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Experimental investigation on the influence of the geometry of carbon fiber specimen used in Split Hopkinson Pressure Bar tests

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Abstract. *This paper presents an experimental investigation of the specimen geometry on the dynamic behavior of woven carbon/epoxy composite laminates under high strain rate. The specimens were manufactured using the Resin Infusion under Flexible Tooling (RIFT) process and they were tested under compression loads using an in-house Split Hopkinson Pressure Bar (SHPB) testing apparatus. The cross sectional area and the length of the specimens were varied in order to investigate their influence on the dynamic behavior of this material. The preliminary results indicate that the specimen geometry definition is crucial to achieve consistent results.*

Keywords: *high strain rate, experimental investigation, geometry definition, carbon fiber laminate.*

1. INTRODUCTION

In recent years, the use of composite materials has increased replacing conventional metallic materials in various industry sectors, like aerospace, military and automotive industries. This trend also increases the need for the experimental characterization of new materials.

In some applications the structures experience dynamic loadings, that occurs in a fraction of time, producing very localized deformations. Examples of such loading type are the bird strikes on aircrafts, ballistic impacts and the collision of debris on artificial satellites.

For dynamic loading cases, the mechanical response is usually different than that obtained from quasi-static tests. This loading type is usually dependent on the loading rate, that defines the strain rate experienced by the material tested. For quasi-static and low velocities impact situations, the use of a standard testing device and the drop test tower are enough.

On high strain rate tests the equipment usually employed is the Split Hopkinson Pressure Bar (SHPB). In the last two decades a lot of articles has been published dealing with dynamic characterization of composite materials, but despite of some recommendations, there is no standardized test specimen geometry, and different researchers use specimens with different dimensions and geometry (Woldesenbet and Vinson, 1997, 1999).

For this reason, it can be difficult to compare results of tests performed by other researchers. In the classical SHPB technique for testing metals, the specimen geometry is cylindrical with length-to-diameter (L/D) ratio close to 0.5 in order to minimize the friction and radial inertia effect.

Among the authors dealing this subject Harding (1993) investigated the effect of the specimen geometry design. He used cylindrical specimens of Permaglass 22FE and HY750 resin with 48 layers, and a strip of woven E-glass fibres type of 11 x 2EC5 and XD927 epoxy resin with 44 layers. He concludes that the results are strongly dependent on the specimen geometry. For cylindrical samples the length vs. diameter ratio doesn't affect the peak stress, but in the thin strip samples the strength and Young's modulus are considerably lower than cylindrical specimens.

More recently (Woldesenbet and Vinson, 1997, 1999) analysed the effect of the geometry of IM7/8551-7 graphite/epoxi used for SHPB tests. Cylindrical and square/rectangular specimens were investigated varying length/diameter ratio for the former and the length for the latter. No correlation was found between L/D ratio and the peak stress/strain for cylindrical specimens and according them the results of square/rectangular samples show similar trend in comparison with cylindrical specimens.

Another contribution, including experimental and numerical analysis was performed by Pankow *et al.* (2009). They tested resin epoxy with square and cylindrical geometries and pointed out that the results obtained with those cross-sectional areas are quite similar.

They noticed that for "softer" materials can be advantageous to use small L/D ratios, because the uniform state of stress is reached quickly and a cleaner signal is produced. Thicker specimens can be used to characterize the strain rate dependence of Young's modulus, because they extended the stress x strain curve with constant strain rate in the linear elastic regime of material.

Characterization of woven carbon fiber reinforced composites, were conducted by Hosur *et al.* (2001), Naik and Kavala (2008), and more recently by Ravikumar *et al.* (2013) and Koerber *et al.* (2015). On these researches are presented data obtained from the dynamic tests, using rectangular geometries.

In this paper an investigation on the effect of specimen geometries made of composite materials commonly used for dynamic tests in the Split Hopkinson Pressure Bar is carried out. An experimental analysis is done varying the geometry of the specimens, namely the length, cross-sectional area and the specimen's overall size.

2. EXPERIMENTAL

2.1 Material and specimen manufacturing

Two planar laminates with layup of size 20.0 cm x 20.0 cm were manufactured with AGP193-P Hexcel carbon woven ply and LY 5052/Araldite resin epoxy system. The thinner laminate consisted of a stack of 30 plies, resulting in a 7.5 mm thick plate. The thickest laminate was composed by a stack of 42 plies, totaling 10.0 mm thick. The impregnation method chosen was the Resin Infusion under Flexible Tooling (RIFT), that is suitable for obtaining affordable composites (Hosur *et al.*, 2001). Figure 1 shows the vacuum bag system at the start of infusion and the curing cycle followed the resin manufacturer recommendations.

Figure 1. Specimen manufacture.

Laminate quality was assessed by C-Scan based ultrasonic technique. For the dynamic tests rectangular specimens of dimensions depicted in Table 1 were prepared using the Extec - Labcut 5000, precision cutting machine that guarantees samples with parallelism tolerance of 0.03 mm.

Table 1. Specimen dimensions used for the tests.

Sample reference	Width [mm]	Height [mm]	Length [mm]
G	7.5	7.5	7.5
J	7.5	7.5	10.0
M	10.0	10.0	10.0

2.2 High strain rate testing and data analysis

The device usually employed to characterize dynamically metals and more recently composite materials at high strain rates (Gama *et al.*, 2004; Koerber *et al.*, 2015) is the Split Hopkinson Pressure Bar (SHPB). In Figure 2 is shown the SHPB available in the Aerospace Structures Laboratory of the Instituto Tecnológico de Aeronáutica - ITA.

The classical compression SHPB is composed essentially by a gas chamber and three cylindrical bars namely the striker, the incident and the transmission bars, schematically represented in Figure 3. In the setup used for current study, bars are made of high strength steel AMS–5629 with Young's modulus of 198 GPa, density of 7,700 kg/m^3 and diameter of 19.05 mm. Striker length is 350.0 mm and incident/transmission bars have 1,000.0 mm.

During the test, sample is sandwiched between the incident and transmission bars. Striker is accelerated by a gas gun up to a initial velocity V_0, when it impacts the incident bar. Then, the compression pulse generated, usually called as incident pulse (ε_i), travels along the incident bar.

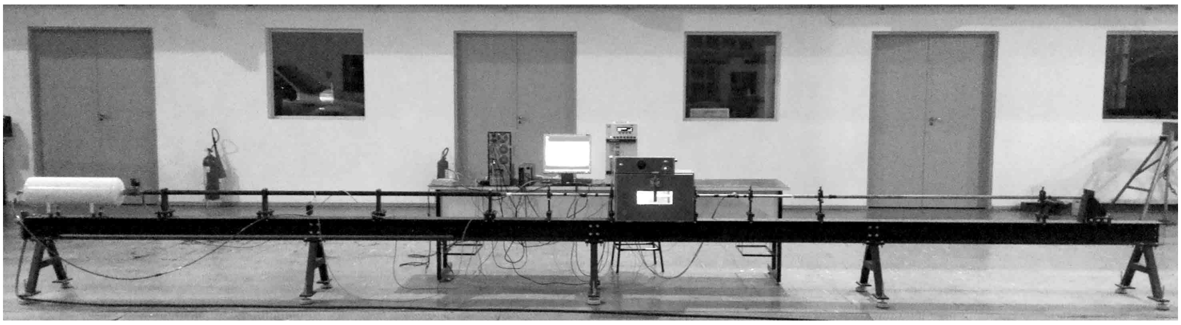

Figure 2. Split Hopkinson Pressure Bar.

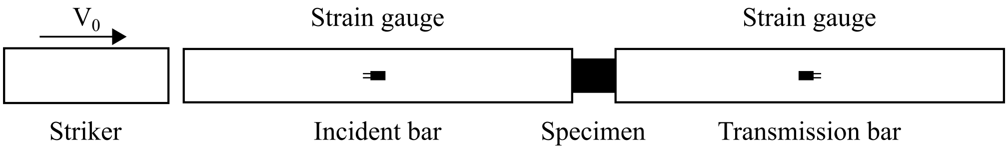

Figure 3. Schematic of Split Hopkinson Pressure Bar used in compression tests.

When the compression pulse reaches the interface bar/specimen it is partially transmitted to sample and the reflected portion travels back as a tensile pulse (ε_r). The signal transmitted to specimen undergo several reflections within it due impedance mismatch between the bars and the sample.

Finally, when the stress inside the specimen increases, it was transmitted to the transmission bar (ε_t). All transient strain history is recorded by two strain-gauges mounted at the middle of incident and transmission bars. These gauges are disposed diametrically opposite to each other to cancel any bending strains. The data is acquired using a high-speed data acquisition system HBM–Genesis 7t at a sample rate of 1.0 MHz.

For long prismatic bars, the stress x strain relation developed can be described conveniently by one-dimensional elastic wave theory (Hosur *et al.*, 2003) and the stress inside the specimen (σ_s) is calculated assuming dynamic force equilibrium developed at the bar ends in contact with the sample, by Equation 1.

$$\sigma_s(t) = \frac{EA}{A_s}\varepsilon_t(t) \tag{1}$$

where E and $\varepsilon_t(t)$ are the Young's modulus and the recorded strain of transmission bar, A and A_s are the cross-sectional areas of the specimen and bars respectively. The specimen strain is obtained by the Equation 2.

$$\varepsilon_s(t) = -\frac{2c_b}{L_s}\int_0^t \varepsilon_r(\xi)d\xi \tag{2}$$

where the wave speed ($c_b = \sqrt{E/\rho}$) inside the bars, L_s is the specimen length and $\varepsilon_r(\xi)$ is the reflected strain measured at the incident bar. The dummy argument (ξ) where used to indicate the start of the reflect pulse in time scale.

Finally, the strain rate is obtained by Equation 3.

$$\dot{\varepsilon}_s(t) = -\frac{2c_b}{L_s}\varepsilon_r(t) \tag{3}$$

3. RESULTS

This section presents the results obtained for dynamic tests conducted on the Split Hopkinson Pressure Bar. For each sample dimensions three tests were performed, resulting in nine stress vs. strain curves. On Table 2 the values for peak stress, strain at peak stress, Young's modulus and average strain rate are showed.

Air pressure of the internal chamber was calibrated in order to ensure approximately the same strain rate in all tests. For samples of 7.5 mm x 7.5 mm x 7.5 mm (type G), the pressure was set to 1.15 bar, specimens of 7.5 mm x 7.5 mm x 10.0 mm (type J) required pressure of 1.25 bar and for samples of 10.0 mm x 10.0 mm x 10.0 mm (type M) the pressure of 1.50 bar was selected.

Table 2. Comparison of dynamic mechanical properties obtained at average strain rate of $530s^{-1}$.

Sample	Peak stress [MPa]	Strain at the peak stress [%]	Young's modulus [GPa]	Strain rate [s^{-1}]
G001	521.1	2.1	24.0	532.9
G002	523.8	2.2	23.9	573.4
G003	506.9	2.3	23.1	573.0
Average	**517.3 ± 7.4**	**2.2 ± 0.1**	**23.7 ± 0.4**	**559.8 ± 19.0**
J001	520.0	2.0	24.3	462.7
J002	530.5	1.9	24.9	545.0
J003	499.6	2.0	24.6	553.0
Average	**516.7 ± 12.8**	**1.9 ± 0.0**	**24.6 ± 0.2**	**520.2 ± 40.8**
M001	505.2	1.6	27.2	535.0
M002	569.6	2.1	29.5	598.7
M003	544.1	1.8	24.9	454.4
Average	**539.6 ± 26.4**	**1.8 ± 0.2**	**27.2 ± 1.9**	**529.4 ± 59.1**

3.1 Specimen length influence

Specimen length influence was analyzed comparing the dynamic responses for samples type G and J. Stress x strain curves for these specimens type are showed on Figures 4 and 5 and according to these plots all samples of the same type exhibit a similar behavior.

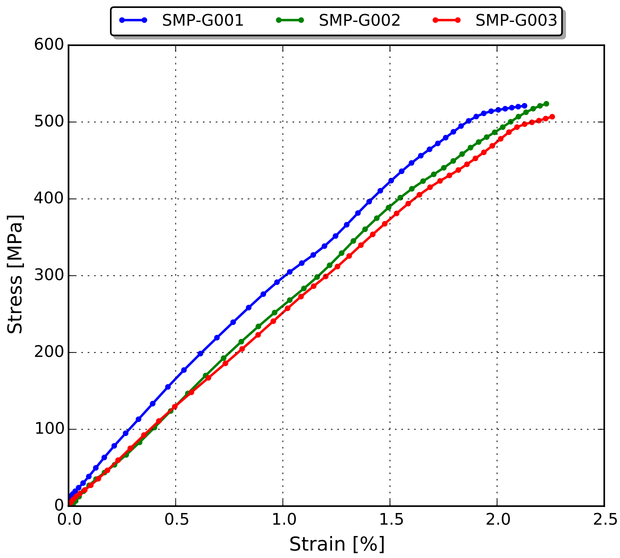

Figure 4. Stress x strain curve for samples of 7.5 mm x 7.5 mm x 7.5 mm.

Table 2 reveals that peak stress and Young's Modulus also match. Failure mode observed on smaller specimens consisted of several delaminations followed by splitting. However, for longer specimens few areas of delamination was observed. For these samples, the final strain achieved were lower than those verified in G samples.

3.2 Specimen cross-sectional area influence

In order to investigate the effect of specimen cross-sectional area, results for samples of 10.0 mm x 10.0 mm x 10.0 mm (type M) were compared with those obtained for type J (7.5 mm x 7.5 mm x 10.0 mm). Figure 6 shows the stress x strain curve for samples type M, and it can be noticed that the results are again, quite repetitive.

The increase on specimen cross-sectional area was followed by a slight peak stress and Young's Modulus increase, however the natural dispersion of result shows no significant discrepancy between the values obtained for samples J and M. Failure modes and strain at the peak stress for the specimens with larger cross-sectional area are essentially the same that those observed on cubic samples of 7.5 mm.

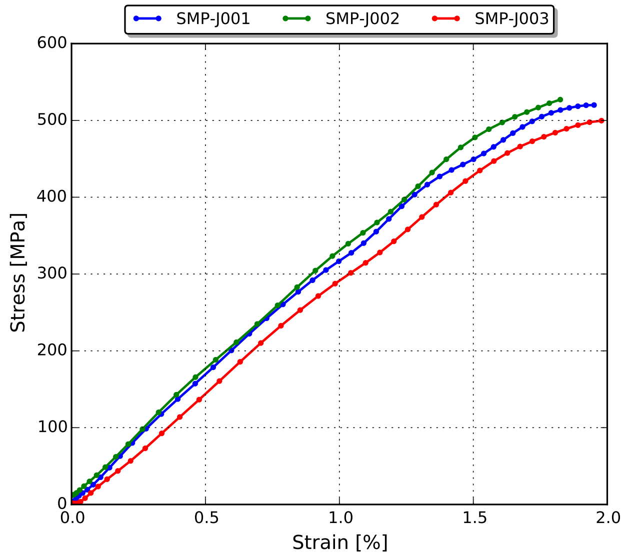

Figure 5. Stress x strain curve for specimens of 7.5 mm x 7.5 mm x 10.0 mm.

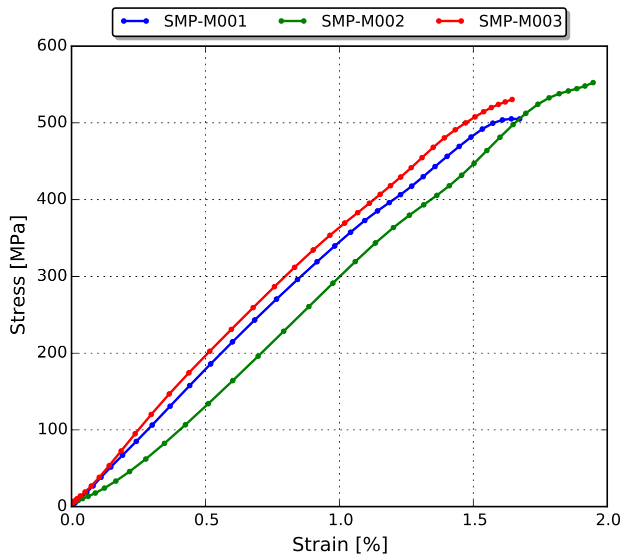

Figure 6. Stress x strain curve for specimens of 10.0 mm x 10.0 mm x 10.0 mm.

3.3 Overall specimen size influence

Finally the effect of overall specimen dimensions was investigated through the comparison of G and M type specimens. Values of peak stress are slightly higher and strain at peak stress are lower for M type specimens. Failure modes presented by these samples are identical.

4. CONCLUDING REMARKS

In this paper an study on the influence of specimen geometry for dynamic tests on the Split Hopkinson Pressure Bar were presented. Results obtained at the same strain rate showed that an increase on specimen length doesn't affect measured dynamic properties.

Similarly, the increase of cross-sectional area of the specimen tends to slightly enhance the peak stress, as well the Young's Modulus, but further test are required to confirm this trend. The results also indicate that strains are more confined in thicker specimens which may explain the lower strain at the peak stress. The effect of overall specimen size showed that for thicker specimens a detailed observation on the failure modes is more evident.

5. ACKNOWLEDGEMENTS

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