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RESIDUAL STRENGTH CRITERION BASED ON DAMAGE METRIC AND FLEXURAL AFTER IMPACT (FAI) TEST FOR COMPOSITE MATERIALS

Ricardo de Medeiros
Murilo Sartorato
EESC/USP - University of São Paulo, São Carlos School of Engineering, Department of Aeronautical Engineering
Av. João Dagnone, 1100 São Carlos, SP, Brazil
medeiros@sc.usp.br, murilosart@gmail.com

Sandra Patricia da Silva Tita
EESC/USP - University of São Paulo, São Carlos School of Engineering, Department of Materials Engineering
Av. João Dagnone, 1100 São Carlos, SP, Brazil
spatstita@gmail.com

Dirk Vandepitte
KU Leuven - Katholieke Universiteit Leuven, Department of Mechanical Engineering - PMA, Belgium.
Dirk.Vandepitte@kuleuven.be

Marcelo Leite Ribeiro
Volnei Tita
EESC/USP - University of São Paulo, São Carlos School of Engineering, Department of Aeronautical Engineering
Av. João Dagnone, 1100 São Carlos, SP, Brazil
malribei@usp.br, voltita@sc.usp.br

Abstract. *Composite materials have been utilized for nearly four decades owing to their beneficial characteristics, such as stability, weight and high stiffness. Particularly, in the aerospace industry the use of composites is justified by reducing structural weight with consequent fuel saving and improving performance. During the service life, a composite structure is subjected to various loading conditions, which can give rise to various defects. Composite laminates are especially sensitive to low velocity impacts since even minor damage can cause considerable reduction in structural integrity. In addition, laminated composite materials are susceptible to damage by out-of-plane impact, often associated with a corresponding reduction of mechanical properties. In fact, the impact energy is absorbed through remarkable internal damage mechanisms without exterior signs detectable by visual inspection. Various types of damages, like delamination, fiber-breakage, matrix cracking and fiber–matrix interfacial debonding can occur, leading to structural failure. To ensure that a damaged structure will not catastrophically fail during service life and will maintain maximum structural efficiency, it is necessary to carry out damage tolerance studies, evaluating the residual properties of the structure after impact. This study present a new criterion to evaluate the residual strength of laminate composite subject to low velocity impact loading. One of the objectives of this research was to investigate the feasibility of an elastic flexural test as an effective metric for the residual properties of an impacted composite. For this, a flexure after impact (FAI) test is used alongside the standard CAI to compare its practicality as a damage tolerance technique. Low-velocity impact tests and residual strength tests are performed using an instrumented drop-weight machine and static test machine, respectively. The experiments were carried out on laboratory specimens, which are flat and rectangular composite plates. Two different stacking sequence and thickness are tested, in order to analyze the influence of these factors on the impact and post-impact response. The residual flexural strength of damaged specimens is evaluated by quasi-static and four-point bending test. The results of drop-weight impact tests and FAI tests on carbon/epoxy laminates are presented. A new criterion based on a relationship between damage metric and FAI analysis is proposed. Thus, these results are normalized by using the project load and the metrics for damage analyses, i.e. if there is no damage in the structure, then the metric returns "zero" value. If the structure is partially damaged then the metric returns a number between one and "zero". Finally, if the structure is totally damaged, then the metric returns a value equal one. Finally, it is discussed the advantages and limitations of this criterion into the context of SHM system (Structural Health Monitoring System).*

Keywords: *Flexure After Impact (FAI), composite laminates, experimental analyses, residual strength, impact testing.*

1. INTRODUCTION

The resistance to impact threat is an important part in the reliability assessment of composites because the impact loads universally exist in the actual application in aeronautics and astronautics, engineering structure, and other fields

(Chenghong *et. al*, 2008). The poor tolerance to accidental low velocity impacts of composite laminates is a limitation to their use in industry (Collombet *et al.*, 1996). Impact damage is considered the primary cause of in-service delamination in composites giving reductions of the compressive residual strength up to 60% (Zheng and Sun, 1998), which is one of the most important aspects that inhibit larger wide-spreading of such structures (Amaro *et al.*, 2006).

Most of the visible damage is a result of high-velocity high-energy impacts, where the impactor perforate into the laminated material. The analyses of such cases are mostly concerned with the estimation of the damage geometry and its influence on the strength of the laminate. On the other hand, most of the invisible damage is the result of low-velocity low-energy impacts. Even though much attention has been devoted recently to the impact problems of composites, the studies are not sufficient especially on the problem caused by invisible damage (Rotem, 1988).

It has been identified that there are at least three dominant failure mechanisms taking place in the composite laminates when subjected to impact loading. These are interlaminar fracture (or delamination), matrix cracking due to transverse shear and translaminar fracture (*i.e.*, fiber fracture/kinking). The first two mechanisms are sensitive to the properties of the matrix material and the last to the fiber performance, especially the failure strain. Depending on the properties of constituents, choice of fiber and matrix types, the fracture process can be a very complex combination of these energy absorption mechanisms (Kim *et al.*, 1993).

The aim of a damage-tolerance study is to evaluate the capacity of a structural element to continue carrying out its functions after an impact; for this reason, in a beam designed to bear bending moments, it is necessary to evaluate the residual flexural properties (Santiuste *et al.*, 2010). Several techniques have been used to assess the impact damage tolerance of composite laminates. These can be generally classified into non-destructive tests (NDT) and destructive tests. Among the NDTs, it can highlight methods such as IR Thermography, Ultrasonic Inspection, C-scan, X-Ray Radiography and Mechanical Impedance Analysis. On the other hand, considering the destructive techniques, the compressive strength after impact (CAI) has been the most popular tool (Kim *et al.*, 1993). However, it is possible to find in the literature other post-impact tests conducted by previous investigators include longitudinal and transverse tensile tests (Wu and Springer, 1988; Wyrick and Adams, 1988; Jang *et al.*, 1992). Iosipescu shear test (Wu and Springer, 1988), short beam shear test (Wu and Springer, 1988; Jang *et al.*, 1992), multi-span beam shear test (Williams and Rhodes, 1982), flexural test (Santiuste *et al.*, 2010) and center-notched flexural test (Maikuma *et al.*, 1990).

The post-impact mechanical properties of composites have been receiving extensive investigation in recent years, most of which devoted to compression properties (CAI). The research on residual flexural properties (FAI), especially the influences and mechanisms of the various factors, are still few (Cromer, 2010). Rotem (1988) studied the influence of the material, testing a carbon/epoxy laminate and a less brittle glass/epoxy laminate. Three-point bending tests were conducted in a drop-weight tower to damage the beam. Afterwards, the residual properties were evaluated by static three-point bending tests. Richardson and Wisheart (1996) reviewed the low-velocity impact responses of composite materials. First the term ‘low-velocity impact’ is defined and major impact-induced damage modes are described from onset of damage through to final failure. Then, the effects of the composite’s constituents on impact properties are discussed and post impact performance is assessed in terms of residual strength. Mouritz et al. (1997) studied the flexural strength and interlaminar shear strength of stitched and non-stitched glass-reinforced plastic (GRP) laminates under conditions of increasing impact energy and increasing number of repeated impacts. The three-point flexural strength and short-beam interlaminar shear strength of the GRP before impact loading were reduced by stitching as a result of stitching damage.

Mariatti *et al.* (2001) carried out studies on the flexural damage behaviors of satin and plain continuous-fiber-impregnated thermoplastic (COFIT) prepreg woven composites. Shim and Yang (2005) investigates experimentally and theoretically the mechanism of damage development in composite laminates subjected to low-velocity impact loading; the focus is to describe the effects of impact and laminate parameters on the residual mechanical properties (Young's modulus and failure strength). Amaro *et al.* (2006) presented the results of a study on carbon-fiber-reinforced epoxy composite in which the residual flexural strength was investigated in terms of different stacking sequence and impact energies. After impact, the specimens were analyzed by ultrasonic C-Scan inspection to obtain the position and the size of the delaminations in the samples. Zhang and Richardson (2007) investigated the low velocity impact induced non-penetration damage in pultruded glass fiber reinforced polyester (GRP) composite materials using an instrumented falling weight impact test machine with a chisel shaped impactor. The characteristics of the impact event, force/time and force/deflection traces were determined. The post impact structural integrity of impacted specimens was evaluated by three point bending tests.

Reyes and Sharma (2010) investigated the low velocity impact behavior of three layer thermoplastic laminates consisting of woven glass fiber and polypropylene for two different fiber volume configurations. The impact damaged plates were tested under four point bend (4 PB) loading conditions. Results showed a reduction in flexural strength and modulus as the impact energy increased. Santiuste *et al.* (2010) focused on an experimental study of flexural after impact behavior of glass/polyester composite beams. The influence of impact energy, beam width, and impactor-nose geometry on the residual flexural strength was evaluated. The residual flexural strength of damaged specimens, evaluated by quasi-static three-point bending tests, was found to depend on the extent of the damage, so that the residual flexural strength was lower in the specimens in which the damage reached the edges of the beam. Cromer (2010) presented a series of low-velocity drop-weight impact tests were conducted on S-2 glass/epoxy samples simply-supported along two edges. The residual compressive strength and flexural properties were measured.

There is a lack of knowledge concerning the flexural residual strength of composite plates. Thus, this work present a new criterion to evaluate the residual strength of laminate composite subject to low-velocity impact loading using flexural testing. For this, a flexure after impact (FAI) test is used alongside the standard compression after impact (CAI) in order to compare its capability as a damage tolerance technique. Low-velocity impact tests and residual strength tests are performed using an instrumented drop-weight machine and static test machine, respectively. The experiments were carried out on laboratory specimens, which are flat and rectangular composite plates. Two different stacking sequence and thickness are tested, in order to analyze the influence of these factors on the impact and post-impact response. The residual flexural strength of damaged specimens is evaluated by quasi-static and four-point bending test. The results of drop-weight impact tests and FAI tests on carbon/epoxy laminates are presented. A new criterion based on a relationship between damage metric and FAI analysis is proposed. Thus, these results are normalized by using the project load and the metrics for damage analyses, *i.e.* if there is no damage in the structure, then the metric returns "zero" value. If the structure is partially damaged then the metric returns a number between one and "zero". Finally, if the structure is totally damaged, then the metric returns a value equal one. Finally, it is discussed the advantages and limitations of this criterion into the context of SHM system (Structural Health Monitoring System).

2. EXPERIMENTAL TESTS

2.1 Material and Specimens

The plates were made of carbon fiber with epoxy resin (Carbon Fiber Reinforced Polymer – CFRP) by filament winding process. This laminate is frequently used in diverse industries, such as the aeronautics, automotive and naval industries, because it has a very good relation between the mechanical properties and weight. Three different types of damage was analyzed, one central hole, another one, an artificial debonding, which was simulated by inserting Teflon tapes within the layers, third one, impact of low-velocity. Table 1 shows the geometric properties, stacking sequence, damage type and energy level of each plate.

Table 1. Composite plates configurations.

Plate ID	Stack Sequence	Damage Type	Impact Energy [J]	Thickness [mm]	Width [mm]	Length [mm]
P01	$[0]_8$	impact	9.5	2.14	245.00	305.00
P02	$[0]_8$	central hole	-	2.13	244.86	305.39
P03	$[0]_8$	impact	9.5	2.15	244.71	305.40
P05	$[0]_8$	impact	9.5	2.15	245.67	304.90
P06	$[0]_8$	impact	9.5	2.13	246.12	304.94
P07	$[0]_8$	-	-	2.15	245.79	305.30
P08	$[0]_8$	-	-	2.13	245.88	303.84
P09	$[0/15/-15/0/15/-15]_s$	impact	19.2	3.30	247.45	306.64
P10	$[0/15/-15/0/15/-15]_s$	impact	19.2	3.36	246.19	305.52
P11	$[0/15/-15/0/15/-15]_s$	impact	19.2	3.43	245.21	305.45
P12	$[0/15/-15/0/15/-15]_s$	impact	19.2	3.41	243.55	305.82
P13	$[0/15/-15/0/15/-15]_s$	-	-	3.37	247.13	306.62
P14	$[0/15/-15/0/15/-15]_s$	-	-	3.29	245.21	304.15
P15	$[0/15/-15/0/15/-15]_s$	delamination	-	3.28	244.87	305.90
P16	$[0/15/-15/0/15/-15]_s$	delamination	-	3.31	244.99	304.27

2.2 Impact tests

This test method covers the damage resistance of multidirectional polymer matrix composite laminated plates subjected to a drop-weight impact event. A flat, rectangular composite plate is subjected to an out-of-plane, concentrated impact using a drop-weight device with a hemispherical impactor. The damage resistance is quantified in terms of the resulting size and type of damage in the specimen.

The drop tower apparatus (Fig. 1(a)) consists of two vertical bars, which guide the falling weight during the test. The test specimens are set at the base of the tower (Fig. 1(b)). The tests have been performed using an aluminum round impactor head with a diameter of 16mm. The round head avoids penetration of the coupon, which would occur if a sharp head were used. A piezoelectric crystal, set between the impactor head and the impactor frame, is used as a load cell for impact force acquisition (Fig. 1(b)). The displacement data have been acquired using a light detector placed at the bottom of the drop tower apparatus, which measures the intensity of a Light Emitting Diode (LED) mounted on the impactor frame. The displacement is set "zero" at the point on the top of the plate, when the impactor touches the specimen for the first time. In this work, the plate specimens have been positioned in a device (Fig. 1(b)). In addition, the impact tests were performed under energy level equal to 9.4J and 19.2J (*c.f.* Tab. 1).

The load cell was plugged on a Kistler^{TM} amplifier (model 5007). This equipment was connected to an acquisition system, which had 11-bit data, with three channels for input and sampling frequency set to 20 kHz. The software was set to recorder samples at 20 kHz frequency and the sample size had 64000 points. The samples were clamped in all borders with a hardened steel fixture assembly.

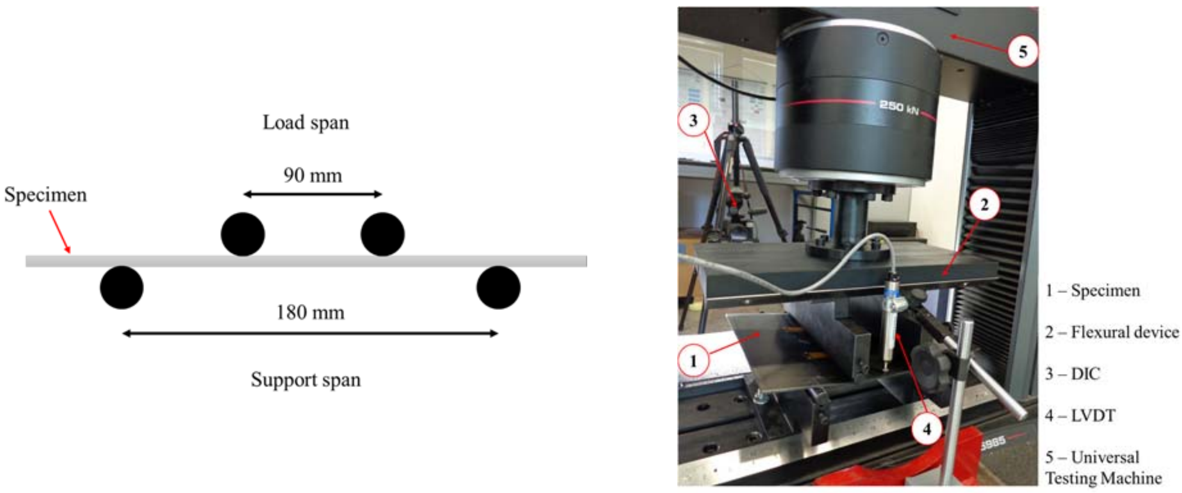
(a) (b)

Figure 1. (a) Experimental set-up of the impact test and (b) test specimen on the basis of the drop tower

2.3 Flexure After Impact tests

The post-impact strength of impacted specimens was evaluated by four-point bending tests under static conditions. The tests were conducted according to the standard ASTM D 6272–10 (ASTM, 2010), since there is no standard to evaluate residual flexural properties. The four-point bending load was applied at a constant cross-head rate of 1.0 mm/min on the specimen impacted side, so that the impacted side underwent a compression stress.

A four-point condition was used so that the maximum axial fiber stress is uniformly distributed over the area between the loading noses, where the damage sites will be situated. This will ensure that the stress path must interact with the damaged material. The tests were performed using a universal testing machine, Instron 5985, with a load cell of 250 kN. The equipment was used to measure load and deflection during four-point flexure. In addition, a LVDT transducers and digital image correlation were used in order to get the deflection of the plate and compare with the universal machine (see Fig. 2(b)). The support span *i.e.* the distance between the supporting cylinders was 180 mm and the load span, *i.e.* the distance between the loading cylinders was 90 mm (see Fig. 2(a)). The span-to-thickness ratio is selected to be 60:1, this large ratio ensures that shear effects are negligible. In order to evaluate the residual flexural strength of the impacted specimens, it was first necessary to know the properties of undamaged and the damaged specimens (*c.f.* Tab. 1).



(a) (b)

Figure 2. (a) Fixture setup for four-point FAI testing and (b) Experimental setup for the flexural test

3. RESULTS AND DISCUSSION

Flexural testing introduces a complex stress pattern in the specimen; therefore, the effect of the damage on residual strength is less easy to analyze (Richardson and Wisheart, 1996). Thus, in order to evaluate the effect of the damage on the laminate composites, the specimens are tested under four-point bending loading conditions. Four-point bend tests are more appropriate than three-point bending in the present study because of several reasons. In three-point bending, the point of load application is at the location of greatest damage and may promote further damage in the specimen. Four-point bending is more suitable for material specimens that experience larger deformation during testing. Figures 3 and 4 show the typical force x displacement curve for all specimens.

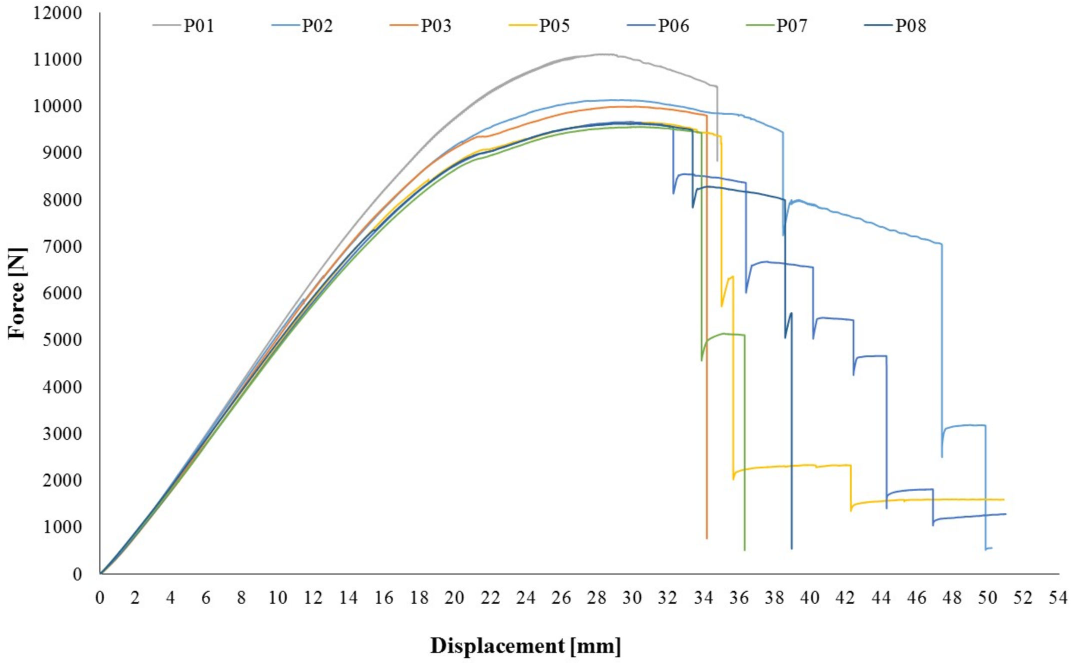


Figure 3. Force *versus* displacement for the specimens with stacking sequence $[0]_8$

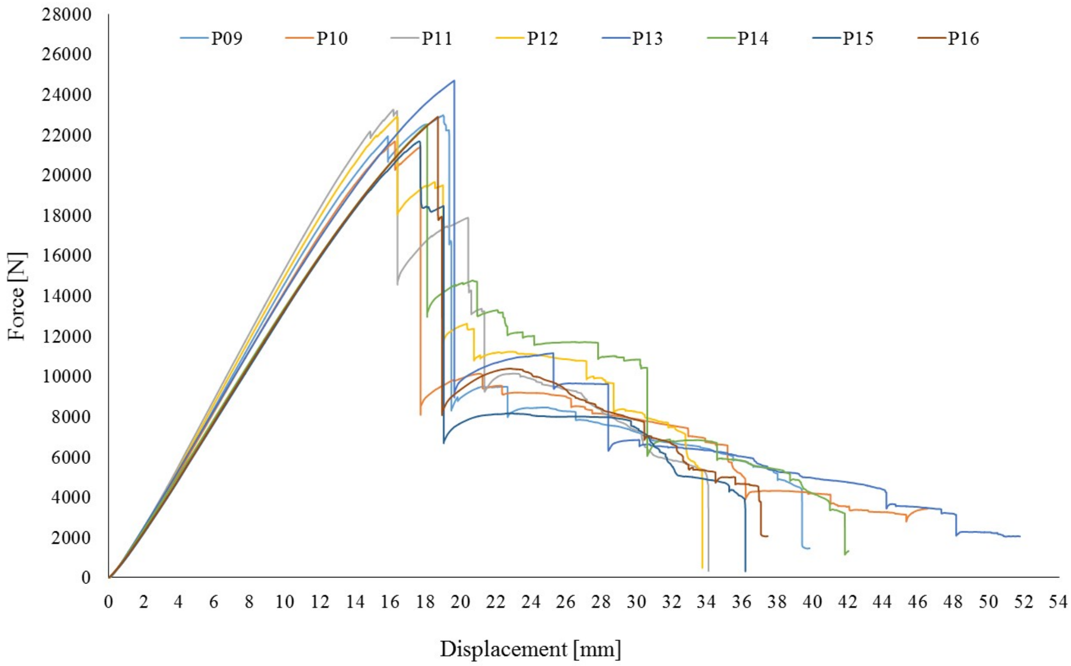


Figure 4. Force *versus* displacement for the specimens with stacking sequence $[0/15/-15/0/15/-15]_s$

Figures 5 and 6 show the moment/inertia *versus* curvature curves of the composites damaged specimens under four-point bending. A new criterion is proposed based on the maximum moment obtained from the undamaged plates. In addition, the two horizontal lines represent the maximum and minimum value allowed. The minimum value was determined dividing the maximum value, for the undamaged plate, by a safe factor (SF) equal to 1.5.

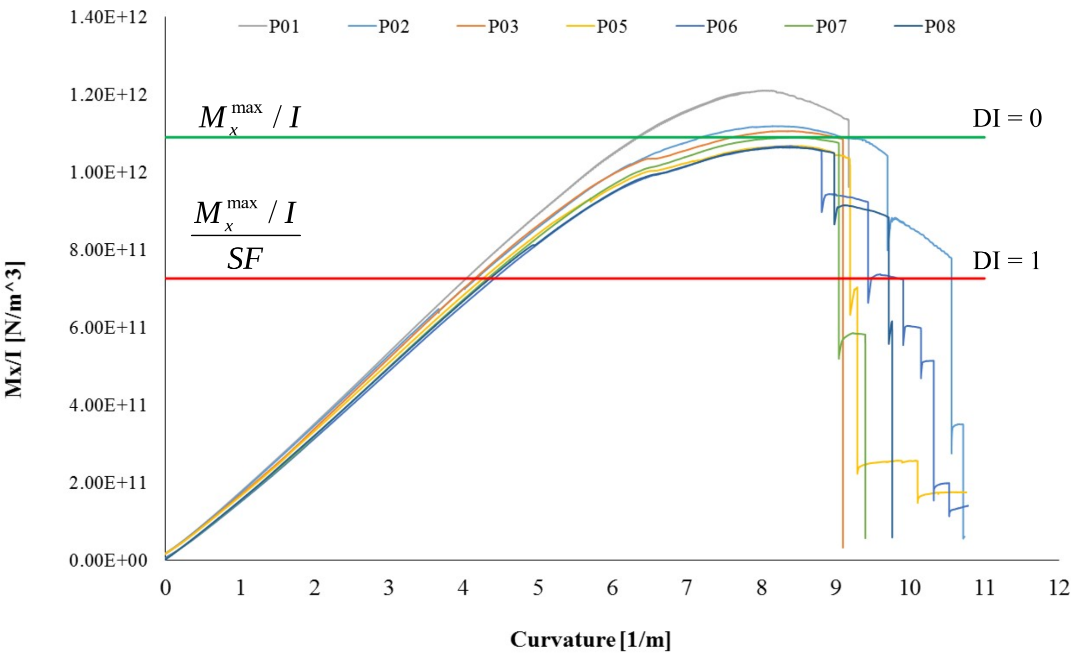


Figure 5. Moment/inertia (M_x/I) *versus* curvature (κ) for the specimens with stacking sequence $[0]_8$

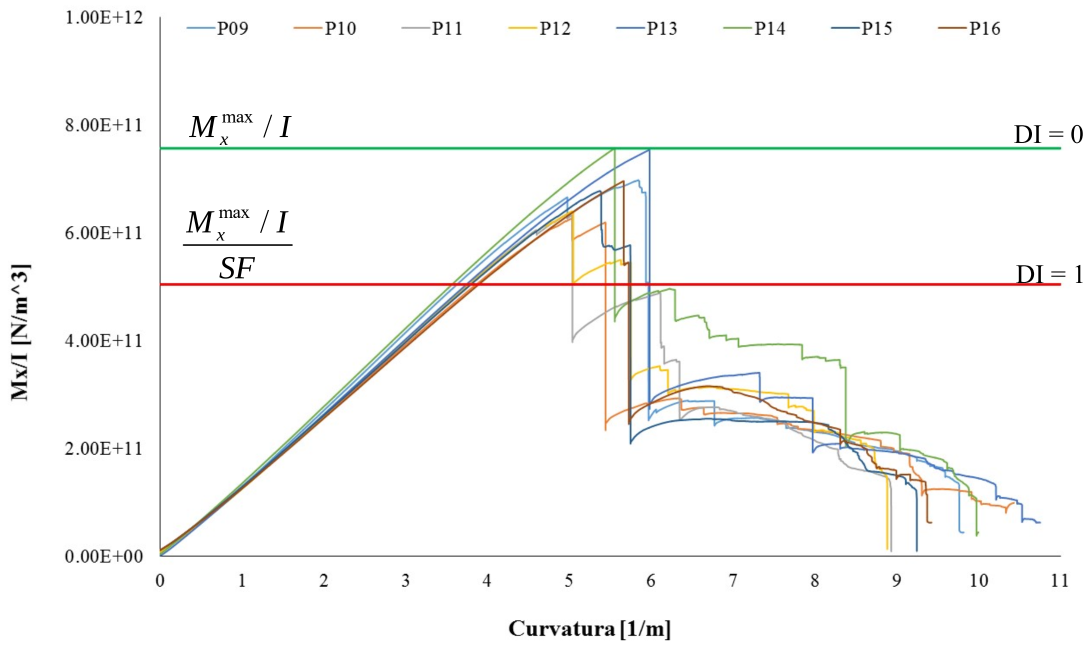


Figure 6. Moment/inertia (M_x/I) *versus* curvature (κ) for the specimens with stacking sequence $[0/15/-15/0/15/-15]_s$

In the Fig. 3, Fig. 4 and Tab. 2. , it is possible to observe that the plates with stacking sequence equal $[0]_8$, due to the stacking orientation the crack, for impact damage parallel the fiber, there are almost no influence on the bending test in the fiber direction. In addition, the higher value for the damaged plates (P01 and P02) can be explained due to the manufacturing process, since these plates showed curvature along the fiber direction.

However, the plates with stacking sequence equal $[0/15/-15/0/15/-15]_s$, presents influence of fiber orientation and type of damage. This fact can be supported by the damage index values. Table 2 shows the maximum moment divided by inertia and the damage index values for each specimen.

Table 2. Damage index considering the safe factor and the maximum moment.

Plate ID	Stack Sequence	Damage Type	M_x^{max} / I [N/m^3]	DI
P01	$[0]_8$	impact	$1.21x10^{12}$	0.000
P02	$[0]_8$	central hole	$1.12x10^{12}$	0.000
P03	$[0]_8$	impact	$1.11x10^{12}$	0.000
P05	$[0]_8$	impact	$1.07x10^{12}$	0.020
P06	$[0]_8$	impact	$1.07x10^{12}$	0.021
P07	$[0]_8$	-	$1.09x10^{12}$	0.000
P08	$[0]_8$	-	$1.06x10^{12}$	0.024
P09	$[0/15/-15/0/15/-15]_s$	impact	$6.98x10^{11}$	0.078
P10	$[0/15/-15/0/15/-15]_s$	impact	$6.27x10^{11}$	0.172
P11	$[0/15/-15/0/15/-15]_s$	impact	$6.34x10^{11}$	0.162
P12	$[0/15/-15/0/15/-15]_s$	impact	$6.40x10^{11}$	0.154
P13	$[0/15/-15/0/15/-15]_s$	-	$7.54x10^{11}$	0.003
P14	$[0/15/-15/0/15/-15]_s$	-	$7.56x10^{11}$	0.000
P15	$[0/15/-15/0/15/-15]_s$	delamination	$6.77x10^{11}$	0.105
P16	$[0/15/-15/0/15/-15]_s$	delamination	$6.96x10^{11}$	0.080

4. CONCLUSION

A series of specimens were damaged using an instrumented low velocity impact machine to introduce non-penetration damage and were then subjected to flexural testing. A new flexure after impact criterion was presented. The analysis showed acceptable results, as expected the stacking sequence $[0°]_8$ showed almost no difference between the undamaged and the damaged structure. However, the stacking sequence [0°/15°/-15°/0°/15°/-15°]s showed some difference between the undamaged and damaged structure. Post impact flexural property testing shows that flexural strength is more sensitive to the presence of localized impact damage than flexural modulus. FAI provides a simple means to test the applicable residual response of a damaged composite structure. Only simple fixtures are required and the nominal test gives both flexural modulus and strength data. It has been shown that the apparent flexural modulus is sensitive to the damage size associated with a particular impact energy level. As a nondestructive test, however, a relationship between the flexural modulus and other residual properties must be established. For this, future works, using the FAI criterion will correlate the damage index, in order to obtain a damage evolution based on the curvature and the moment. Also, it will correlate the damage index provide by the FAI criterion and the damage index provide by the vibration based method.

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