Use of the Split Hopkinson Pressure Bar on Performance Evaluation of Polymer Composites for Ballistic Protection Purposes

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Abstract

This article presents a review of the split Hopkinson pressure bar uses on evaluation of polymer composites ballistic material?s dynamic mechanical properties A small introduction concerning the equipment is given, followed by a summarization of the most recent published studies relating to dynamic compressive tests used to study dynamic properties of ballistic polymeric composites such as Young's modulus,

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Index terms— hopkinson bar, high strain rate, ballistic composites, failure mechanisms.

1 Introduction

esearches on materials applicable to individual ballistic shielding (ballistic helmet and vest), ballistic vehicles and facilities have the great challenge of increasing the resistance to impact and reducing the product weight, being, therefore, an area of great domain of the polymeric composites 1 . The evaluations of the performance of these materials for ballistic armor purposes do not follow the usual standards of characterization of composites, since they are subjected to high strain rates, close to 10 4 s -1 , when they are hit by ammunition of small guns (revolver and pistol), as well as fragments of grenades. The drilling power of such weapons is one of the main threats to individual shielding apparatuses (ballistic helmet and vest) and vehicles 4 . Thus, the mechanical assay to be chosen in order to study the dynamic behavior of a polymeric composite for ballistic protection purposes must be capable of imposing near-to-ballistic impact deformation rates 10 . 1 From this perspective, the dynamic compression test in a split Hopkinson pressure bar has been considered one of the best and most indicated methods for a more detailed evaluation of the dynamic response of polymeric composites for ballistic protection, since it is robust and has a great capacity to achieve uniaxial compression strengths in steady regime of strain rates 11 .

The objective of the present work is to emphasize the importance of the use of the Hopkinson Bar in the evaluation of polymeric composites for ballistic applications. Initially, a brief review of the technical aspects associated with the use of the Hopkinson Bar in dynamic compression tests is presented. Subsequently, the paper presents a review of some recent scientific articles which used this equipment to study dynamic properties of ballistic polymeric composites such as Young's modulus (E), maximum stress (? max), strain at maximum stress (? ?), tenacity (J) and maximum strain (? max), as well as the sensitivity of these properties to changes in the applied strain rate (d? dt).

2 II.

3 Split Hopkinson Pressure Bar

The Split Hopkinson Pressure Bar, or simply Hopkinson Bar, is a mechanical characterization equipment used for dynamic compression tests aiming to investigate the response of a material when subjected to high strain rates (10 2 ? 10 4 ?? ?1) [11][12][13] . The equipment was named after the work of Bertram Hopkinson in 1914, who used a cylindrical bar to experimentally estimate the pressure reached by explosive detonations and ammunition shots 14 . The structure currently in use, however, was conceived by Kolsky in 1949 15 , with some variations, mainly in the propulsion system and in the electronic signal receiving apparatus. In a broad way, it is composed of a gas chamber, an impact or, an incident bar and a transmitter bar. Figure 1 shows a schematic drawing of the equipment, with the names of its main components. In a basic description of its operation, the striker reaches the end of the incident bar driven forward by a large volume of gas suddenly released within the propulsion system.

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for Ballistic Protection Purposes As a consequence of the impact of the striker on the incident bar, a compressive stress wave begins its propagation. This wave, upon reaching the interface between the incident bar and the sample, has part of it reflected (voltage pulse) and the remainder is transmitted through the sample as a compression wave 17 . Strain-gauges are installed at half the length of each of the two bars of the equipment, capturing the vibration coming from the propagation of mechanical waves. An oscilloscope receives the signals captured, passing them on to an amplification system, which generates charts of Voltage (mV) vs. Time (ms). The voltage values as a function of time obtained by the strain-gauges are converted into elastic strain values of the bars. We have, then, ? i (t), ? r (t) and ?t (t) as the elastic strains generated, respectively, by the incident, reflected and transmitted pulse. These values, in turn, are used in a mathematical model to calculate the tension (?), strain (?) and strain rate (??? ????) values which act in the sample; all as a function of time.

The formulations are presented in (1) to (3): ??(??) = ?? ?? ?? ?? ?? ?? (? ?? + ? ?? + ? ??) (1) ?? = ?2?? ?? ?? ?? ? (? ?? + ? ?? + ? ??) ?? 0**(2)**???? ???? = ?2?? ?? ?? ?? (? ?? + ? ?? + ? ??)**(3)**

where ?? ?? is the speed of propagation of mechanical waves in the bar, ?? ?? and ?? ?? are the cross-sectional areas of the bar and sample, and ?? ?? is the modulus of elasticity of the bar material. These equations are known as the three-wave model. These three equations, however, were developed considering some boundary conditions which must be verified so that the values adequately represent the properties of the material. The conditions are the following 11,13,17,20,21 3. The incident bar/sample and sample/transmitter bar interfaces shall be perfectly flat, with full contact between the sample and the bars. 4. The materials of the sample and bars must have close mechanical impedance. This, in turn, is the product between density and the speed of propagation of the material,(4):?? = ????**(4)**

1. The material of the sample cannot be compressible, i.e., the density of the material must not vary with the impact. 2. The test shall take place at stress equilibrium, that is, the stress applied at the incident bar/sample interface shall be convergent with the one generated at the sample/transmitter bar interface. 3. The strain rate to which each sample is subjected must be constant, that is, it cannot vary with the strain of the sample. 4. The sample must have a geometry that minimizes the interfacial friction and inertia effects, since these phenomena generate propagation of bi and/or three-dimensional waves.

Following the conditions outlined above, the mathematical model commonly used presents coherent and reliable results, but there is a natural and acceptable lag between the result obtained by pure application of the theoretical model of one-dimensional wave propagation and the practical result of a dynamic compression test. In the first case, the result would be a pulse of rectangular shape and without oscillations, while the pulse of a test has a trapezoidal profile and oscillations in its plateau (Figure 2). This is due to the propagation of mechanical waves in cylindrical bars being three-dimensional in nature, which implicates the existence of multiple wave frequencies 19,22,23 .

5 III. Application of Hopkinson Bar at Armor Materials

In polymeric composites to be used in ballistic protection, the main fibers used as reinforcements are: glass, aramid and ultra-high molecular weight polyethylene (UHMWPE) 2,3 .

Glass fibers are usually employed in structural polymer composites, whose applications in defense systems are in transportation and constructions susceptible to ballistic impacts and/or wave propagations from explosions, such as bunkers, aircrafts and military vehicles 1,4,5 . Aramid fibers were developed in 1965 and are routinely used in individual ballistic shielding apparatuses (helmets and ballistic vests), and can also be used in collective shielding apparatuses (military vehicles, utilitarian vehicles and facilities), with DuPont (Kevlar ®) and Teijin (Twaron ®) as its main producers [6][7][8] . Ultra high molecular weight polyethylene (UHMWPE) fibers, in turn, were developed in the late 1980s and began to excel in the area of individual ballistic vests during the 1990s 9 . Currently, the prepregs of UHMWPE fibers already dominate individual shielding markets that once were dominated by the aramid fibers, given that they also have high modulus of elasticity and tenacity, but a considerably lower density 3,5 . Its most known producers are DSM (Dyneema ®) and Honeywell (SpectraShield ®). Table 1 compiles the articles addressed in this work, listing the authors of the articles, the composites studied, the processing used and the strain rates imposed to the material.

Govender et al. 37 tested, in a Hopkinson Bar, glass fiber/vinyl ester resin composites, comparing the results of ? max with those of the quasi-static compression test, identifying an increase of 10%. Failure analysis of the samples under optical microscopy indicated delamination, fracture of fibers and fracture plane at 45 o in relation to the longitudinal axis.

Tasdemirci et al. 38 impacted samples of glass fiber/PS composites, evaluating E and ? max to compare the dynamic and quasi-static behaviors, in longitudinal, transverse and across thickness directions. In all of these, the properties cited increased significantly under dynamic assay.

Zainnudin et al. 39 exposed glass fiber/epoxy (pure and nanostructured) composites to interspersed UV radiation/condensation treatments with different durations. The dynamic properties, E and ? max , decreased as the UV/condensation treatment time increased. Compared with equivalent treatment conditions, the nanostructured matrix samples had superior properties than pure matrix composites, under all conditions, which was attributed to better interfacial adhesion, and therefore less delamination in comparison with the other compositions.

Kim et al. 40 produced glass fiber/polyester (pure and CNT) and glass fiber/polyurethane (pure and CNT) composites. Dynamic compression tests were used to compare the impact absorption capacity of each composite, with and without the treated fiber layers, and found that the greatest ? max and J were obtained by the glass fiber/polyurethane/CNT composite.

Arbaoui et al. 41 studied the compressive properties in the plane (fiber-weft direction), E, ? max and ? ? , of glass fiber woven fabric/vinyl ester resin composites, of bi-or three-dimensional woven fabrics. The 3D woven fabric composites showed superior properties at all rates employed, especially for ? max , in which the 2D woven fabric showed a decline in the highest rates employed.

Tarfaoi et al. 42 processed glass fiber/epoxy composites, presenting in a dynamic test a reasonable sensitivity to the increase of d? dt , when displaying greater ? max and J whilst receiving greater impact pressures.

Using high-speed infrared camera, the authors verified that the impact energy was dissipated through matrix rupture, delamination and fiber breakage; mechanisms which became more present as d? dt increased. Researchers Woo and Kim 43 processed aramid/phenolic resin prepregs, which presented, in tests of dynamic compression, sensitivity to small variations of d? dt , with linear growth of ? max (233%) and J (211%). The variable ? ? of the composite, on the other hand, presented a slight reduction (16%) with the increase of d? dt . SEM images and acoustic emission signals indicated matrix rupture, delamination, fiber tearing and rupture as the main failure mechanisms. The researchers concluded that with the increase of the impact energy, the samples presented fragile fractures in greater volume and faster, reducing its strain capacity, justifying the reduction of ? ? . In the subsequent work by the same authors 44 , a hybrid woven fabric composed of carbon fibers (weft) and paraaramid (warp) was used, with the same resin and same fiber/matrix ratio as Woo and Kim 43 . The properties showed sensitivity to variations of d? dt , but more discreet.

The ? max , however, were 1.6x higher than those obtained in the previous study 43 . In addition to all failure mechanisms present in the aramid fiber composite, there was a fragile fracture of the carbon fibers, which contributed to increase the impact resistance of the material, expressed in the increase of ? max .

Chouhan et al. 46 worked with aramid/PP-co-AM (10%) composites, testing samples with different amounts of fabric layers (16, 24 and 30) and therefore different e/d ratios, in order to study the quality of the results obtained in each geometry, observing the best dynamic properties in the 24-layer composite. Kapoor et al. 45 , in turn, tested, at 6 different strain rates, the composite that presented the best conditions in Chouhan et al. 46 , developed equations for the dynamic properties as a function of d? dt and compared the results with those of Woo and Kim 43 . The composite presented second-order growth of J and linear growth of ? ? , therefore greater than the aramid/phenolic resin tested in 43 . The higher impact absorption capacity of the material was associated with the ductility of the thermoplastic matrix and the higher fiber/matrix adhesion ensured by the presence of maleic anhydride.

Bandaru et al. 47 manufactured aramid/PP and aramid/basalt/PP composites, testing all of them on a Hopkinson Bar. The composite of hybrid woven fabric obtained superior results of E and ? max due to higher fiber/matrix adhesion of the basalt/PP composite. The fragility of the basalt, however, made the hybrid composites present a decrease in ? ? with the increase of d? dt , whereas the homogeneous aramid/PP composite showed growth in this value in the same situation, corroborating the results obtained with two-dimensional fabrics 45,46 . Qian et al. 48 tested samples of aramid/PA 6 composite plates, with different fiber/matrix ratios, analyzing the response of each material to the increase in the impact energy, as well as the influence of the variation in the thickness/diameter ratio on the dynamic properties of the material. They concluded that, regardless of the composition, all of them presented sensitivity to d? dt and compositions with higher fiber volume presented higher E and ? max ; and smaller ? max . Chouhan et al. 46 1370-4264 Maleic anhydride was used as a compatibilizer in the polypropylene matrix to increase the fiber/matrix adhesion.

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Bandaru et al. 47 Cao et al. 49 studied mechanical and energy absorption properties of aramid/non-Newtonian fluid by subjecting composites of different fiber/matrix ratios to the same impact energy. Higher percentages of non-Newtonian fluid ensured an increase of E and J, which was attributed to the ability of the matrix to, once it adhered to the fibers, hinder the interlaminar shear and delamination of the composite. Noting this result, He et al. 50 modified the research material using as a matrix a stiffening gel soaked with a non-Newtonian fluid. In comparison to 49 , the values of E did not present significant variations and there was a 10% decrease in J.

Pagnocelli et al. 16 used the dynamic compression test on samples taken from 5 different regions of aramid/vynil-ester ballistic plates in order to verify if the distribution of the matrix through the fabrics occurred homogeneously during processing. The authors used ? max and J in this comparison, verifying that the peripheral regions obtained statistically equal properties, while the central region obtained mechanical property values 20% lower, an event associated to the fact that this region accumulated a larger volume of resin, making it fragile.

Rabbi et al. 51 used the tests in a Hopkinson Bar to compare two aramid/epoxy composites: one flat and one auxetic woven fabric. In both cases, the epoxy resin was impregnated with short Nylon fibers®, to study the dynamic responses of composites with or without short fibers in the matrix. The authors observed that all composites showed an increase in the values of ? max and ? max as a function of d? dt , and this sensitivity was higher for plane aramid/pure epoxy resin fabric composites. For the composite of auxetic fabric, however, the nanostructured resin was more efficient than the pure one. This was due to the greater spacing in the auxetic fabric, with the short fibers being able to penetrate through the fabric and remain oriented along the direction of impact, increasing the strength of the composite.

Shaker et al. 52 tested homogeneous and hybrid composites of several aramid and UHMWPE fibers, all processed with LDPE matrix. The stress-strain and J behaviors were studied by the researchers, who verified that, in all d? dt , the unidirectional/LDPE homogeneous composite CT736

® showed the highest ? max values, while the hybrid composite CT736

® fabric + Artec ® fabric/LDPE presented the best results of J. Shi et al. 53 investigated the energy absorption variation of UHMWPE/LDPE composites by modifying the fiber angulation by rotating the prepreg lamina in relation to the adjacent one. The researchers observed a significant increase in J in multi-oriented fiber composites.

Zhu et al, 55 subjected to dynamic compression tests samples of UHMWPE/polyurethane which underwent hydrothermal treatment. The ? max of samples treated for 12 days increased with d? dt ; the opposite occurred with samples that underwent 24 days of treatment. Effects of matrix plastifying dominated the dynamic compression properties for the first 12 days, while the degradation of the fiber/matrix interface and the expansion of the internal gaps played more important roles in samples that underwent 24-hour treatment.

Asija et al. 56 tested ballistic prepreg Golden Shield ® composites, treated for 4 hours in non-Newtonian fluid, comparing it with the untreated composite. Both had sensitivity to d? dt ; and the treated composite presented steep growth of ? max and J, while the pure composite presented softer growths. The silica nanoparticles present in the fluid, when lodging between the fibers require greater efforts for the occurrence of failure mechanisms such as interlaminar and interfiber shear. The same group 57 , in a subsequent work, used a PP-co-AM polymeric foam film to absorb the non-Newtonian fluid, with further co-processing with GoldShield ® ballistic prepregs. The results in the dynamic compression test of these composites were much lower than in the previous work, since there was no efficient interaction of the non-Newtonian fluid with the UHMWPE fibers, only with the PP-co-AM foam film.

Fin et al. co-processed Tensylon ® and aramid/EVA prepregs in 3 different compositions, in addition to their respective homogeneous composites. Subject to dynamic compression tests, all at the same rate, the composites showed linear growth of ? max and J as a function of the increase of the percentage of Tenylon ® layers; and the homogeneous composite of this material presented, therefore, the most expressive results.

IV.

7 Conclusion

It can be understood from this review that the dynamic compression test in split Hopkinson pressure bar is an efficient method for evaluating the efficiency of ballistic polymeric composites, although there is still limited literature on the subject. Whether comparing it to the quasi-static regime or using several dynamic tests, the authors investigated the effect of an increase in the strain rate (d? dt) in compression properties. The ballistic composites are sensitive to this parameter, presenting Parker and Ramesh 54 used the Hopkinson Bar in UHMWPE/polyurethane composites, Dyneema HB80 ® , processed via compression at different pressures, 1 ksi and 5 ksi. The composite submitted to processing at higher pressure presented higher stiffness, E, and also larger J.

an increase in Maximum Stress (? max) and Tenacity (J). The comparison between articles indicates that composites with thermoplastic matrices tend to have growing properties related to strain (? ? and ?max), while the thermo rigid composites have decreasing properties as higher rates are applied. The authors also sought to observe and understand the several failure mechanisms during impact, and matrix rupture, delamination and fiber rupture were highlighted. [1] [2]

[2]Use of the Split Hopkinson Pressure Bar on performance evaluation of polymer composites for ballistic protection purposes

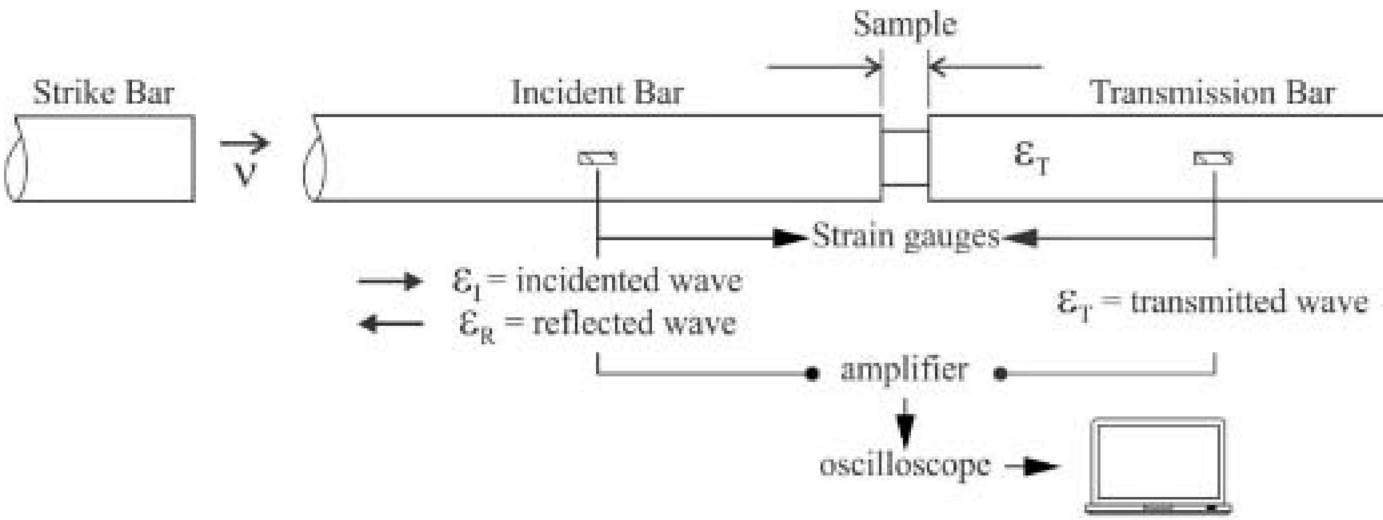

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Figure 1: Figure 1 :

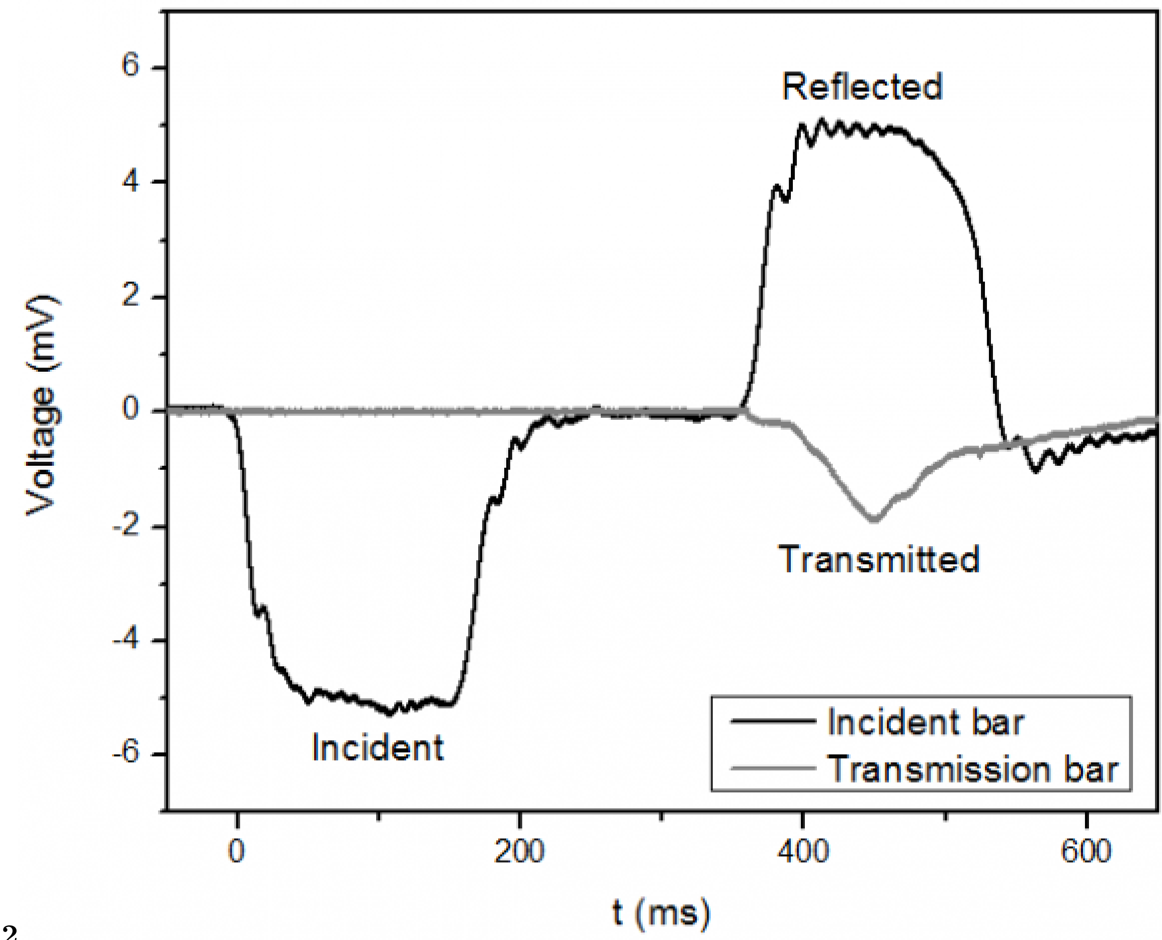

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Figure 2: Figure 2 :

1

Observations	Use of a conical striker to reduce the variation of the strain rate between tests.
Strain Rates (s^{-1})	~520
Processing	RTM
References Composites studied	Govender et al. 37 Plain glass fiber fabric E/vinyl ester (Derakane? 8084)

Figure 3: Table 1 :

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