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Tensile behavior of polycarbonate over a wide range of strain rates

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ABSTRACT

The effect of strain rate on the tensile behavior of polycarbonate was investigated under uniaxial tension loading conditions. The experiments were carried out using a conventional servo-hydraulic testing machine, a moderate strain-rate testing apparatus and a split-Hopkinson tension bar system. The tension stress–strain responses at various strain rates ranging from 0.001 s^{-1} up to 1700 s^{-1} were obtained. Experimental results show that the strain rate greatly influences the tensile behavior of polycarbonate. The value of yield strength is found to increase with increasing strain rate. A viscoelastic constitutive model consisting of a nonlinear spring and a nonlinear Maxwell element was proposed to describe the tension stress–strain behavior of polycarbonate over a wide range of strain rates. The correlation between the experimental data and the model results is good.

1. Introduction

Polycarbonate has been used extensively as a structural material in engineering applications such as automotive and aircraft components due to its good transparency and excellent impact resistance. It is important for structure design to understand the mechanical response of polycarbonate at various strain rates if such polymeric material is subjected to dynamic loading. While a huge volume of the literature exists on mechanical behavior of polycarbonate at different temperatures and strain rates [1–10], numerous studies have focused on the quasi-static tension and dynamic compression behavior of polycarbonate. Due to the experimental difficulties, there is little published work on tensile properties of polycarbonate at moderate and high strain rates. Compared with the compression tests, tension tests can provide more understanding on damage, failure and fracture behavior of materials. On the other hand, the polymers have different responses under tensile and compressive loading conditions. Therefore, it is necessary to know the tensile responses of polycarbonate at moderate and high strain rates.

The purpose of the present paper is to investigate the rate-dependence of the tensile behavior of polycarbonate over a wide range of strain rates. A split-Hopkinson tension bar, a moderate strain-rate testing system and a conventional hydraulically driven material testing system were used to conduct the high strain-rate, moderate strain-rate and quasi-static tension tests, respectively. Based on the experimental results, a viscoelastic constitutive model was proposed to describe the obtained tension stress–strain responses at different strain rates.

2. Experimental details

2.1. High strain-rate tension testing

The split-Hopkinson bar is an effective tool for investigating the dynamic behavior of materials at strain rates ranging from $10^2\,s^{-1}$ to $10^4\,s^{-1}$ [10–13]. In the present paper, high strain-rate tension tests for three different rates of 370 s^{-1}, 800 s^{-1} and 1700 s^{-1} were carried out using a tension version of split-Hopkinson bar, which is schematically illustrated in Fig. 1 [14]. The tensile loading stress pulse was generated by means of the plastic deformation of the pre-fixed metal bar (made of Ly12cz aluminium alloy, Chinese brand, strain rate insensitive material). The geometry of the specimen was dumb-bell shaped flat plate with a gage section and two connection ends and the specimen was connected to the input/output bars using a kind of high-strength adhesive, as shown in Figs. 2 and 3. The input and output bars were made of steel and have the same diameter of 14 mm.

The incident strain $\varepsilon_i(t)$, reflected strain $\varepsilon_r(t)$ and transmitted strain $\varepsilon_t(t)$ were recorded as functions of time t using strain gages on the input/output bars, respectively. Based on the one-dimensional elastic wave propagation theory, the stress, strain and strain-rate histories in the specimen can be calculated as follows:

$$\sigma_s(t) = \frac{EA}{2A_s}[\varepsilon_i(t) + \varepsilon_r(t) + \varepsilon_t(t)] = \frac{EA}{A_s}\varepsilon_t(t) \quad (1)$$

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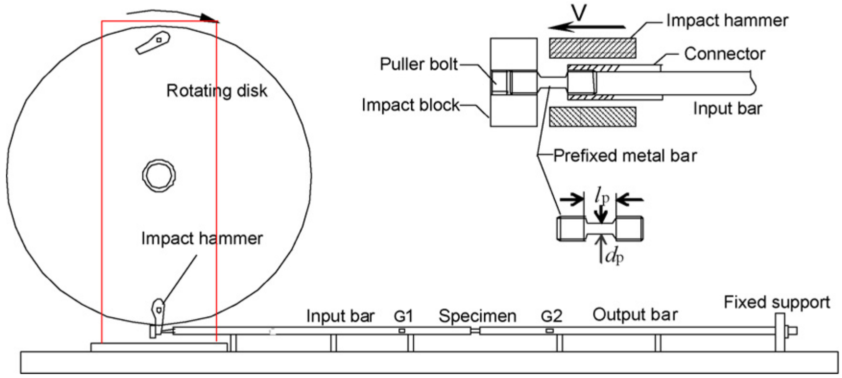

Fig. 1. Schematic diagram of the split-Hopkinson tension bar.

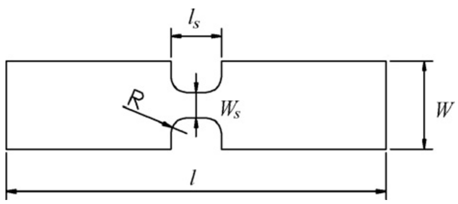

Fig. 2. Specimen geometry for high rate tests.

$$\varepsilon_s(t) = \frac{C_0}{l_s}\int_0^t [\varepsilon_i(\tau) - \varepsilon_r(\tau) - \varepsilon_t(\tau)]d\tau = \frac{2C_0}{l_s}\int_0^t [\varepsilon_i(\tau) - \varepsilon_t(\tau)]d\tau \tag{2}$$

$$\dot{\varepsilon}_s(t) = \frac{C_0}{l_s}[\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)] = \frac{2C_0}{l_s}[\varepsilon_i(t) - \varepsilon_t(t)] = -\frac{2C_0}{l_s}\varepsilon_r(t) \tag{3}$$

where C_0 (=E/ρ, E and ρ are the Young's modulus and density of the input/output bar, respectively) is the longitudinal wave velocity in the bar. A is the cross-sectional area of the input/output bar. A_s and l_s are the cross-sectional area and the gage length of the specimen, respectively.

The experimental principle of the Hopkinson bar testing requires that there exists the state of stress equilibrium and homogeneous deformation in the gage section of the specimen during the process of loading. Experimental investigation indicated that the loading stress pulse travels back and forth inside the specimen more than three times to reach dynamic stress equilibrium, so the rising time of the incident stress pulse should be controlled carefully to meet such requirement. As for the specimen, the longer gage length of specimen will lead to a stress oscillation in the specimen due to the effect of longitude inertia. However, the shorter gage length will disturb the homogeneous deformation in the specimen. Furthermore, the constant strain-rate state in the specimen during the loading should be ensured to obtain the reliable results of stress–strain responses of materials. As expressed in Eq. (3), reflected strain-gage signal measured on the input bar indicates the strain-rate history in the specimen. The shape of the reflected signal depends on the waveforms of incident and transmitted pulses. The constant strain-rate state requires that a flat platform should exist in the reflected wave. Therefore, the matching relation between the specimen dimensions and the shape of the incident stress pulse should be found to reach the stress equilibrium, homogeneous deformation and constant strain-rate state in the specimen. In the present set-up, the amplitude of the stress pulse is determined by the diameter of the prefixed metal bar. The rising time and duration of the stress pulse are controlled by the length of the prefixed metal bar and the impact velocity of the disk. The strain rate for any particular test can be altered by way of changing the impact velocity and/or the diameter of the prefixed metal bar. In the present investigation, the $d_p \times l_p$ of the fixed metal bar were 5 mm × 35 mm, 7 mm × 20 mm and 10 mm × 10 mm, corresponded to the strain rates of 370 s^{-1}, 800 s^{-1} and 1700 s^{-1}.

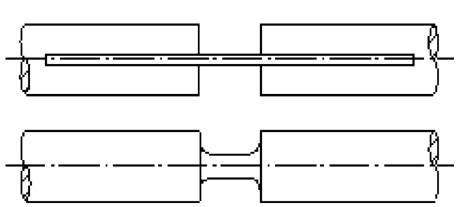

Fig. 3. Specimen connection to the input/output bars.

Compared with the general metal material testing, the transmitted signal in polycarbonate testing is weak due to the low-strength property of polycarbonate. Therefore, a semiconductor strain gage with a high gage factor was attached to the surface of the output bar instead of the conventional strain gage to increase the amplitude of the transmitted signal. Furthermore, a high resolution digital oscilloscope, Nicolet Integra 40, together with a low-noise amplifier, were used to record the transmitted signal.

2.2. Moderate strain-rate and quasi-static tension testings

Tension tests at strain rates ranging from 10^{-1} s^{-1} to 10^1 s^{-1} were carried out on the moderate strain-rate testing set-up, as shown schematically in Fig. 4. The set-up is composed of a loading device, a specimen and a data acquisition system [15]. The main parts of loading device include a hydraulic power unit, a piston rod, a flange and a connector. The piston rod is screwed to the flange and the connector is threaded with the front grip. The tensile spec-

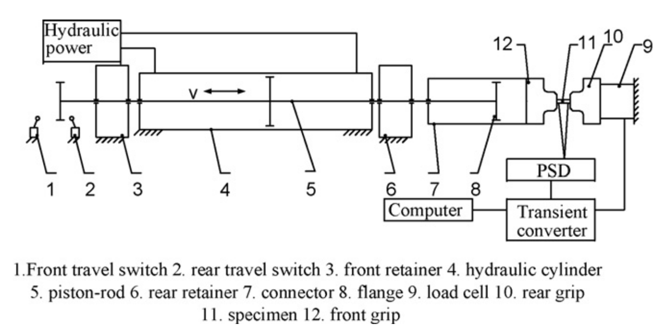

Fig. 4. Schematic representation of moderate strain-rate testing set-up. 1. Front travel switch, 2. rear travel switch, 3. front retainer, 4. hydraulic cylinder, 5. piston rod, 6. rear retainer, 7. connector, 8. flange, 9. load cell, 10. rear grip, 11. specimen and 12. front grip.