ELSEVIER

PII: S0266-3538(96)00117-0

Composites Science and Technology 57 (1997) 287-292

0266-3538/97/$17.00

AN EXPERIMENTAL INVESTIGATION OF COMPRESSIVE FAILURE STRENGTH OF FIBRE-REINFORCED POLYMER-MATRIX COMPOSITE PLATES UNDER IMPACT LOADING

Han Zhao & Gérard Gary

Laboratoire de Mécanique des Solides, Ecole Polytechnique, 91128 Palaiseau, France

(Received 22 May 1996; revised 19 August 1996; accepted 30 August 1996)

Abstract

This paper presents an experimental investigation on the compressive failure strength of fibre-reinforced polymer-matrix composite plates under impact loading. A new viscoelastic split Hopkinson pressure bar (SHPB) is used to measure those properties. Experimental problems such as dispersion corrections in viscoelastic bars are analysed. Significant increases of the compressive failure strength with the strain rate are found. It is also observed that the failure strength is sensitively higher when the loading is in the fibre direction. It is then in agreement with theoretical and experimental results under quasi-static loading. © 1997 Elsevier Science Limited. All rights reserved

Keywords: viscoelastic SHPB, rate sensitivity, failure strength, fibre-reinforced composite, dynamic testing

1 INTRODUCTION

The compressive failure is a design limiting feature of polymer-matrix fibre composite plates. For example, the compressive strength is always much less than the tensile strength. Recent researches indicate that this decrease is due to a failure in which the dominant mode is localised compressive plastic buckling. An extensive review of those problems is given by Budiansky and Fleck.[1]

Most studies on the compressive failure strength of composite plates concern quasi-static loading. As the polymer-matrix composite is going to be involved in dynamic loading situations, compressive failure strengths under impact loading are often required to be taken into account in designs. Typically, in automobile crashes, the composite plates, when used, are subjected to a compressive impact loading.

The impact resistance of composite materials has been the subject of much research work. 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] which corresponds to the most frequently found situations. Other tests to determine the energy-absorbing capacity or the tensile impact behavior have also been reported.[5,6] An excellent review of work in this field has been published by Cantwell and Morton.[7] As indicated by them, there are no standard impact tests for composites because it is hardly possible to predict their behaviour from one type of loading to another. Therefore, one should try to perform experiments under conditions similar to those of the real application, and it is thus necessary to perform compressive impact tests to obtain the failure strength.

This paper presents an original testing method to measure the compressive failure strength of composite plates by using a viscoelastic split Hopkinson pressure bar (SHPB). Some initial comparative results for glass-fibre/polymer-matrix composites with different fibre directions are presented.

2 IMPACT TEST MEASUREMENT TECHNIQUES

To test composite plates under impact, there are various possible testing configurations.[7] For relatively low strain rates, Charpy or Izod pendulum tests, drop-weight tests, and rapid servo-hydraulic machines can be used. On the other hand, in the range of high strain rates, SHPB or gas-gun impact tests are employed. To perform a compressive failure test, all of these configurations could be used. However, the measuring technique is more or less well adapted. The pendulum test is reasonably accurate mainly for the measurement of energy absorption. Signals obtained with drop-weight impact tests or servo-hydraulic machine tests often contain perturbations which are due to the vibration of the testing machine.[8] It has been proved for instance that 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 for studying the constitutive laws of materials at high strain rates.[11,12] The SHPB test has gained a great popularity in the past decade and many pieces of research work have contributed to improving the accuracy of the setup.[13,14] This technique for fast compression tests has been extended to tensile loading 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 been also studied. Corrections have been proposed by Davies and Hunter,[17] and more recently by Malinowski and Klepaczko.[18] A two-dimensional numerical simulation by Bertholf and Karnes[19] gives a general verification of those corrections. The assumption of the homogeneous state in the specimen has been also critically analysed by means of the transient wave simulation by Jahsman[20] and by Gary and Zhao.[21]

The split Hopkinson pressure bar technique has been adapted to tests of composite materials to obtain mechanical properties in tension or in compression. However, specimens used in compression have a cylindrical form.[22,23] To perform a compressive impact test with SHPB, some specific difficulties such as low impedance specimen effects or prevention of buckling effects must be solved (see below).

3 USE OF SHPB TECHNIQUE

3.1 Classical SHPB analysis

A SHPB setup is composed of long input and output bars with a short specimen placed between them. 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 the specimen:

$$F_{\text{input}}(t) = S_B E(\epsilon_i(t) + \epsilon_r(t)) \quad V_{\text{input}}(t) = C_0(\epsilon_i(t) - \epsilon_r(t))$$

$$F_{\text{output}}(t) = S_B E \epsilon_t(t) \quad V_{\text{output}}(t) = C_0 \epsilon_t(t) \tag{1}$$

In order to obtain the stress–strain curve of the specimen from the forces and the velocities at both specimen faces, the simplified analysis is limited to the hypothesis of the homogeneity of stresses and strains within the specimen. The result is in the form of eqn (2)

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

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

An improved analysis consists of using the average of the two forces in the calculation of the stress.

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

3.2 Viscoelastic SHPB setup

To use the SHPB technique to measure the compressive failure strength, one must overcome a major difficulty, which consists in too low a specimen/bar impedance ratio.

Considering a purely elastic specimen as an example, the reflected wave and the transmitted one can be calculated from the incident wave by using the following relationships:

$$\epsilon_r(t) = \frac{1-r}{1+r}\epsilon_i(t), \quad \epsilon_t(t) = \frac{r}{(1+r)^2}\epsilon_i(t)$$

with

$$r = S_s\rho_s C_s / S_B \rho_B C_B \tag{3}$$

where S_B, ρ_B, C_B and S_s, ρ_s, C_s are, respectively, the cross section, the density and the wave speeds of the bar and of the specimen. r is the impedance ratio.

If the specimen impedance is too small compared with the impedance of the bars, the transmitted wave will be weak, and one has to use a more sensitive measuring device to amplify the signal. On the other hand, $\epsilon_r(t)$ is almost equal to $-\epsilon_i(t)$ according to eqn (3). The input force cannot be then precisely measured because of the difference of two almost equal values and there is no way to improve that. In the case of testing polymer-matrix composite plates, the use of metallic bars leads to too low a ratio of impedances. Even when the cylindrical specimen has the same cross-sectional surface as the bar, the impedance ratio is low because of the material difference, as shown by Griffiths and Martin.[22] Thus, the SHPB setup made of a low-impedance material is needed, for example PMMA or Nylon bars. These low-impedance bars always exhibit viscoelastic behaviour. As compared with a conventional SHPB, the use of viscoelastic bars in a SHPB setup introduces the following complications. The first is due to the wave dispersion in a viscoelastic bar, and the second concerns the calculation of stress and particle velocity from the measured strain. Finally, the projectile length limitation is not the same as in the elastic case.

The wave dispersion in an elastic bar has been studied by Davies.[24] On the basis of the Pochhammer and Chree longitudinal wave solution[25,26] for an infinite cylindrical elastic bar, 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.[27,28] They also have shown that the effect of geometry cannot be neglected, except for very thin bars.

Assuming that the exact solution for the harmonic wave propagation in an infinite linear viscoelastic rod can be represented by a combination of harmonic waves for all frequencies, the complete 3D analysis of a linear viscoelastic infinite bar leads to the frequency equation. The solution of this equation gives a dispersive relation between wavenumber ξ and frequency ω.[29]

Once the dispersive relationship is known, one can calculate the wave propagated $u_z^p(t)$ at a distance Δz from the measured wave $u_z^m(t)$ as follows.

$$u_z^p(t) = FFT^{-1}[e^{i\xi(\omega)\Delta z} FFT[u_z^m(t)]] \tag{4}$$

The forces and particle velocities associated with a viscoelastic wave can be calculated from the strain by means of Fourier analysis. When the constitutive relationship (complex modulus) of the bar is known, one can find the Fourier coefficients of the stress and of the particle velocity.

If a viscoelastic projectile is used together with a viscoelastic SHPB setup, a very substantial time extension of the incident wave, in comparison to the duration of an equivalent elastic one, is observed. It is then indispensable to use a shorter projectile and this will reduce significantly the maximum strain imposed on the specimen.[30]

4 EXPERIMENTAL

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

The contact conditions between the composite plate and the bars could induce a dispersion of the results. 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 and the probability of elastic buckling is increased with such supporting conditions. To eliminate those effects, the chosen solution is to use honeycomb structures as complementary supports (Fig. 1). Those structures are just placed in contact with the plates so that they can induce a reaction to prevent the 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 setup.

The material to be tested is an industrially made glass/epoxy composite plate of 3 mm thickness. Square specimens 36 mm × 36 mm are cut from it. By using the viscoelastic SHPB made of PMMA (Young's

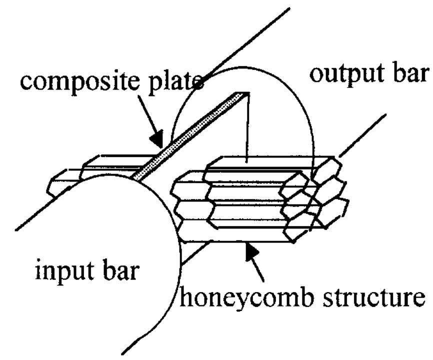

Fig. 1. Detail of the experimental device.

modulus being about 6×10^9 MPa), forces and velocities at both ends of the specimen are measured. By means of the conventional analysis (eqn (2)) the average stress and strain rate can be calculated. A typical result is shown in Fig. 2.

The composite plates exhibit an apparent elastic–plastic behaviour before failure and they give a response like that of metal beams under impact compression for which a buckling model under impact has been developed.[31] A similar model used for those tests indicates that only local buckling can occur. Experimental results in the fibre direction (0°) are shown in Fig. 3. The increase of the failure strength with the strain rate is observed.

5 INFLUENCE OF THE FIBRE DIRECTION

The compressive failure model of Budiansky and Fleck[1] indicates a failure strength dependent on the fibre direction. In order to investigate the influence of the fibre orientation, impact tests are done in the fibre direction (0°) and in the direction perpendicular to the fibre (90°) for one-directional fibre plates. Similar results as shown in Fig. 3 have been obtained in the direction perpendicular to the fibre (90°).

The fibre direction does indeed have an influence on the failure strength. A significantly higher failure strength is obtained in the fibre direction (0°) in quasi-static and dynamic cases (Fig. 4). This is in agreement with theoretical results.[1] It shows also that the failure strength in the fibre direction (0°) is more rate sensitive than that in the direction perpendicular to the fibre (90°).

The results presented above are calculated from the classical SHPB analysis (eqn (2)). The use of such an analysis is correct when the stress and strain fields are homogeneous. This hypothesis is not exactly verified as it can be seen on the example in Fig. 5. To obtain a more accurate and detailed interpretation of the measurements (forces and velocities), a transient calculation using a failure model must be performed. 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

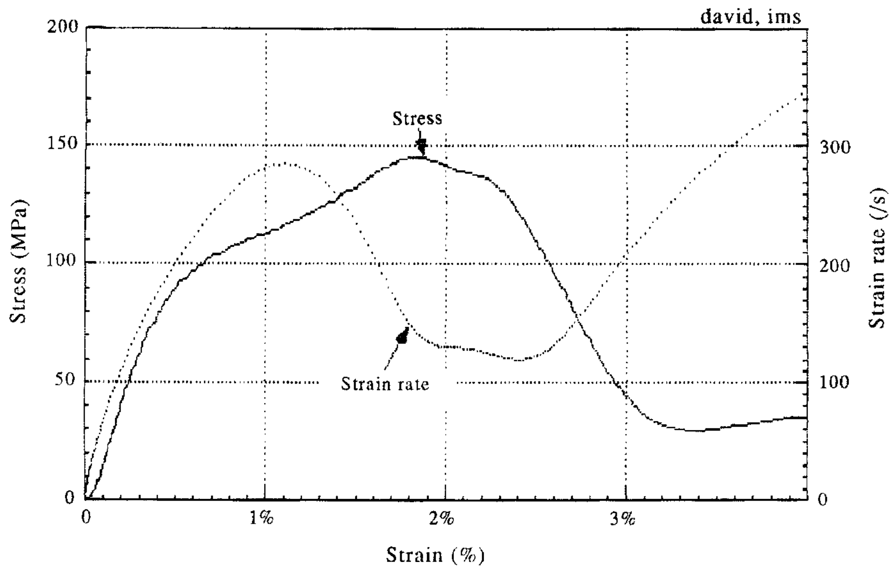

Fig. 2. Stress and strain rate versus strain.

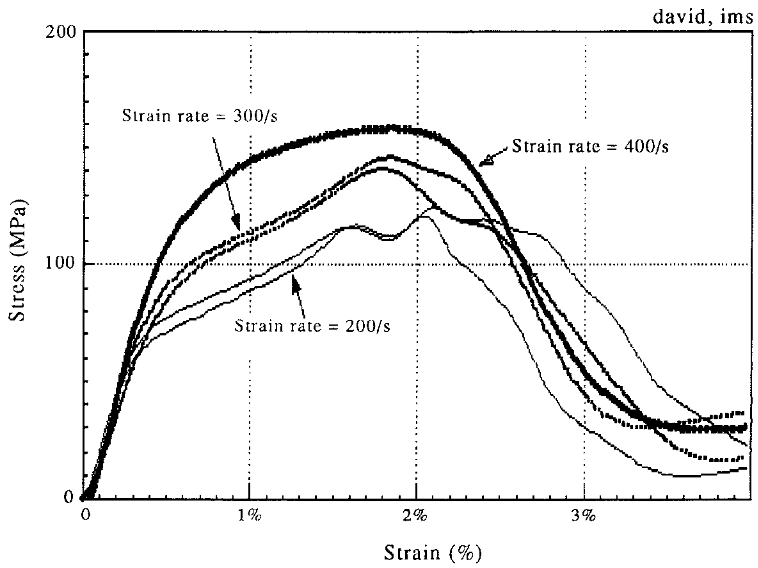

Fig. 3. Influence of strain rates.

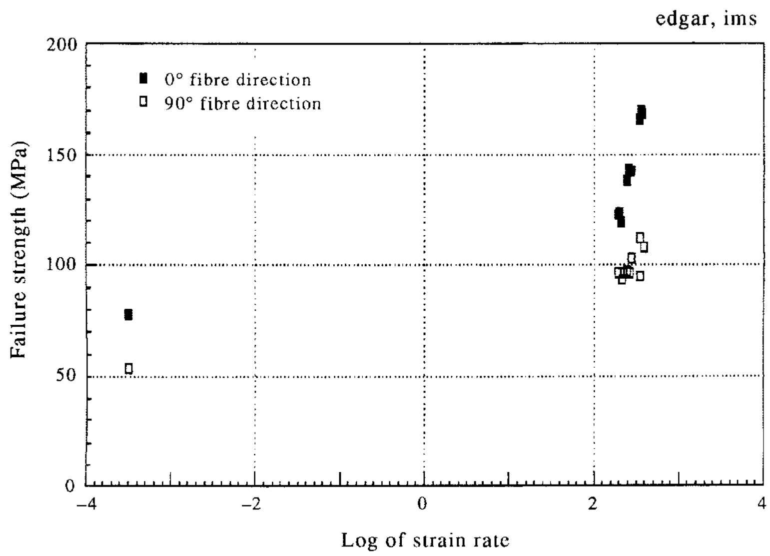

Fig. 4. Failure strength versus strain rates.

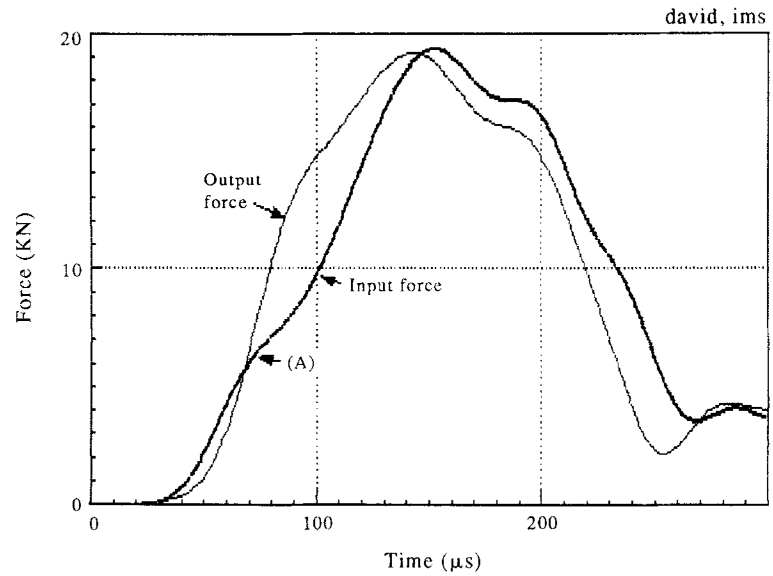

Fig. 5. Input and output forces.

A, Fig. 5). This point could be related to the damage initiation in the composite plate.

6 CONCLUSIONS

The use of a viscoelastic SHPB setup allows for the measurement of the compressive failure strength of fibre-reinforced polymer-matrix composite plates. This experimental technique is indispensable to obtain an accurate measurement under impact loading when low impedance specimens are used. In particular, the measurement of the input force shows that the classical analysis can be improved.

Experimental results on the compressive failure strength of glass-fibre/epoxy-matrix composite plates under dynamic loading are analysed. It is observed that the failure strength is rate sensitive. As predicted by the theory used for quasi-static loading, it is also found that the fibre orientation has an influence on the failure strength.

REFERENCES

1. Budiansky, B. & Fleck, N. A., Compressive failure of fibre composites. *J. Mech. Phys. Solids*, **41** (1993) 183–211.
2. Davies, C. K. L., Turner, S. & Williamson, K. H., Flexed plate impact testing of carbon fibre-reinforced polymer composite. *Composite*, **16** (1985) 279–285.
3. Liu, D. & Malvern, L., Matrix cracking in impacted glass/epoxy plate. *J. Compos. Mater.*, **21** (1987) 595–609.
4. Glinicki, M. A., Vautrin, A., Soukatchoff, P. & Brazier, J. F., Plate impact testing method for GRC materials. *Cement & Concrete Compos.*, **16** (1994) 241–251.
5. Harding, J. & Welsh, L. M., A tensile testing technique for fibre-reinforced composites at impact rates of strain. *J. Mater. Sci.*, **18** (1983) 1810–1826.
6. Harding, J., Impact damage in composite materials. *Sci. Engng Compos. Mater.*, **1** (1989) 41–68.
7. Cantwell, W. J. & Morton, J., The impact resistance of composite materials—A review. *Composite*, **22** (1991) 347–362.
8. Beguelin, P. & Barbezat, M., Caractérisation mécanique des polymères et composites à l'aide d'une machine d'essai rapide, *Proc. 5th Journée Nationale Dymat*, France, 1989.
9. Tan, T. M. & Sun, C. T., Use of statical indentation laws in the impact analysis of laminated composite plates. *J. Appl. Mech.*, **52** (1985) 6–12.
10. Genin, D., Endommagement de plaques composites sous sollicitation de choc. PhD thesis, Université Claude Bernard-Lyon I, Lyon, 1993.
11. Hopkinson, B., A method of measuring the pressure in the deformation of high explosives by the impact of bullets. *Phil. Trans. Roy. Soc.*, **A213** (1914) 437–452.
12. Kolsky, H., An investigation of mechanical properties of materials at very high rates of loading. *Proc. Phys. Soc. Lond., Ser. B*, **62** (1949) 676–700.
13. Kolsky, H., *Stress Waves in Solids*. Clarendon Press, Oxford, 1963.
14. Lindholm, U. S., Some experiments with the split Hopkinson pressure bar. *J. Mech. Phys. Solids*, **12** (1964) 317–335.
15. Harding, J., Wood, E. D. & Campbell, J. D., Tensile testing of materials at impact rate of strain. *J. Mech. Engng Sci.*, **2** (1960) 88–96.
16. Duffy, J., Campbell, J. D. & Hawley, R. H., On the use of a torsional split Hopkinson bar to study rate effects in 1100-0 aluminium. *J. Appl. Mech.*, **38** (1971) 83–91.
17. Davies, E. D. H. & Hunter, S. C., The dynamic compression testing of solids by the method of the split Hopkinson pressure bar. *J. Mech. Phys. Solids*, **11** (1963) 155–179.
18. Malinowski, J. Z. & Klepaczko, J. R., A unified analytic and numerical approach to specimen behavior in the split Hopkinson pressure bar. *Int. J. Mech. Sci.*, **28** (1986) 381–391.

19. Bertholf, L. D. & Karnes, J., Two-dimensional analysis of the split Hopkinson pressure bar system. *J. Mech. Phys. Solids*, **23** (1975) 1–19.
20. Jahsman, W. E., Reexamination of the Kolsky technique for measuring dynamic material behavior. *J. Appl. Mech.* (1971) 77–82.
21. Zhao, H. & Gary, G., On the use of SHPB techniques to determine the dynamic behavior of materials in the range of small strains. *Int. J. Solids Struct.*, **33** (1996) 3363–3375.
22. Griffiths, L. J. & Martin, D. J., A study of the d ynamic behavior of carbon-fibre composite using the split Hopkinson pressure bar. *J. Phys. D: Appl. Phys.*, **7** (1974) 2329–2341.
23. Sierakowski, R. L., Nevill, G. E., Ross, C. A. & Jones, E. R., Dynamic compressive strength and failure of steel reinforced epoxy composites. *J. Compos. Mater.*, **5** (1971) 362–377.
24. Davies, R. M., A critical study of Hopkinson pressure bar. *Phil. Trans. Roy. Soc.*, **A240** (1948) 375–457.
25. Pochhammer, L., Uber die Fortpflanzungsgeschwindigkeiten Kleiner Schwingungen in einem Unbergrenzten Isotropen Kreiszylinder. *J. für die Reine und Angewande Mathematic*, **81** (1876) 324–336.
26. Chree, C., The equations of an isotropic elastic solid in polar and cylindrical co-ords., their solutions and applications. *Cambridge Phil. Soc., Trans.*, **14** (1889) 250–369.
27. Follansbee, P. S. & Franz, C., Wave propagation in the split Hopkinson pressure bar. *J. Engng Mater. Tech.*, **105** (1983) 61–66.
28. Gong, J. C., Malvern, L. E. & Jenkins, D. A., Dispersion investigation in the split Hopkinson pressure bar. *J. Engng Mater. Tech.*, **112** (1990) 309–314.
29. Zhao, H. & Gary, G., A three dimensional analytical solution of longitudinal wave propagation in an infinite linear viscoelastic cylindrical bar: Application to experimental techniques. *J. Mech. Phys. Solids*, **43** (1995) 1335–1348.
30. Zhao, H., Gary, G. & Klepaczko, J. R., On the use of a viscoelastic split Hopkinson pressure bar. *Int. J. Impact Engng* (in press).
31. Gary, G., Dynamic buckling of an elastoplastic column. *Int. J. Impact Engng*, **1** (1983) 357–375.