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Impact testing of polymeric foam using Hopkinson bars and digital image analysis

Jiagui Liu [a], Dominique Saletti [b], Stéphane Pattofatto [c], Han Zhao [a,*]

[a] Laboratoire de Mécanique et Technologie (LMT-Cachan), ENS-Cachan/CNRS-UMR8535/Université Pierre & Marie Curie, 61, avenue du président Wilson, 94235 Cachan cedex, France
[b] Laboratoire de Biomécanique (LBM), Arts et Mtiers ParisTech, Paris, France
[c] Snecma Villaroche, Safran Group, Rond Point René Ravaud-Réau, 77550 Moissy-Cramayel, France

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ABSTRACT

The present investigation aims at testing polymeric foam under impact loading using large diameter nylon Hopkinson bars and optical field measurements. Accurate average stress-strain relations can be obtained when soft large diameter polymeric pressure bars and the appropriate data processing are used. However, as there are generally no homogeneous strain and stress fields for polymeric foams, an optical field observation is needed. In contrast to quasi-static tests where the digital image correlation (DIC) measurement is commonly used, technical difficulties still remain for the reliable use of DIC under impact conditions. In this paper, an accurate synchronization method based on the displacement measurement of the end of pressure bars (calculated by a robust DIC algorithm) is preferred to conventional MCDL box time synchronization. Also, the bar end displacement measurement offers a complementary calibration method for the tension/strain conversion coefficient. Strain fields are obtained for tests on foam sample at impact velocities up to 20 m/s. The localized strain fields permit better understanding of the observed stress plateau from SHPB results. The relevance of the present method for establishing mechanical response of polymeric foam is then demonstrated.

1. Introduction

Polymeric foams are widely used in lightweight design and energy-absorbing applications in the automotive and aeronautical industries [1,2]. Their behavior under quasi-static loading can be characterized with conventional testing techniques. Analytical/numerical approaches have also been developed to give a reasonable prediction of their mechanical behavior [3–7]. However, for the determination of their behavior under impact loading, needed for energy-absorbing applications, the known analytical/numerical approaches cannot easily be generalized. It is, therefore, an important goal to develop reliable experimental approaches to characterize polymeric foams under impact loading.

Indeed, the testing of polymeric foams at relatively high strain rates has been an interest of investigators since the 1960s [8,9]. Experimental results using different techniques such as the falling weight or impacting mass devices [10–12], rapid hydraulic testing machine [13–15] and also split Hopkinson bars [16–18] have been reported.

Hopkinson bars are widely used to characterize the mechanical behavior of materials under impact strain rates ranging from 10^2 s^{-1} to 10^4 s^{-1}, and they provide more accurate measurement than drop weight and high-speed testing machines for this range. In order to improve the signal/noise ratio for foam testing, common metallic bars with quartz-crystal piezoelectric force transducers [18] or large diameter soft nylon pressure bars [19,20] have been

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* Corresponding author.
E-mail address: zhao@lmt.ens-cachan.fr (H. Zhao).

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used. For instance, typical overall stress-strain curves at high strain rates were obtained with such a nylon pressure bar method for polymeric foams [21,22].

However, it is apparent that the aforementioned test results (under static as well as impact loading rate) are only the average stress-strain relations with an assumption of homogeneous stress and strain fields within the foam specimen, which is unfortunately not true for most foam-like materials. Such non-uniform or rather localized strain fields have been observed in a number of studies [7,19,23]. Hence, field observation techniques are needed and they can be associated with digital image correlation (DIC) [24,25].

However, in contrast to more common uses of photography and DIC for foam testing under static loading [26–28], only a few preliminary studies with high-speed imaging have been reported under impact loading rates [29–33] because of synchronization difficulties and poor image resolution from a high-speed camera.

In this paper, an optical field measurement along with large diameter nylon Hopkinson bars is highlighted in the experimental setup for the polymeric foam characterization. Nylon Hopkinson bar methods and the associated data processing are briefly recalled in section 2. Technical points of the strain field measurement on the basis of high speed imaging, such as time synchronization accuracy as well as the DIC method with poor image resolution, will then be discussed. Finally, typical test results for a polymeric foam are given as an example to illustrate the needs of an accurate field measurement.

2. Conventional tests on the polymeric foams

2.1. Foam specimen and quasi-static tests

Conventional quasi-static compressive tests on polymeric foams can be performed using a universal testing machine. Polymeric foam supplied by the company EADS was studied as an example. The density is 70 Kg/m^3, the diameter of a unit cell is about 0.8 mm and the thickness of the cell wall is about 50 μm from microscopic observations. Samples tested in this study were cylinders of 60 mm in diameter and 40 mm in height.

An MTS 810 testing machine was used to crush the specimen centrally sandwiched between the two platens. The lower platen rises at a constant speed of 0.2 mm/s during loading, which ensures a nominal strain-rate of 5×10^{-3} s^{-1}. Three tests were carried out and the repeatability is good (see in Fig. 1). The mechanical response is typical for cellular materials, which exhibit a linear elastic period, a long plateau and a densification phase.

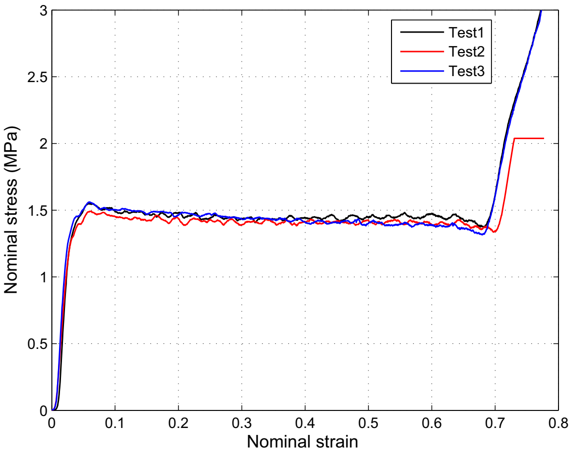

Fig. 1. Three nominal stress-nominal strain curves from quasi-static loading.

2.2. Impact tests with SHPB

Dynamic tests were performed using nylon Hopkinson bars. A typical SHPB is made of long input and output pressure bars with a short specimen sandwiched between them. The impact between the projectile and the input bar generates a compressive longitudinal incident pulse $\varepsilon_i(t)$ in the input bar. Once this incident pulse reaches the specimen-bar interface, one part is reflected as the reflected pulse $\varepsilon_r(t)$ in the input bar and the other part transmitted as the transmitted pulse $\varepsilon_t(t)$ in the output bar. With the gauges glued onto the input bar and output bar, one can record these three pulses.

The transmitted wave can be shifted to the output bar-specimen interface to obtain the output force/velocity and, at the same time, the input force/velocity can be determined via incident and reflected waves shifted to the input bar-specimen interface. Forces and velocities on the both faces of the specimen are then obtained as follows:

$$\begin{aligned} F_{input} &= S_B E(\varepsilon_i(t) + \varepsilon_r(t)), \\ F_{output} &= S_B E \varepsilon_t(t) \end{aligned} \quad and \quad \begin{aligned} V_{input} &= C_0(\varepsilon_i(t) - \varepsilon_r(t)), \\ V_{output} &= C_0 \varepsilon_t(t) \end{aligned} \tag{1}$$

where F_{input}, F_{output}, V_{input}, V_{output} are forces and particle velocities at the input and output interfaces, S_B, E and C_0 are the cross-sectional area, Young's modulus and longitudinal wave speed in the pressure bars, respectively.

The SHPB system used for this study consists of two 3 m long nylon bars of 62-mm diameter (density 1200 kg/m^3 and wave speed 1800 m/s). The use of the nylon bars multiplies by 20 the impedance ratio between the foam sample and the pressure bar (thus the signal/noise ratio) with respect to classical steel bars. However, because of the use of large diameter viscoelastic bars, the reasoning in Eq. (1) should be amended by considering the wave dispersion effect in the wave shift from its measuring points to the bar/specimen interfaces [34,35]. Consequently, the correction of this dispersion effect on the basis of a generalized Pochhammer's wave propagation theory is performed in data processing [19].

Another technical issue is the calibration of the coefficients between the strain and the measured tension because this coefficient may be influenced by many factors such as gauge factors, the gain of the amplifier, room temperature and humidity. The principle of the calibration for the input bar relies on the basis of energy conservation, i.e., the kinetic energy of the projectile should be equal to the sum of the kinetic energy and the elastic energy carried by the incident impulse in the input bar, provided that the