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DYNAMIC BEHAVIOR OF MONOLITHIC AND COMPOSITE MATERIALS BY SPLIT HOPKINSON PRESSURE BAR TESTING

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ABSTRACT

A Split Hopkinson Pressure Bar (SHPB), an experimental apparatus for testing of solid materials at high strain rates, was in-house designed and realized by the Mechanical Engineering Dept. of WSU: it can test different types of materials and provide their dynamic mechanical properties (e.g. Young's modulus, hardening or plasticization coefficients, yield strength). This SHPB works at strain rate levels between 1000 and 3000 s-1 and impact speeds between 6 and 9 m/s. The specimen is simply a 6 mm dia. 3 mm long cylinder. The apparatus and its software were benchmarked by means of tests on Aluminum and Titanium, whose mechanical properties are well known, and later successfully applied to non-metallic materials like Nylon, Epoxy, Carbon fiber and glass fiber reinforced composites.

KEYWORDS – non-metallic materials, metallic materials, Split Hopkinson Pressure Bar, SHPB, stress – strain curves, strain rate – strain curves, dynamic mechanical properties.

INTRODUCTION

The SHPB at WSU is actually an assembly of three coaxial rods (Striker, Input and Output bars). All rods can slide horizontally on supports which offer low friction resistance to the horizontal movement. The specimen (a small cylinder) is sandwiched between the input and the output bar. The striker bar is shot against the input bar by an air gun. The impact generates a shock pulse wave along the input bar (incident wave). The latter is partly reflected back at the Input bar - specimen interface (reflected wave), and partly transmitted to the output bar (transmitted wave). Strain gage rosettes glued on the input and output bars convert the Incident, Reflected and Transmitted waves into an analogical signal that can be grabbed, logged and recorded. Under some hypotheses, the recorded strains in the input and output bars can be post-processed to reconstruct the behavior of the specimen. The SHPB in WSU was designed for relatively low-speed impact behavior, such as the one in low speed crash, of materials commonly used in automotive structure, e.g. in bumpers. This type of simulation requires relatively low speed but long pulse waves (in order to obtain the possibly maximum total deformation of the specimen). This can be achieved only with relatively long striker bars and, consequently, long input and output bars. In a few words we can say that the peculiar features of the WSU's machine are:

1. Relatively long striker bar, to achieve long pulses;
2. Low impact speed to get a strain rate in the low range of attainable values;
3. Full electronic equipment to track the signals;
4. Dedicated software to post-process the data acquired through the electronics.

ANALYTICAL ASPECTS

The incident wave generates a strain in the input bar called ε_i; in the same way the reflected wave generates a strain ε_r in the input bar and the transmitted wave generates a strain ε_t in the output bar. In a simplified approach the strain rate, the strain and the stress <u>in the specimen</u> are given by.

$$\frac{d\varepsilon}{dt} = -\frac{2C\varepsilon_r}{l_s} \tag{1}$$

$$\varepsilon = -\frac{2C}{l_s} \cdot \int_0^t \varepsilon_r dt \tag{2}$$

$$\sigma = \frac{AE}{A_s} \cdot \varepsilon_t \tag{3}$$

where C is the speed of sound in the bars, l_s, A_s are the length and cross section area of the specimen, A is the cross section area of the bars. It is clear that ε_r, ε_t, ε, $\frac{d\varepsilon}{dt}$ and σ are functions of time and that combining together the functions for stress and strain, is possible to reconstruct the σ – ε diagram of the specimen.

SPURIOUS EFFECTS

Some phenomena add difficulty to the use of the SHPB, with respect to the simple theory described in the previous section. These phenomena can be considered disturbances to the experiments, and their effect can be minimized, but not completely eliminated. Among the sources of errors are:

1. Lack of one-dimensionality of the pulse waves: this effect was considered negligible (length-to-diameter ratio for the bars >> 100);
2. poor alignment of the bars: minimized by a suitable system of supports.
3. irregular specimen – bars contact: the specimen and the bars butts were well worked.
4. friction between the specimen and the bar butts (lubrication);

5. electronic noise: the noise is partly digitally filtered by the software for signal processing, but it remains surely a main source of errors;
6. the Pochhammer – Chree effect: a software has been written to mathematically reconstruct the waves at the interfaces (they are recorded at the bars' half-length);
7. the signal synchronization: the three waves are recorded and converted as strain vs. time data files ($\varepsilon_i(t)$, $\varepsilon_r(t)$, $\varepsilon_t(t)$); then they are shifted, aligned and synchronized till they have a common time basis by a dedicated software.

EXPERIMENTAL ASPECTS

THE EXPERIMENTAL APPARATUS

The SHPB at WSU is formed by three coaxial cylindrical bars of hard steel. Their characteristics are as follows:

Striker bar: Diameter: 12.7 mm, Length: 1295 mm
Input and output bars: Diameter: 12.7 mm, Length: 3048 mm

The input and output bars can slide on Nylon bearings (kept in place and aligned by steel supports with screws for adjustment); Strain gage rosettes (two twin-strain-gage rosettes in each bar) are glued on the surface of the input and output bar at mid-length: each bar is thus equipped with a full Wheatstone bridge with opposed strain gages to record the compression / tensile pulse waves eliminating spurious bending waves. The striker bar is shot by an air gun and driven to the impact point by a plastic tube. An optical gate records the speed of the striker bar just before the impact and triggers the recording of the signals from the strain gage rosettes.

SPECIMEN GEOMETRY

The specimen for compression tests with the SHPB is a small cylinder to be sandwiched between the input and output bars. Many authors suggest a (empirical) length-to-diameter ratio of 1:2 for the specimen, therefore, in the experiments here described all specimens had the following dimensions:

Nominal diameter *d*:	6 mm
Nominal length l_s:	3 mm

RESULTS AND DISCUSSION

The following materials were tested:

1. Aluminum alloy 6061 T561;
2. Commercially Pure Titanium Grade 2 (ASTM B265);
3. Epoxy resin by Buehler;
4. Composite laminate Toray T300 fiber / 5208 Cytec Fiberite epoxy resin (the direction of compression was orthogonal to the plane of the laminae);
5. Nylon;
6. Randomly oriented chopped Glass Fiber reinforced composite;

See Fig. 1 to 6 for the stress vs. strain and strain rate vs. strain curves for all materials. The resulting properties are summarized in Tab. 1.

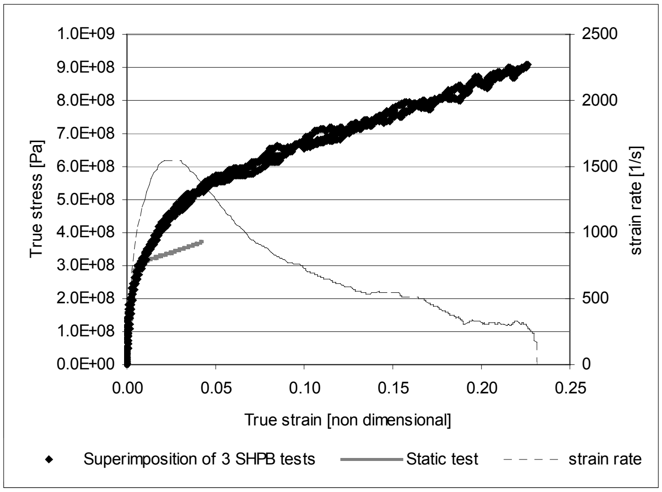

Fig. 1 -Static and SHPB test on Aluminum alloy 6061T651; strain rate in SHPB testing: max 1550 1/s, average 700 1/s

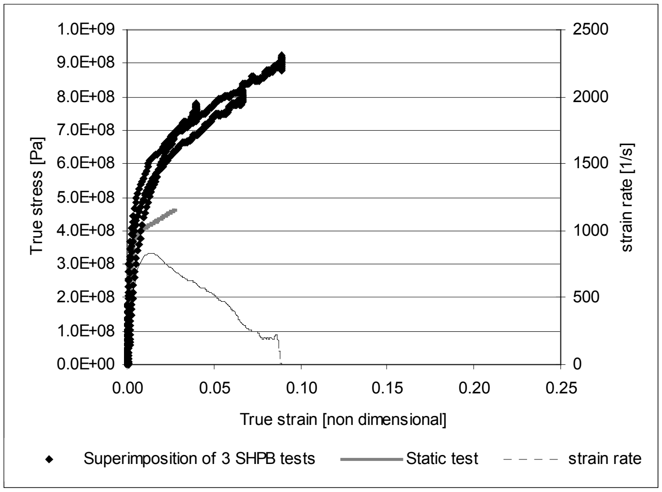

Fig. 2 -Static and SHPB test on Commercially Pure Titanium Grade 2 ASTM B265; strain rate in SHPB testing: max 820 1/s, average 480 1/s

In all the tests on metals the specimens did not reach fracture; the maximum attainable deformation is a complex function of the strain rate, the pulse wave duration and the material response to the applied load. Metals which exhibit strong strain hardening (e.g. Titanium alloys) can be much less deformed than metals with low strain-hardening coefficients (e.g. Aluminum alloys; in fact Aluminum alloy maximum deformation is about twice greater than Titanium in the same conditions, see Fig. 2 and 3). In tough materials with low resistance and low strain hardening the pulse wave duration (which is proportional to the length of the striker bar) can be enough to break the specimen (that is what happened in testing composites and monolithic polymers).

The first part of the test, the one corresponding to the elastic part of the stress – strain curve, exhibits the fastest change in the value of the strain rate, therefore, the Young's modulus can be just estimated in an SHPB test, especially in materials where mechanical characteristics are strongly strain-rate dependant. After plasticization (when substantial plasticization occurs) the strain rate varies much more slowly an average value can be taken as representative of the test conditions. Nevertheless in literature often only the maximum strain rate (peak strain rate) is given.

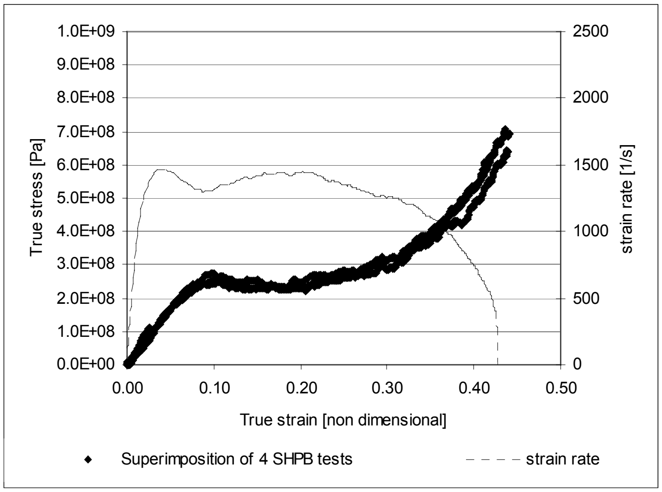

Fig. 3 - SHPB test on Epoxy Resin; strain rate in SHPB testing: max 1460 1/s, average 1190 1/s

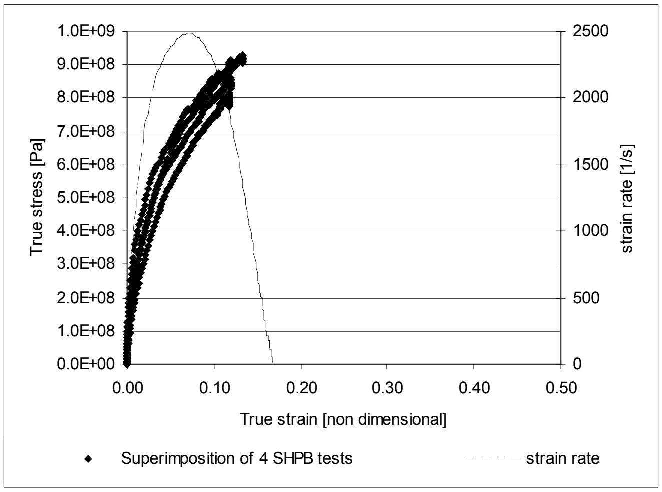

Fig. 4 - SHPB test on T300 fiber/5208 Cytec Fiberite Epoxy matrix composite; strain rate in SHPB testing: max 2490 1/s, average 1770 1/s

The results of a test with the SHPB must be carefully interpreted prior any practical usage.

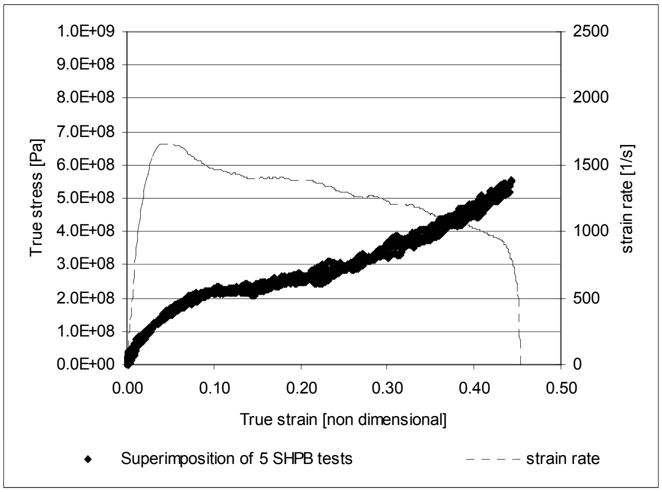

Fig. 5 - SHPB test on Nylon; strain rate in SHPB testing: max 1550 1/s, average 700 1/s

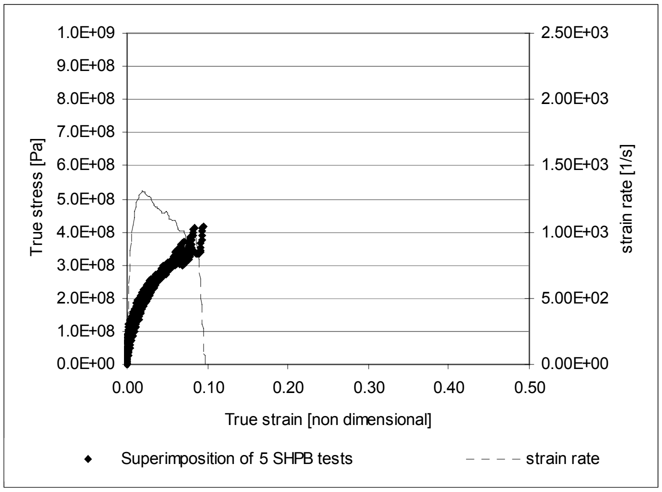

Fig. 6 - SHPB test on Randomly Oriented Chopped Glass Fiber reinforced composite; strain rate in SHPB testing: max 1500 1/s, average 900 1/s

A certain amount of scattering in the results of the test is due to small differences in the material behavior, in the value of the strain-rate even in test nominally performed in identical conditions, and in the synchronization of waves as carried out by the software. In Fig. 1 to 6 several curves for each material have been superimposed on the same plot: the correct characteristic curve for each material would be (for example) the best-fit curve for a set of successful curves obtained in the same conditions.

Material	Mechanical property	Static comp. test	Dynamic comp. test (SHPB)
Aluminum Alloy 6061 T561	Young [GPa]	60	60
	$Y_{s0.2\%}$ [MPa]	305	253
	$Y_{s1\%}$ [MPa]	323	360
	Max.str.rate [s^{-1}]	$\cong 10^{-5}$	$\cong$ 1500
C.P. Titanium Grade 2 (ASTM B265)	Young [GPa]	90	90
	$Y_{s0.2\%}$ [MPa]	386	460
	$Y_{s1\%}$ [MPa]	419	570
	Max.str.rate [s^{-1}]	$\cong 10^{-5}$	$\cong$ 850
Epoxy resin By Buehler	Young [GPa]	NA	3
	$Y_{s0.2\%}$ [MPa]	NA	250
	$Y_{s1\%}$ [MPa]	NA	260
	Max.str.rate [s^{-1}]	NA	$\cong$ 1500
T300 fiber / 5208 Cytec Fiberite Epoxy resin	Young [GPa]	NA	30
	$Y_{s0.2\%}$ [MPa]	NA	280
	$Y_{s1\%}$ [MPa]	NA	400
	Max.str.rate [s^{-1}]	NA	$\cong$ 2500
Nylon	Young [GPa]	NA	3
	$Y_{s0.2\%}$ [MPa]	NA	180
	$Y_{s1\%}$ [MPa]	NA	190
	Max.str.rate [s^{-1}]	NA	$\cong$ 1700
Rand. chopped Glass Fiber reinforced composite	Young [GPa]	NA	20
	$Y_{s0.2\%}$ [MPa]	NA	150
	$Y_{s1\%}$ [MPa]	NA	200
	Max.str.rate [s^{-1}]	NA	$\cong$ 1300

Tab. 1 – Material properties measured in the experiments (NA = Not Available)

CONCLUSIONS

1. High strain rate compressive testing of different materials (including metals, plastics and composites) have been performed by means of the SHPB installed at the Mechanical Engineering Department of WSU. The repeatability and reliability of the results appears good.
2. The output of the apparatus is a conventional true stress vs. true strain graphic or data file, but other data are available such as strain rate, engineering stress, engineering strain.

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