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Analysis of impact energy absorption by lightweight aramid structures

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ABSTRACT

This paper presents and analyses the behaviour of aramid composite plates subjected to low and medium impact energies. In order to study the material behaviour under impact loading, experimental tests have been performed using a drop-weight tower and a pneumatic gas gun within the range of impact energies ($20 \leq E_{imp} < 600$ J). The plates are impacted by hemispherical impactor and spherical projectile for drop-weight and impact tests, respectively. The influence of areal density is also evaluated in terms of absorption energy. Energy Profile Diagrams (EPD) are used to identify the penetration and perforation thresholds enabling the definition of the no-penetration, penetration and perforation zones. The results revealed that there is a greater energy absorption capacity in thin plate than in thick plate for low impact energy values. However, areal density is relevant in the energy absorption capacity for high impact energy values.

Keywords:

Aramid composite
Ballistic impact
Drop-weight tests
Areal density
Absorption energy

1. Introduction

Aramid fibers are of great interest due to their low weight, high specific strength and high stiffness compared to other materials such as for example metals. They also have a high energy absorption capacity due to their damage tolerance and failure mechanisms, which provides good ballistic impact performance [1]. Therefore, aramids are widely used in the development of structural impact and associated protective systems in several fields, mainly for personal protections such as combat helmets and vest proofs in military industry.

Another application is related to armored military vehicle subjected to impact [2]. The type of structure for this application consists of two armors: primary and secondary. Primary armor is the exterior protection, whose function is to mitigate the effect of projectile impacts, being made of high strength metals. However, even if the projectile is stopped, debris can appear behind the armor. For that reason, a secondary structure is used behind the primary armor to calm down this effect, known as spall liners. These spall liners are made of high performance fibers such as aramid or ultra-high molecular weight polyethylene (UHMWPE). The spall liners are structures with high capacity of energy absorption. During a ballistic impact event, the target offers resistance to penetration/perforation of the projectile into itself. The incident kinetic energy of the projectile is absorbed by the target through various damage and energy absorbing mechanisms. In other words, energy transfer takes place from the projectile to the target. Thus, energy absorption can be classified into non-penetrating impacts

(referred as low-velocity impacts), and penetrating impacts (referred as high-velocity impacts) [3].

The energy absorption mechanisms in aramid composites are identified as: the compression of the target directly below the projectile, compression in the region surrounding the impact zone, the shear plugging of the projectile into the target, the tensile deformation-tensile failure of yarns/layers of primary and secondary yarns, conical deformation on the back face of the target and the energy absorbed due to delamination, matrix cracking and friction between the moving projectile and the target [4].

In this work, different tests are conducted to analyze the mechanical behavior of aramid composites from low impact energies to medium impact energies. The analysis under low impact energies is carried out in a drop-weight tower, involving higher impactor masses than in ballistic impacts. However, the basic mechanisms for delamination can be also applicable to ballistic impact events [5]. Studies referred to analyze the energy absorption and failure mechanisms under low impact energies have been mainly developed in CFRP and sandwich structures. However, there is a lack of knowledge to address the response of aramid composites at low impact energies using drop-weighted tower. Studies present in scientific literature which analyze the response of aramid composites subjected to low impact energies, have been carried out using reinforced materials such as nanoclay or graphene inclusions [1,6,7]. Reis et al. [1] developed low impact velocity tests on Kevlar/epoxy composite with filled matrix, cork powder and nanoclays. They concluded that the additive used increases the

Fig. 1. Drop-weight testing equipment. (a) Drop-weight tower CEAST Fractovist 6785. (b) Impactor with hemispherical tip of 20 mm diameter. (c) Support fixture.

Table 1
Resume of the drop-weight impact tests.

	Mass (kg)	Impact Velocity (m/s)	Impact Energy (J)
Thin Plates	3.815	3.16	19.54
	3.815	4.37	37.04
	7.815	3.72	55.87
	7.815	4.24	71.59
Thick Plates	7.815	1.58	22.29
	7.815	3.40	46.01
	7.815	4.43	77.86
	13.815	3.61	92.12
	18.815	3.51	119.19
	13.815	4.44	139.51
	18.815	4.02	156.21
	18.815	4.24	173.68

maximum impact load, being that dependence more accused for high impact energies; and that the nanoclay was the additive which presented better results.

Taraghi et al. [6] investigated the low-velocity impact response of woven Kevlar/epoxy laminated composites enhanced with different weight percentages of multi-walled carbon nanotubes under ambient and low temperature conditions. They concluded that the addition of 0.5% multi-walled carbon nanotubes (MWCNTs) may increase in 35% the energy absorption at ambient temperature, while the addition of 0.3% MWCNTs increase the energy absorption capability about 34% at low temperature. Recently, Rahman et al. [7] analyzed the effect of nanoclay and graphene inclusions on the low-velocity impact resistance of Kevlar-epoxy laminated composites. They showed that nanoclay is more effective than graphene in impact resistance and in the absorption of impact energy.

The present work focuses on the analysis of the mechanical behavior at low impact energies of aramid composites subjected to hemispherical impactor, considering two different areal densities (low and high), being their values within the most commonly used range of areal densities in combat helmets. From this study, the energy absorption capacity at low impact energies is analyze.

To complete this energy absorption analysis, impact tests with spherical projectile have been carried out, since it produces the same stress state as the hemispherical impactor in the drop tower tests. In the scientific literature, experimental impact tests with spherical projectile have not been conducted for the analysis of the mechanical behavior of aramid composites, despite of this type of projectile may be considered as a fragment simulant according to STANAG 2920 for the calculation

Fig. 2. Impact testing equipment. (a) Experimental set-up scheme. (b) Gas-gun. (c) Specimen support Fixture.

Table 2
Resume of gas cannon impact tests.

	Impact Velocity (m/s)	Impact Energy (J)
Thin Plates	337	96.53
	350	104.12
	363	112.00
	383	124.69
	408	141.49
	447	169.84
	507	218.49
Thick Plates	579	284.95
	608	314.21
	624	330.97
	633	340.59
	667	378.16
	684	397.68
	714	433.33
	824	577.13

Fig. 3. Perforation of a thick plate impacted by a spherical projectile. Image sequence to measure impact and residual velocities.

Fig. 4. Contact force vs time curves for different impact energies. (a) Thin plates (with 4.43 kg/m² areal density). (b) Thick plates (with 8.86 kg/m² areal density).

Fig. 5. Variation of main impact parameters. (a) Maximum contact force. (b) Contact time.

of ballistic limit or V_{50} velocity [8]. There are fewer experimental drop-tower impact tests than ballistic tests, being remarkable in this last case, the study over combat helmets and plates. Combat helmet tests have been generally performed to study trauma and V_{50} due to impact of ammunition or fragment [9–12]. Plate tests have been useful to

improve the knowledge about mechanical behavior of aramid composites subjected to impact of different projectiles [13–15]. Van Hoof [14] carried out experimental tests using Fragment-Simulated Projectile (FSP) and conical projectiles. It was concluded from this study that the relationship between the maximum backplane displacement and the

Fig. 6. Typical absorbed energy-time curve.

Fig. 8. Comparison between thick and thin plates of the absorbed energy vs impact energy.

impact energy is nearly linear. Silva et al. [15] reported experimental and numerical simulations of ballistic impact on Kevlar®-29/Vynilester laminates (2.4 mm of thickness) impacted with FSP.

The main goal of this work is to study the mechanical behavior of aramid composites in a wide range of impact energies, covering from low to medium values, using spherical impactor geometry. From these results, the Energy Profile Diagram (EPM) can be developed; defining the penetration and perforation limits of the aramid plate. The analysis is complemented by the influence of thickness on the energy absorption capacity, using plates with two different areal densities.

This paper is structured as follows: the introduction is presented in the first section, later on the experimental procedure and equipment are described, then the most significant results for drop-tower tests and impact tests are shown in the third section. The fourth section focuses on the overall analysis of material behavior in the considered range of impact energies. Finally, the main conclusions are described.

Fig. 9. Procedure carried out to measure the damaged area.

Fig. 7. Energy vs time curves for different impact energies. (a) Thin plates (with 4.43 kg/m² areal density) and (b) Thick plates (with 8.86 kg/m² areal density).

Fig. 10. Comparison between thick and thin plates of the damaged area vs impact energy.

2. Experimental procedure

2.1. Material

In this study, a Kevlar Fiber Reinforced Polymer Composite (KFRPC), made of Kevlar 129 fiber (K-129) and polyvinyl butyral resin (PVB), has been used. Plain wave woven fabrics were selected for each layer. The plates were molded using thermoforming manufacturing process.

Laminated composites with two different nominal thicknesses, thin (3.7 mm) and thick (7.4 mm) laminates, were selected. Thick plates have more than 20 layers of prepreg aramid and thin plates have more than 10 layers. The plates were manufactured in a $400 \times 400 \text{ mm}^2$ format and cut by water jet, being the dimensions of the specimens $150 \times 100 \text{ mm}^2$, and the areal density of the thin and thick plates 4.43 kg/m^2 and 8.86 kg/m^2 respectively.

A complete range of impact energies have been studied, using the two most commonly used equipment (drop-weight tower and gas-gun) to analyze the mechanical behavior against impact at low and medium impact energies respectively. In both cases, the impactor used has hemispherical shape.

Using only the drop-weight tower, it would have been impossible to obtain the penetration of the specimens, due to the limitations of the device. Using only the gas cannon, the time evolution of the energy absorbed by the plates could not have been analyzed.

2.2. Drop weight-testing equipment

Low velocity impact tests on Kevlar composite laminates were performed using an instrumented drop-weight tower, INSTRON-CEAST Fractovist 6785 (Fig. 1a). The tests were carried out on specimens of $150 \times 100 \text{ mm}$, with different areal densities 4.43 kg/m^2 and 8.86 kg/m^2 , from now on denominated as thin plates and thick plates respectively.

The impactor is made of stainless steel and has a hemispheric tip of 20 mm diameter (Fig. 1b). All specimens were hit in the middle of the plate with the impactor bar which is free fall accelerated through a guide. The specimen clamping device consists of a solid steel body (stiff enough to ensure that the transmitted force during the impact does not

affect the results) on which the plate is horizontally placed and has a rectangular and centered hole of dimensions $125 \times 75 \text{ mm}^2$. To restrain the specimens during the impact, the samples were centrally positioned over the cut-out with four neoprene tip clamps, as it is shown in Fig. 1c.

The impactor bar was instrumented, registering the contact force during the impact. After the first impact, an anti-rebound system held the impactor to avoid multiple hits on the specimen. Different impact energies, in the range of $E_{imp} \in [20-173] \text{ J}$, were selected for each testing configuration, being all these energies below the one that produces the perforation of the laminate. Tests were carried out at room temperature (20°C), eight energies were tested for thick plates and four in the case of thin plates, resulting in a total of 12 experimental tests resumed in Table 1. All tests were carried out following the ASTM D 7136/d 7136M - 07 standard [16].

Displacement sensors measure the displacement of the striker during the loading and load cell measures the force along time. Data Acquisition System (DAS) acquires the signal coming from striker during the impact and records the impact force value at each time step. Each test provides a record of the load applied to the beam by the impactor. By using this load-time data and assuming the hypothesis of permanent contact between the specimen and the impactor, the displacement of the contact point can be determined by successive integrations (Eqs. (1) and (2)), and from the force-displacement curve, the absorbed energy up to failure is obtained.

$$x(t) = \int_0^t \left[v_0 - \int_0^t \frac{F(t)-P}{m} dt \right] dt \quad (1)$$

$$E(t) = \int_0^t F(t) \left[v_0 - \int_0^t \frac{F(t)-P}{m} dt \right] dt \quad (2)$$

2.3. Gas-gun equipment

Perforation tests were conducted using a pneumatic 7.62 mm caliber gas gun barrel to launch spherical projectiles onto thin and thick aramid composite plates (the impact testing equipment is shown in Fig. 2). Tests were carried out at room temperature (20°C), eight energies were tested for thick plates and seven in the case of thin plates, resulting in a total of 15 experimental tests resumed in Table 2. The maximum velocity of the projectile, denoted as impact velocity V_0 (Table 2), is reached at the end of the tube. Both impact and residual velocities of the projectiles were measured during the impact tests using a Photron FastCam SA-Z digital high-speed camera. In Fig. 3, the procedure followed to measure both velocities is shown.

The aramid composite specimens were clamped along two points in the front and back of specimens; sliding effects is not observed during the test. The tests were conducted using spherical projectiles released at different impact energies, in the range of $E_{imp} \in [96-577] \text{ J}$. The projectiles were made of a maraging steel with a heat treatment to reach a yield stress close to $\bar{\sigma}_y = 2 \text{ GPa}$. The projectile presents a diameter $\phi = 7.5 \text{ mm}$ and a mass of $M_p \approx 1.7 \text{ g}$.

3. Experimental results

3.1. Low impact energies (drop-weight tower)

3.1.1. Contact force and contact time

Contact force curves as a function of time for thin and thick plates are presented in Fig. 4a and 4b respectively. The curves obtained from the drop weight test presented high fluctuations along the loading part of them. These fluctuations appear due to Eigen modes and the progressive damage generated in the specimens. To avoid the influence of these Eigen modes (regular oscillations), a smoothing process has been carried out in the contact force vs time curves within Fig. 4, both for thin and thick plates. Although all traces show the same trend, it can be seen the apparition of some remaining oscillations in the loading part of

(a)

(b)

Fig. 11. Visual inspection for damaged area. Impact energy increase from left to right and from the top to the bottom. (a) Thick plates. (b) Thin plates.

the curve corresponding to $E_{imp} = 19.54$ J (thin plate). In this last case, as the energy is lower than in the rest of the tests, the effects of the impact are less localized, producing a greater local deformation.

In Fig. 4b can be observe that the curve corresponding to $E_{imp} = 22.29$ J is quite different from the others in terms of initial slope, which is due to the fact that the damage produced in the specimen for this case was restricted to the indentation of the impactor, and did not progress to the rest of the specimen.

The maximum contact force (peak load) clearly rise with increasing impact energy for thick plates, except in the case of $E_{imp} = 139.51$ J for which the increasing trend breaks (Fig. 5a) as the impact was not produced in the center of the plate. In the case of thin plates, the maximum contact force remains almost constant for all impact energies tested. As it can be notice, the maximum contact force for an impact energy of 55.87 J is barely higher than for the rest of energies. This is

due to the decentering of the impactor in this particular case. On the other hand, the contact time slightly increase for both types of plates till a limiting value of approximate 20 ms (Fig. 5b).

3.1.2. Absorbed energy

Typical absorbed energy curve as a function of time is shown in Fig. 6, where the different types of energies are defined. The impact energy (E_{imp}) corresponds to the maximum value of the curve. After that, a reduction in the energy occurs reaching a constant value which determine the absorbed energy by the plate (E_{abs}). The difference between impact and absorbed energies define the elastic recovered energy: $E_{rec} = E_{imp} - E_{abs}$.

In Fig. 7 the absorbed energy curves for different impact energies are shown, both for thin and thick plates (Fig. 7a and 7b respectively). In all cases, absorbed energy increases with increasing impact energy,

Fig. 12. Residual velocity V_r versus impact velocity V_0 .

except in the case of thick plate and impact energy of $E_{imp} = 22.29$ J. In this last case almost all the energy is absorbed by the plate and no recovery energy is produced, as the damage is mainly produced by the indentation of the impactor.

In Fig. 8 the comparison between thin and thick plates in terms of absorbed energy is presented, being this variable considered in terms of percentage. This percentage is calculated as the ratio between the absorbed and the impact energy. As it was previously mentioned, the absorbed energy increases with impact energy, being able to adjust it to a logarithmic curve for both areal densities. From this figure, two important aspects can be deduced. On the one hand, the necessary impact

energy for the plate to absorb 100% of it, known as saturation energy (E_{sat}), is higher for thick plates ($E_{sat_thin} \approx 80$ J and $E_{sat_thick} \approx 200$ J). On the other hand, for the same value of impact energy, thin plates absorb a greater amount of energy than thick plates, due to the absorption energy mechanisms involved. For the range of energies studied, the predominant absorption energy mechanisms for thin plates are: the tension by secondary yarns, the delamination and the matrix cracking; while for thick plates, the predominant absorption energy mechanisms are: compression in the region up to which the transverse stress wave travels along the in-plane directions, tension by primary yarns and friction [17].

3.1.3. Damaged area

The damage analysis has been carried out through visual inspection. The methodology followed consists on the measure of the area enclosed by the join of the end points of the creases generated after the impact, as shown in Fig. 9.

Fig. 10 shows the influence of the impact energy on the damaged area, for both areal densities, being this area considered in terms of percentage. This percentage is calculated as the ratio between the damaged area and the total area of the specimen. As it occurred for absorbed energy (Fig. 8), the same trend is observed for both areal densities, following a logarithmic curve.

A direct relation between damaged area and absorbed energy exists, as it can be found between the comparison of Figs. 8 and 10. For a same value of impact energy, both absorbed energy and damaged area are higher in thin plates. Moreover, for the range of impact energies considered, the difference between the damaged area for thin and thick plates remain nearly constant with impact energy. It can be estimated that the threshold impact energy to produce damage in the plate is proportional to the areal density of it.

As mentioned before, damaged area increases with impact energy, as observed in Fig. 11 by means of a visual inspection. It is also observed a common characteristic in all of them: the damage is propagated following always the same directions, 0° , 90° , $\pm 45^\circ$ according to standard [16]. As previously mentioned, the predominant absorption energy mechanisms for thin plates are the tension by secondary yarns,

Fig. 13. Impacted face and side view pictures of damaged specimens.

Fig. 14. Failure modes of the perforation process for the different plates.

the delamination and the matrix cracking, which are less localized failure mechanisms and therefore the damaged area appears to be more irregular.

3.2. Medium impact energies (gas-gun)

3.2.1. Residual velocity

The residual velocity versus impact velocity ($V_r - V_0$) curves for both areal densities are shown in Fig. 12. The ballistic limits (V_{bl}) were found to be 376 m/s and 608 m/s respectively for thin and thick specimens. Comparing the ratio of the ballistic limits with the corresponding areal densities, it is found that $\frac{\rho_{thick}}{\rho_{thin}} = 2 > 1.61 = \frac{v_{bl}^{thick}}{v_{bl}^{thin}}$. This may mean that more impact energy is required to perforate the thin plate compared to the thick plate; therefore, strain rate is a parameter that is playing an important role in the process.

According to Hu et al. [18,19] the mechanical properties of composites change with the strain rate, resulting in an increase of the stiffness and maximum stress. In addition, the out-of-plane compression behavior is more dependent on strain rate than in-plane compressive behavior because matrix compressive deformation is dominant for the

former.

The results shown in Fig. 12 have been fitted via the expression proposed by Recht and Ipson [20] as follows

$$V_r = (V_0^{\kappa} - V_{bl}^{\kappa})^{1/\kappa} \quad (3)$$

where κ is a fitting parameter depending on the projectile shape and describes the trend of the relationship, determined as $\kappa = 2.52$ for the thin plate and $\kappa = 2.32$ for the thick plate. In addition, it is highlighted that the impact velocity tends faster to the $V_r = V_0$ curve (black line in Fig. 12) for thin plates. This indicates the high energy absorption capacity of thick plates.

3.2.2. Failure mode

Due to the specimen geometry and clamping system used, total failure by delamination occurs on all specimens, see Fig. 13. Two zones are found according to literature: primary and secondary [17]. Primary zone is conformed by the yarns located directly below the projectile providing the resistive force to the projectile penetration into the target. The rest of the fibers are considered as secondary fibers and can deform and contribute to energy absorption. According to Reis et al. [1],

Fig. 15. Energy Profile Diagram. (a) Thin plates, (b) Thick plates.

delamination is initiated at the center of impact, and propagated to the directions of warp and fill fibers. In addition, matrix cracking could be occurring.

In order to compare failure modes between thin and thick plates, a cut in the medium cross section of penetrated plates has been performed. The impact event can be divided in different stages depending on the predominant failure mechanisms. The main failure mechanism in the first stage is driven by compression due to the projectile strike on the target. As the projectile penetrates, bulge formation on the back face is formed and delamination is generated along the thickness. Finally, the projectile exits through the back face due to the tensile breakage of the last fibers. The main difference found between thin plates and thick plates is that delamination takes place earlier in thin plates, see Fig. 14. Thick plates absorb more energy in the first stage of compression due to impactor-plate contact. In addition, the absorbed energy due to friction between projectile and target is negligible for thin plates, and remarkable for thick plates.

4. Discussion

The Energy Profile Diagram (EPD) has been developed for aramid fiber composite material subjected to impact loading with hemispheric geometry impactor. The diagram has been obtained for both areal densities, Fig. 15a and 15b for thin and thick plates respectively, presenting three different zones.

Zone I denotes the range of impact energies for which no penetration is produced in the specimen. A portion of the impact energy is absorbed by the material while the remainder corresponds to the elastic recovery energy of the specimen (E_{rec}), producing the striker bounce. This first zone, is bounded above by the perforation threshold of the target; and as it is observed, depends on the areal density of the specimen. For thin and thick plates, the thresholds are approximately 80 J and 200 J respectively. A dependence with the areal density of the plate is observed, being this dependency not proportional. In this region, as no perforation occurs, it is assumed that there is no fiber failure and therefore, the energy absorption is produced through indentation of the striker, matrix cracking and delamination (Fig. 11).

Zone II of the diagrams delimits the impact energy values for which penetration on the plates is produced. In this region the target completely absorbs the impact energy through different failure mechanisms, among which fiber failure appears. Therefore, a linear dependence between absorbed and impact energies can be considered within this region for both areal densities. The upper boundary of zone II, is defined by the ballistic limit of the target, from which it is produced the complete penetration (perforation) of the material. The corresponding values of impact energy, obtained from the tests carried out with the gas cannon, are approximately 120 J and 310 J, for thin and thick plates respectively. A non-proportional dependence with the thickness of the specimen is again observed.

Table 3 shows the approximate penetration and perforation limits for both areal densities. It shows that the relationship between limits is independent with the areal density, being these values close to 55%.

Zone III of the EPD includes the energies for which the perforation of the plates occurs. Once the perforation limit is reached, a percentage of the impact energy is consumed on the deformation and failure of the target, while the remaining energy constitutes the residual kinetic energy of the projectile.

Table 3

Energy penetration and perforation limits for both areal densities.

	Thin	Thick
Energy penetration limit [J]	78	198
Energy perforation limit [J]	121	311
Ratio	1.55	1.57

Fig. 16. Comparison between Energy Profile Diagrams for thick and thin plates.

It should be noted that although the EPD diagram has not been made in the same device, the impactors have the same nose-shape impactor (spherical), so the same failure mechanisms are produced.

In Fig. 16 a comparison of both EPD, for thin and thick plates, is shown. As it is observed, the differences between both areal densities are more pronounced from the point in which perforation limit is reached.

5. Conclusions

In this work an experimental analysis of dynamic response of aramid composites was carried out considering the influence of areal density of the specimens. A wide range of impact energies, covering from low to medium values, was selected. This fact allows to include all situations that could occur in the impact event: no penetration, penetration and perforation of the plate. Low impact energies were obtained by means of a drop-weight impact test, while medium impact energies were obtained using a gas cannon. In both cases the impactor geometry was spherical in order to keep the same stress state.

The main results are resumed in the Energy Profile Diagram (EPD) for both areal densities. From these diagrams two parameters of interest could be observed: penetration limit and perforation limit.

Below the penetration limit (zone I), the absorbed energy for thin plates is greater than for thick plates, increasing with the impact energy in both cases. Additionally, this increment in the absorbed energy corresponds to an increment of the damaged area. In this zone the main failure mechanisms are: tension by secondary yarns, the delamination and the matrix cracking for thin plates, and matrix cracking and delamination for thick plates.

Above the perforation limit (zone III) the trend is reversed, observing a reduction in the absorbed energy while the impact energy increase. In this zone, the absorbed energy for thick plates is much greater than for thin plates for a same value of impact energy.

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