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Dynamic testing of fibre polymer matrix composite plates under in-plane compression

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Experimental investigations of the failure strength of fibre reinforced polymer matrix composite plates under compressive impact loading is presented in this paper. A split Hopkinson pressure bar (SHPB) is used to measure these properties. The specimen being a plate, its cross-sectional area is small compared with the area of the bars and the failure strength is weak. One has to then use low impedance bars made of a viscoelastic material. Subsequent experimental problems, such as dispersion corrections in viscoelastic bars, are analysed. One also has to use a special anti-buckling device to prevent the overall buckling of the specimen. It is shown that the presented SHPB system provides a precise measurement of forces and displacements at both ends of the specimen. A special attention is then given to the analysis of the test, especially in situations where a non-homogeneous state of stress in the specimen in observed.

Keywords: Dynamic testing; A. Polymer-matrix composites

1. Introduction

Compressive failure is a design limiting feature of fibre polymer matrix composite plates as it is always much less than the tensile one. Recent research indicates that this decrease is mostly due to a localised compressive plastic buckling. A review of these problems is given by Budiansky and Fleck [1], mainly concerning studies on the compressive failure strength of composite plates under quasi-static loading.

As the fibre polymer matrix composite is going to be involved in dynamic loading situations, compressive failure strengths under impact loading are required. In the crash situation of automobiles, composite plates, when used, are indeed submitted to an in-plane compressive impact loading.

For fibre reinforced composite plates, most studies at high strain rates report the strength of the composite plates under transverse localised impact or piercing behaviour [2–4]. It corresponds to the most frequently found situations. Meanwhile, other tests to determine the energy absorbing capacity or the tensile impact behaviour are also reported [5,6]. A review of works in this field has been written by Cantwell and Morton [7]. As indicated by Cantwell and Morton, there are no standard impact tests for composites because it is hardly possible to predict their behaviour from one type of loading to another.

The plates to be studied were provided by a car company. The aim of our study was to evaluate their capability to absorb energy in a crash situation where they were loaded in compression. Therefore, the experiment is performed in a condition similar to the real application.

This paper presents a testing method specially developed to measure the compressive failure strength of composite plates using a viscoelastic split Hopkinson pressure bar (SHPB). Some experimental results for glass fibre polymer matrix composites are shown to illustrate the validity of the used technique.

2. Impact test measurement techniques

To test composite plates under impact, there are various testing configurations [7]. For relative low strain rates, Charpy or Izod pendulum tests, drop-weight test and rapid servo-hydraulic machine can be used. On the contrary, in the range of high strain rates, SHPB or gas gun impact tests are employed. To perform a compressive failure test, all

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those configurations could be used. The pendulum test is significantly accurate mainly for the measurement of the energy absorption. Signals obtained with drop-weight impact tests or servo-hydraulic machine tests often contain perturbations due to the vibration of the testing machine [8]. It has been proved that, for instance, those measurements depend on the location of the sensors [9,10].

An adequate measurement technique for impact loading is the Hopkinson bar, which is a widely used experimental technique to study constitutive laws of materials at high strain rates [11,12]. The SHPB test has gained a great popularity in the past decades and many works have contributed to improve the accuracy of the set-up [13,14] and to extend the technique to the tensile (by Harding et al. [15]) and to the torsional loading (by Duffy et al. [16]). The three-dimensional effects in the specimen such as radial inertia and friction have also been studied by Davies and Hunter [17], and more recently by Malinowski and Klepaczko [18]. These corrections are in agreement with a two-dimensional numerical simulation by Bertholf and Karnes [19]. The assumption of the homogeneous state in the specimen has also been critically analysed by means of the transient wave simulation by Jahsman [20] and by Gary and Zhao [21].

For composite specimens having a cylindrical form, the SHPB technique has already been used in tension or in compression [22,23]. To perform a compressive impact test on plates with SHPB, some specific difficulties such as low impedance specimen effects or prevention of buckling effects will be solved.

3. Use of SHPB technique

3.1. Classical SHPB analysis

A SHPB set-up is composed of long input and output bars with a short specimen placed between them (Fig. 1). By the impact of a projectile at the free end of the input bar, a compressive longitudinal incident wave $\epsilon_i(t)$ in the input bar is developed. This incident wave will induce a reflected wave $\epsilon_r(t)$ in the input bar and a transmitted wave $\epsilon_t(t)$ in the output one. With strain gages cemented on the two bars, one can record those three waves, which allow for the determination of the forces and particle velocities at both faces of the specimen.

Assuming that F_{input}, F_{output}, V_{input},V_{output} denote forces and particle velocities at the specimen-bar interfaces and S_B, E and C_0 are, respectively, the cross-section of the bars, Young's modulus, and the longitudinal wave speed, the following equations are used to obtain forces and velocities at both ends of specimen:

$$\begin{aligned} F_{\text{input}}(t) &= S_B E[\epsilon_i(t) + \epsilon_r(t)] \quad & V_{\text{input}}(t) &= C_0[\epsilon_i(t) - \epsilon_r(t)] \\ F_{\text{output}}(t) &= S_B E \epsilon_t(t) & V_{\text{output}}(t) &= C_0 \epsilon_t(t) \end{aligned} \tag{1}$$

In order to obtain the stress–strain curve of the specimen from the forces and the velocities at both specimen faces, the classical analysis is based on the hypothesis of the homogeneity of stresses and strains within the specimen. The result is in the form of the following equations:

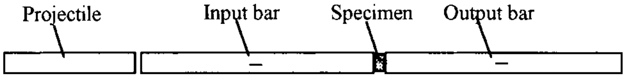

Fig. 1. SHPB set-up.

$$\dot{\epsilon}_s = \frac{V_{\text{output}}(t) - V_{\text{input}}(t)}{l_s} = -\frac{2C_0\epsilon_r(t)}{l_s} \tag{2a}$$

$$\epsilon_s = -\int_0^t \frac{2C_0\epsilon_r(\tau)}{l_s}\, d\tau \tag{2b}$$

$$\sigma_s(t) = \frac{F_{\text{output}}}{S_s} \tag{2c}$$

where l_s is the length of the specimen and S_s is the cross sectional area of the specimen.

3.2. Limitations of the classical analysis

The assumption of the homogeneity of stresses and strains within the specimen is obviously not correct at the early stage of the test due to the transient effects: the loading starts at one face of the specimen whereas the other face remains at rest. When low impedance materials are tested, the time for the waves to travel through the specimen becomes longer. Moreover, when viscoelastic materials are tested, this effect is increased and the use of an inverse method can be necessary to find a constitutive model for the material tested [21,24]. As it will be seen further in Fig. 5, such a situation occurs for the testing of fibre reinforced polymer plates. The independent measurement of the input and output forces is then needed.

3.3. Viscoelastic SHPB set-up

The tested plates have a small cross sectional area compared with the area of the bars because of their small thickness. As the material strength is also weak, the compressive crushing failure strength is small. To use the SHPB technique to measure it, one must overcome a major difficulty. Indeed, when the force in the specimen is small compared to the force associated with the incident wave, the transmitted wave will be weak, and one has to use a more sensitive measuring device to amplify the signal. On the contrary, $\epsilon_r(t)$ is almost equal to $-\epsilon_i(t)$ according to Eq. (1). The input force then cannot be precisely measured because the difference of two almost equal values is nearly zero. The use of common metallic bars to test composite specimens is then difficult, even when the specimen is cylindrical and has the same cross sectional surface as the bar, as shown by Griffiths and Martin [22,23]. Thus, an SHPB set-up made of a low impedance material is needed, for example, PMMA or nylon bars.

These polymeric low impedance bars always demonstrate a viscoelastic behaviour. As compared with a conventional SHPB, the use of viscoelastic bars in a SHPB set-up introduces the following complications. The first is due to the wave dispersion in a viscoelastic bar. The second concerns the calculation of stress and particle velocity from the measured strain.

The wave dispersion in an elastic bar has been studied by Davies [25]. On the basis of the Pochhammer and Chree's longitudinal wave solution for an infinite cylindrical elastic bar [26,27], a dispersion correction has been proposed. Even though the Pochhammer–Chree solution is not exact for a finite bar, it is easily applicable and sufficiently accurate for long bars. Such a correction is then accepted and applied by many authors [28,29].

This approach is extended to the case of viscoelastic bars [30,31]. The solution of this equation gives a dispersive relation between wave number ξ and frequency ω. Once the dispersive relation is known, one can calculate the wave propagated at a distance Δz, $u_z^{\mathrm{p}}(t)$, from the measured wave $u_z^{\mathrm{m}}(t)$ as follows

$$u_z^{\mathrm{p}}(t) = \mathrm{FFT}^{-1}\{\mathrm{e}^{\mathrm{i}\xi(\omega)\Delta z}\mathrm{FFT}[u_z^{\mathrm{m}}(t)]\} \qquad (3)$$

Such a correction is very important, especially when dealing with viscoelastic bars. In our case, the input bar is 40 mm in diameter and 3 m long. Fig. 2a and b illustrates this point in the case of a test without specimen where the equality of input and output forces has to be checked. The result without dispersion correction shows a significant gap between both forces.

The forces and the particle velocities associated with a viscoelastic wave can be calculated after the strain using the Fourier analysis. When the constitutive relation (complex modulus) of the bar is known, the stress and the particle velocity are derived from the strain in the frequency domain by using the Fourier coefficients [31].

3.4. Validation of the method

In order to give an experimental demonstration of the accuracy of the method, we put a Nylon bar and an aluminium bar in contact so that the force and the particle velocity at the interface measured by those two bars should be the same. Since the measurement by an aluminium bar is considered reliable, the precision of measurement with the Nylon bar can be then evaluated [31]. The comparison of the two measurements is shown in Fig. 3a and b. This experiment provides also a global verification of the validity of the use of viscoelastic bars.

3.5. Anti buckling device

As mentioned by Budiansky and Fleck [1], the most frequent mode of compression failure for composite plates is the localised plastic buckling. The experimental aim is then to determine the failure strength of the studied composite plate in this mode of failure. Therefore, other modes of failure should be avoided in the test.

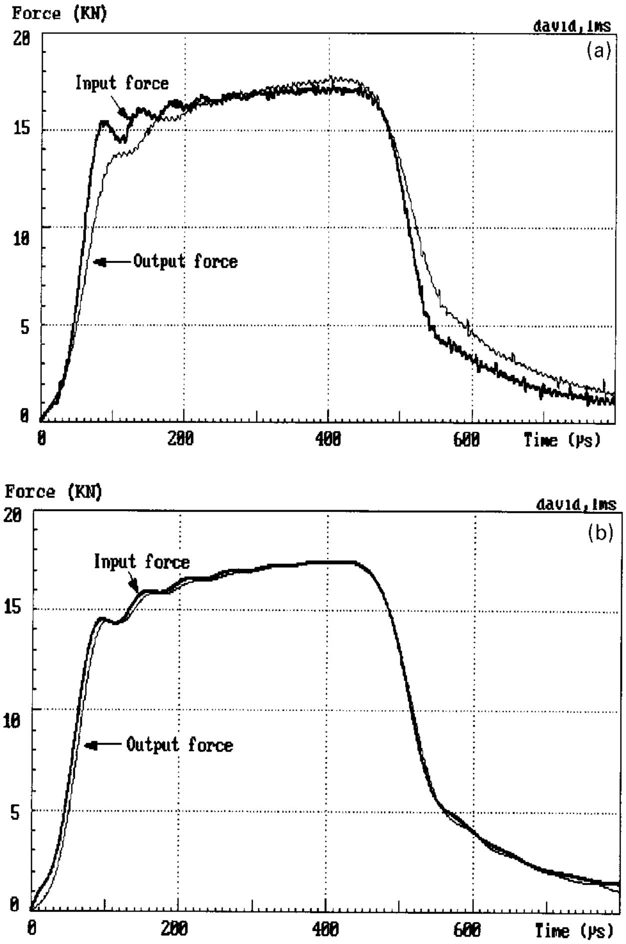

Fig. 2. (a) Input and output forces without dispersion correction. (b) Input and output forces with dispersion correction.

The composite plate is not attached to the bar in order to prevent the perturbations of measurements due to additional interfaces [5,6,22,23]. It is then just in contact with the bars which actually increase the probability of elastic buckling. To eliminate these effects, honeycomb structures are used as complementary supports (Fig. 4). These structures are just placed in contact with the plates so that they can induce a reaction to prevent overall elastic buckling. Since their stiffness is very weak in the direction of the bars, they cannot perturb the axial measurements made with the SHPB set-up.

4. Experimental results

4.1. Imperfect equilibrium

The material to be tested is an industrially made glass/epoxy composite plate of 3 mm thickness. The details of the manufacturing process and the exact fibre volume fraction have not been given by the providers. Square specimens

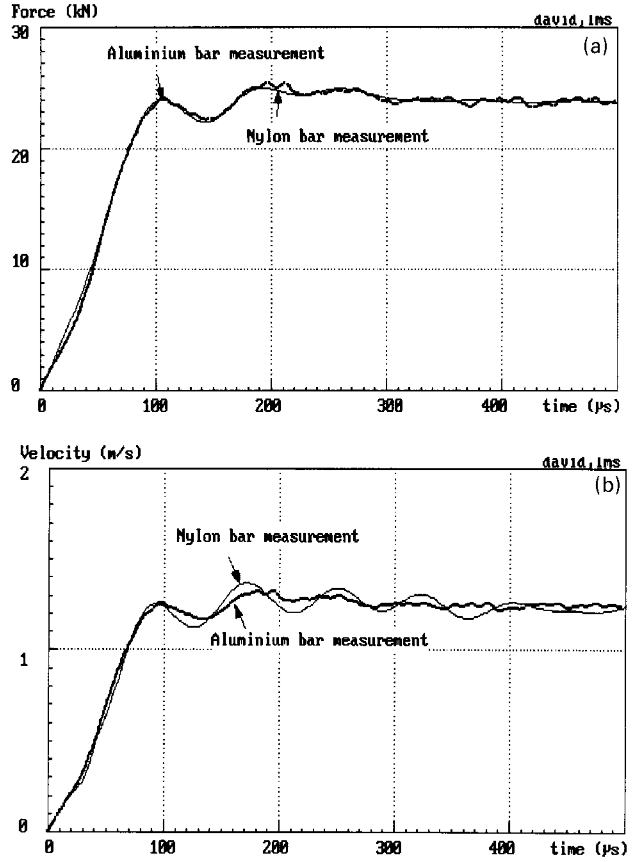

Fig. 3. (a) Impact Nylon bar–Aluminium bar: comparison between force measurements of Nylon bar and that of aluminium bar. (b) Impact Nylon bar–Aluminium bar: comparison between velocity measurements of Nylon bar and that of aluminium bar; the precision of the measured velocity is less good than that of the force because it is proportional to the difference between incident wave and reflected wave (which are two great values of same sign in this configuration) whereas the force is the sum.

36mm × 36mm are cut from it. Using the viscoelastic SHPB made of PMMA (Young's modulus being about 6×10^9 MPa), forces and velocities at both ends of the specimen are measured. A typical result is illustrated in Fig. 5.

The hypothesis of homogeneous stress and strain fields along the specimen is not exactly verified. Indeed, as the input force and the output force are not equal (Fig. 5) the stress field cannot be uniform along the specimen length. Such an observation has been confirmed by high-speed photography in a similar situation [31]. To obtain an accurate and detailed interpretation of the measurements (forces and velocities), a transient calculation using a failure model must be performed following the inverse calculation technique [21,24] used for concrete [33,34] and polymers [32]. Such a calculation could explain, for instance, the unusual observation of the output force becoming greater than the input one after a short time (at point A, Fig. 5). This point could be related to the damage initiation in the composite plate.

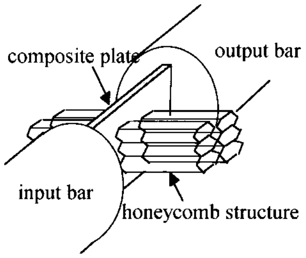

Fig. 4. Detail of the experimental anti-buckling device.

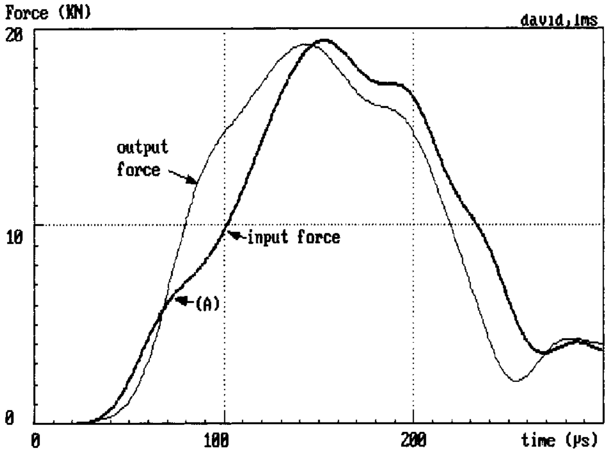

Fig. 5. Input and output forces of a SHPB test on a composite plate.

4.2. Simplified analysis

For an industrial application, and considering that the deviation from equilibrium is not very important, using the conventional analysis (Eqs. (2a), (2b) and (2c)—where the average force is set equal to the output force—is sufficient to study the influence of the strain-rate on the mean response of the plates. A typical result is shown in Fig. 6. It is seen on this figure that the strain rate is not constant during the test. It is assumed that failure occurs when the force starts decreasing. Then, the reference strain-rate for the test will be conventionally taken as the maximum value of the strain rate obtained before failure. In the example of Fig. 6, this value equals 282/s.

The composite plates exhibit a non-linear behaviour with a strain-rate sensitivity (Fig. 7). To confirm the strain rate effect, quasi-static tests in compression have been done. The tests have been performed with a "Instron" standard testing machine using the same anti-buckling device and same specimens as for dynamic tests. The loading rate, equal to 0.5 mm/min, corresponds to a strain rate of $2.3\ 10^{-4}$/s. It is observed, in Fig. 8, that the influence of the fibre direction does not depend on the loading rate and that the strain-rate effect increases more rapidly when the loading is in the fibre direction (0°).

5. Conclusions

Experimental results on the compressive failure strength

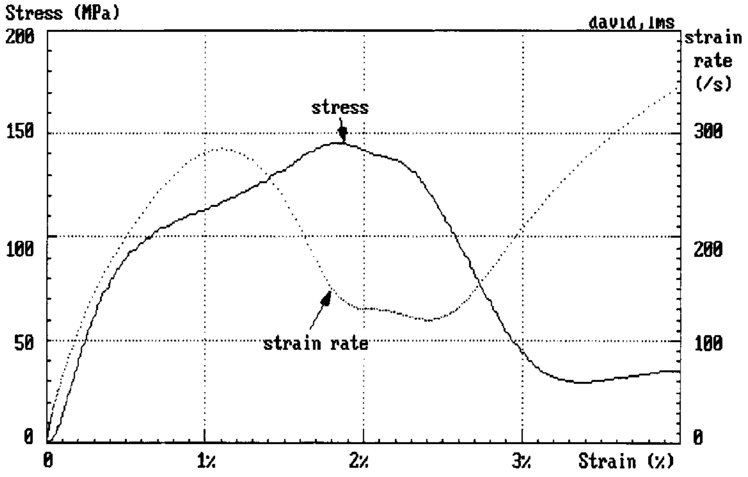

Fig. 6. Stress and strain rate vs. strain for a SHPB test on a composite plate.

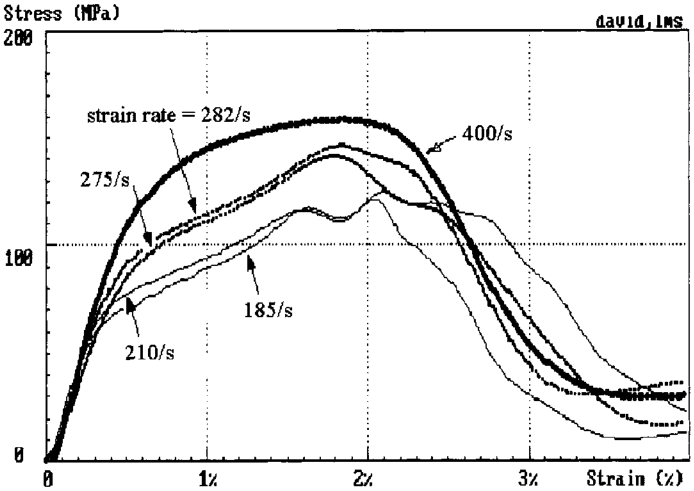

Fig. 7. Stress–strain responses of composite plates under various loading rates. The failure strength increases with the strain rate.

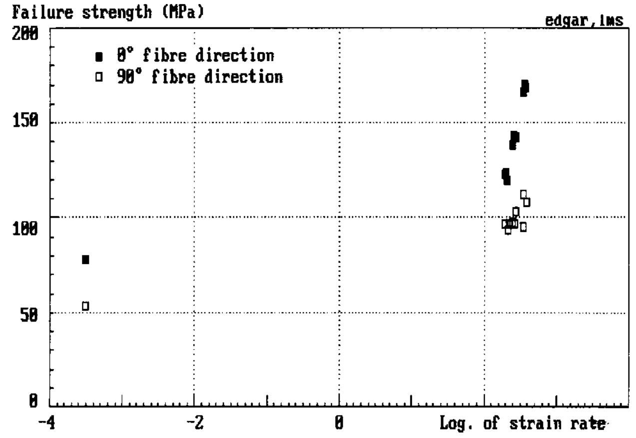

Fig. 8. Influence of strain rate on the failure strength of composite plates under dynamic compression.

of glass fibre epoxy matrix composite plates under dynamic loading are analysed. It is shown that the use of a viscoelastic SHPB set-up is an indispensable technique to obtain accurate measurement under an in-plane impact loading when low impedance specimens are used. The situation is especially critical for reinforced polymer matrix composite showing a relatively low failure strength. In particular, the measurement of both input and output force is made possible.

It is observed that the failure strength is rate sensitive and that the fibre orientation has an influence on the failure strength.

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