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Behaviour characterization of polymeric foams over a large range of strain rates

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Abstract: The testing and modelling of the mechanical behaviour of some polymeric foams involved in the automotive industry are presented. A variety of current experimental arrangements over a large range of strain rates has been reviewed. Recent improvements of a particularly useful technique for impact loading – the split Hopkinson bar, are presented. A phenomenological model is developed to describe experimental data. Difficulties for 3-dimensional testing and modelling are also discussed.

Keywords: crash test, material behaviour, polymeric foams, SHPB, strain rates.

1 Introduction

Polymeric foams are quite widely used for many industrial reasons. In the automotive industry, they are used for the damping of noises, for the body protection in case of collisions, or for the manufacture of anthropomorphic dummies used in crash tests.

Modelling of mechanical properties of polymeric foams over a large range of strain rates are then needed. For example, in the study of the crashworthiness, anthropomorphic dummies have been used to investigate the response of the human body and to analyse the interaction with the inhabitant compartment. In order to evaluate the occupant protection by numerical crash simulations in the early phases of car design, the characterization of the mechanical behaviour of polymeric foams and their strain rate sensitivity is indispensable.

Experimental and theoretical works on mechanical properties of polymeric foams have been reported in the open literature, especially under quasi-static loading. Indeed, the quasi-static behaviours of various polymeric foams have been obtained

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with ordinary testing machines. Many constitutive foam models have been also proposed, which are based on a micromechanical analysis allowing for the determination of global cellular structure response from the study of a single cell. An extensive review can be found in the book of Gibson and Ashby [6].

The behaviour of polymeric foams at relatively high strain rates has been an interest of investigators since 1960s. Experimental results using different devices such as the falling weight or impacting mass technique [4,10,16,18,20], rapid hydraulic testing machine [3,13,19], split Hopkinson bar have been reported [14,15]. Phenomenological constitutive models at high strain rates [3,4,13,16,19,20] and those based on the micromechanical analysis are also developed [12,17].

In the domain related to the crash simulation, actual researches on the foam constitutive relation are more or less focused on phenomenological models because of their simplicity. However, parameters of those models are often identified by means of an inverse approach and from experimental data obtained in complex testing configurations, where the testing control and measuring accuracy are not always satisfactory.

In this paper, different testing arrangements are reviewed and commented. The recent improvements of split Hopkinson bars technique are presented. A simple phenomenological model will be also proposed. The validity of commonly used assumption of homogeneous stress and strain fields in a test at high strain rates is checked. Finally, difficulties in actual 3-dimensional testing and modelling are discussed.

2 One-dimensional experimental arrangements

2.1 Standard testing machine and falling weight technique

The quasi-static behaviour of polymeric foams can be obtained with ordinary testing machines. It is a well-controlled technique, provided that the suitable device is used for the force measurement when the very weak foams are tested.

Experimental techniques differ when the strain rate is more or less important. Rapid hydraulic testing machine [3,13,19] or falling weight arrangements [4,10,16,18,20] are techniques often reported in the literature. However, even those techniques can provide a suitable mechanical loading over a large range of strain rates, the quality of measuring approaches associated with those techniques decreases with the increase of the strain rates. This is because of the assumption of an instantaneous equilibrium in the loading frame as well as the measuring device, which neglect any wave propagation effect. This is why those measuring techniques begin to lose the accuracy at medium strain rates ($\dot{\epsilon} > 10/\text{s}$) and the special short loads cells [7] has to be used. For the high strain rates ($\dot{\epsilon} > 200/\text{s}$), it is very difficult to obtain reliable results using those devices.

2.2 Standard Split Hopkinson Pressure Bar test

For high strain rates, the Split Hopkinson Pressure Bar (SHPB) is a widely used experimental technique to study constitutive relationship of materials [8,9]. Rinde and Hoge [14,15] have performed tests on polymeric foams at high strain rates with SHPB.

A typical SHPB setup is composed of long input and output bars with a short specimen placed between them. The impact of the projectile at the free end of the input bar develops a compressive longitudinal incident wave $\varepsilon_i(t)$ (Figure 1). Once it arrives at the bar specimen interface, a reflected wave $\varepsilon_r(t)$ is developed in the input bar, whereas a transmitted wave $\varepsilon_t(t)$ is induced in the output bar. From those basic experimental data (incident, reflected and transmitted waves), forces and velocities at both faces of the specimen can be calculated.

$$\begin{aligned} F_{\text{input}}(t) &= S_b E_b (\varepsilon_i(t) + \varepsilon_r(t)) & \text{and} & & V_{\text{input}}(t) &= C_b (\varepsilon_i(t) - \varepsilon_r(t)) \\ F_{\text{output}}(t) &= S_b E_b \varepsilon_t(t) & & & V_{\text{output}}(t) &= C_b \varepsilon_t(t) \end{aligned} \quad (1)$$

where E_b , S_b , C_b denote Young's modules, cross sectional area and wave speed of the bar.

Taking into account the wave propagation effect in the loading frame, the SHPB test is then well adapted for the tests at high strain rates.

2.3 Special SHPB arrangement for foam testing

However, uses of the SHPB device for foam testing raise two technical difficulties. One consists of a too low impedance ratio between the foam specimens and metallic split bars. This leads then to imprecise measurements of the input force, output forces and output velocity. For example, Rinde and Hoge [14,15] have to use quartz crystals for the measurement of specimen stress, which are not sufficiently accurate at the early stage of loading so that it was not possible to measure the apparent Young modulus and the yield stress.

The use of low impedance bars which are generally viscoelastic is then proposed. Two 3m long Nylon bars of 40 mm of diameter (density 1200 kg/m³ and speed 1700 m/s) are used. It provides an improvement of about 20 times the impedance ratio, comparing to a classical steel bar (density being 7850 kg/m³ and wave speed 5000 m/s). Uses of viscoelastic bars in a SHPB setup introduces however the complications such as the wave dispersion in a viscoelastic bar [21], the calculation of stress and particle velocity from the measured strain and the projectile length limitations [25].

Another particular feature of foam testing is the need to achieve a large maximum strain (up to 80%) for the study of the densification, associated with a significant increase of the stress. Ordinary SHPB arrangements can not measure till such strains, even if such strains are easily reached because of the very low resistance of foams. Indeed, measuring technique using bars is based on the superposition principle which implies that the stress, the strain and the particle velocity at any cross-section can be considered as the algebraic sum of those values associated with

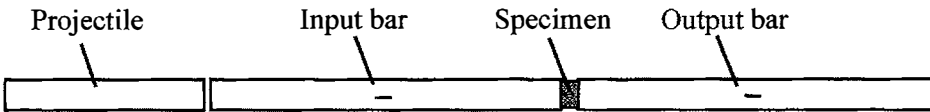


Figure 1 Classical SHPB arrangement.

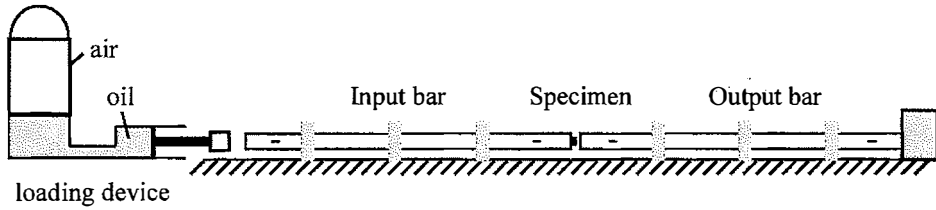


Figure 2 'Slow bar' arrangement.

the two elementary waves propagating in opposite directions at this cross-section (Equation 1). Such a technique requires then a separate recording of each single wave propagating in the bar. This is classically realized by using a long bar and a short pulse to insure the existence of a particular cross-section where those waves are not superimposed. The measuring duration of a given SHPB is then limited. To overcome this measuring limitation, one has to investigate the multiple reflections in bars [2]. A two-gauge method has been reported to separate the two waves in elastic bars [11] and viscoelastic bar [24]. This two gauges method provides an unlimited measuring duration and gives consequently sufficient maximum strain.

The use of such an unlimited measuring technique can be also applied to perform tests at medium strain rates (from 10 to 200 s^{-1}), provided that a suitable loading device is used. For example, Figure 2 shows an experimental arrangement called 'slow bar' bar [24] which uses the bars as measuring device and a high speed oil jack as loading device.

3 Some experimental results and phenomenological models

3.1 Testing results

With suitable techniques, the experimental data over a large range of strain rate can be then obtained. However, all those techniques just provide measurements of force, velocity or displacement at both faces of specimen (SHPB test) or sometimes only at one face of specimen (Standard machine, falling weight). One has to suppose that stress and strain fields in the specimen are homogeneous in order to deduce an average stress-strain relation.

Under this assumption, some general features of testing results are presented in the following. Most polymeric foams exhibit strong rate sensitivities. Their mechanical properties depend also on the temperature and moisture [6]. Typical rate sensitivity (at the constant temperature of 22°C) on a flexible foams (76 kg/m^3) used in automotive industry are shown in Figure 3. The specimen is a 40 mm diameter and 40 mm length cylinder. Quasi-static test has been performed at a constant speed of loading. Results at medium strain rates are obtained using the 'slowbar' technique. Finally, a Nylon Hopkinson bar provides results at high strain rates. At a strain rate of $250/\text{s}$, Standard Hopkinson bar gives 27% of strain. With the two-measurement method, the measured strain is increased up to 70%. The cyclical loading of the SHPB test is due to the round trip of wave in incident bar.

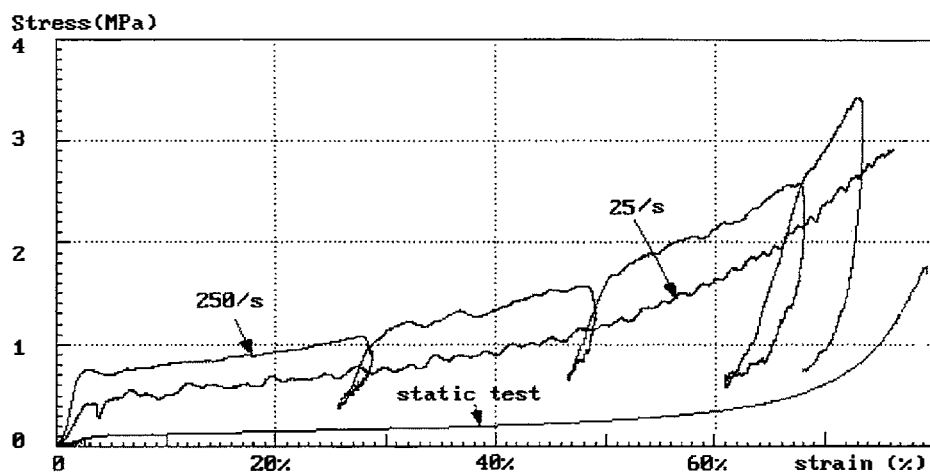


Figure 3 Typical testing results for static and dynamic strain rates.

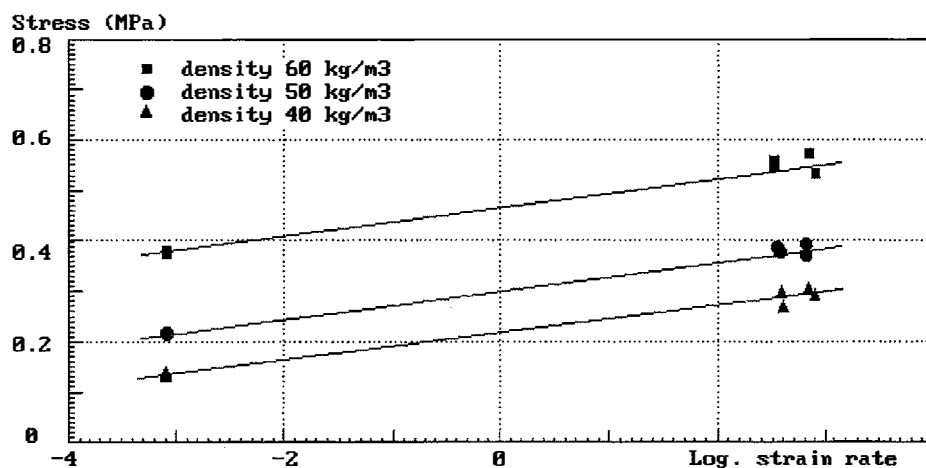


Figure 4 Influence of the density on the rate sensitivity.

The density of foams is an industrial parameter to adjust its properties. The experimental data obtained from presented testing arrangements shows that, at room temperature, static as well as dynamic stress levels increase with the density. However, the rate sensitivity is nearly the same for foams of different densities. Figure 4 shows the rate sensitivity of polyurethane rigid foams as a function of its density. It suggests that the rate sensitivity of foams mostly depends on the materials of which they are made.

Another interesting feature is the weak effect of the cell damage of foams, especially for the flexible foams. Figure 5 shows stress strain curves derived from three successive SHPB tests on the same sample (diameter 40 mm, length 20 mm, density 105 kg/m³) in the same testing condition (strain rate 325/s) within an interval

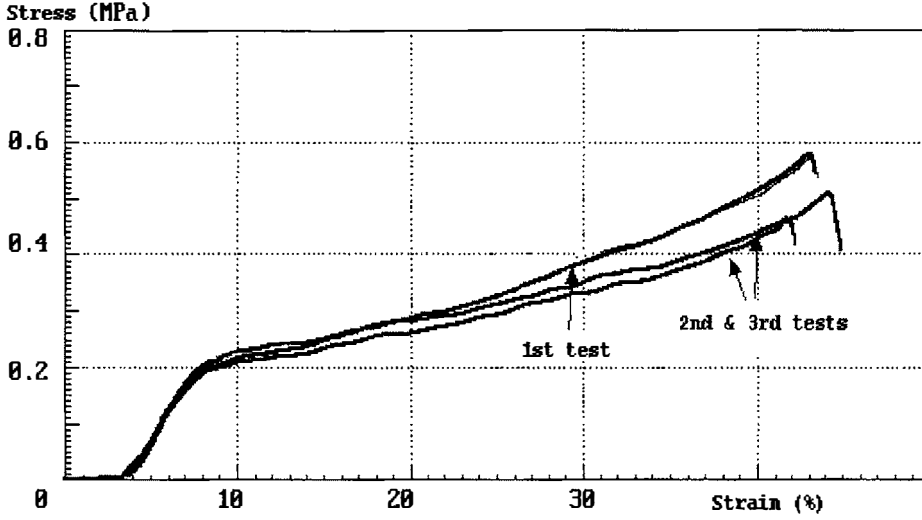


Figure 5 Foam cell damage effect.

of 15 minutes. The deformation of this kind of foams is mostly due to elastic bulking of the hollow polymeric structure.

3.2 Phenomenological modelling

A set of stress-strain responses of foams over a large range of strain rates makes their behaviour modelling possible. In the numerical simulation, one uses in general the phenomenological models rather than physical models deduced from micro-mechanical considerations [5,25]. It is probably because of the simplicity of phenomenological models. For instance, a simple model involving few coefficients but giving a satisfactory curve fitting is presented in the following.

Experimental observations in Section 3.1 give two indications. The absence of significant permanent deformation suggests a hyper elastic behaviour and the weak influence of the density on the rate sensitivity shows that the viscosity of foams is derived from that of the basic polymeric materials. The behaviour of foam is considered as the sum of an elastic part describing the progressive densification of the hollow polymeric structure and a viscoelastic part due to the viscosity of the elementary polymeric materials of which foams are made.

$$\sigma = \sigma_{\text{elas}} + \sigma_{\text{vis}} \quad (2)$$

The elastic part is modelled by a hyperbole where the parameter h is evidently the asymptote strain related to the initial foam porosity and k is a parameter having the same dimension as a stress (Equation 3).

$$\sigma_{\text{elas}} = \frac{k}{h - \varepsilon} \quad (3)$$

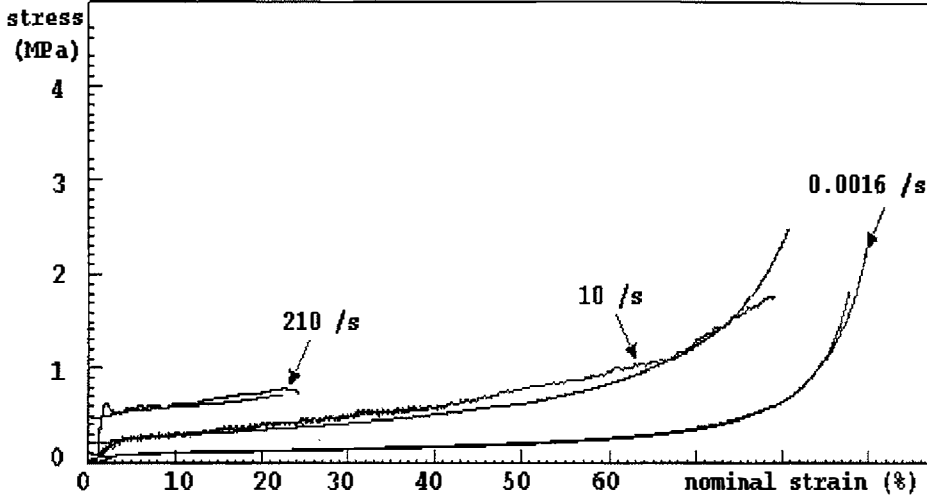


Figure 6 Experimental results on foams, Compared with a model.

The viscoelastic part is chosen as a usual power law, but multiplied by a term due to progressive densification of the hollow polymeric structure. The parameter h is the same asymptote strain and η is a parameter having a dimension of the stress (Equation 4). $\dot{\varepsilon}_0$ is the reference strain rate.

$$\sigma_{vis} = \frac{\eta}{h - \varepsilon} \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)^n \quad (4)$$

As it can be observed in Figure 6, this four-parameter model gives good results over a large range of strain-rates (where $h = 0.96$, $k = 0.7$ MPa, $\eta = 0.3$ MPa, $n = 0.21$, $\dot{\varepsilon}_0 = 0.0016/s$).

4 Discussions

4.1 Specific problems in analysing impact tests on foams

The experimental average stress-strain relation obtained above is significant only when the assumption of homogeneous stress and strain fields is verified. In order to check this hypothesis, a high-speed image acquisition device is used to observe the strain field of specimens during tests. This strain field is generally not axially uniform, at least at the early stage of the loading models [26]. Here, it is emphasized that this non-homogenous strain field is due to characteristics of some foam, independent of the experimental arrangement used in the test. In order to study the stress field in the specimen, additional load cell is needed in a test with a standard testing machine or a falling weight equipment. For a SHPB test where the forces at both faces are recorded, the input force could be about the twice of the output one at the early stage of the test models [22].

It is then proposed to use the superabundant measurement of the force as a tool to check if the assumption homogeneity can be used. On the one hand, when the difference between the two forces is small, the average stress-strain relation can be safely used. On the other hand, when this difference is quite significant, the superabundant measurement of the forces and particle velocities at both specimen faces can be used to produce the information on material behaviour in another way. Indeed, in order to obtain the material behaviour, an identification technique based on an inverse calculation method can be used in such cases, as used in the case of concrete and rocks models [22]. It is assumed that an appropriate form of the material behaviour is known, with parameters to be determined. Using a part of data as input data, (velocities for example), another part of data (the two forces) is used to determine those parameters that give the best fit between the measured and calculated forces. Theoretical analyses [1] show that this inverse technique can provide good results if an appropriate form of the material behaviour of foams is found.

4.2 3-dimensional characterisations

The testing and modelling of foams discussed above concerns only one-dimensional case whereas 3D models are needed for numerical calculations. A rather easy way to generalise one-dimensional model consists to use von-Mises equivalent stress-strain like in the classical plasticity theory. More theoretically pertinent models can be used, provided that complementary 3-dimensional testing data is available.

However, the most difficult tasks for behaviour characterization of foams lie in the 3-dimensional testing, especially at relative high strain rates. The usual testing method involving 3-dimensional effect can not be easily applied for foams. For example, in a simple shearing test, It would be very difficult to realize a good fixture for a very weak foam sample. A test under lateral confinements is also difficult. Indeed, one can neither apply an air nor an oil pressure on foams and one can not use a rigid ring confinement (friction being important comparing with the foam resistance and Poisson's coefficient very weak). In general, loading and boundary conditions in 3-dimensional tests for foams are not really known and controlled. In addition, for high strain rates, the wave propagation effects in the sample make the stress and strain fields non-homogeneous.

Most reported investigations use an inverse identification technique. They try to determine parameters of a given model, using a sophisticated 3-dimensional test. It would be better, in author's opinion, to perform simpler 3D tests in which the measuring precision can be well controlled, because identifications by an inverse method are very sensitive to the noises of the measurement [1].

For this purpose, a double-side indentation of a 60 mm diameter foam specimen (length 36 mm) is performed with a SHPB arrangement of 40 mm diameter (Figure 7). The advantage of such tests lies in their simplicity so that no supplementary interface is needed. It is consequently certain that the difference between this test and compression one is due and only due to foam properties.

Figure 8 shows the comparison between stress-strain curves obtained from indentation tests and compression ones. A difference of about 30% of the stress level is found at the same testing condition. In addition, differences between those two

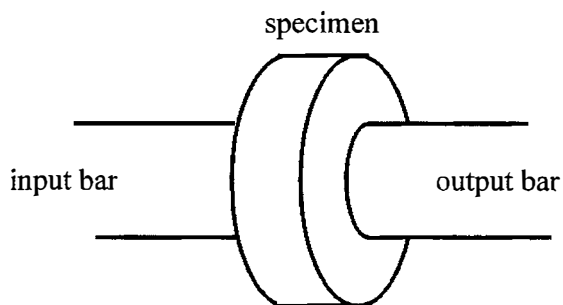


Figure 7 Double indentation test arrangement.

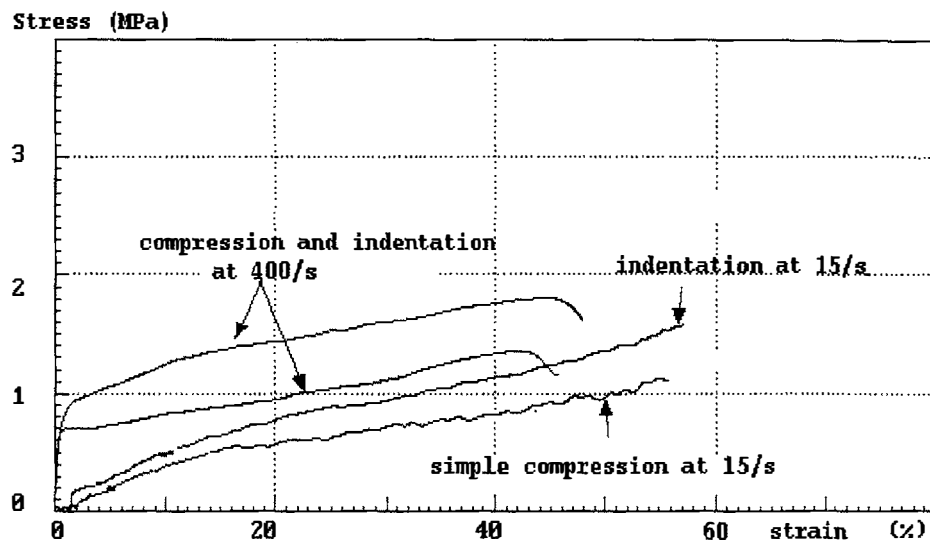


Figure 8 Comparison between indentation and compression tests.

kinds of tests vary with the strain rate, which indicate that the 3-dimensional feature is not independent of the strain rate effect.

5 Conclusion

In this paper, different experimental arrangements for the testing of polymeric foams over a large range of strain rates have been discussed. It is shown that Split Hopkinson bar technique gives accurate results, provided that a special processing is applied for the signals recorded at two points of each bar. With a special 'slow bar' arrangement, it is also possible to test foams at medium strain-rates (from 10 to 200 s^{-1}).

The knowledge of the response of foams over a large range of strain-rates makes its constitutive modelling possible. A rather simple phenomenological constitutive model correctly describes their one-dimensional behaviour.

In order to determine parameters of 3-dimensional models by an inverse method, one has to perform well-controlled 3-dimensional tests. For this purpose, an indentation test is proposed, using SHPB bar techniques.

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