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Failure Criteria Analysis of Laminate Composite Materials

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ABSTRACT

This paper deals with the development of a numerical simulation methodology for estimating damages in laminate composite materials caused by a low-speed impact. Experimental tests were performed on laminate plates reinforced with woven carbon fibers and epoxy resin. Three thickness plates were evaluated. The impact loads were transversal and punctual. Two lamina failure criteria were evaluated. The first is the maximum stress. The second is a proposed modification of the Hashin failure criterion. Four lamina degradation criteria were evaluated too. The numerical contact loads between the plate and impactor were well represented. The numerical damaged areas and lengths were similar or greater than the experimental results.

Keywords : Criterion damage; Failure criteria; Impact; Laminate composite materials; Damage strength.

1 INTRODUCTION

RARELY, damage caused by low velocity impact are detected with the naked eye. Since they cannot be found, the harm caused by low velocity impact in composite materials are considered potentially hazardous. In general, the cracking of the matrix and fiber breakage are the initial damage prior to delamination. The stiffness of the damaged material and therefore the structure can be significantly reduced by damage. This loss of stiffness may even cause a catastrophic failure. For these reasons, it is important to develop tools that enable analysis of structures of composite materials under low velocity impact. The numerical analysis of damage caused by low velocity impact has been made mainly by the finite element method (FEM). Lakshminarayana and murthy, [1]; Luo *et al*. [2] made a dynamic analysis of a structure using a commercial program to predict damage to the material without regard to the progressive failure analysis aid. Zhao and Cho [3] analyzed the onset of damage in a composite material using 8 noded shell elements. Ganapathy and Rao [4] analyzed the damage in a laminated curved shell element using a double curvature of 48 degrees of freedom. Li *et al*. [5,6] presented a numerical model to simulate the process of low velocity impact based on a Mindlin plate element of 9 nodes. Sahli et *al.* [7] presents a dynamic formulation of the boundary element method for stress and failure criterion analyses of anisotropic thin plates. Laminates reinforced polymer composites (RPC) have an excellent combination of stiffness, strength and low weight are very attractive features for the development of structures. The structural efficiency is the ratio between strength and density or between stiffness and density. The reinforced polymeric composite materials may have a high structural

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efficiency compared to the commonly used materials: aluminum alloys, steel or titanium alloys. Another major advantage of RPC laminates is that their anisotropic properties allow the engineer developing the material properties together with the geometric and functional characteristics of the structure. Thus, one can achieve a desired performance, enabling the weight function optimization of the fiber orientation of the laminate and the design load [8]. According Icardi [9], composite laminates are materials that appear as the best candidate for many applications in structural projects. He points out that although these materials are not ductile and possess little strain energy reserves, they are able to dissipate a lot of energy through its various local failure modes.

In this paper, the material properties of laminas used in the bodies of impact tests are characterized. The whole experimental campaign and the data processing method of the low-speed tests are described. Regarding the numerical simulation, the different methodologies and configurations of numerical models are presented.

2 FAILURE CRITERIA

The concept of failure in laminated materials can be classified into three levels: lamina failure criterion, the laminate failure criteria, and the criteria for structural failure. The study of a failure criterion of a lamina defines the possible states of tension in which the failure occurs. When evaluating the failure of the laminate, it is questioned if this occurs when only one of the lamina fails or when all fail. In the latter case, the numerical analysis must consider the progressive failure of the laminas, being necessary to use theories of damaging the lamina.

The last level of failure criterion is structural. The focus of this criterion is the fulfillment of the objective of the structural part in a project. Defines a permissible damage criterion in part designed. The simplest failure theories are the maximum stress criteria and maximum strain [10]. Mendonça [11] reports that the criterion of maximum stress was presented by Jenkins [12]. It is an extension of the maximum stress theory used for isotropic materials. This theory states that the principal stresses of the material should be less than the resistance of strain on their load directions.

Widespread failure criteria assume composite laminas homogeneous, anisotropic and combine the different fault types in a polynomial approximation. The most popular general failure criterion is the quadratic failure criterion of Tsai and Wu [13]. Other popular generalized failure criteria are: Hill, Tsai-Hill and Hoffman. However, the use and interpretation of the Tsai-Wu criterion show some intrinsic problems. The representation of different failure modes in a single approach function is not very consistent. Expressions not physically expected are found, e.g .: fault with dependent traction biaxial loading of compression admissible. Another problem is difficult to characterize the material failure mode. This information is very important for the progressive failure of study laminates. Hashin and Rotem [14] and Hashin [15] founded a new generation of criteria failure, where the various material failure modes are described by individual equations. In this paper, we propose a modification of this criterion for the application in laminates bidirectional tissues.

2.1 Hashin failure criterion modified for enhanced laminas with a bidirectional woven fiber

The Hashin failure criterion was established for the analysis of a reinforced lamina unidirectional fibers. It proposed a change to a better characterization of failure in laminas reinforced with a tissue bi-directional fibers.

First, as fibers are oriented in both directions of this lamina, the failure modes in the fiber and the matrix used by Hashin are replaced by the failure modes 1 and 2 in the direction of the lamina. This failure criterion "Hashin modified" will be used in numerical simulation of this work.

2.2 Failure criteria of a laminate

According to Hinton, Kaddour and Soden [16], evaluation of failure of a laminate subjected to static loads can be made with four different criteria:

1) The occurrence of the first failure of a lamina ("first ply failure").
2) The last resistance to the end of the laminate failure ("last ply failure").
3) The strain response.
4) Other qualitative characteristics.

Whatever the laminate failure criterion, it is necessary that the analysis considers the lamina material, the expected loading conditions and the geometrical factors: direction stacking sequence and thicknesses of the laminae.

2.3 Structural failure criteria

According to Rawlings and Matthews [10], the failure of a structural component occurs at the moment when it can no longer fulfill its function for which it was designed. Hinton and Soden [17] disclose that there is no universal definition of what constitutes a failure of a composite structure.

However, the development in damage prediction area enables a better approach to gauge the possible damage to the laminate structure over its useful life or in manufacturing. When you master a technology to quantify more accurately the intra laminar damage or inter laminar failure due to loads project applicants (impact, fatigue loads and so other factors) it creates an important link to the criteria definition structural failure. As to date there is no comprehensive numerical or analytical methodology, simple and able to quantify the strength and damage tolerance of RPC laminate structure, a project with this material requires generous safety margins in numerical analysis and / or needs experimental results with previous tests [17]. When a structural part has an important function for the safety of its users, or when its good feature is very important for the economic viability of a project, experimental tests with the play itself are required or highly recommended to prove their strength properties and tolerance the damage. The definition of a structural failure criterion for laminated material parts of RPC is extremely important at the beginning of a project. Choosing an inappropriate structural failure criterion may result in a change of the same throughout the product development. As the current numerical tools require a large safety margin, a new structural failure criterion may require rework or even reset a wide campaign of structural tests.

2.4 Lamina degradation criteria

In numerical analysis, it is found after a failure of a lamina, following determination of what property must be degraded through their degradation laws. According to Mathews [10], to date, there is no universally accepted approach of the properties and stiffness reduction factors to be used after the failure of a lamina.

A first degradation model, called D01 assumes that each failure mode causes the complete degradation of the modulus of elasticity in the corresponding loading direction.

A second model, called D02, adds the fault in the modulus of elasticity in the direction 2 and the degradation of the Poisson's ratio as this failure mode occurs. Another reasonable assumption is degrading the modulus of elasticity in the direction 2 when failure occurs in the direction tensile 1. This type of degradation is expected in more unidirectional laminates (the criterion degradation D03).

Whereas the compression failure modes or traction at direction 1 also degrade the modulus of elasticity in the direction 2, is defined as the fourth model D04 degradation.

3 OVERVIEW OF TEST

The purpose of the test developed in this study is more comprehensive. In addition to determining the crack or failure of the plate, seeks to measure the contact forces and damaged areas on the plated with different levels of energy.

The bodies of evidence are square plates with side 350 mm. Plates were assayed laminated with epoxy resin and reinforced with carbon fiber tissue 10, 20 and 30 layers thick (Table 1). Each lamina has a thickness of 0,21 *mm*.

Table 1
Thicknesses of the test plates.

Plate	Thickness
$[0, 90]_{10}$	2.1 *mm*
$[0, 90]_{20}$	4.2 *mm*
$[0, 90]_{30}$	6.3 *mm*

The dimensions of the cylinder and the tip of the impactor shown in Fig. 1 and its masses were measured and shown in Table 2 and Table 3. Initially, tests were conducted to estimate the energy threshold which damaged the plates 10 to 30 layers. Then the test campaign was made with energy impact higher energy threshold of damage to the board.

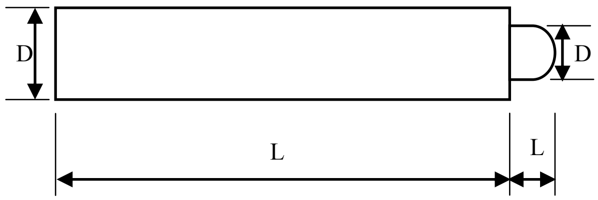

Fig.1
Dimensions of impactor test.

Table 2
Roller cylinder data.

Mass Nominal	Material	Mass (*kg*)	*Lc* (*mm*)	*Dc* (*mm*)
5	Steel	4.92	400	44.77
11	Steel	10.84	801	46.96

Table 3
Point impactor data.

Material	Mass (*kg*)	*Lp* (*mm*)	*Dp* (*mm*)
Steel	0.172	45.45	25.01

4 RESULTS AND ANALYSIS

The results of numerical and experimental testing of low speed impact simulations are presented and analyzed in this section. Initially, we select the most appropriate conditions of the numerical boundary and evaluate the structural flexibility of each plate. The forces acting on the impactor over time (experimental and numerical) are presented and compared. Initially, it is a qualitative analysis of the curves of the forces acting on the impactor 11kg with two failure criteria (Maximum stress and Hashin Modified), and the four types of damage (D01, D02, D03 and D04).
To quantitatively analyze the numerical results, it was necessary to evaluate the parameters that depend on these power curves. They were: the damage initiation of force (F_{th}), the maximum force in the event just (F_{max}), the impact time (T_{imp}) and the return energy of the impactor (E_r). Trend lines of these parameters as a function of impact energy are also drawn for analysis of experimental results. Following the analysis, verifying experimentally the low influence of the mass of the impactor in the damage resistance of the laminated plate to the low speed impacts. Settling the mass of the impactor and the numerical model boundary condition, the forces acting on the plate and damages are obtained numerically using different criteria of failure and damage. These results are presented and compared with the experimental results. For the next energy level E_{th} of each plate are also made comparisons with analytical results.

In this paper, the results of the forces acting on the impactor are normalized in relation to damage initiation forces (F_{th}) of each plate thickness, obtained experimentally. These values are given in Table 4. The lengths of the damage and the damaged areas are also normalized. This normalization was performed with respect to extension values damage $h_{ref.}$ (31 *mm*) and the damage area $A_{dref.}$ (550 mm^2) obtained in the experimental 44*J* impact test with a weight of 11*kg* in plate $[0.90]_{30}$. The experimental results of impacts that cause no damage on the plates $[0,90]_{10}$ and $[0.90]_{30}$ are presented in Table 5 and Table 6 respectively.

Table 4
Strength Values threshold of damage of the plates.

Plate	Experimental F_{th} (*N*)	Analytical solution F_{th} _*a* (*N*)	Numerical solution maximum tension F_{th} _*n* (*N*)	Numerical solution Hashin Modified F_{th} _*n* (*N*)
$[0.90]_{10}$	2200	2018	2830	2820
$[0.90]_{20}$	5750	5708	6080	6080
$[0.90]_{30}$	11000	10486	11620	11620

Table 5
Experimental measurements of V_i, E_i, F_{max}, T_{imp} and $\Delta t_{F=0}$ whose impacts caused no damage to the plate $[0.90]_{10}$.

CDP	*m (kg)*	V_i *(m/s)*	E_i *(J)*	F_{max}/F_{th}	T_{imp} *(ms)*	$\Delta t_{F=0}$ *(ms)*
06-10	5	1.27	4.0	0.66	17.7	0.59
08-10	5	1.71	7.3	0.95	15.8	0.29
06-10	11	0.91	4.6	0.66	26.1	2.54
08-10	11	1.15	7.3	0.98	28.6	2.05

4.1 Evaluation of influence of mass of the impactor

Based upon the results presented in Table 5 and Table 6, the impact energy measured experimentally that caused no damage to the laminated boards with impactors 5 *kg* and 11 *kg* are displayed in Table 7. It is found that, for the same board and the same level of energy, delamination occurs not due to mass change.

All results tested with 11*kg* mass defining, for each plate thickness, a trend line of the damage area (A_d) as a function of impact energy. Comparisons of these trend lines with areas of damage to the experimentally obtained mass 5 *kg* are made in Fig. 2.

Table 6
Experimental measurements of V_i, E_i, F_{max}, T_{imp} and $\Delta t_{F=0}$ whose impacts caused no damage to the plate $[0.90]_{30}$.

CDP	*m (kg)*	V_i *(m/s)*	E_i *(J)*	F_{max}/F_{th}	T_{imp} *(ms)*	$\Delta t_{F=0}$ *(ms)*
06-30	5	3.51	31.35	0.96	5.6	0.10
06-30	11	2.48	34.00	0.94	8.2	0.20

Table 7
Experimental impact energy without the occurrence of delamination.

Plate	*m (kg)*	E_i *(J)*
[0,90]10	5	4.0
	11	4.6
	5	7.3
	11	7.3
[0.90]30	5	31.4
	11	34.0

Based on comparisons of the values of areas of experimental damage A_d, one can conclude that the same energy impacts performed with different masses damage similar areas. Trend lines of experimental results on the F_{max} and E_r plate $[0.90]_{10}$ with all the results tested with 11*kg* mass are compared with those obtained with the 5 *kg* weight in Fig.3 and Fig. 4. Similarity is also observed in these results.

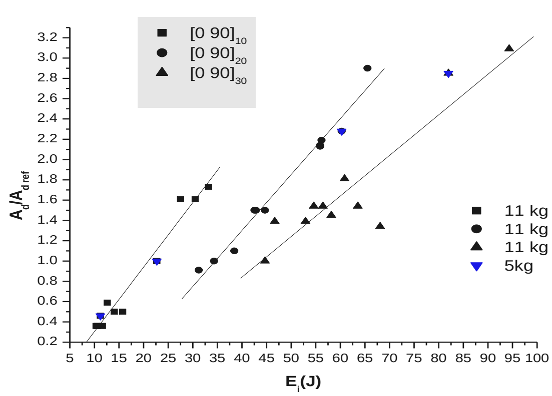

Fig.2
Comparison of experimental damage area with impactors of 5 and 11*kg*.

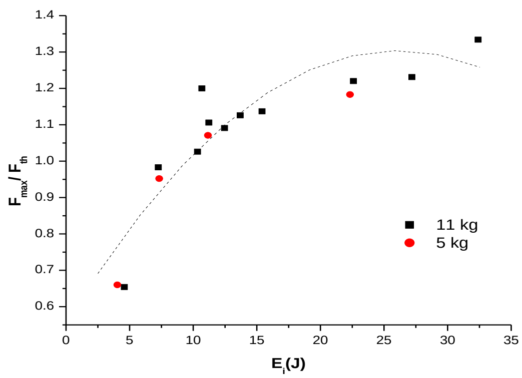

Fig.3
Comparison of F_{max} obtained experimentally with impactors of 5 *kg* and 11 *kg* on plate $[0.90]_{10}$.

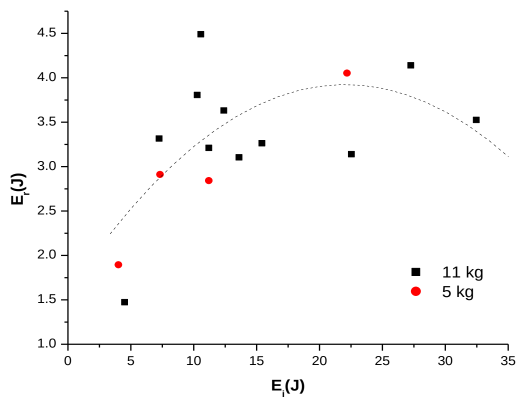

Fig.4
Comparison of E_r obtained experimentally with impactors of 5 *kg* and 11 *kg* on plate.

4.2 Impact time

The impact times of the specimens with higher impact energies E_{th} are shown in Fig. 5. Linear trend curves of these experimental results for each plate are drawn.

It is observed that, for the same impact energy with increasing plate thickness, the impact time decreases. This is because with the increased stiffness of the plate greater forces and accelerations occur. With the increase of impact energy, there is an increased impact time. This is explained by the occurrence of damage on the plate. With the damage, the maximum force response of the plate is limited to a value of F_{th}. It requires a longer time of impact for what the impulse force of the plate can return the impactor. As the F_{th} value increases with the thickness of the plate, the slope of the curves in Fig. 5 decreases as the thickness of the plate increases. As the F_{th} value increases with the thickness of the plate, the slope of the curves in Fig. 5 decreases as the thickness of the plate increases.

It appears that the impact times obtained numerically were good. The differences of the numerical results of T_{imp} compared to the experimental mean values are shown in Fig. 6 to Fig. 8, graphical comparisons are presented.

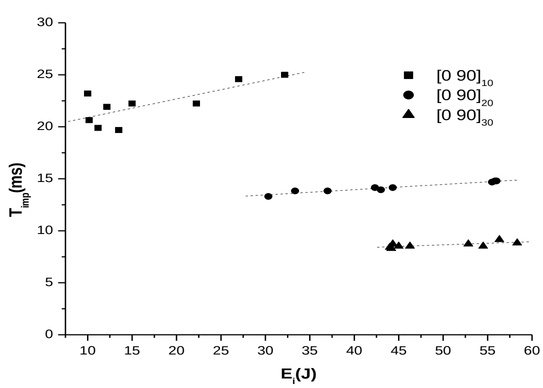

Fig.5
Impact time (T_{imp}) experimental with the impactor $m = 11kg$.

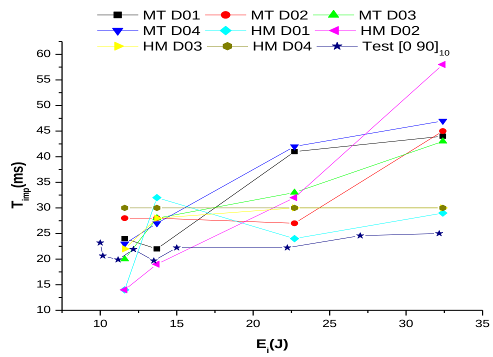

Fig.6
Comparison of time impact T_{imp} numerical and experimental, $[0.90]_{10}$.

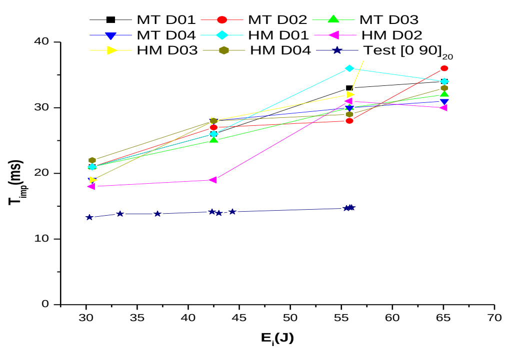

Fig.7
Comparison of time impact T_{imp} numerical and experimental, $[0.90]_{20}$.

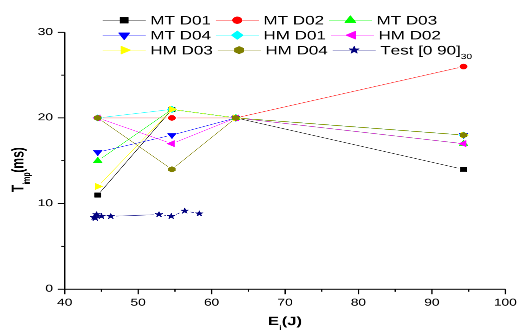

Fig.8
Comparison of time impact T_{imp} numerical and experimental, $[0.90]_{30}$.

4.3 Impactor energy return

The energy return of the impactor E_r is its kinetic energy at the end of their contact with the plate. This energy is a very valuable number to evaluate the response of numerical simulation in relation to the experimental result. A good correlation with this value is a strong indication that the strength of the curves over time should be close. The impactor return speed in the experiment was determined by amount of movement at the time. This value was calculated by subtracting the amount of movement on the impact of beginning by impulse force. This impulse strength was calculated by integrating power over time with the trapezoidal rule using a spreadsheet.

Fig. 9 presents the experimental results of E_r, when they are higher than E_{th}. We drew up a line of results per plate trend. It can be seen that the greater the plate thickness, larger It will be the return energy of the impactor, because the thicker plates are less susceptible to impact damage. Fig. 9 shows that the return energy of the impactor tends to assume a constant value, regardless of the impact energy. Therefore, the greater the impact energy greater it will be the loss of energy of the impactor. This indicates that a lower energy return percentage (E_r / E_i) as the impact energy increased, Fig. 10.

Return energies of numerical simulations and experimental are compared to each plate, in Fig.11, Fig. 12 and Fig. 13. With the exception of numerical simulation with criteria Hashin Modified on plate $[0.90]_{10}$ the numerical solutions tended to have an increased energy return impactor with increasing energy. As the experimental E_r value remained constant, how much the impact energy, higher were the mistakes of E_r values. At the experiment, this return energy difference may be being dispelled by further damage on the plate, or other losses of friction and damping unaccounted for numerical simulations. There is also the possibility of experimentally plate have a higher strain energy or a greater kinetic energy of vibration at the end of contact.

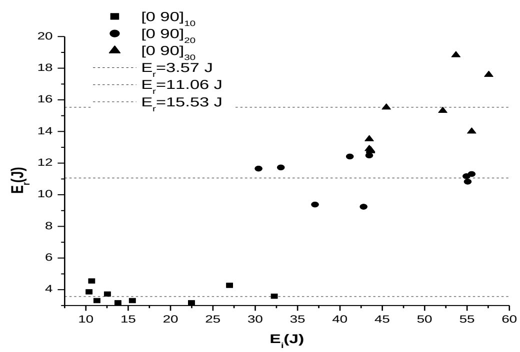

Fig.9
Experimental results of energy return E_r by the impactor 11*kg*.

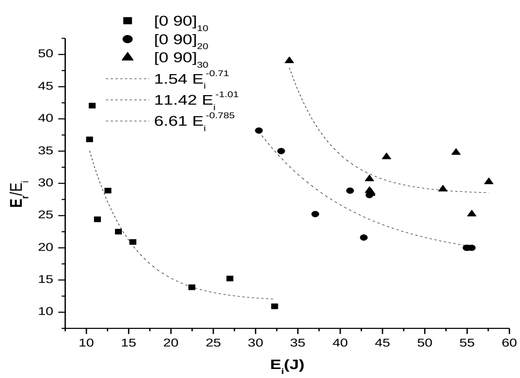

Fig.10
Experimental results of E_r/E_i by the impactor 11*kg*.

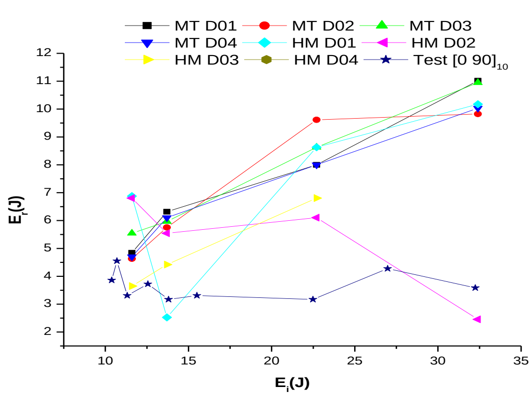

Fig.11
Return power comparison E_r numerical and experimental, $[0.90]_{10}$.

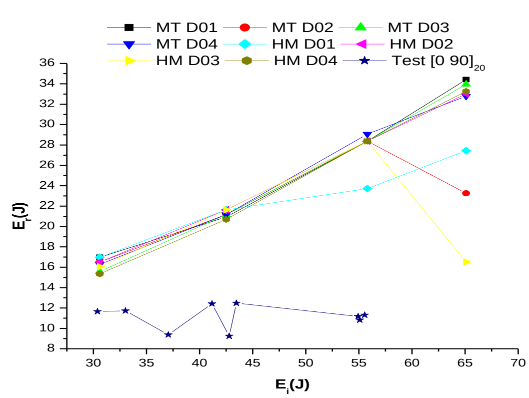

Fig.12
Return power comparison E_r numerical and experimental, $[0.90]_{20}$.

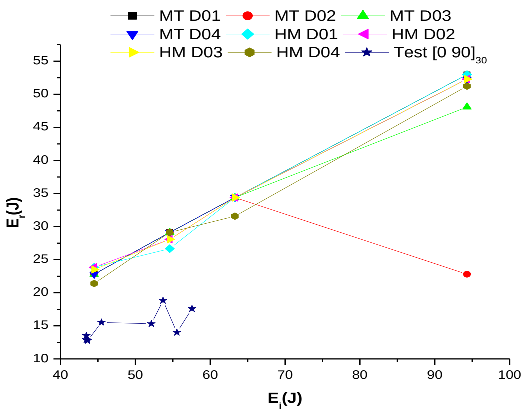

Fig.13
Return power comparison E_r numerical and experimental, $[0.90]_{30}$.

5 CONCLUSIONS

According to the literature review, the numerical models to represent the structural strength of the laminated material usually have limitations to represent its non-linear behavior and complex failure modes of the plate and the laminate.

The numerical method developed to simulate the damage resistance of the laminated plate reinforced with bidirectional woven carbon fiber and epoxy resin showed good results. However, it also showed limitations in its application.

The proper choice of a failure criterion and degradation depend on the thickness of the laminated plate, and the impact energy level that is desired to evaluate. However, the failure criterion based on Hashin theory, with the criterion degradation called D02, were the numerical model that can be used for all thicknesses of plates and all power levels assessed in this study.

The developments of the contact forces between the impactor and the plate over time obtained numerically were satisfactory. In certain cases, excellent results were estimated.

An extrapolation of the results is not recommended, as the failure mode laminate materials may be different. It is suggested the analysis of the failure criteria and degradation studies with other stacking sequences and other impact energy levels.

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