Low Velocity Impact on Polyethilene and Aramidic FRP Laminates

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1. INTRODUCTION

Composite laminates of polymeric matrix present well-known advantages in several respects, but have also some vulnerabilities including weaknesses exhibited under impact loading.

The number of variables involved on studies of impact is high, ranging from the velocity at impact to the shape of the colliding object, the relative stiffness and masses, the location of contact versus geometry and supports of the laminate and, ultimately, the materials, the stacking sequence, environmental conditions and other well known factors like thickness relative to wave length span and attack angle.

The complexity of the problem is increased by the distinct failure modes that may take place. Part of the energy imparted to thin composite plates, for low levels of energy, is consumed on elastic bending and vibrations, while the remaining energy causes inelastic strain and damage. The main failure modes are caused by delamination and matrix cracking although rupture or strength of the fibers may have influence. Kevlar fibers, for instance, are known to be effective on resisting penetration.

The analytical difficulties and the array of interfering parameters advise the generation of experimental test data to understand differences on the behaviour of the laminated plates and to allow analytical modelling e.g. of delamination and dynamic contact deformation.

This paper is restricted to low velocity impact, normal to the surface of laminated plates reinforced either with Kevlar 29 or with Dyneema, i.e. aramidic or tough polyethilene fibers. Factors like stacking sequence, curing conditions, relative mass, stiffness or shape of striker are not examined. The questions addressed report to impacts at speeds not exceeding 5m/s, the main objective of the study being the comparative analysis of the recorded responses and their interpretation associated to the properties of Kevlar and Dyneema.

The interest on low velocity tests stemmed from the need to relate the behaviour of the laminates with impact velocity as a natural sequence of the same effort with ballistic tests (approximately 350m/s) performed with the same materials in a different program.

The paper dwells essentially on macroscopic phenomenology, although the help of micromechanics to interpret results and better the models is viewed as necessary.

Impact tests were performed using a Rosand Precision Impact tester, with a hemi-spherical headed striker indenting the laminated plates at the centre of a circle of 100mm diameter rigidly held by a steel ring. The radius of the ring and the low velocity do not allow neglect of boundary effects and the results cannot be extrapolated for different support conditions. Analytical studies of the interaction of ring and plate would be complex and defeat the purpose of the experimental tests that remain valid as a tool to compare results and failure modes.

A complete search of the literature is not presented since numerous articles can be found on the behaviour and mechanisms of failure of composite laminates subjected to low energy impact especially in the last decade [e.g.l-3J. Abrate [l] surveys the importance of damage on dynamic response and briefly describes models to predict indentation and contact stress laws, experimental techniques and their suitability. Measurement of damage and its accumulation is also mentioned and the threshold of its evidence examined in [2] that argues the importance of the drop off of maximum transmitted force versus deflection on the characterization of tests at low speed and low energy.

The importance of the relative stiffness and inertia of impactor and plates and the insufficiency of the energy of impactor as a characterizing parameter are established in [4] and bear relevance in this study. Chang et al. [5] characterized impact damage of and bear relevance in this study. Chang et al. [5] characterized impact damage of laminated composites for velocities from 2m/s to 30m/s covering a range that exceeds that considered in the present study.

Impact on thermoplastic composites has been addressed for instance by Fukuda et al. [6] who studied the weakening of the elasticity modulus due to cumulative impacts on panel plates.

Cairns and Lagace[7] did significant early work, using kinematic assumptions identical to those of C. T. Sun [8], and suggest simple models to help characterize analytically transient response. They also showed that, whereas plate material properties are important for low velocities, the mass of the striker is a factor when speed reaches higher values, pioneering the recognition that energy level alone is not enough to characterise the phenomenon. The Kevlar plates of their experiments, having lower mass than graphite plates, develops lower contact forces. Also, their smaller bending stiffness permits larger acceleration away from the striker, thus reducing contact time, reinforcing effects linked to its lower transverse stiffness.

Morton and Godwin [9] describe efforts to modify the toughness of the matrix to improve the transverse impact damage tolerance of CFR epoxy composites as well as to reduce processing times.

Plates made out of prepreg epoxy glass fabric were subjected to impact by Hong and Liu [10] and the extent of damaged area was measured and reported, together with other quantities. The authors confirmed the direct relationship between impact energy and delaminated area and that bending effects prevails for low speed impact.

2. TESTS OF PLATES OF KEVLAR 29

The Kevlar 29 laminates were processed with vinyl ester resin, with a curing temperature of 125° C, and eleven plies originating a thickness of 1.8mm. One plate with only six plies was also tested. All tests took place at 18°C. Accumulated damage was analysed by means of sequences of three or five strikes of 1J, 3J or 5J.

Table 1 shows typical results for single strikes with an indenter of m=3.867kg. The maximum deflection of the point under the punch and the corresponding transmitted force and work performed by the applied force is shown. It is seen that an increase of nominal energy from 2J to 10J causes an increase of 1.81 times on the maximum deflection, while a change to 20J causes a deflection 2,26 times larger, i.e. energy dissipation grows rapidly, mostly due to a higher level of damage imposed on the plate. If one looks at the peak of the transmitted force, the same ratios, for the same energy increases, are 3.11 and 4.96. The times for peak deflection to be reached were, respectively, 4.96, 4.02 and 3.54ms and for maximum force 4.12, 3.1 and 2.68ms. The maximum deflection for 2J is indicated as the last reading, since zero velocity had not yet been reached when the indenter was retrieved to avoid multiple collisions. The higher the energy the earlier the deflection reaches a maximum value.

Table 1 - Kevlar 29 plates – Single strikes at different energy levels

Nominal energy(J)	2 J	10 J	20 J
Max. deflection(mm)	3.05	5.68	7.15
Max. Force (N)	1067	3450	3502
Energy at max.(j)	2.00	10.20	20.27
Peak time for defl-(ms)	4.96	4.02	3.54

Time to reach peak values, when these take place before the impactor is automatically arrested sheds some light on behaviour of the laminates. Consider, in addition to values above, e.g. the first hit of nominal 3J on a plate. Maximum value of transmitted force is reached at 4.22ms, equals F_{max}=1.40 kN, when striker is still moving with v=0.33 m/s and deflection is 3.92mm; maximum deflection is reached at t=5.18ms, when F=1.10 kN and was found to be d_{max} 4.08mm. There is, again, a delay from time of maximum transmitted force to that of maximum deflection.

A second strike of 3J in the same point leads to: F_{max} 1.80kN at t=3.12ms, when v=0.391 m/s and d=3.OOmm, whereas d_{max} =3.17mm occurs at t=4.0ms, when F=1.51 kN.

The peak values take place earlier for second strike, maximum deflection occurs later than maximum force and its magnitude decreases.

Table 2 illustrates the effects for each of three repeated strikes of 1 J, for a different plate, at a single point, and the response for one strike of 2J and one strike of 3J on the same plate. The results show, e.g., that first strike deflection (1.95mm) is 20% higher than the response for second hit, while the second and the third deflections differ by only 3%, well within the error expected due to non exact repeatability of tests. Similar results are found at different energy levels. It is advanced that the laminate dissipates energy on a wider area created by previous damage due to the first impact and much less elastic deformation takes place in the second strike, resulting on a smaller deflection.

If the effects of two repeated impacts of 1J, on same point, are added, it is found 3.47mm versus 2.89mm of a single strike of 2J. The addition of three separate impacts of 1J compared with a single 3J hit leads, respectively, to 5.04mm and 3.88mm. The ratios are 1.20 and 1.29, a trend confirmed by other generated data of higher damage caused by "adding strikes" for same total energy.

Fig. 1 shows the deflection of the contact point for Kevlar plates and energies of 1, 3, 10, 20J. The increase of the peak value is clearly recognizable as is the earlier unloading with increase of the nominal energy at impact.

Table 2 - Kevlar Responses after each of 3 strikes of 1J, one of 2J and one of 3J

Nominal energy (J)	1st (1J)	2nd(1J)	3rd(1J)	2J,single	3J, single
Max. deflection (mm)	1.95	1.52	1.57	2.89	3.88
Force at max. (N)	731	937	1010	1109	1399

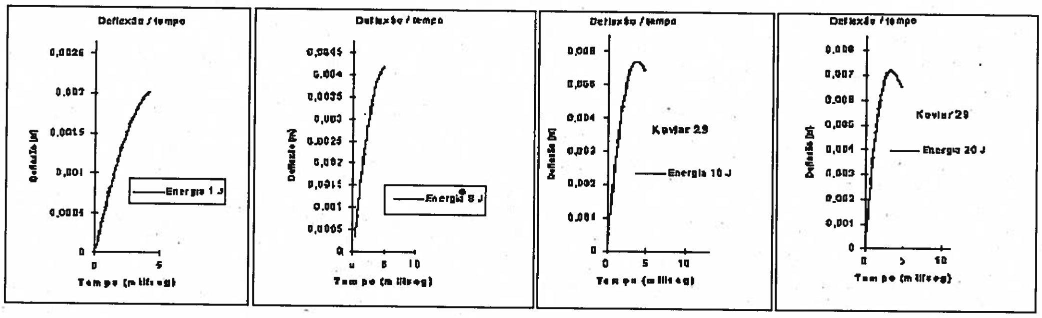


Fig. 1- Maximum deflection for Kevlar plates and energies of 1, 3, 10 and 20J

Fig. 2 shows, in the upper side, the force transmitted for a strike of 1 J, repeated three times, while below it depicts the corresponding deflection under the impactor. One can notice that the first strike imposes larger displacement than the following, even though the corresponding peak forces show a reverse situation.

Fig. 3 relates force and deflection for a 3J impact. The curve locates the point at which there is a sudden change of behavior that is believed to correspond, in general, to the onset of nonlinear damage.

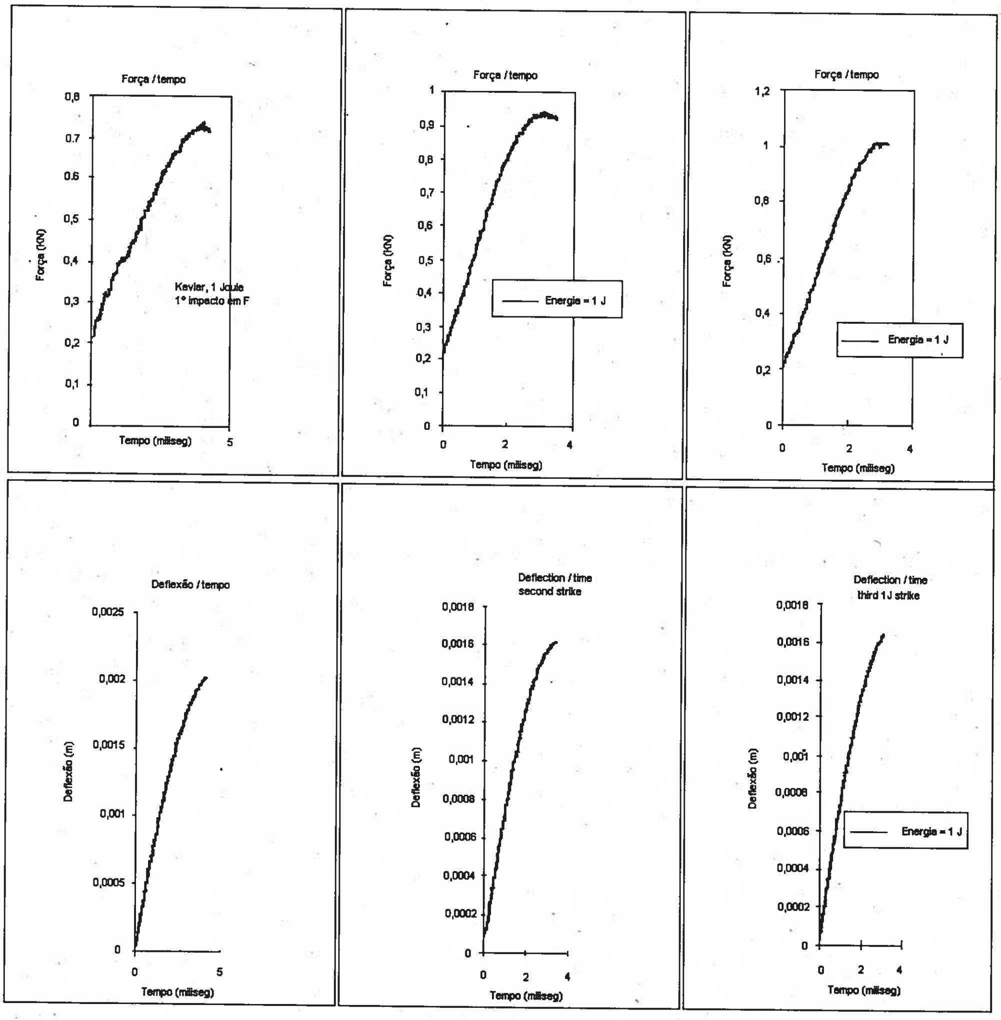


Fig.2 - Deflection and force for repeated strikes of 1J (Kevlar).

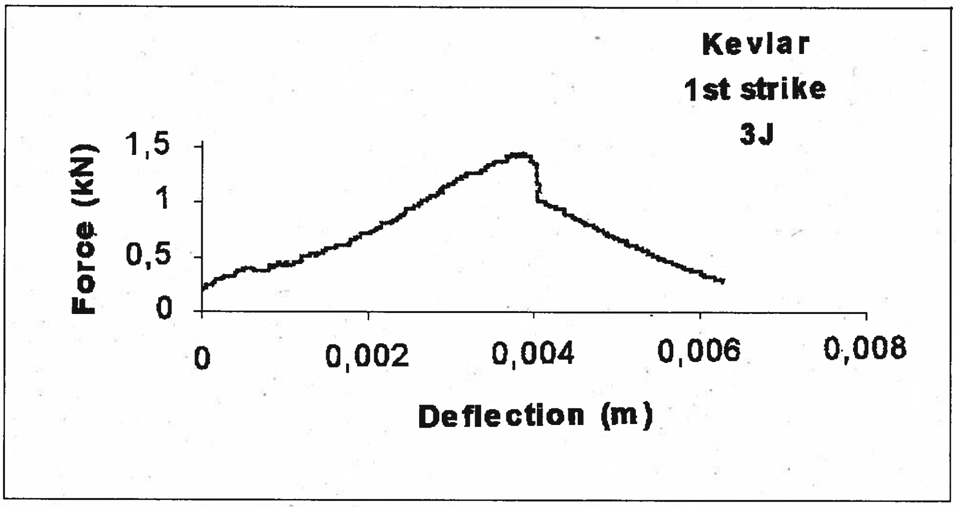


Fig. 3 - Kevlar plate hit with single strike of 3J. Force-deflection curve

3. TESTS OF PLATES OF DYNEEMA

The plates reinforced with high tenacity polyethylene fibers (Dyneema) were processed with eight plies, have a thickness of 1.7mm, areal density of 150g/m2 and were pressed with a thermoplastic stamilex film with a melting temperature of 120°C. The plates tested were cut into rectangles of 200x300mm.

Tensile tests were made in agreement with ISO 527 with some problems deriving from delamination and sliding underneath the jaws of the MTS 100 kN machine used. The averaged results indicated Young modulus, E= 3540MPa, failure stress σ_u=289MPa and strain at failure ε_u= 5.6%.

Depending on thickness of the plate, in general, thermoplastic matrices are associated with significant damage on the tension face, even at low energies, and the strain on that face is believed to control damage initiation. This property is somewhat less evident with Dyneema due to the ductility of the Dyneema matrix, associated with its high toughness. A thermoplastic matrix responds more nonlinearly, causes higher damping and spreads damage into larger regions than corresponding thermosetting matrices.

Fig. 4 shows permanent damage due to strikes at 1J nominal energy, on plate 23-1 of Dyneema. Points on the left side were hit three times at the 1J energy level and reveal larger irreversible damage.

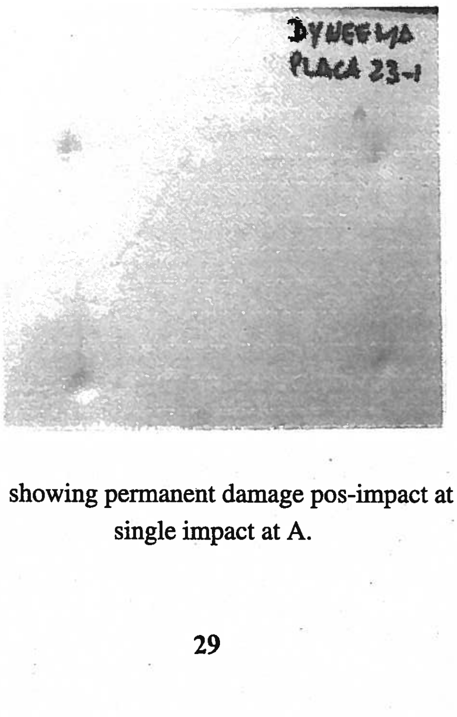


Fig. 4 - Partial picture of plate 23-1 showing permanent damage pos-impact at 1J level. Three impacts at B and single impact at A.

Table 3 summarizes, as with Kevlar 29, the effects of single strikes of increasing energy and shows that the maximum value of the deflection is reached faster for higher energies. It is also seen that the transmitted peak force grows at *softening* rate. For example, for 1J impact, if the "stiffness" - i.e. normalized maximum force divided by deflection- is considered as unit, then it is found 0.81 for 10J and 0.75 for 20J, i.e. this change of *stiffness* with impact energy predicts a softening of the plates when impact energy increases.

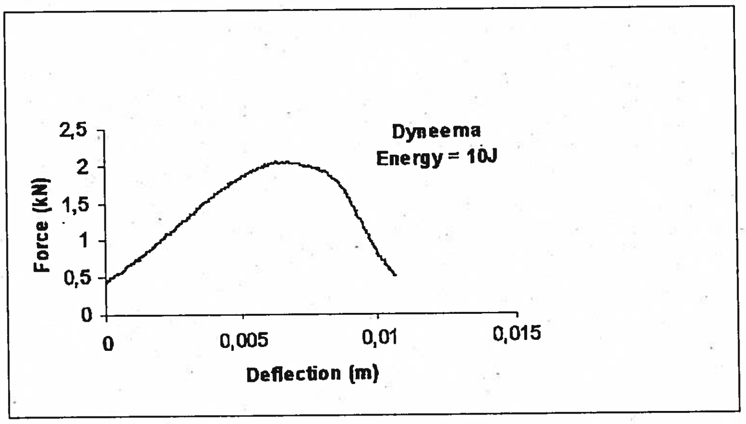
Table 3 - Dyneema plates (22A, 23-2 & 23-2). Single strikes of increasing energy.

Energy (J)	1 J	10 J	20 J
Max. deflection (mm)	1.98	6.20	8.92
Max. force (kN)	0.794	2.010	2.667
Time at max. deflection (ms)	4.26	3.46	2.66

Dyneema plates have high toughness and, in general, tougher resins have a higher glass transition temperature Tg and low viscosity to impregnate more easily the fibers. Those properties are favourable for low velocity impact and add to a much better behaviour under environmental aggression than laminates made of epoxies and aramidic fibers. On the other hand, Dyneema plates suffer pronounced indentation even at lower impact energies, as seen in Fig. 4, hurting the chances to use them without modifying the properties that suit them to ballistic impact.

Fig. 5 shows force versus deflection for 10J and for 1J and contrary to the curves shown for Kevlar 29 no dropoff is seen. However, for repeated strikes of 1J the dropoff pattern appears again as shown in Fig. 6.

Finally, Table 4 shows evolution of maximum deflection after damage caused by previous impacts of 1J, confirming smaller displacements due to higher dissipation after (accumulated) damage.



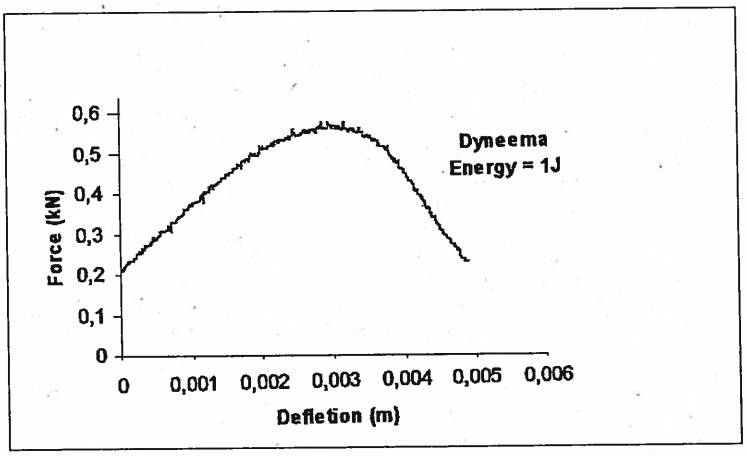


Fig. 5 - Force deflection curves for 1 and IOJ, Dyneema plates

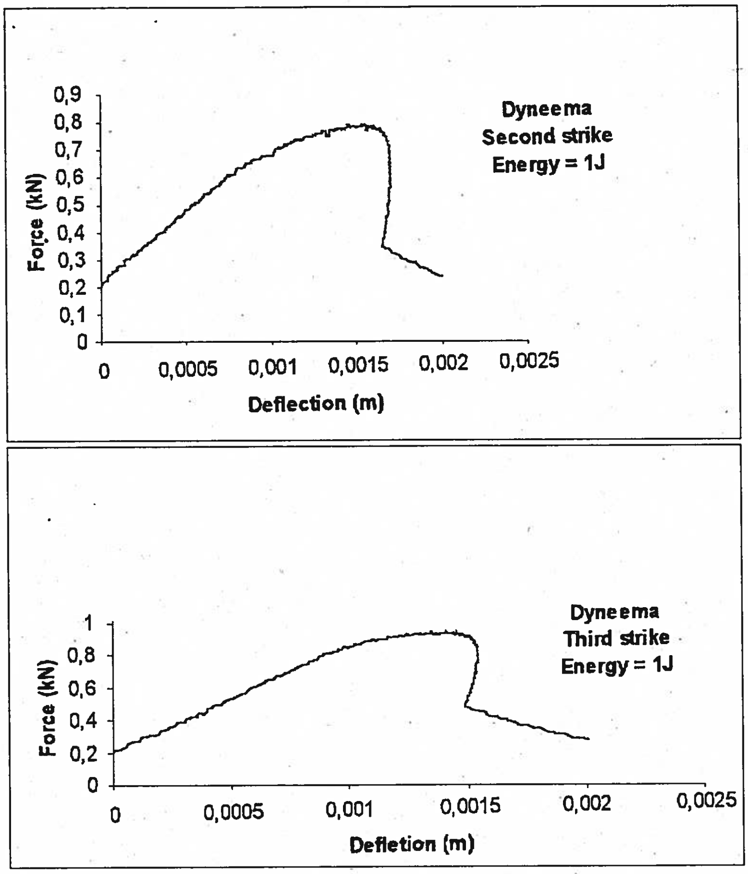


Fig. 6 - Force deflection curves for second and third strike at 1J- Dyneema plates

Table 4 - Peak values for three consecutive strikes of 1J

Strike	1st	2nd	3rd
Max. deflection mm	2.16	1.45	1.40
Max. force (N)	564	770	901

4. CORRELATION OF RESULTS AND CONCLUSIONS

The text has already provided comparison of results obtained, but some additional trends are identified hereafter. Table 5 shows results for Dyneema and Kevlar plates impacted once at 10 and 20J. Transmitted force is considerably higher for Kevlar 29 plates, where peak values appear with some delay with respect to Dyneema material, that exhibits higher damping. First strike deflection is higher for Dyneema plates.

Fig. 7 shows the force transmitted to a Kevlar 29 and a Dyneema plate when hit by the punch animated of an energy of 20J. It can be argued that, despite the curve being a time history, that the representatiôn for Dyneema is typical of a more dissipative behaviour, transmitting smaller force and reaching peak at a later time.

Table 5 - Characteristic Values for Impact on Kevlar and Dyneema Plates at 10 and 20J

Material	Dyneema		Kevlar	
Nominal Energy at impact	20J- (3.19m/s)	10J- (2.26m/s)	20 J- (3.20 m/s)	10 J- (2.27m/s)
Max. deflection (mm)	8.92	6.20	7.15	5.68
Maximum force (N)	2667	2010	5502	3450
Time for peak force(ms)	3.58	3.58	2.68	3.10
Time at max. defl. (ms)	2.66	3.46	3.54	4.02

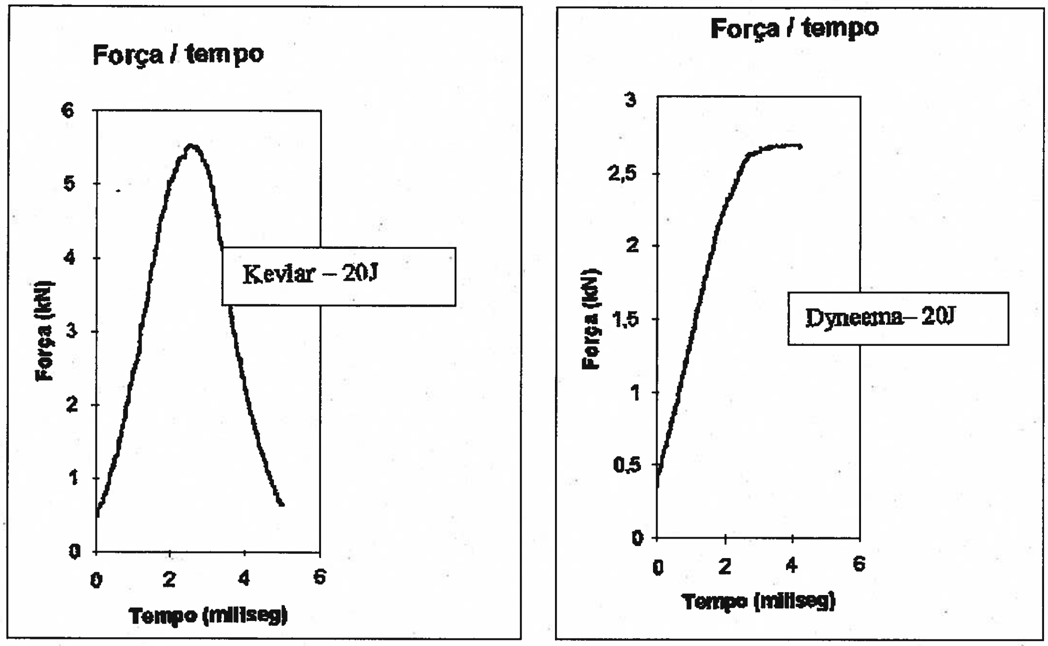


Fig. 7 - Transmitted force, for 20J impact, on Dyneema and on Kevlar plates.

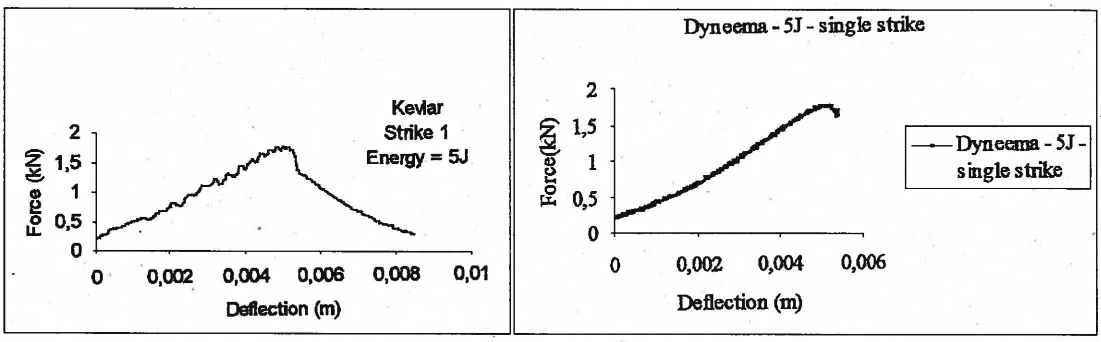


Fig. 8 - Response of Kevlar and Dyneema ptates for SJ

Fig. 8 shows force vs. deflection for SJ and a single strike. The force vs. time peaks at 4.36ms for Dyneema and at 2.42ms for Kevlar, with maximum deflection of 5.4mm reached for Kevlar when the descending branch initiates, at 5.14ms. For Dyneema, the deflection is 5.4mm at 4.86ms and peak force is reached at 4.Oms.

Preliminary conclusions can be summarised. Laminates with lower bending stiffness allow higher "radiation damping" i. e. acceleration away from impactor, reducing impact forces, fact evidenced by Dyneema versus Kevlar. This effect is strengthened for laminates of lower mass, which also exhibit lower contact forces.

Forces transmitted by impactor to plates reach maximum values earlier than the corresponding maximum deflection.

Dissipation of energy in Dyneema plates is achieved through large "plastic" deformation, whereas Kevlar plates deform more locally, facing delamination for higher forces. Damage accumulation shows that first strike deflection is substantially larger than the following and that e.g. one impact of 3nJ is less damaging than n times 3J, for both materials.

It appears that strikes following a first one find material already damaged, thus dissipating most energy and causing smaller elastic displacement.

Incipient damage is more difficult to locate for Dyneema plates that undergo irreversible deformation for low velocity impact. The points corresponding to maximum force are easily detected and a diagram of maximum forces vs. maximum deflections will be analysed as soon as enough tests are available for its generation.

In general, modelling impact requires consideration of indentation, e.g. based on Tan and Sun non-linear Hertz type relations, to describe local effects. Such studies to separate indentation from the remaining displacement due to global response and examine the contact force to compare expected behaviour with data found experimentally will also be undertaken in the future.

Acknowledgement- support of Portuguese Ministry of Defense through Project 2/95 is gratefully acknowledged. Cooperation of colleagues from INEGI (Porto) was also essential and is thanked.

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