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Dynamic compressive mechanical response of a soft polymer material

J.T. Fan [a,*], J. Weerheijm [a,b], L.J. Sluys [a]

[a] Faculty of Civil Engineering and Geosciences, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, The Netherlands
[b] TNO Defence, Security and Safety, Rijswijk, The Netherlands

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ABSTRACT

The dynamic mechanical behaviour of a soft polymer material (Clear Flex 75) was studied using a split Hopkinson pressure bar (SHPB) apparatus. Mechanical properties have been determined at moderate to high strain rates. Real time deformation and fracture were recorded using a high-speed camera. Fracture micrographs were examined to explore the deformation and fracture mechanisms. Crazing and microcracking mechanisms were indicated to be decisive for the dynamic response and impact resistance of this soft polymer material. The stress–strain curves at various strain rates were derived to investigate the strain rate sensitivity. The yield stress shows a rate-dependent behaviour. Temperature rise was also measured by an infrared radiation (IR) camera to investigate the transformation of strain energy at different strain rates. It is of crucial significance to understand the deformation and fracture mechanisms, to study the rate-dependent behaviour as well as to develop a new impact-resistant framework for real engineering application.

1. Introduction

Recently, there has been a growing interest in the development of polymers for application at service conditions of dynamic loading and high-strain-rate deformation in aircraft and automotive components, as well as for military protection measures [1–14]. At the Netherlands Organisation for Applied Scientific Research (TNO), it was found that the material Clear Flex 75 (CF 75 in short) is very promising to be used in transparent armour concepts [14]. Clear Flex® is a commercially available product consisting of Part A and Part B. These two parts are water white clear urethane liquid pre-polymers. CF 75 polymer, which is a polyurethane elastomeric material, was prepared by mixing Part A and Part B with a weight ratio of $A{:}B = 1{:}1.75$. It has a branched structure of molecular chains with a random distribution and is a transparent, flexible and UV resistant polymer with a glass transition temperature of 2 °C [14]. However, data on the mechanical properties and the inherent mechanical response mechanisms at quasi-static and dynamic loading conditions are unknown. This data and knowledge on the dynamic mechanical response are paramount for the design of transparent armour systems [15–18]. A combined computational and experimental research programme was defined to study and model the dynamic response of the hybrid material system consisting of a CF 75 polymer matrix and solid particles. In the computational part, the challenge is to develop a multi-scale modelling approach suitable for dynamics in the impulsive loading regime. In the experimental part, the input data for the multi-scale modelling are generated, but moreover the dynamic response mechanisms are studied in detail. The split Hopkinson pressure bar (SHPB) has been widely used to determine the stress–strain curve at high strain rates for a variety of engineering materials [6,7,10–18]. It is noted that the applicability of the SHPB technique needs to be examined carefully before reliable dynamic experimental data can be produced [17]. Recent modifications on the SHPB apparatus have been done for testing soft materials with valid testing conditions [18–21].

In this research, a servohydraulic Instron-8810 testing machine and a modified SHPB setup for testing soft material were employed to obtain quasi-static and dynamic compressive stress–strain curves of CF 75 polymer material. During the dynamic testing, a high-speed camera was used to record the dynamic deformation process under the high-speed loading, and an infrared radiation (IR) camera was used to measure the temperature rise in the dynamic event. Deformation and fracture behaviour at higher strain rates were systematically investigated, which is of interest to understand the dynamic mechanical response mechanism and the inherent physical origins. Besides, on the basis of the experimental results at various strain rates, strain rate sensitivity of the yield stress and temperature rise induced by strain energy were analysed.

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* Corresponding author.
E-mail addresses: J.Fan@tudelft.nl, Jitang_fan@hotmail.com (J.T. Fan).

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2. Experimental procedures

2.1. The quasi-static mechanical properties test

Quasi-static compression tests were carried out on cylindrical specimens of 5 mm length and 10 mm diameter at room temperature, by using a computer-controlled, servohydraulic Instron-8810 testing machine at a strain rate of about 0.01/s. Three specimens were tested to ensure the repeatability of the mechanical tests. For each specimen, the loading–unloading cycle was carried out with an increase in sequential stress amplitude. The results from the test of one specimen are shown in Fig. 1 as representative result. In the quasi-static tests, CF 75 polymer was not loaded up to failure.

Fig. 1(a) shows a representative true stress–strain relation of CF 75 polymer material under quasi-static compressive loading at a strain rate of 0.01/s. Herein, cyclic compressive loading–unloading experiments were conducted to resolve the deformation behaviour under the quasi-static stress. At the beginning of loading, the stress–strain curve is nonlinear which is typical for the soft polymer material [22]. It does not demonstrate an obvious yield point, but instead a relatively large deformation region where the specimen undergoes a significant straining with a small increase in stress. The stress–strain curve in this region is almost horizontal. With the increase of strain, a final barrelling behaviour occurs. At the release of loading, an unloading path is formed, which differs from the loading path resulting in a hysteresis loop. This is typical viscoelasticity behaviour involving both elastic and viscous components [23]. Hysteresis in the polymer material during cyclic compressive loading could be due to the changes in the orientation or waviness of individual molecular chains during loading–unloading cycles [23].

In addition, by carefully comparing the loading curves tested at different load amplitudes, it was found that a higher stress is needed to obtain the same strain in a sequential loading cycle. That suggests that the CF 75 polymer material becomes stiffer upon the deformation. The tangent modulus, i.e. the slope of the stress–strain diagram, was calculated to quantify the stiffness of CF 75 polymer material at any specified stress or strain [24], as shown in Fig. 1(b). Obviously, during the static deformation process, the tangent modulus is small at the beginning with a slow increasing tendency, and afterwards raises sharply with a fast increasing tendency until the maximum value of 370 MPa at the true strain of 94%. The values of tangent modulus at 10%, 20%, 30%, 50%, 70% and 90% strain were calculated as 6.6, 7.0, 8.2, 15.5, 58 and 335 MPa, respectively. The CF 75 polymer material is very soft, almost without mechanical stiffness at low deformation strain. When the deformation strain is about 70%, it becomes very stiff displaying a sharp climb of stress with a limited strain increase.

2.2. The dynamic mechanical properties test

A split Hopkinson pressure bar (SHPB) was developed at TU Delft for performing the dynamic mechanical tests. It consists of the general components, which include a striker bar that is propelled by a high-pressure gas gun, an incident bar, a transmitter bar, an absorber, strain gauges, a strain transducer with signal conditioners and a means of digital storage (Fig. 2(a)). All three bars are made of aluminium with Young's modulus $E = 71.7$ GPa; Density $\rho = 2700$ kg/m^3; and Poisson ratio $\nu = 0.33$. Their dimensions are respectively 400 mm, 2000 mm and 2000 mm in length and all with 20 mm diameter. The schematic drawing is shown in Fig. 2(b). The tested specimen is a circular cylinder with 10 mm diameter and 5 mm length, which is positioned in between the incident bar and transmitter bar. For the current SHPB setup, the sample rate of the data acquisition system is $2.5 * 10^6$ samples/s; the pulse duration is about 155 μs, the velocity range of the striker bar is 5–50 m/s and the resultant range of strain rates is 500–7000/s for the given specimen size.

The working principle of the SHPB has been reported extensively in literature [25–32]. In a dynamic compression test, a striker bar is propelled using a high-pressure gas gun and strikes the end of the incident bar in a plane impact. This generates a uniaxial compression wave, which travels through the incident bar. When the specimen, clamped in between the incident and transmitted bars, is reached, part of the wave is reflected and part is transmitted through the interface with the specimen. The stress wave propagates through the specimen into the transmitted bar. A series of wave reflections occur, due to impedance mismatches between the specimen and bars. The incident and transmitted stress waves are measured in real time, using strain gauges on the incident and transmitted bars. It is assumed that the two bars remain elastic and initially wave dispersion is ignored. With these assumptions, the measured stress waves can be easily used to reconstruct the load conditions on the specimen. The following equations are used to extract the stress–strain curve of the tested material from a SHPB test, based on the dynamic wave propagation theory [29–32].

In the specimen, the engineering stress, $\sigma_S(t)$ is:

$$\sigma_S(t) = E \cdot \frac{A_0}{A} \varepsilon_T(t) \qquad (1)$$

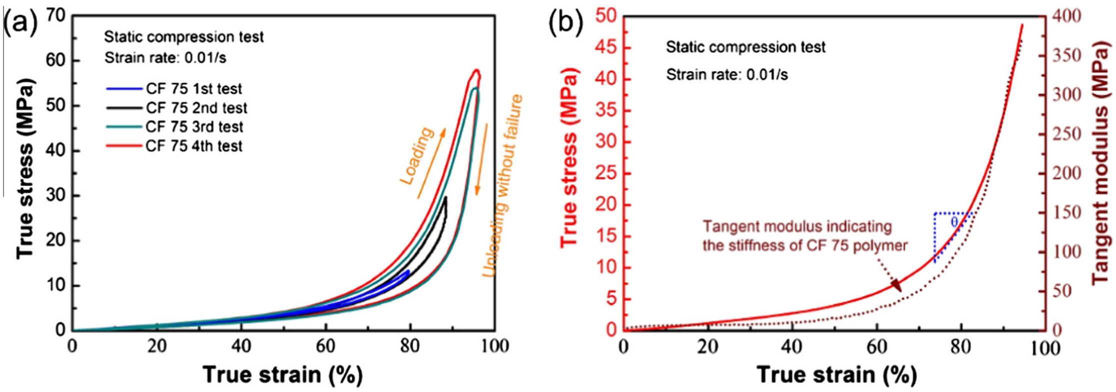

Fig. 1. Quasi-static uniaxial compression tests on the CF 75 polymer material: (a) loading–unloading curves of axial true stress–strain relation to suggest the revisable performance and high compressibility and (b) tangent modulus, calculated from the quasi-static compressive true stress–strain curve, indicating the increasing stiffness with the increase of strain.