Dynamic Characterisation of Composite Materials at High Strain-Rate

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ABSTRACT: This paper describes an experimental method to perform high-strain-rate mechanical tests in materials, based on the split Hopkinson bar technique (SHBT). The experimental set-up was redesigned to perform tension tests in composites specimens and its instrumentation are also presented. Different experimental set-ups for tensile tests are presented and discussed, referring their advantages and limitations. The stress wave propagation in slender bars and some preliminary results obtained with metallic specimens are shown.

1 INTRODUCTION

1.1 The motivation

Current restrictions in pollution emissions and reduction in transportation costs impose new design solutions and advanced materials to build lighter structures. However, this reduction in weight shouldn’t lead to less comfort or security, which is to say the dynamic response of materials and structures should be completely understood to optimise structural behaviour. The implementation of new experimental and numerical methodologies plays a very important role in the characterisation of the dynamic response properties and in the assessment of failure criteria. This is valid for material basic research and also in the complete understanding of mechanical behaviour of structural solutions.

Composites are applied in most high technology structures were impact events occur, e.g. aerospace and ballistic. Experimental dynamic characterisation is fundamental to evaluate the material response under impact loads and in numerical simulation algorithms optimisation.

1.2 State of the art

Strain rates from 100 s\(^{-1}\) up to 5×10\(^3\) s\(^{-1}\) are characteristic of many practical events and engineering processes, such as: explosive forming, blast loading, metal working, structural impact and terminal ballistic. The majority of available mechanical materials properties were obtained in classical tensile test, with very slow rate specimen deformation. Optimal design require’ precise and complete material data under realistic test conditions. It is well know, that materials behaviour is slightly different at high strain rates. The Split Hopkinson Pressure Bar (SHPB) device performs compression tests in materials at strain rates near 10\(^3\) s\(^{-1}\), and is the most commonly used method for this purpose. Other devices, applying SHBT, have been developed in order to allow tensile tests at this strain rates. These set-ups have been applied with relative success in the dynamic characterisation of composites.

2 THE SPLIT HOPKINSON PRESSURE BAR

2.1 Description of the set-up and its operation

The SHPB device was firstly proposed by Kolsky (1949) and updated by many others. Traditionally, the device is composed by a gas gun and three lined up cylindrical slender bars. The first bar, known as impactor, is accelerated by the gas gun and strikes the second bar. The specimen is located between the second and third bars, known as input and output bars respectively. Both are strain gages instrumented wired in full bridge circuit to allow impact stress wave characterisation. Whenever possible, cylindrical shaped specimens should be used. Follansbee (1985) recommended specimen diameter equal or smaller than the bars diameter and having about the same length. A schematic representation of the experimental set-up is shown in Figure 1.

The impact produces an elastic strain wave, the incident wave – \(\varepsilon_i(t)\), that propagates along the input bar. Part of the incident wave will be reflected at the bar/specimen interface going backwards as a reflected wave – \(\varepsilon_R(t)\). The wave going along the output bar is called the transmitted wave – \(\varepsilon_T(t)\).
The bars remain elastic. If the strain induced in
the specimen exceeds the material yield limit, a
plastic deformation is generated. Deformation in
specimen governs the amplitude of reflected and
transmitted waves.

![Figure 1. Schematic representation of the experimental set-up.](image)

The input bar has the strain gages bonded at the
haft length, so that the longest incident and reflect
waves can be measured independently. At the output
bar only one wave is measured, so the strain gages
can be bonded near the specimen and at the same
distance from the free end. This way, a shorter bar
can be used. In Figure 2 a Lagrangian presentation of
the wave history is shown.

![Figure 2. Lagrangian diagram of the three waves history on
SHPB](image)

Meyers (1994) and Nicholas (1984) proposed a
similar set-up to perform tension tests. However,
several difficulties have to be overtaken to generate a
tension pulse and to obtain the specimen fixture, as
discussed in Section 3. Torsional bar apparatus can
also be constructed to study dynamic shear behav-

A tension pulse can be obtained by a tubular im-
parator striking a bolt head input bar or by reflection
of a compress pulse at a free end, Meyers (1994). In
what refers the specimen fixture, a bad design of the
gripes leads to impedance mismatching and spurious
wave reflections.

### 2.2 The governing equations

When the specimen is being deforming, the strain
rate within the specimen is linearly dependent from
the amplitude of the reflected wave. On the other
hand, the stress is linearly dependent from the am-
plitude of the transmitted wave. These two recorded
signals can be used to calculate the dynamic stress-
strain curve. The strain rate $\dot{\varepsilon}$ is calculated as

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

where $V_1$ and $V_2$ are the interface velocities and $L$
the specimen length. These velocities can be ex-
pressed in terms of strain $V_1=c_0(\varepsilon_I-\varepsilon_R)$ and $V_2=c_0\varepsilon_T$,
obtaining

$$\dot{\varepsilon}(t) = \frac{c_0}{L}\left[\varepsilon_I(t)-\varepsilon_R(t)-\varepsilon_T(t)\right].$$  \hspace{1cm} (2)

The strain is found by integrating the strain rate
from $0$ to $t$,

$$\varepsilon(t) = \frac{c_0}{L}\int_0^t \left[\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)\right] dt.$$  \hspace{1cm} (3)

The average stress in the specimen can be ob-
tained by

$$\sigma(t) = \frac{F_1(t) + F_2(t)}{2A},$$  \hspace{1cm} (4)

where the forces acting at the two interfaces are
$F_1=A_0E_0(\varepsilon_I+\varepsilon_R)$ and $F_2=A_0E_0\varepsilon_T$. In these expressions,
$E_0$ is the elastic modulus and $A_0$ is the cross-
sectional area of the bars. For equilibrium at test
specimen, $F_1(t) = F_2(t)$ and $\varepsilon_I + \varepsilon_R = \varepsilon_T$, thus:

$$\sigma(t) = E_0 \frac{A_0}{A} \varepsilon_T(t),$$  \hspace{1cm} (5)

$$\dot{\varepsilon}(t) = -\frac{2c_0}{L} \varepsilon_R(t),$$  \hspace{1cm} (6)

$$\varepsilon(t) = \frac{-2c_0}{L} \int_0^t \varepsilon_R(t) dt.$$  \hspace{1cm} (7)

Thus, the dynamic stress-strain behaviour of the
specimen can be determined by the measurement of
the three waves at elastic pressure bars.

The main difficulty in this process is to shift the
three waves in time with good accuracy. This shift-
ing is needed because the incident wave is recorded
prior reaching the bar/specimen interface and the
transmitted/reflect wave pair is recorded after
reaching the interface, as shown in Figure 2. Fur-
thermore, as reported by Follansbee (1985) and Gary
(1997), a small separation of 25$\mu$m between the
specimen and the bar, caused by roughness or lack of
accurate positioning, even at particle velocities about
10m/s in bar, will require 2.5$\mu$s for firm contact
bar/specimen and specimen/bar. This delay is not
negligible and can change the timing relation be-
tween the reflected and transmitted waves.

The strain rate, the stress-strain diagram and the
forces acting in specimen interfaces can be obtained
from the three recorded waves. Data processing
software can be developed to perform these calcu-
lation. In this work a software package, DAVID, de-
veloped at l’École Polytechnique, Palaiseau – France was used, Klepasczko & Gary (1998).

The most common way to display the results is in a dynamic stress-strain diagram. This diagram exhibits different curves at growing strain rates. An alternate way of display high strain rate data is in a stress vs log strain rate diagram for fixed values of strain. However, the most important data concerning the material dynamic behaviour is its yield strain at different strain rates. This property is of particular importance at high speed metal working fabrication processes.

2.3 Set-up and Software

During this work a SHPB set-up was designed and constructed at LOME facilities. This set-up includes two steel 18mm diameter bars and a gas gun equipped with a pneumatic valve. Electronic equipment allows the measurement of the impact velocity and dynamic strain in both bars. Signal conditioning and wide band amplification is also provided by adequate equipment. A Gage PCI card assembled in a PC bus is used to record the signal at 1 MHz sample rate.

The DAVID data processing software, uses the experimental data array to compute the strain rate, the stress-strain diagram and the forces acting in specimen interfaces. This software also works in tension tests as well. Figure 3 shows the three recorded wave signal and the computed stress-strain curve obtained for a 10mm diameter specimen of brass.

3 THE SPLIT HOPKINSON TENSION BAR

3.1 Set-ups for tension

Wave reflections happens in any section where mechanical impedance change in bar occur. The impedance is defined as

\[ Z = Ap c_0 , \]

and for a single material slender bar it depends only on the cross section area.

When the wave front reaches a cross section with a different area value, part of the wave begins to reflect, and will continue reflecting until the wave passes through. If two different areas are located near each other, part of the wave is trapped between them with many forward and backward propagation.

The main problems in set-ups for tension are how to fix the specimen without generating reflections in wave propagation and how to generate traction pulses. The use of grips without impedance match generates many reflections in wave propagation. Using a solid input bar and a hollow tube output bar, it is possible to perform tension tests using compressive pulse, Lindholm & Yeakley (1968). The specimen has a complex top-hat geometry for this purpose, as shown in Figure 4, very easy to obtain in metals but not recommended for composites. The test is conducted in the same manner as a compressive test.

An other way to perform a tension test consists in directly generate a traction pulse in the input bar, as shown in Figure 5. A longer bolt head input bar is used to drive a hollow tube impactor, with the same inner diameter and area.

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**Figure 3.** Strain waves recording and stress-strain diagram obtained for a brass specimen.

**Figure 4.** Specimen configuration for tensile tests, with hollow tube output bar.

**Figure 5.** Impactor and input bar configuration for direct tension pulse.
In this processes it is necessary to fix the specimen on both bars, usually threads are used for metals. However, for composites, different types of grips have been attempted.

When generated by a tubular impactor, the incident wave has not a smooth rectangular pulse shape. To overcome this limitation, a different set-up, shown in Figure 6, was proposed by Nicholas (1981). The threaded tensile specimen is fixed between two bars and a split shoulder or collar is pleased around it. The specimen is bolted until the bars are snug against the collar, in order to provide that the specimen only responds at traction solicitation and the collar only at compression.

When a regular impactor generates a compression pulse in a longer output bar, part of the wave propagates through the collar and part reflects. No damage occurs in specimen, because the thread slackness. When the wave reaches the free end of the input bar it reflects as a tension wave; this is the incident wave – $\varepsilon_I(t)$ that will be recorded at strain gage 1. The specimen will be dynamic stressed, the collar is unable to support any tensile load, part of the incident wave will be reflected at the interface, going back as reflected wave – $\varepsilon_R(t)$ and part goes along the output bar as transmitted wave – $\varepsilon_T(t)$ and recorded in strain gage 2.

### 3.2 Set-ups for tension in composites

Composites dynamic behaviour characterisation is quite different from metals, as anisotropy, lack of plastic deformation, delamination and buckling behaviour are just same aspects that regulate the main applications of composite materials.

The relevant characteristics are to be taken in tension mode, so two problems has to be solved, the tension wave generation that can be performed as described above and a quite more complicate: the test specimen fixing.

To fix composite specimens at bar ends the author has been developing a specific grip design, as shown in Figure 7. To provide a good impedance matching, the cross section has a constant area value. To prevent damage at specimen surfaces, eliminate peak stresses values caused by compressive forces and improve a better adherence with bars, a special material attenuator film is used.

The grips are part of the bars. The bar ends have a conic thread and are diametrically splitted by a slit where the specimen is inserted. A compression ring with a outer diameter large enough to compensate the area loss caused by the slit, is thread at bar to fix the specimen.

### 3.3 Specimen shape

The SHBT requires impedance matching between specimen and bars. A set-up is designed specifically for a material and specimen size and the grips design required a specimen shape. Composite materials have no plastic deformation but some of them have high elastic deformation prior breakdown and specimens need to be quite long to be representative, so a long pulse wave – $\varepsilon_I(t)$ has to be generated. The set-up proposed is made from 25 mm diameter aluminium bars and designed for specimens up to 1 mm thick, from 10 up to 20 mm large and from 20 up to 50 mm long.

It is also possible to perform tests in necked specimens aiming notch stress concentration factor evaluation, see Figure 8.
4 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 very 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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6 REFERENCES