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Material Behaviour

Effect of strain rate on the compression behaviour of a woven fabric S2-glass fiber reinforced vinyl ester composite

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Abstract

Quasi-static (~10^{-3}s^{-1}) and high strain rate ($>$ 500 s^{-1}) compression behavior of an S2-glass woven fabric/vinyl ester composite plate was determined in the in-plane and through-thickness directions. In both directions, modulus and failure strength increased with increasing strain rate. A higher strain rate sensitive modulus was found in the through-thickness direction while a higher strain rate sensitive failure strength was found in the in-plane direction. In the in-plane direction, the failure mode was observed to change from splitting followed by "kink banding" (localized fiber buckling) to predominantly splitting at increasing strain rates, while it remained the same in the through-thickness direction.

Keywords: S2-glass; Vinyl ester; Composite; Compression; High strain rate

1. Introduction

Fiber reinforced polymeric composites have superior specific energy (energy per kg) absorbing properties as compared with common engineering metallic materials [1]. They are, therefore, preferred materials to be used in impact-related applications, in which the absorption of deformation energy is an important design parameter. As the loading rate increases beyond quasi-static strain rates (10^{-3} s^{-1}), as in the case of a projectile impinging on an armor structure, the deformation behavior of the dynamically loaded structure becomes of great concern to design engineers, since there is much evidence in the literature that mechanical properties at high strain rates can differ greatly from those of quasi-static rates, see the review article on strain rate effects in composites given in [2].

In this study, quasi-static (~10^{-3}s^{-1}) and high strain rate ($>$ 500 s^{-1}) compression behavior has been determined for an S2-glass woven fabric/vinyl ester composite, which is currently being investigated for its performance as the backing plate in integrated armor [3]. The compression behavior of similar composites, different in fiber architecture and/or fiber volume fraction, has been previously studied at quasi-static and high strain rates [3,4]. Emphasis is given to the failure modes of the composite operative at quasi-static and high strain rates.

2. Materials and testing methods

S2 glass fiber woven fabric/vinyl ester composite plates 11 mm thick were produced using a vacuum injection molding process followed by a 2 h curing process at 100 °C. The void content was less than 1% and the

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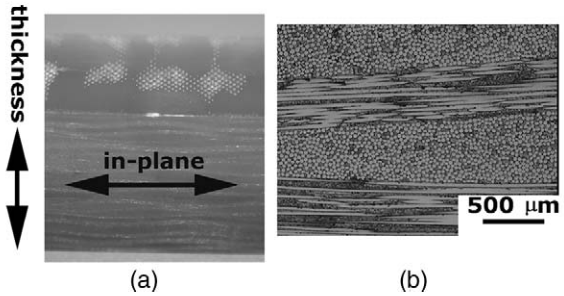

Fig. 1. (a) Edge-on view of composite plate and testing directions and (b) composite microstructure showing fiber architecture.

fiber volume fraction was approximately 50% determined microscopically. Detailed information on the fabrication process is given elsewhere [3]. Compression tests were conducted in the through-thickness (normal to the fiber plane) and in-plane directions as shown in Fig. 1(a) and (b). High strain rate tests were conducted on cylindrical samples, 10 and 6 mm in length and diameter respectively, using a Split Hopkinson Pressure Bar set-up, while quasi-static tests were conducted on both cylindrical and cubic samples with a length of 10 mm. Multiple loading of the sample in the SHPB was avoided by using a transmitter bar shorter than the incident bar, similar to the SHPB set-up used in [4]. Detailed information on the used SHPB is given elsewhere [5]. Scanning electron and optical microscopy techniques were further performed on the tested and failed samples to determine operative failure modes.

3. Results and discussion

Typical stress-strain curves of the composite at quasi-static and high strain rates are shown in Figs. 2 and 3 for in-plane and through-thickness directions respectively. The curves are nearly linear at the beginning but become non-linear at the later stage of the deformation. The modulus of the composite samples was calculated in the linear region of the curves, as depicted in Figs. 2 and 3, and used to determine the effect of strain rate on the modulus of the composite for in-plane and through-thickness directions. It is also found that the stress-strain curves of the cylindrical and cubic samples are very similar. The maximum points on these figures, as marked with arrows, are considered as the failure stresses and the corresponding strains as the failure strains.

The approximate modulus of the composite calculated from Figs. 2 and 3 was found to be strain rate sensitive in both directions (Fig. 4). The average modulus of the composite increases from 24.5 to 27.5 GPa in the in-plane and from 8 to 14 GPa in the through-thickness directions as the strain rate increases from quasi-static ($1.6 \times 10^{-3} s^{-1}$) to high strain rates ($> 500\ s^{-1}$), proving a higher strain rate sensitive modulus in the through-thickness direction. Within the studied strain rate regimes, the average failure stress of the composite also

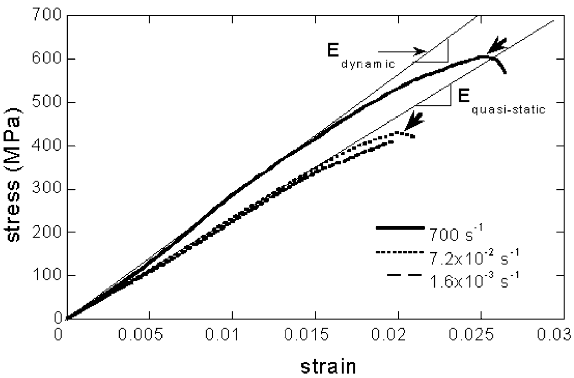

Fig. 2. Compression stress-strain curves of the composite in in-plane direction at different strain rates.

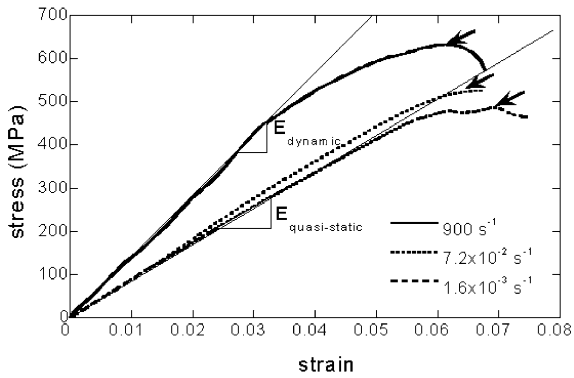

Fig. 3. Compression stress-strain curves of the composite in through-thickness direction at different strain rates.

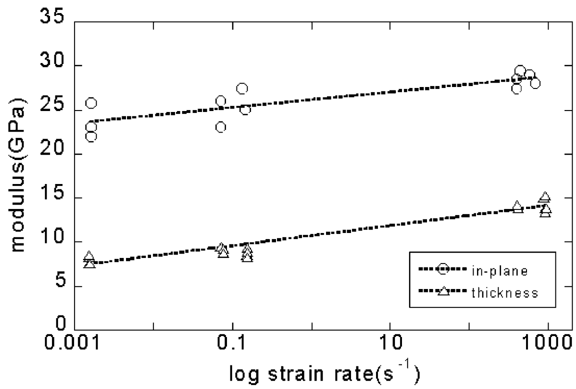

Fig. 4. Modulus vs log strain rate in in-plane and through-thickness directions.

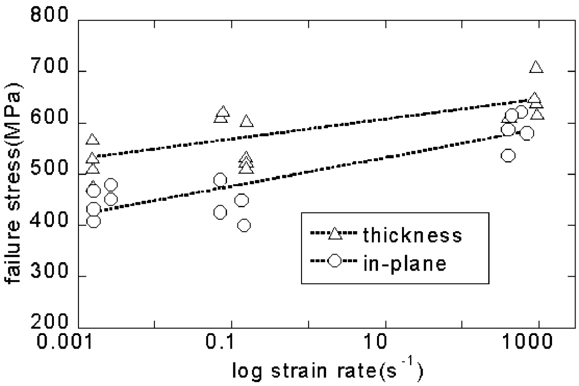

Fig. 5. Failure stress vs log strain rate in in-plane and through-thickness directions.

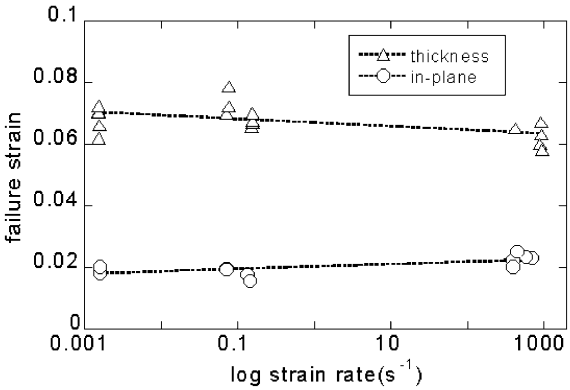

Fig. 6. Failure strain vs log strain rate in in-plane and through-thickness directions.

increases with increasing strain rate from quasi-static to high strain rates (Fig. 5); 450–600 MPa in the in-plane and 530–650 MPa in the through-thickness directions, showing a higher strain rate sensitive failure stress in the in-plane direction. The average failure strains show very slight strain rate dependence: in the in-plane direction, the failure strain increases as the strain rate increases from 0.018 at $1.6 \times 10^{-3}\mathrm{s}^{-1}$ to 0.023 at 500 s^{-1} (Fig. 6). However, the average failure strain in the through-

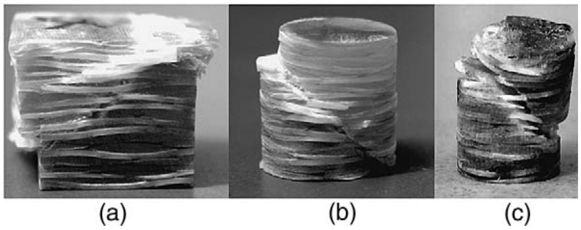

Fig. 8. Photographs of failed samples tested in through-thickness direction: (a) quasi-static cubic, (b) quasi-static cylindrical, and (c) high strain rate (700 s^{-1}) cylindrical.

thickness direction decreases slightly with increasing strain rate from quasi-static to high strain rates: 0.067 at 1.6 x 10^{-3} s^{-1} to 0.063 at 900 s^{-1} (Fig. 6).

The strain rate sensitivity of the matrix modulus was shown in a previous study [4]. The modulus was found to increase from 4 GPa at quasi-static to 8 GPa at 1000's s^{-1}. Studies on similar composites, but with different fiber type and fiber orientation, have also shown strain rate sensitive mechanical properties [3,4]. The measured higher rate sensitive modulus in the through-thickness direction in the present study is, therefore, most likely due to the matrix dominated mechanical properties in this direction.

Photographs of the failed samples tested at quasi-static and high strain rates in in-plane and through-thickness directions are shown sequentially in Figs. 7 and 8. Failure at quasi-static strain rates in the in-plane direction occurred at nearly 45 degrees to the loading axis both for cubic and cylindrical samples (Fig. 7(a) and (b)). At high strain rates, however, the composite failed by axial splitting (Fig. 7(c)) in two or more pieces along the loading axis (A and B in Fig. 7(c) and (d)). In the through-thickness direction failure occurred similarly at 45 degrees to the loading direction for both quasi-statically and dynamically tested cubic and cylindrical samples, see Fig. 8.

Figure 9 shows photographs of a compressed cubic test sample in the in-plane direction at various strains. Until about the maximum stress, no damage was observed macroscopically, but afterwards a crack, probably started from the edge of the sample as marked by

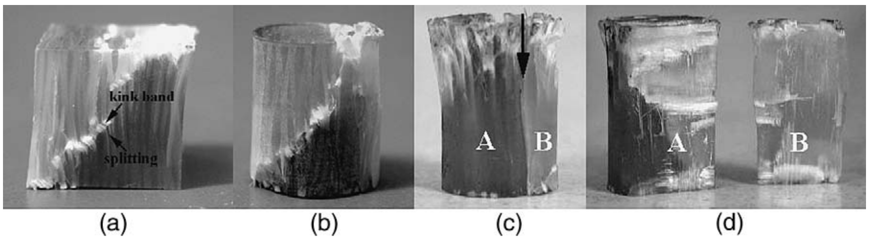

Fig. 7. Photographs of failed samples tested in the in-plane direction: (a) quasi-static cubic, (b) quasi-static cylindrical, (c) high strain rate (700 s^{-1}) cylindrical, and, (d) split pieces of high strain rate tested specimen.

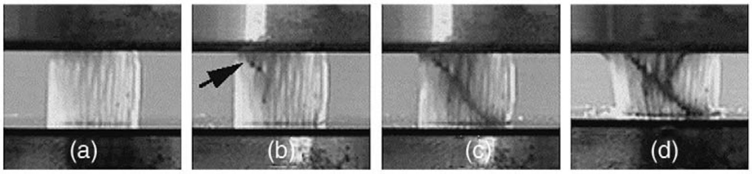

Fig. 9. Photographs of specimen tested in the in-plane direction at various strains (a)–(d).

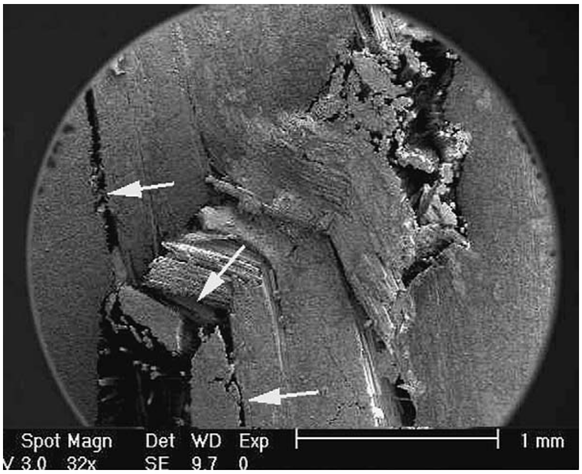

Fig. 10. SEM micrograph showing kink banding and axial splitting in sample tested at quasi-static strain rate.

the arrow in Fig. 9(b), proceeded along the diagonal of the sample. Microscopic observations clearly showed that axial splitting and kink banding (localized fiber buckling) were the main failure mechanisms of the composite in this direction (Fig. 10). Since the axially split regions were bent by the kink bands, as depicted in Fig. 10 by arrows, axial splitting occurred before the kink band formation. A similar quasi-static strain rate failure mechanism was also found for a unidirectional glass fiber reinforced vinyl ester composite [4]. It was also proposed that the relaxation of the surrounding matrix due to splitting resulted in matrix softening, leading to microbuckling and kink band formation [4]. However, at high strain rates the failure mode was solely axial splitting as depicted in Fig. 11 and test specimens split into two or more pieces. A possible explanation for the observed change in failure modes, from axial splitting and fiber kinking to axial splitting at increasing strain rates might be due to the lack of sufficient time for kink band nucleation and growth at increasing strain rates [4].

Figure 12 shows photographs of a compressed test sample in the through-thickness direction at various strains. Similarly, until about maximum stress macroscopically no damage was observed, but afterwards a crack started from the one of the specimen edge and proceeded diagonally in the sample. In this direction,

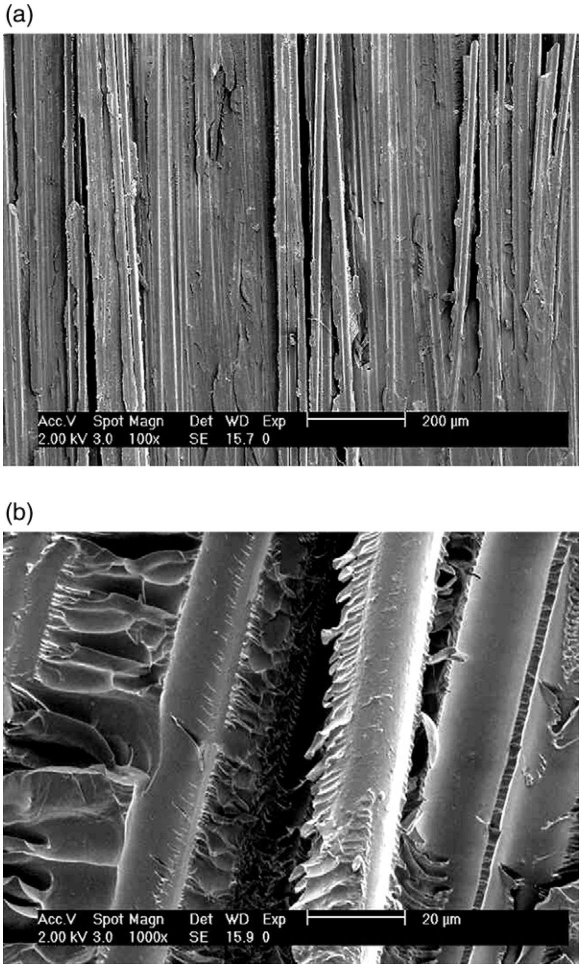

Fig. 11. SEM micrographs of high strain rate tested sample showing (a) axial splitting, and (b) magnified view of fiber debonding and matrix fracture.

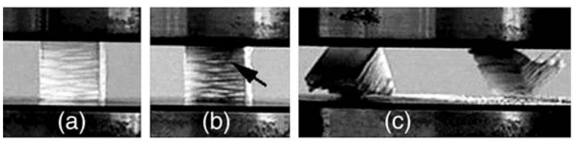

Fig. 12. Photographs of specimen tested in thickness direction at various strains (a)–(c).

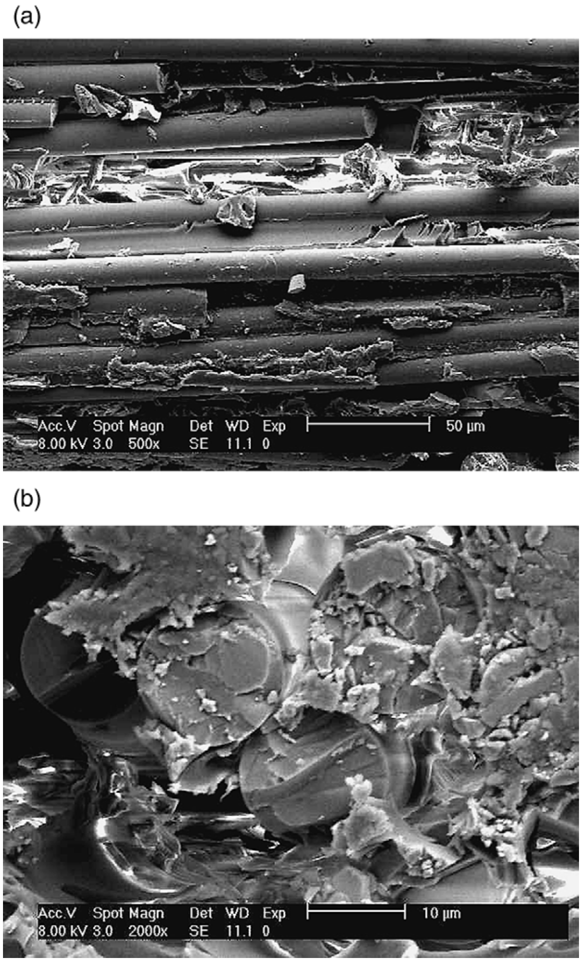

Fig. 13. SEM micrographs of sample tested in through-thickness direction at quasi-static strain rates, showing (a) matrix fracture and (b) matrix and fiber fracture.

depending on fiber orientation, matrix and fiber fracture were observed (Fig. 13(a) and (b)).

4. Conclusions

In this study quasi-static ($\sim 10^{-3} s^{-1}$) and high strain rate ($> 500\ s^{-1}$) compression behavior of an S2-glass woven fabric/vinly ester composite were determined in in-plane and through-thickness directions. At higher strain rates an increased modulus and failure strength were found in both directions. A higher strain rate sensitive modulus in the thickness direction and higher strain rate sensitive failure strength in the in-plane direction were measured. In the in-plane direction, failure occurred by axial splitting followed by kink banding at quasi-static strain rates while only axial splitting occurred at high strain rates. In the through-thickness direction, failure modes at quasi-static and high strain rates were very similar. The strain rate sensitive mechanical behavior is attributed to the strain rate sensitive matrix properties.

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