Characterisation of a Composite Material for ballistic protections

F.J. Ferreira[1], M.A. Vaz[2], F.Q. Melo[3], J. Justo[1]

Summary

An experimental method for materials characterization at high-strain-rate, based on the split Hopkinson bar technique (SHBT), is described. The redesign and instrumentation of the experimental set-up for tension tests are also reported. Experimental results obtained with composite materials test-specimens for ballistic shield applications are also presented and discussed.

Introduction

Nowadays an increasing interest in the development of advanced materials and solutions for personal protection has been reported. The new military strategies are focused in the improvement of personal protection and weight saving equipment. Advanced solutions in the field of composite materials revealed a better compromise for this application and have been used in the construction of helmets, bullet proof jackets and vehicle shields where high performance composite laminate material had lent an important contribution. In this application area it is important to mention Kevlar® composites where the assessment of their mechanical properties is not completely disclosed, given the restricted military area for their applications. It is recognized that this type of composite materials, given their lightweight, good conformability and resistance high energy absorption, are well adapted to meet the requirements they must perform. The implementation of new experimental and numerical methodologies plays a very important role in the characterisation of the dynamic properties and in the assessment of failure criteria.

Materials and Specimen Preparation

Strain rates from 100 s^{-1} up to $5x10^3$ s^{-1} are characteristic of many practical events as high strain rate engineering processes. The majority of available mechanical proprieties of materials were obtained in classical tensile test at very slow strain rate. Optimal designs require precise and complete material data under realistic test conditions, once materials behaviour depends on the strain rates. The Split Hopkinson Pressure Bar (SHPB) device can perform compression tests at strain rates close to 10^3 s^{-1}. In laminate

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[1] - Institute Superior of Engineering of Porto, Inst. Polytechnique of Porto

[2] - Department of Mechanical Engineering and Industrial Management, Univ. of Porto

[3] - Department of Mechanical Engineering, Univ. of Aveiro

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composites the most relevant performance is drawn from tensile tests; alternatively the set-up was adapted to allow this objective at the same strain rates.

Set-up for high strain rate tests

The SHPB device is composed by a gas gun and three lined up cylindrical slender bars; the impactor, which is accelerated by the gas gun strikes the second bar, the input bar and the output bar. The specimen is located between the input and output bars. Both bars are instrumented with strain gages wired in a full bridge circuit. A schematic representation of the set-up is shown in Figure 1.

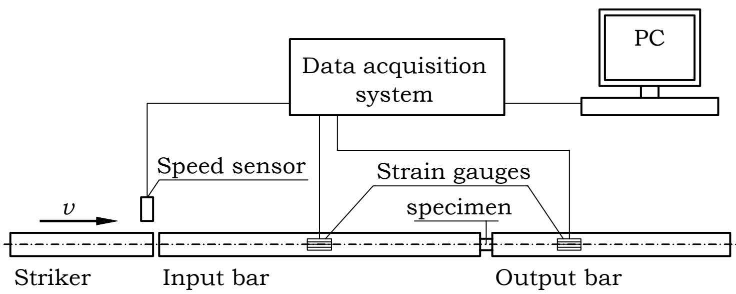

Figure 1: Schematic representation of the experimental set-up.

The input bar strain gages is located at haft length allowing the independent measurement of the longest incident and reflected waves. The output bar is needed to measure the transmitted wave. In tension tests some set-up redesign is needed. Here a tension pulse can be obtained by a tubular impactor striking a bolt head input bar and the specimen fixture withstands tensile loads. The specimen grips must have a smooth cross section area variation for constant mechanical impedance and grip tightly; otherwise a poor design leads to impedance mismatching and spurious wave reflections. The adopted solution shown in Figure 2 with a detail about the grip design for tensile tests, proved to be reliable and efficient.

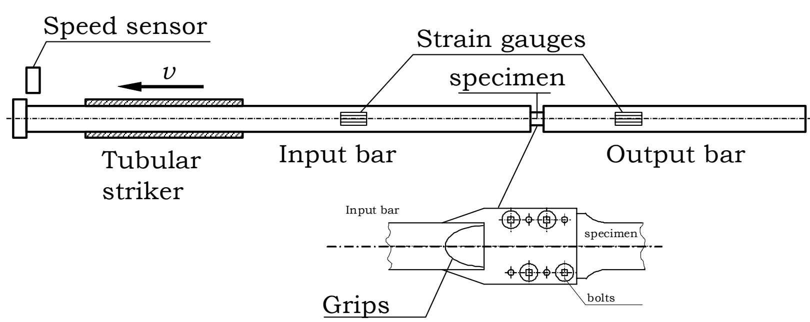

Figure 2: Schematic representation of the experimental set-up for tensile tests and detail of the grips for laminate specimens.

Wave reflections happens in any bar section if the mechanical impedance changes. When the wave front reaches a cross section with a different area, part of the wave begins to reflect, and will continue reflecting until the wave passes through. The grips are part of the bars. The efficiency of the adopted grip design solution is displayed in Figure 3, were the incident pulse is compared with the symmetric of the reflected wave.

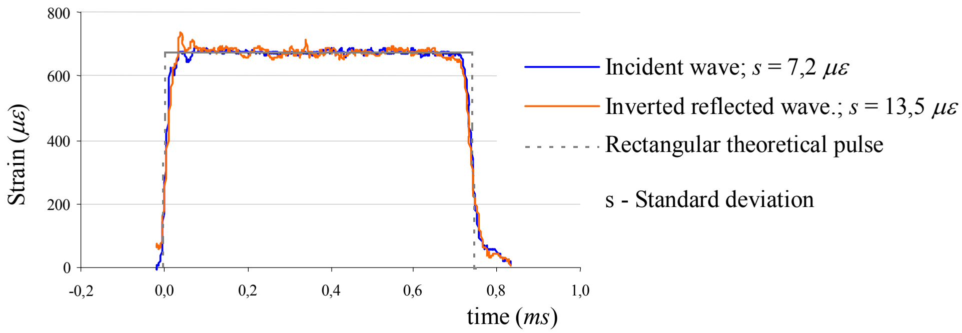

Figure 3: Comparison between incident and symmetric reflected waves.

The specimen strain rate is linearly dependent from the reflected wave amplitude; while the stress linearly depends on the transmitted wave amplitude. The strain rate is calculated from

$$\dot{\varepsilon} = \frac{\mathrm{d}\varepsilon}{\mathrm{dt}} = \frac{\mathrm{V_1(t) - V_2(t)}}{\mathrm{L}}, \tag{1}$$

where V_1 and V_2 are the interface velocities and L is the specimen length. These velocities can be expressed in terms of strain $V_1 = c_0(\varepsilon_I - \varepsilon_R)$ and $V_2 = c_0\varepsilon_T$,. Having integrating the strain rate from *0* to *t* it gives

$$\varepsilon(t) = \frac{c_0}{L}\int_0^t \left[\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)\right] dt \tag{2}$$

The average stress in the specimen can be obtained by

$$\sigma(t) = \frac{F_1(t) + F_2(t)}{2A}, \tag{3}$$

where the forces acting at both interfaces are $F_1 = A_0E_0(\varepsilon_I + \varepsilon_R)$ and $F_2 = A_0E_0\varepsilon_T$. E_0 and A_0 are, respectively, the elastic modulus and the cross-sectional area each bar. For the test specimen equilibrium, $F_1(t) = F_2(t)$ and $\varepsilon_I + \varepsilon_R = \varepsilon_T$, thus:

$$\sigma(t) = E_0\frac{A_0}{A}\varepsilon_T(t)\ , \qquad \dot{\varepsilon}(t) = \frac{-2c_0}{L}\varepsilon_R(t) \qquad \varepsilon(t) = \frac{-2c_0}{L}\int_0^t \varepsilon_R(t)dt \tag{4}$$

The dynamic stress-strain specimen behaviour can be determined on measuring three waves at the elastic bars and shifting them accurately in the time. This is needed as the incident wave is recorded prior reaching the bar/specimen interface while the transmitted/reflect wave pair is recorded after reaching the interface. The strain rate, the stress-strain diagram and the forces acting in specimen interfaces can be obtained from the three recorded waves. In this work a software package, DAVID, developed at l'Ecole Polytechnique, Palaiseau – France was used, Klepasczko & Gary (1998).

The characterisation of the dynamic behaviour of composite materials is different from metals, this ruled by aspects as anisotropy, lack of plastic deformation; delamination and buckling behaviour. Such characteristics determine the specimen design for tension mode using laser cut specimens as depicted in Figure 4.

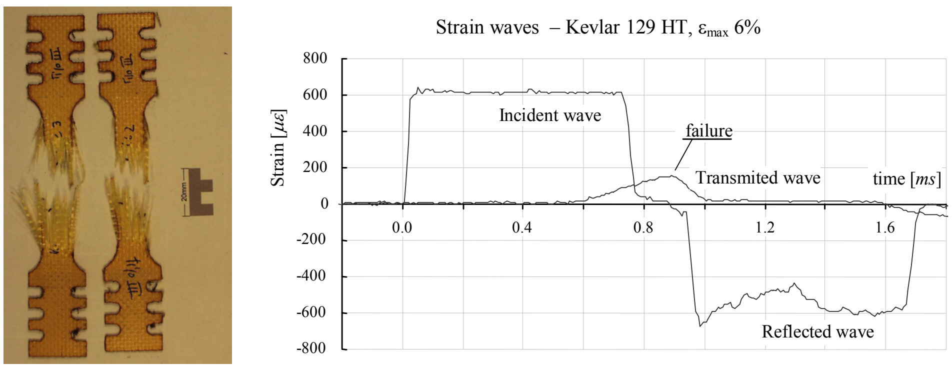

Figure 4: Geometry of a Kevlar® 129 HT specimen after test and recorded signals.

Figure 5 evidences the influence of the deformation rate in the material properties in a tensile test performed at different strain rates. As expected, there is a considerable material hardening depending on the applied strain rate.

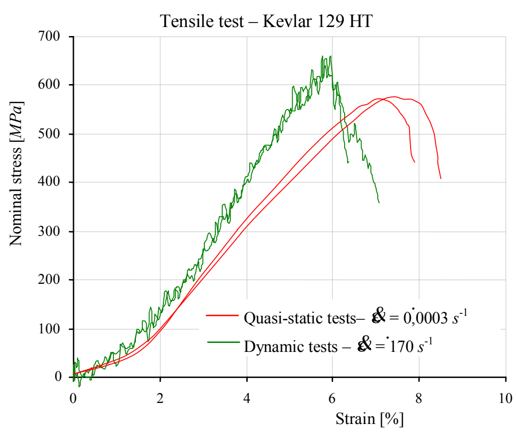

Figure 5: Comparison of stress-strain curves in quasi-static and dynamic condition

Graphical results apply to Kevlar® 129 HT type, an advanced material usual in military application. As shown in previous figure, a typical high frequency noise results from the high gain of the electronic amplifiers used in the set-up. Electronic filtering could be included but would reduce the output bandwidth, impairing useful information.

Conclusions

The SHPB proved to be a powerful method to obtain the stress-strain curves of materials when submitted at high strain rates. It has the advantages of being a quite simple experimental equipment, with direct dynamic calibration of the system from the impactor velocity measurement, and continuous measurement of forces and displacements on both ends of the specimen.

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