delaminations. The delaminations increase the flexibility of the structure and new intra-ply damages occur close to the delaminations. The intra-ply damages evolution increase the interlaminar shears that promotes new discrete damages between adjacent plies, forming a “reverse pine tree” shape at the plate thickness (Fig. 2(b)). This progressive failure process stops when the impact energy isn’t more enough to activate any failure mechanic. Besides, according to Abrate (1998), the delaminated plies show the damage shape like a “peanut shape” oriented in the same direction of the fibers in each ply (Fig. 2(c)).

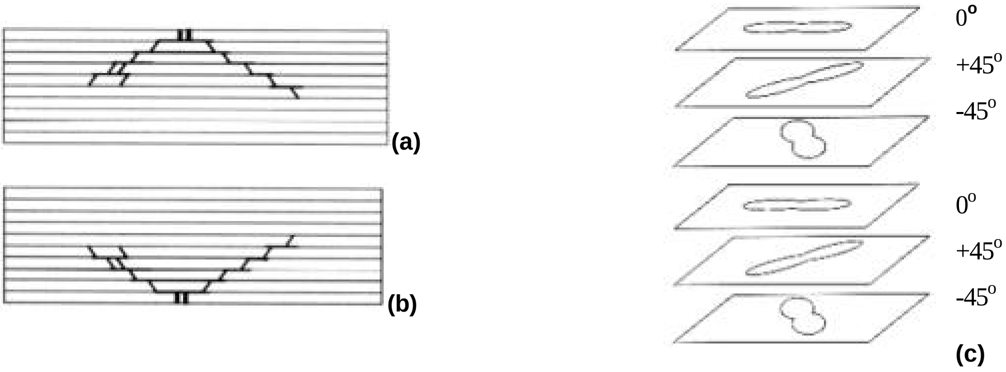


Figure 2 – Delaminated plies: (a) Thick laminate (“pine tree”); (b) Thin laminate (“reverse pine tree”); (c) “Peanut shapes” (Abrate, 1998)

Energy: impact, absorbed and elastic

If an object with mass m impacts a composite plate with a velocity equal v_o, the Impact Energy of the impacter E_i can be expressed by:

$$E_i = \frac{mv_o^2}{2} \tag{1}$$

Besides, the Impact Energy E(t) transferred from object to the target (composite laminate plate) can be expressed by:

$$E(t) = \frac{mv_o^2}{2} - \frac{m(v_i(t))^2}{2} \tag{2}$$

where the velocity of the impacter $v_i(t)$ can be obtained by:

$$v_i(t) = v_o - \frac{1}{m}\int_0^t F_{exp}dt \tag{3}$$

The experimental impact force F_{exp} is measured during impact event. Thus, it’s possible to evaluate the Impact Energy, which reaches the composite plate, as well as, the Absorbed Energy and the Elastic Energy (Fig. 3). The Absorbed Energy could be understood as “Released Energy’, because the failure mechanics activated during the impact event release energy. However, the literature considers those release energies as a fraction of impact energy, which is absorbed by the structure and isn’t transformed on elastic vibrations (Elastic Energy).

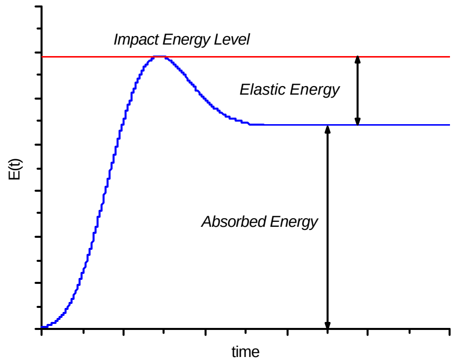


Figure 3 – Impact Energy, Absorbed Energy e Elastic Energy

In other words, the Impact Energy E(t) transferred from object to the target (composite laminate plate) is absorbed by the failure mechanics activated. Thus, each failure mechanic, i.e., intra-ply failures and/or delaminations absorb a fraction of impact energy. Therefore, the amount and the type of failure mechanics activated will influence on the Absorbed Energy values. However, the amount and the type of failure mechanics activated depends on the some factors:

- Mass and velocity of the impacter (Impact Energy Level);
- Geometry of the impacter;
- Geometry of the structure;
- Type of fiber and/or matrix used for manufacturing of the composite structure;
- Stacking sequence of the plies.

For this work, it was verified the influence of the impact energy level and the stacking sequence.

MATERIAL AND METHODS

American Society for Testing and Materials (ASTM) standards were followed to manufacture the specimens and to realize the experimental tests. It's important to note that the fabrication of the specimens and the experimental tests were executed at Leuven Composites Processing Centre (LCPC) of Katholieke Universiteit Leuven (Belgium).

Fabrication of the specimens

The prepreg M10 (epoxy resin reinforced by carbon fiber unidirectional) from Hexcel® was used for manufacturing of the composite plates.

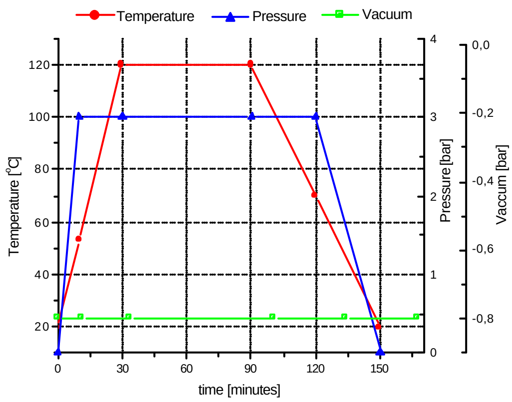


Figure 4 – Cure cycle

After hand-lay-up process used to stack the plies, the composite plate was put in the auto-clave with vacuum system set to -0,8 Bar (-0,08 MPa). According to Hexcel®, the complete cure cycle for M10 occurs when this material is processed at 120°C, under a pressure with range from 0.3 to 5.0 Bar during 60 minutes (Fig.4). After cure process, the composite plates were cut on square shapes (length and width equal 120 mm and thickness equal 1.8 mm), using diamond saw in order to guarantee the tolerances specified by standards.

Impact and indentation tests

For the impact tests under low velocity, drop-tests were realized following the specifications by FD Method described on the ASTM D5628-96 and using a drop tower. Table 1 shows the values for dimensions of square specimen, as well as, impact mass (m), height of falling impact mass (h), impact velocity (v_o) and Impact Energy (E_i). Figure 5(a) shows the specimen fixed by two circular steel disks that had a hole with a diameter equal 80 mm. Thus, in fact, circular composite plates with boundary clamped by two circular steel disks attached (using four bolts under torque equal 27Nm) were evaluated under impact conditions specified at Tab.1.

Figure 5(b) shows the geometry of the aluminium dart with mass equal 0.0513 kg. The support of mass (Fig.5(c)) and the load cell (Fig.5(c)) with the aluminium dart has total mass equal 1.205 kg shown by Tab.1. The instrumented drop tower showed at Fig. 5(c) has an optic sensor fixed at the base and a LED ("Ligth Emitting Diode") attached to the support of the mass, which permits to measure the displacement of the support in function of the time. Thus, numeric methods to derivate the displacement measured were applied in order to obtain the velocity and acceleration of the support during the impact event. On the other hand, the load cell measures the force during the impact event. The load cell was plugged on a Kistler® amplifier (model 5007) that sends signal to the computer. In the computer, there is a system for data acquisition with 11 bits, three channels for input data and sampling frequency set to 19 kHz. Thus, the acceleration of the load cell was obtained dividing the force measured by the impact mass. Numeric methods to integrate the acceleration measured were applied in order to obtain the velocity and displacement of the load cell during the impact event. In fact, not only the measures from support and numeric methods to derivate, but also, the measures from load cell and numeric methods to integrate produce errors for determination of the displacement, velocity and acceleration of the dart. Therefore, in order to minimize the errors, both measures (from load cell and from support) were used to determine the displacement, velocity and acceleration of the dart.

Table 1 – Specifications for drop-tests

Stacking Sequence	Length [mm]	Thickness [mm]	m[kg]	h [m]	v_o [m/s]	E_i [J]
$[0]_{10}$	120	1.8	1.205	0.5	3.13	5.91
	120	1.8	1.205	0.2	1.98	2.36
$[0/90/0/90/0]_s$	120	1.8	1.205	0.5	3.13	5.91
	120	1.8	1.205	0.2	1.98	2.36
$[+45/-45/+45/0/90]_s$	120	1.8	1.205	0.5	3.13	5.91
	120	1.8	1.205	0.2	1.98	2.36
	120	1.8	2.205	0.5	3.13	10.82
	120	1.8	2.205	0.2	1.98	4.33

The indentation tests were realized using universal machine equipment in order to produce a quasi-static loading under velocity equal 10 mm/min on the specimens with the same geometry and the same boundary conditions used for drop-tests. Thus, each circular composite plate was loaded from zero to the maximum force value reached at respective drop-test. After that, the load was removed till zero under velocity equal 10 mm/min, too.

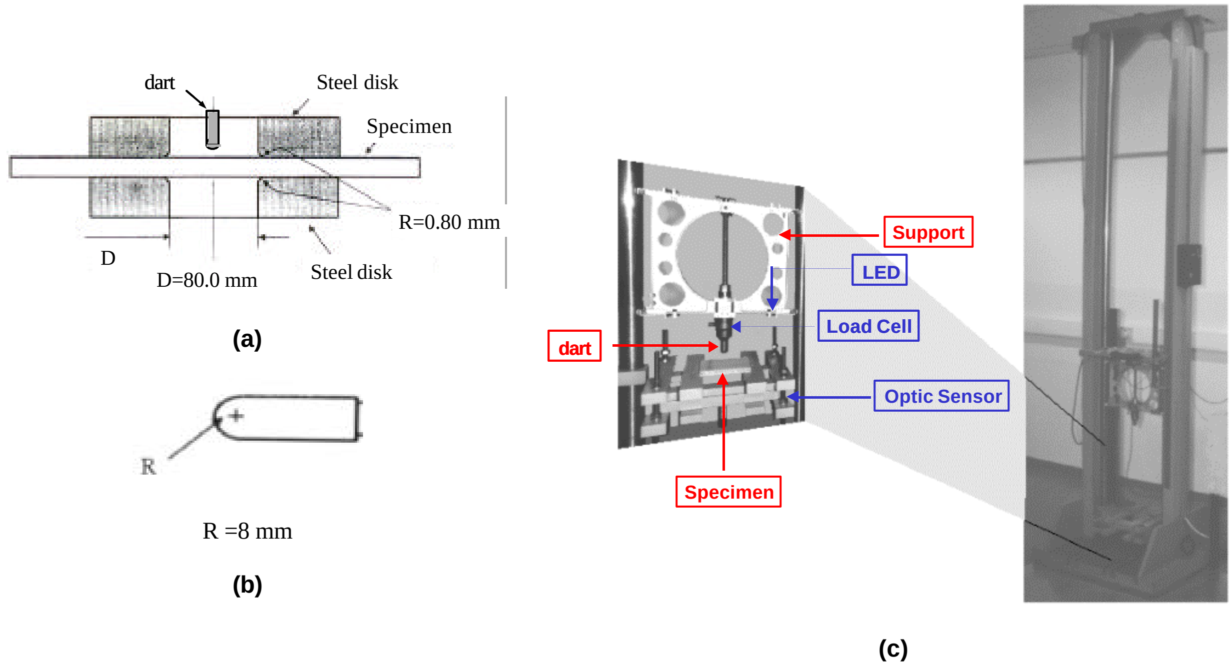


Figure 5 – (a) Composite plates clamped by two circular steel disks; (b) Geometry of the dart; (c) Drop tower at LCPC of Katholieke Universiteit Leuven (Belgium)

NDE by ultrasonic C-Scan technique

According to Abrate (1998), non-destructive evaluation techniques can be used to determine the principal failure mechanics that occur when a composite structure is impacted. However, the destructive evaluation techniques are used in order to verify more details about failure mechanics. In fact, non-destructive and destructive techniques are used in conjuction to improve the information quality, increasing the accuracy of inspection results, but, this approach also increases the costs. In this work, only the NDE by ultrasonic C-Scan technique was used, because, this technique is applied on large scale by aeronautic industries. The C-Scan equipment (Fig.6) was set with the frequency equal 5 MHz and set to cover a square area (length equal 30 mm) of the composite plate impacted by the dart, using the increment for scanning equal 298.4 μm.

Figure 6 – Ultrasonic C-Scan equipment at LCPC of Katholieke Universiteit Leuven (Belgium)

Some C-Scan equipment can be used to inspect the extension of the damage at a specific layer. Thus, it's possible to determine with accuracy the location and the extension of the delaminations. However, the ultrasonic C-Scan equipment at LCPC of Katholieke Universiteit Leuven (Belgium) didn't offer that tool. Therefore, the image captured is a superposition of the damaged regions on each layer, i.e., all failure mechanics are projected in the same plane. Althought, there was this limitation, it was possible to indentify the principal failure mechanics at composite plates impacted.

RESULTS AND DISCUSSIONS

First, it is shown the impact test results (force-time, displacement-time and energy-time graphics) and images from ultrasonic C-Scan technique. Second, it is shown the indentation test results, comparing the force-displacement graphics between quasi-static and impact loading.

Impact test results and NDE images

Results for laminate $[0]_{10}$

Figure 7(a) shows force-time graphics for composite plates with stacking sequence equal $[0]_{10}$, considering two impact energy levels (5.91 J and 2.36 J).

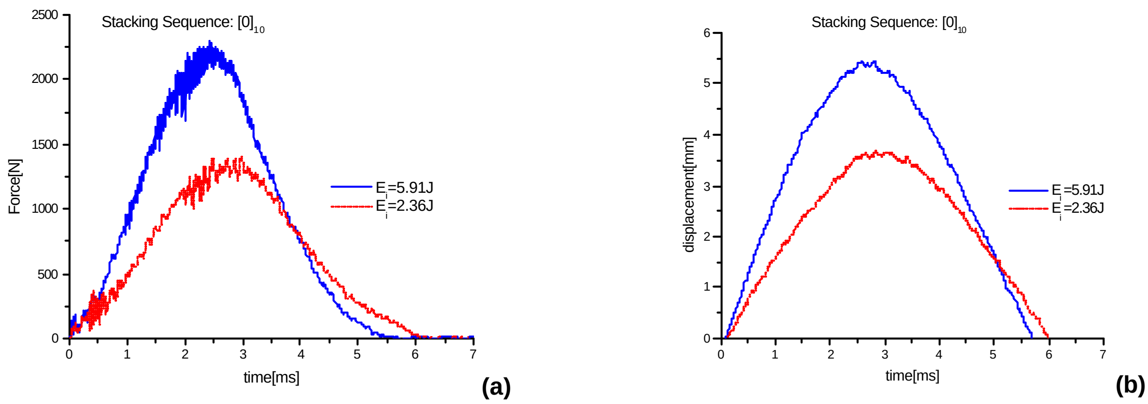


Figure 7 – Results for laminate $[0]_{10}$: (a) force-time; (b) displacement-time

There is a region with inertia oscillations of high frequency (from 0 to 1 ms) due to initial contact between specimen and dart at force-time graphic (Fig. 7(a)). From 2 ms, there are some oscillations with more intensity that show damage occurred, not only for specimens under E_i equal 5.91 J where maximum impact force is equal 2,250 N, but also, for specimens under E_i equal 2.36 J where maximum impact force is equal 1,300 N. Due to the stacking sequence equal $[0]_{10}$, the principal failure mechanic is the matrix rupture, reducing a little the global rigidity of the structure. Therefore, there isn't an abrupt drop of the impact force value after the progressive damage process initiation (Fig. 7(a)). The contact time depends on the impact energy level; so, the contact time is higher (6 ms) for specimens impacted by impact energy equal 2.36 J than by impact energy equal 5.91 J. Thus, as high of the contact time as low of the impact energy, and the mechanical behavior of the specimen tends to quasi-static response.

Figure 7(b) shows the displacement-time graphics for composite plates with stacking sequence equal $[0]_{10}$, considering two impact energy levels (5.91 J and 2.36 J). For impact energy equal 5.91 J, the dart penetrated into the specimen 5.4 mm. However, for lower impact energy (2.36 J), the dart penetrated into the specimen only 3.6 mm. Thus, the specimen impacted by 5.91 J was damaged more than specimen impacted by 2.36 J.

Figure 8(a) shows the energy-time graphic for composite plates with stacking sequence equal $[0]_{10}$, considering the impact energy equal 5.91 J. It is verified that specimens have absorbed energy equal 4.42 J, so, only 25% of the impact energy is converted on elastic vibrations. However, the specimens impacted by 2.36 J have just 1.2 J for absorbed energy (Fig. 8(b)), converting 50% of the impact energy on elastic vibrations. Thus, the specimens impacted by 2.36 J show less failure mechanics. This observation can be confirmed, using the images from ultrasonic C-Scan technique.

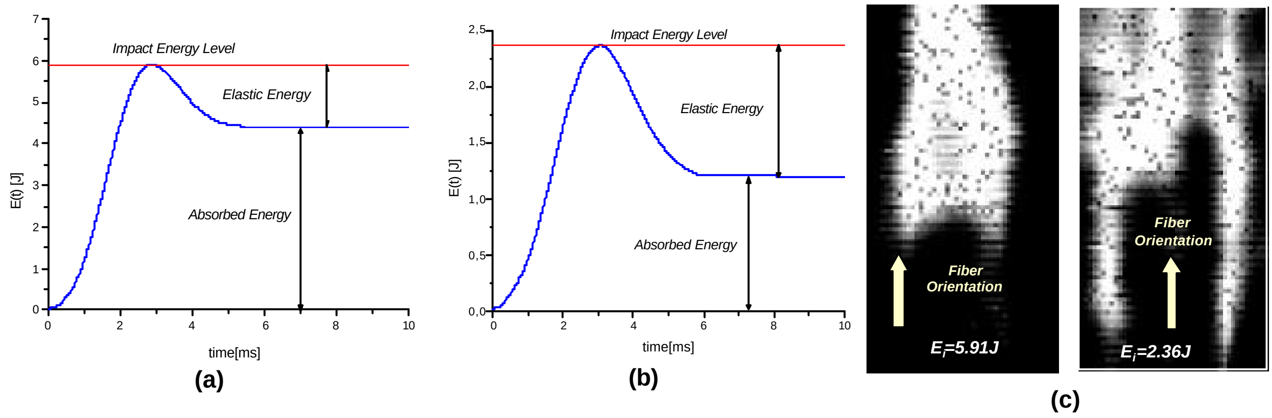


Figure 8 – Results for laminate $[0]_{10}$: (a) energy-time for 5.91 J; (b) energy-time for 2.36 J; (c) Results for laminate $[0]_{10}$: C-Scan images

Figure 8(c) shows the ultrasonic C-Scan images for composite plates with stacking sequence equal $[0]_{10}$, considering the impact energy equal 5.91 J and equal 2.36 J. Specimens impacted by 5.91 J show damages more concentrated close to the impact region. However, specimens impacted by 2.36 J show damages more distributed at the matrix represented by cracks oriented to the fibers. Besides, it was possible to observe that some fibers failure at the opposite side of the impact for the specimens impacted at 5.91 J. This observation can explain why these specimens absorbed 75% of the impact energy, where the failure mechanics of fibers release more energy than failure mechanics of the matrix.

Results for laminate $[0/90/0/90/0]_s$

Figure 9(a) shows force-time graphics for composite plates with stacking sequence equal $[0/90/0/90/0]_s$, considering two impact energy levels (5.91 J and 2.36 J).

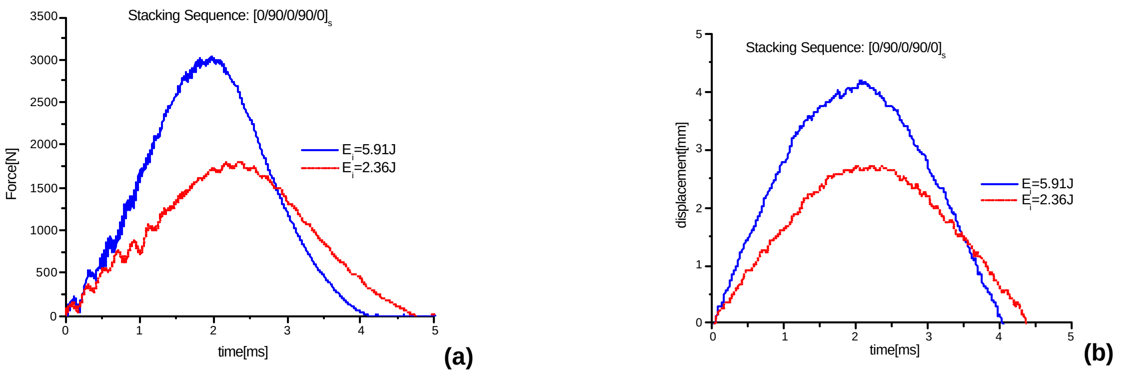
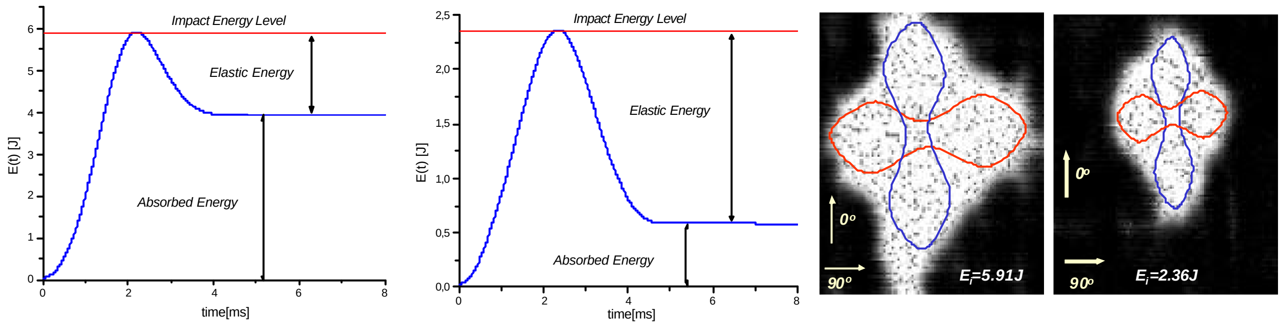


Figure 9 – Results for laminate $[0/90/0/90/0]_s$: (a) force-time; (b) displacement-time

There is a region with inertia oscillations of high frequency (from 0 to 1.2 ms) due to initial contact between specimen and dart at force-time graphic (Fig. 9(a)). From 1.8 ms, there are some small oscillations that show damage occurred, not only for specimens under E_i equal 5.91 J where maximum impact force is equal 3,000 N, but also, for specimens under E_i equal 2.36 J where maximum impact force is equal 1,750 N. Due to the stacking sequence equal $[0/90/0/90/0]_s$, the main failure mechanics are the matrix rupture and delaminations, reducing a little the global stiffness of the structure. Therefore, there isn't an abrupt drop of the impact force value after the progressive damage process initiation (Fig. 9(a)). The contact time depends on the impact energy level; so, the contact time is higher (4.5 ms) for specimens impacted by impact energy equal 2.36 J than by impact energy equal 5.91 J. Thus, as high of the contact time as low of the impact energy, and the mechanical behavior of the specimen tends to quasi-static response.

Figure 9(b) shows the displacement-time graphics for composite plates with stacking sequence equal $[0/90/0/90/0]_s$, considering two impact energy levels (5.91 J and 2.36 J). For impact energy equal 5.91 J, the dart penetrated into the specimen 4.2 mm. However, for lower impact energy (2.36 J), the dart penetrated into the specimen only 2.37 mm. Thus, the specimen impacted by 5.91 J was damaged more than specimen impacted by 2.36 J.

Figure 10(a) shows the energy-time graphic for composite plates with stacking sequence equal $[0/90/0/90/0]_s$, considering the impact energy equal 5.91 J. It is verified that specimens have absorbed energy equal 3.96 J, so, only 33% of the impact energy is converted on elastic vibrations. However, the specimens impacted by 2.36 J have just 0.58J for absorbed energy (Fig. 10(b)), converting 75% of the impact energy on elastic vibrations. Thus, the specimens impacted by 2.36 J show less failure mechanics. This observation can be confirmed, using the images from ultrasonic C-Scan technique.



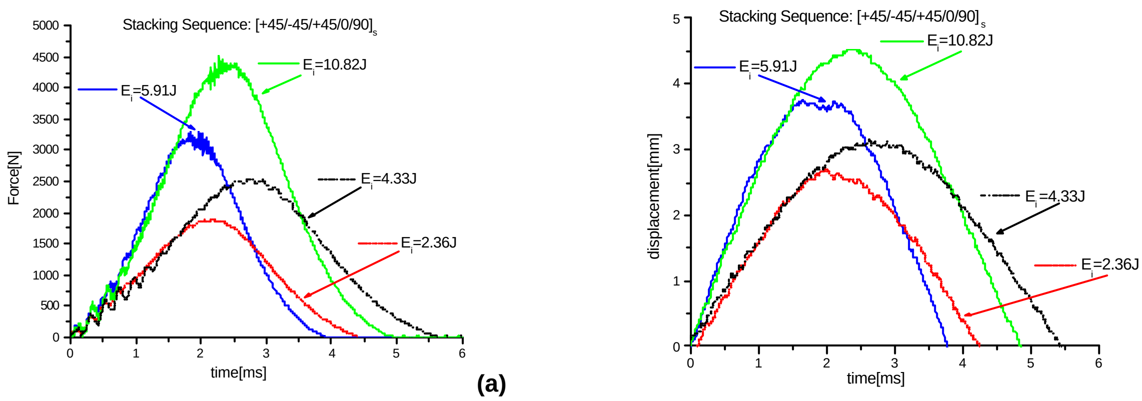
(a) (b) (c)

Figure 10 – Results for laminate $[0/90/0/90/0]_s$: (a) energy-time for 5.91 J; (b) energy-time for 2.36 J; (c) Results for laminate $[0/90/0/90/0]_s$: C-Scan images

Figure 10(c) shows the ultrasonic C-Scan images for composite plates with stacking sequence equal $[0/90/0/90/0]_s$, considering the impact energy equal 5.91 J and equal 2.36 J. Due to the stacking sequence equal $[0/90/0/90/0]_s$, there are more layers oriented at 0^o than at 90^o, so, there are more cracks aligned to 0^o. Besides, there are "peanut shapes", which represents delaminations, at both directions (0^o and 90^o). The area damaged for the specimens impacted by 5.91J (340 mm^2) is higher than the specimens impacted by 2.36 J (150 mm^2). This calculus can explain why the specimens impacted by 2.36 J just absorbed 25% of the impact energy, where many failure mechanics can't be activated for the stacking sequence equal $[0/90/0/90/0]_s$ by this impact energy level, and the mechanical behavior of the specimen tends to elastic response.

Results for laminate $[+45/-45/+45/0/90]_s$

Figure 11(a) shows force-time graphics for composite plates with stacking sequence equal $[+45/-45/+45/0/90]_s$, considering four impact energy levels (2.36 J , 4.33 J, 5.91 J and 10.82 J).



(a) (b)

Figure 11 – Results for laminate $[+45/-45/+45/0/90]_s$: (a) force-time; (b) displacement-time

The dynamic responses for the specimens impacted by 5.91 J and by 10.82 J are very similar and reaches maximum impact force equal 3,300N and 4,500 N respectively. However, these dynamic responses are different of response for the specimens impacted by 2.36 J and by 4.33 J, which reaches maximum impact force equal 1,900 N at 2.36 J and 2,500 N at 4.33 J (Fig. 11(a)). Besides, the specimens impacted by 5.91 J and by 10.82 J show many oscillations close to the maximum impact force that represent many types of failure mechanics, for example: cracks at the matrix, delaminations between layers oriented at $0^o/90^o$ and at $45^o/0^o$, as well as, some fibers ruptures. However, there are just some oscillations close to the maximum impact force for specimens impacted by 2.36 J and by 4.33 J (Fig. 11(a)) that represent few damages. In fact, the specimens impacted by lower energy have a response that tends to quasi-static response. However, the specimens impacted by mass equal 2.205 kg with impact energy equal 4.33 J and 10.82 J show that the contact time is higher than the specimens impacted by mass equal 1.205 kg (Fig 11(a)). Besides, Fig. 11(b) shows that as high the impact energy as high the penetration of dart into the composite plate.

Figure 12 (a) shows the energy-time graphic for composite plates with stacking sequence equal $[+45/-45/+45/0/90]_s$, considering the impact energy equal 5.91 J. It is verified that specimens have absorbed energy equal 4.0 J, so, only 32% of the impact energy is converted on elastic vibrations. The specimens impacted by 10.82 J have the highest absorbed energy (Fig. 12(c)), because 8.8 J was absorbed by many failure mechanics. On the other hand, the specimens impacted by 2.36 J have a very low absorbed energy level (0.8 J), converting 66% of the impact energy on elastic vibrations (Fig. 12(b)). Finally, the specimens impacted by 4.33 J (Fig. 12(d)) show that the absorbed energy is equal 2.6 J, converting only 40% of the impact energy on elastic vibrations. Thus, the specimens impacted by 2.36 J show less failure mechanics. This observation can be confirmed, using the images from ultrasonic C-Scan technique.

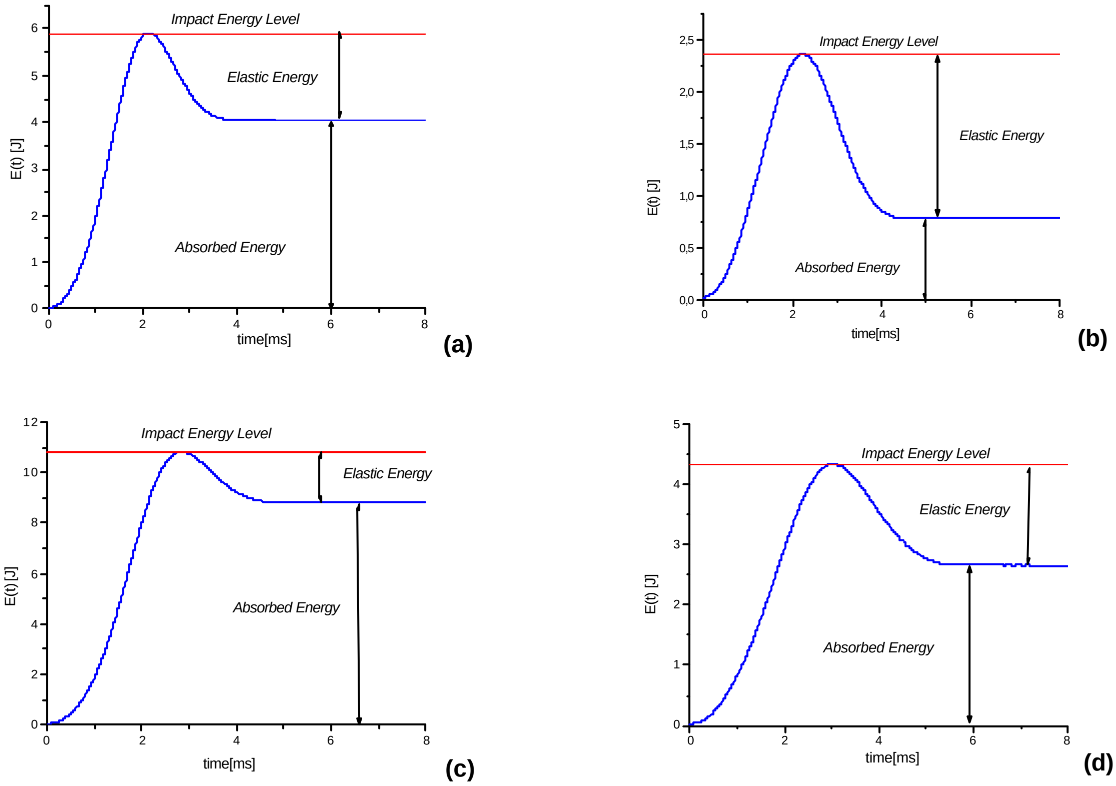


Figure 12 – Results for laminate $[+45/-45/+45/0/90]_s$: (a) energy-time for 5.91 J; (b) energy-time for 2.36 J; (c) energy-time for 10.82 J J; (d) energy-time for 4.33 J

Figure 13 shows the ultrasonic C-Scan images for composite plates with stacking sequence equal $[+45/-45/+45/0/90]_s$, considering the impact energy equal 5.91 J, 2.36 J, 10.82 J and 4.33 J.

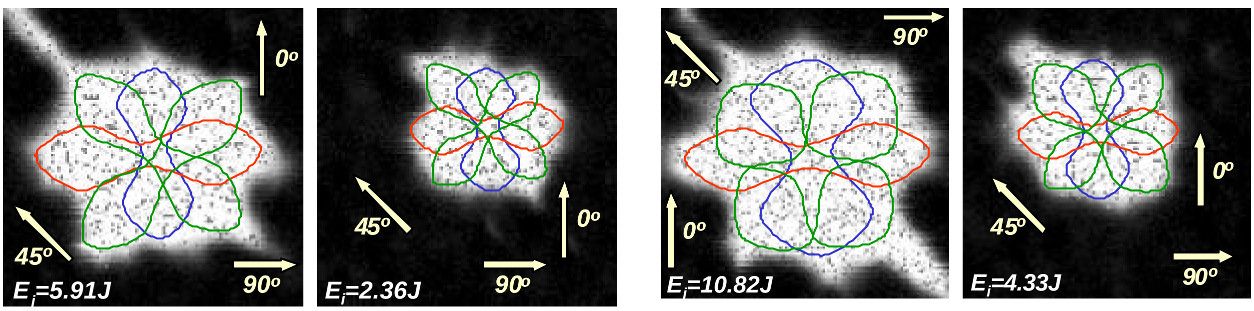


Figure 13 – Results for laminate $[+45/-45/+45/0/90]_s$: C-Scan images

Due to the stacking sequence equal $[+45/-45/+45/0/90]_s$, there are more layers oriented at $+45^o$ than at other direction, so, there are more cracks aligned to $+45^o$. Besides, there are "peanut shapes", which represents delaminations, at four directions (0^o, $+45^o$, -45^o and 90^o). The areas damaged for the specimens impacted by 5.91 J (360 mm^2) and by

10.82 J (450 mm^2) are higher than the specimens impacted by 2.36 J (165 mm^2) and by 4.33 J (211 mm^2). These calculi can explain why the specimens impacted by 10.82 J absorbed 81% of the impact energy, where many failure mechanics are activated for the stacking sequence equal $[+45/-45/+45/0/90]_s$ by this impact energy level. The mechanical behavior of the specimen tends to a complete inelastic response where the dart is almost retained by the composite plate.

Indentation test results

Results for laminate $[0]_{10}$

Figure 14 shows the force-displacement graphics for composite plates with stacking sequence equal $[0]_{10}$. In general, at the initial of loading step, the indentation and the impact curves have similar inclination that represents non-linear behavior due to the contact phenomenon. However, the indentation curves don't show the oscillations inherent for the dynamic response obtained from drop-tests. Besides, when the load reaches the maximum force, which is equal to the maximum force obtained at drop-test, the indentation curves don't show oscillations due to failure mechanics of the composite plate are activated. Thus, for the same level of load, the indentation curves show lower displacement than impact curves, because, there are more failure mechanics activated during the impact event than quasi-static event. Besides, the failure mechanics for composite plate under quasi-static loading concentrate closer to the region where the dart contacts the specimen. However, the failure mechanics showed by plates impacted are more distributed.

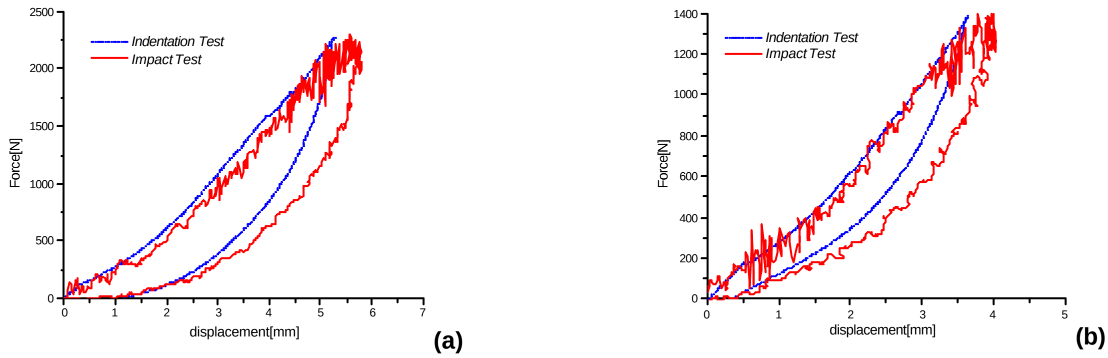


Figure 14 – Results for laminate $[0]_{10}$: (a) maximum force at 2,250 N; (b) maximum force at 1,300 N

Therefore, the failure mechanics for composite plate under impact loading reduce more the structure global stiffness than the failure mechanics concentrated. This observation can explain why the inclination of indentation curve is very different of inclination presented by the impact curve, during the step, which the loading is removed until zero.

Results for laminate $[0/90/0/90/0]_s$

Figure 15 shows the force-displacement graphics for composite plates with stacking sequence equal $[0/90/0/90/0]_s$.

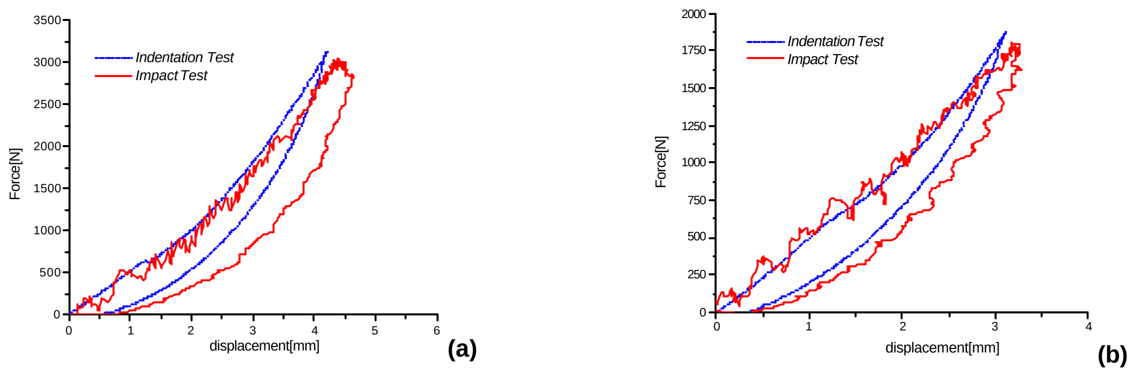
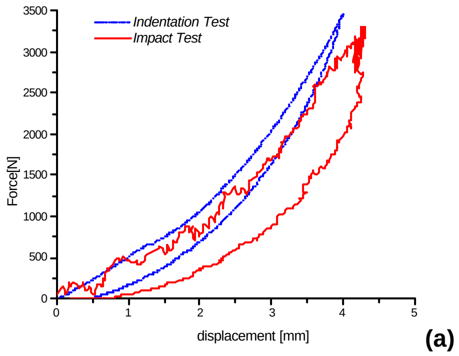


Figure 15 – Results for laminate $[0/90/0/90/0]_s$: (a) maximum force at 3,000 N; (b) maximum force at 1,750 N

In general, at the initial of loading step, the indentation and the impact curves have similar inclination represents non-linear behavior due to the contact phenomenon. However, the indentation curves don't show the oscillations inherent for the dynamic response obtained from drop-tests. Besides, when the load reaches the maximum force, which is equal to the maximum force obtained at drop-test, the indentation curves don't show oscillations due to intra-ply failures and delaminations activated. Thus, Fig 15(a) shows for the same level of load that the indentation curve has lower displacement than impact curves, because, there are more failure mechanics activated during the impact event than quasi-static event. However, Fig. 15(b) shows that the inclination of indentation curve is similar of inclination presented by the impact curve not only the loading step, but also, during the step, which the loading is removed until zero. Because, the specimens impacted by 2.36 J (maximum impact force equal 1,750 N) just absorbed 25% of the impact energy and the mechanical behavior of the specimen tends to elastic response. Therefore, many failure mechanics aren't activated for the stacking sequence equal $[0/90/0/90/0]_s$ by neither impact event nor indentation test.

Results for laminate $[+45/-45/+45/0/90]_s$

Figure 16 shows the force-displacement graphics for composite plates with stacking sequence equal $[+45/-45/+45/0/90]_s$.



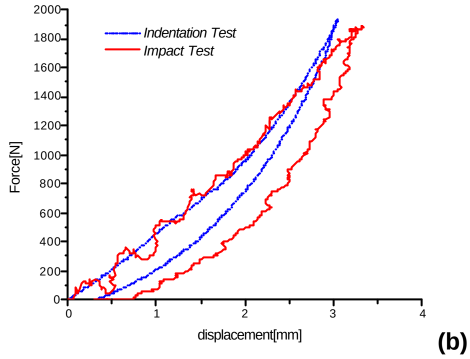
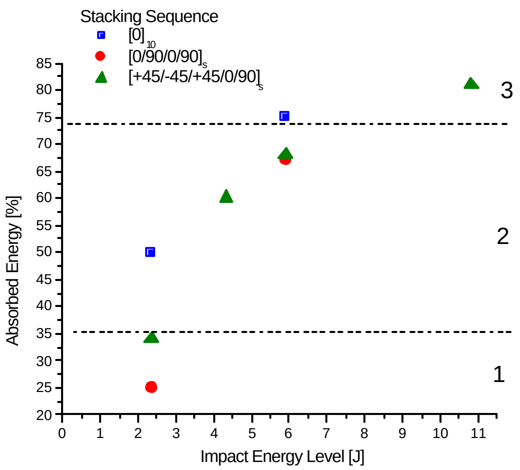


Figure 16 – Results for laminate $[+45/-45/+45/0/90]_s$: (a) maximum force at 3,300 N; (b) maximum force at 1,900 N

Figure 16(a) shows from the initial to the final of loading step, the indentation and the impact curves have different inclination. Because, the specimens with stacking sequence equal $[+45/-45/+45/0/90]_s$ impacted show many types of failure mechanics that are distributed at composite plate. However, the failure mechanics for composite plate under quasi-static loading concentrate close to the region where the dart contacts the specimen. These failure mechanics reduce less the structure global stiffness than the failure mechanics distributed. However, the Fig. 16(b) shows that the inclination of indentation curve is similar to inclination presented by the impact curve not only the loading step, but also, during the step, which the loading is removed until zero. Because, the specimens impacted by 2.36 J (maximum impact force equal 1,900 N) converted 66% of the impact energy on elastic vibrations. Although, the inclinations for two curves are similar, there is an offset between both curves due to the difference between the failure mechanics shown by impact event (more distributed) and by quasi-static event (more concentrated).

CONCLUSIONS

It is verified that stacking sequence and impact energy level can influence on the dynamic response of composite plates. The graphics of force-time and energy-time, as well as, the images from ultrasonic C-Scan technique are used in order to compare the mechanical behavior of the specimens, which is represented by graphic of Absorbed Energy versus Impact Energy Level. Figure 17 can be divided on three regions.



***Region 3**: the specimens show many type of failure mechanics, for example: fiber rupture, matrix crack and delaminations; so, the fraction of absorbed energy is very high (over 75%)*

***Region 2:** the specimens show some failure mechanics, which are matrix crack and delaminations; so, the fraction of absorbed energy is intermediate between 35% and 75%*

***Region 1**: the specimens have a quasi-elastic behavior, because the fraction of absorbed energy is very low (under 35%) due to failure mechanics are not activated*

Figure 17 – Absorbed Energy x Impact Energy

In general, the indentation test can be used to represent a drop test when the impact energy level is low and the specimen has a quasi-elastic behavior. Because, the indentation curves don't show the oscillations inherent for the dynamic response obtained from drop-tests and there are more failure mechanics activated during the impact event than quasi-static event. Besides, the failure mechanics shown by impact event are more distributed and by quasi-static event are more concentrated. Thus, the structural global stiffness reduces with more intensity for drop-test. Finally, it's very important to comment that the experimental test results for this work were used to validate and calibrate a composite material failure model developed by the authors and this failure model will be shown in a future publication.

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