Composites: Part A 42 (2011) 462–470

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

# High strain rate characterisation of unidirectional carbon–epoxy IM7-8552 in longitudinal compression

H. Koerber, P.P. Camanho *

DEMec, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

ARTICLE INFO

*Article history:*
Received 19 April 2010
Received in revised form 3 September 2010
Accepted 2 January 2011
Available online 20 January 2011

*Keywords:*
A. Polymer-matrix composites (PMCs)
B. Impact behaviour
B. Mechanical properties

ABSTRACT

This paper presents an experimental investigation of the strain rate effect on unidirectional carbon–epoxy IM7-8552 loaded in longitudinal compression. A dynamic compression fixture was developed for a split-Hopkinson pressure bar to test flat rectangular specimens. The dynamic experiment was designed by finite element analysis, using an axis-symmetric elastic model of the test setup. Due to the linear specimen stress–strain behaviour, ramp-shaped incident pulses were used, to ensure a constant strain rate and dynamic equilibrium throughout the test. The results from the split-Hopkinson pressure bar experiments at an average strain rate of about 100 $s^{-1}$ were compared with quasi-static test results using the same test setup. It was found that the longitudinal compressive modulus is not strain rate sensitive while a significant increase was observed for the longitudinal compressive strength.



## 1. Introduction

It is widely accepted that the longitudinal *tensile* properties of UD carbon–epoxy composites are not strain rate sensitive, as demonstrated in an early study by Harding and Welsh [1] and confirmed in a recent study by Zhou et al. [2]. For the longitudinal *compressive* properties however, a variety of results were reported by different authors. Hsiao and Daniel [3] used a falling weight impact tower and thick composite specimens with bonded steel end caps. They reported an increase of longitudinal compressive strength at higher strain rates but found no rate effects for the longitudinal compressive modulus of elasticity. Hosur et al. [4] tested cubic compression samples using a recovery split-Hopkinson pressure bar and observed a significant increase for the modulus and a relatively small increase for strength under dynamic loading. Bing and Sun [5] proposed an extrapolation method to obtain the longitudinal compressive strength over a wide range of strain rates from off-axis compression test specimens and reported a linear increase of the longitudinal compressive strength with increasing strain rate. Yokoyama and Nakai [6] tested cubic rectangular specimens with a conventional split-Hopkinson pressure bar (SHPB) and reported an increase for the initial compressive modulus but concluded that the compressive strength is not strain rate sensitive. Wiegand [7] studied the high strain rate compressive behaviour in fibre direction using flat rectangular specimens, made from a cross-ply laminate and tested in a SHPB with clamped slotted end caps, and observed a linear increase of the compressive strength over a wide range of strain rates.

The above examples show that the effect of strain rate on the longitudinal compressive behaviour of carbon–epoxy composites is still subject of debate.

In particular the rate effect on the longitudinal compressive modulus needs to be investigated further. From those authors that used a SHPB for the dynamic tests, Hosur et al. [4] and Yokoyama and Nakai [6] reported an increase of the modulus with increasing strain rate whereas Bing and Sun [5] found no strain rate effect. Wiegand [7] excluded the modulus from his study since dynamic equilibrium was established late in the experiment.

The objective of the present paper is to identify the effects of strain rate on the longitudinal compressive modulus and on the longitudinal compressive strength of carbon–epoxy composites using a SHPB for the dynamic tests. Significant attention is given to the reliability of the SHPB experiment by addressing potential issues such as dispersion correction, dynamic stress equilibrium and pulse shaping to obtain constant strain rate experiments which allow a direct comparison of the dynamic results with the quasi-static reference case. If dynamic equilibrium is achieved early in the test, the entire dynamic specimen stress strain curve can be used and the dynamic longitudinal compressive modulus can be measured with confidence.

## 2. Design of dynamic experiment

A comprehensive review of the SHPB experimental technique is given by Gray III [8] and Gama et al. [9]. The SHPB experiment used

* Corresponding author. Tel.: +351 225081716; fax: +351 225081445.
*E-mail address:* pcamanho@fe.up.pt (P.P. Camanho).

1359-835X/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compositesa.2011.01.002

here was developed using the finite element (FE) program ABAQUS [10] to evaluate different incident pulse shapes $\varepsilon_I$ and the corresponding reflected and transmitted wave signals $\varepsilon_R$ and $\varepsilon_T$, respectively. As pointed out by Nemant-Nasser et al. [11] a monotonically increasing ramp-like incident pulse is best suited to obtain a constant strain-rate SHPB test if the specimen behaviour is linear-elastic up to failure. The pulse shaper, generally a small disc made of a ductile metal such as copper or aluminum, is placed between the striker- and incident-bar. A variety of pulse shapes can be obtained, depending on the material constants of the SHPB bar material, the elastic-plastic stress–strain behaviour and the dimensions of the pulse shaper, as well as the impact-velocity and length of the striker bar. Since it is difficult to obtain the required incident pulse shape by trial and error, the pulse shaping analysis proposed by Nemat-Nasser et al. [11] was used to determine the parameters for the ramp-like incident pulse.

Due to the higher strength of the longitudinal carbon–epoxy specimen compared to the strength of the bar material of the SHPB, Tungsten-Carbide (TC) inserts with a diameter of 12 mm and a thickness of 5 mm were placed on both sides of the specimen. The high strength and very stiff TC-inserts reduce the stress concentrations at the specimen ends and avoid indentation of the bar-ends [12]. To ensure that the reflection and transmission of the bar strain waves occurs at the specimen end-surfaces and not at the bar/TC-inserts, the mechanical impedance of the TC-inserts must be equal to the mechanical impedance of the 18 mm steel bars. The mechanical impedance $Z$ is defined as $Z = A\rho c$, where $A$ is the cross-section perpendicular to the direction of the longitudinal wave, $\rho$ is the material density and $c$ is the longitudinal wave velocity.

A specimen fixture, referred to as Dynamic Compression Fixture (DCF), was designed to align and stabalise the relatively thin rectangular specimen. The final design of the dynamic experiment is shown in Fig. 1.

The specimen gauge length is the entire specimen length since the friction between DCF-plate and specimen surface is insufficient to transfer the load into the specimen via shear. Therefore the load introduction in the experiment can be seen as a supported end-loading method. The relatively low amount of transverse pre-compression, applied to the specimen due to the DCF-plate and a *finger-tight* tightening of the screws, is considered to not affect the experimental results and was consistently maintained for the quasi-static and dynamic tests. To allow an undisturbed passing of the bar strain waves, a gap was left between the SHPB-bars and the TC-insert support. Also, the DCF-plates were chamfered, leaving only a minimal contact surface at the TC-insert/specimen-interface (Fig. 1). With the specimen fixture, additional parts are introduced into the SHPB setup, and it must be ensured that those additional parts do not influence the bar waves and subsequently the dynamic specimen stress response, which is calculated from these waves via SHPB analysis [8].

Using a simple linear-elastic axis-symmetric model (ABAQUS element type CAX4R), two FE simulations were performed to verify that the bar waves are not influenced by the parts of the DCF. For the first simulation (Fig. 2a) all parts of the DCF were included while in the second simulation (Fig. 2b) the DCF was removed. A comparison of the two simulations, using an ideal triangular pulse as obtained from a 500 mm long striker-bar fired at a velocity of 5 m s$^{-1}$ and an appropriate pulse shaper, is shown in Fig. 2c where it is seen that the bar-strain response is very similar in both cases.

It is important to note that the comparison of the bar strain wave response with and without DCF parts, shown in Fig. 2c, can only be done with the FE model and should be understood as a way of checking the functionality of the designed DCF fixture. The actual rectangular specimen is too thin and can not be tested without being supported by a fixture. It is further noted that the bar strain wave response shown in Fig. 2c resulted from a linear-elastic simulation, without considering specimen failure. It will be shown later that in a real SHPB experiment, the amplitude of the transmitted wave is lower due to the failure of the specimen.

In the FE model, the striker-bar and the pulse shaper were not included. Instead, the incident pulse $\varepsilon_I$ was applied directly at the impact end of the incident-bar via a distributed surface pressure. A zero-friction contact was defined between all parts except for the contact between the TC-insert and the TC-insert support, were a fixed connection was assumed. The assumption of a zero-friction contact is justified since the main purpose of the FE simulations is to check the influence of the DCF parts on the wave propagation rather then modelling realistic friction behaviour at the interfaces. For the screw connection between the DCF-plate and the DCF-frame, connector elements were used (see Fig. 2a). The cross-sectional area of the specimen in the axis-symmetric FE model corresponds to the cross-sectional area of the actual rectangular specimen. The elastic material properties and densities of all parts used in the simulation are summarised in Table 1. The orthotropic elastic mechanical properties of the composite specimen were taken from an earlier quasi-static material characterisation program and are presented in Table 2 [13].

When analysing the simulation results, a small relative motion was observed between the DCF-frame/DCF-plate unit and the specimen at the transmission-bar end, which can be contributed to inertia effects. In the dynamic experimental results section it will be shown that failure occurred at either the incident-bar side, the transmission-bar side or at both interfaces. Therefore it was

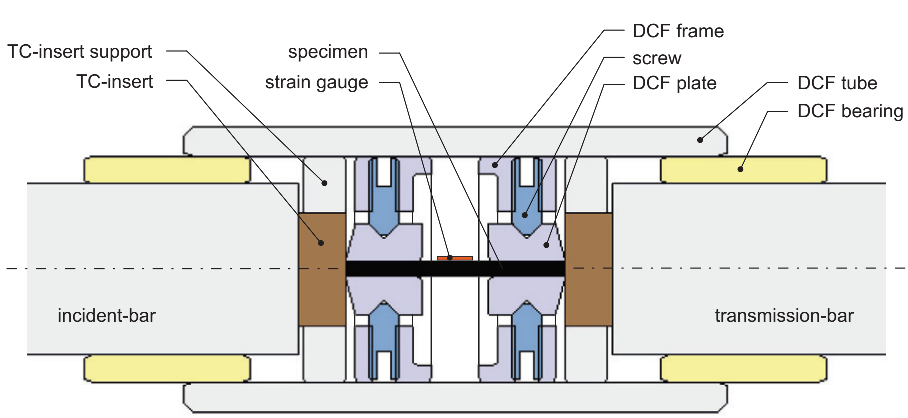


**Fig. 1.** SHPB test setup with dynamic compression fixture (DCF). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)