# STRAIN RATE EFFECTS ON THE STRENGTH OF SOME GLASS-FIBRE REINFORCED POLYMER COMPOSITES

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**SUMMARY:** The sensitivity to increasing compressive strain rates was measured in terms of the maximum strength of glass-fibre reinforced composites (GRP). Strain rates from quasi-static level ($0.005s^{-1}$) to intermediate level ($10s^{-1}$) were achieved on a servo hydraulic test machine, and high strain rates (in excess of $1000s^{-1}$) were achieved using a Hopkinson bar. The strength of the woven GRP composite, when tested in the in-plane direction, depended on the mechanism of deformation and failure. Strength levels were higher when deformation occurred uniformly over the specimen geometry while delamination type failure resulted in lower strength levels. The strain rate effects in the normal direction (through-thickness loading) showed the strength increased by 20% between strain rates of $0.1s^{-1}$ and $11.0s^{-1}$ and this was followed by a 20% decrease at high strain rates.

The maximum strength of the short fibre composites were found to be sensitive to increasing compressive strain rate. The maximum strength was also found to be affected by the difference in resin systems. The composite with polyester resin was significantly stronger higher strength at all strain rates than the composite with vinylester resin. Post failure examination showed greater wetting and adhesion between glass fibres and polyester resin than between the same glass fibres and vinylester resin.

**KEYWORDS:** naval composites, mechanical properties, strain rates, fracture behaviour.

## INTRODUCTION

Composites reinforced by glass fibres have currently achieved significant acceptability as structural materials in applications such as naval mine countermeasure ships. In service, these ships may be subjected to impact loading from ballistic attack and underwater shock. Therefore, there is a need to study the dynamic response of glass reinforced polymer composites and relate the extent of the changes in their mechanical properties to the rate of strain.

Mechanical properties of glass-fibre reinforced (GRP) composites are known to be sensitive to strain rates [1-4]. However, the degree of sensitivity is suggested to depend on the fibre-resin compatibility, which can be defined in terms of the chemical and mechanical bonding between the constituents [5]. Both these factors could affect the elastic deformation and fracture behaviour when such composites are loaded externally at increasing strain rates. Generally, delamination fracture between the plies results in lower strength, whereas, fracture which involves fibre pullout and fibre failure results in a significant increase in strength [5]. In previous studies [6, 7], some generic composite materials were investigated for their response under increasing compressive strain rates ranging between $0.005s^{-1}$ (quasi-static) and $10s^{-1}$ (intermediate), which encompasses the potential underwater shock strain rates on naval platforms. This paper reports on the extension of the above study to strain rates exceeding $1000s^{-1}$, which approximates ballistic impact strain rates. These strain rates were achieved in compression by using a modified Hopkinson bar. The effect of strain rate on the maximum strength of the composites was determined. An attempt was made to understand the fracture behaviour of the composites through scanning electron microscopy (SEM) and optical microscopy.

## EXPERIMENTAL

Materials studied were (i) a woven GRP composite consisting of $0^{\circ}/90^{\circ}$ woven roving (WR) alternating with chopped strand mat (CSM) and an isophthalic polyester resin matrix, Synolite 0288-T1®; (ii) a short-glass-fibre composite in a polyester resin matrix; and (iii) a short-glass-fibre composite as in (ii) but with vinylester resin (Derakane 8084®) matrix. The resin content in (i) was 47+/-3 wt% while composites in (ii) and (iii) had 58 wt% resin. A common usage of short fibre composite is as fillet material in structural joints, eg. T-joints.

The composite in (i) was manufactured in a plate form approximately 10mm thick and had 16 plies (8 plies of $630gm^{-2}$ WR alternating with 8 plies of $300gm^{-2}$ CSM). The short-fibre composite in (ii) and (iii) consisted of E-glass proprietary chopped fibres, and was moulded into a rod configuration after mixing with a resin. In the finished product the composites consisted of a random orientation of glass fibres in a resin matrix and an equal amount of void content due to air entrapment from the mixing process.

Two specimen geometries were used in the study. A cube geometry approximately 10mm x 10mm x 10mm was used in testing of woven roving composite up to $10s^{-1}$ and a solid-cylindrical geometry approximately 10mm x 10mm was used in tests at higher strain rates, Fig. 1. In tests on the short-fibre composites a similar geometry was used for all strain rates. A cube is a suitable geometry for testing laminates for their orthotropic properties however, a solid-cylindrical specimen geometry was used due to constraints placed by the Hopkinson bar test method. Loading of test specimens belonging to the woven GRP composite was in the in-plane and normal (through thickness) directions as shown in Fig. 1. In the case of the short-fibre composite, there was no particular directionality of glass fibres.

All tests at quasi-static ($0.005s^{-1}$) to intermediate ($10s^{-1}$) strain rates were conducted in stroke control using a servo-hydraulic test machine. The test machine was interfaced with a Tekronics® data acquisition system, which recorded load and displacement. Stress was calculated as engineering stress by dividing the registered load by the cross-sectional area of the specimen.

In tests at high strain rates a modified Hopkinson bar was used to achieve strain rates in excess of $1000s^{-1}$. This equipment and data analysis was described elsewhere [8]. Essentially, a stud gun was used to drive an impact bar to compress a specimen against a strain-gauged receiver bar.

## RESULTS AND DISCUSSION

Fig. 2 illustrates the variation of compressive strength (maximum stress) of the woven GRP with strain rate in the in-plane and the normal loading directions. In the normal direction the strength increased by approximately 20% from strain rates of $0.1s^{-1}$ to $10s^{-1}$. From the maximum value at $10s^{-1}$ the strength decreased by approximately 20% at strain rates from $1 \times 10^3 s^{-1}$ to $4 \times 10^3 s^{-1}$. Marked differences in behaviour were observed when the loading was in the in-plane direction. The strength increased approximately 30% between strain rates of $0.005s^{-1}$ and $1s^{-1}$. Increasing the strain rate to $10s^{-1}$ resulted in the maximum stress falling to the level that was observed at $0.005s^{-1}$. The apparent transition from increasing to decreasing strength with strain rate for in-plane loading is difficult to explain. However, there was some indication of changing fracture mode with strain rate. The reduction in strength was due to fracture of specimens occurring by delamination between the interplies, Fig. 3 (b). When deformation occurred uniformly over the specimen geometry, Fig. 3 (a), the strength was found to be higher. The scatter in the results in the in-plane loading direction increased with strain rate. The scatter may have occurred in the in-plane direction simply because the fibre buckling and /or delamination would not have taken place evenly. In addition, random sampling may have introduced a bias from the warp-weft differences (warp approx. 15% heavier than weft), variations in fibre bundle repeat distance and the difference in their waviness. Stiffness and strength of unidirectional composite have been shown to be affected by fibre waviness [9-11]. A more detailed study is required to trace the effects on mechanical properties of the small-scale architectural variations mentioned above. This study has shown that the maximum stress level in the normal direction was higher than the in-plane direction by approximately 36% (90 MPa) and 56% (140 MPa) at $0.005s^{-1}$ and $11.0s^{-1}$, respectively.

Fig. 4 illustrates the variation of maximum stress with strain rate in the short-fibre composites having two different resin systems. Results in both cases show a linear increase in maximum stress with increasing strain rate. In the composite with vinylester resin, the maximum stress level increased by approximately 33% (35 MPa) between $0.005s^{-1}$ and $11.0s^{-1}$. In the case of the composite with polyester resin, an increase in maximum stress of 37% (57 MPa) was observed over the same strain rate range. At high strain rates ranging from $1 \times 10^3 s^{-1}$ to $4 \times 10^3 s^{-1}$, the results showed the maximum strength ranged between 40 MPa to 90 MPa in the vinylester resin short fibre composite. By comparison the strength was between 155 MPa to 225 MPa in the polyester resin short-fibre composite. As shown in Fig. 4, there was some scatter in the results at high strain rates and between the two resin systems, the composite with the polyester resin has significantly higher strength at all strain rates.

The difference in strength may be due to the variation in the compatibility of the resin with glass fibres and the level of fibre-matrix interactions. Both short-fibre composites had a similar weight percent of fibres, hence the level of fibre-matrix interactions should be potentially similar. In addition, the distribution of voids was observed to be similar in both types of short-fibre composites. Fractured composite specimens, examined under SEM, showed significantly more adhered resin on the fibre surface for the polyester matrix (Fig. 5 (a)) than for the vinylester matrix (Fig. 5 (b)). Improved wetting and adhesion between fibre and resin, will effectively cause greater fibre-matrix interactions under load and therefore result in increased resistance to deformation and fracture.

## CONCLUSIONS

Compressive behaviour, in terms of maximum stress (ultimate strength), of glass fibre composites was studied from quasi-static strain rates ($0.005s^{-1}$) to high strain rates of $1000s^{-1}$ and above. In the case of woven GRP composite loaded in the in-plane direction, progressive cracking in between plies (delamination) resulted in low maximum strength levels. Loading in the in-plane direction first increased the maximum strength with strain rate, which then decreased markedly at intermediate strain rates. At high strain rates, the in-plane compressive strength varied significantly, making a precise estimate of maximum strength difficult. In the normal direction (through thickness) the maximum strength increased by 20% between strain rates of $0.1s^{-1}$ and $11.0s^{-1}$ and this was followed by a 20% decrease at strain rates between $1x10^3s^{-1}$ and $4x10^3s^{-1}$.

The compressive strength of the short fibre composite showed an increase from quasi-static to intermediate strain rates. The composite with polyester resin has a higher maximum strength at all strain rates than the vinylester resin composite. A noticeable decrease in strength occurred at high strain rates for the vinylester resin composite. The overall resistance to deformation and fracture of the polyester resin composite was far superior to the vinylester resin composite. The observed behaviour may be due to a higher degree of fibre-resin adhesion between polyester resin and glass fibres.

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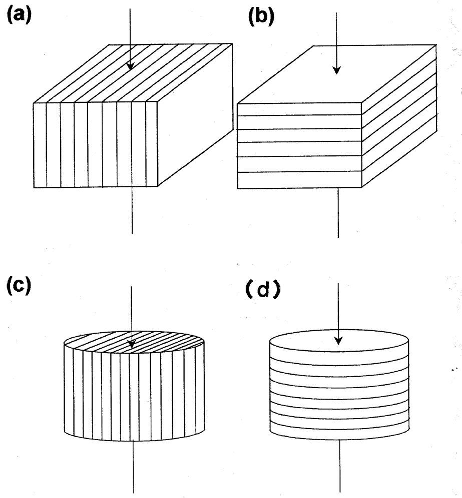



Fig. 1. Specimen geometries and directions of loading with respect to ply planes, (a & b) cubical and (c & d) circular specimens. In-plane loading (a & c) and normal loading (b & d).

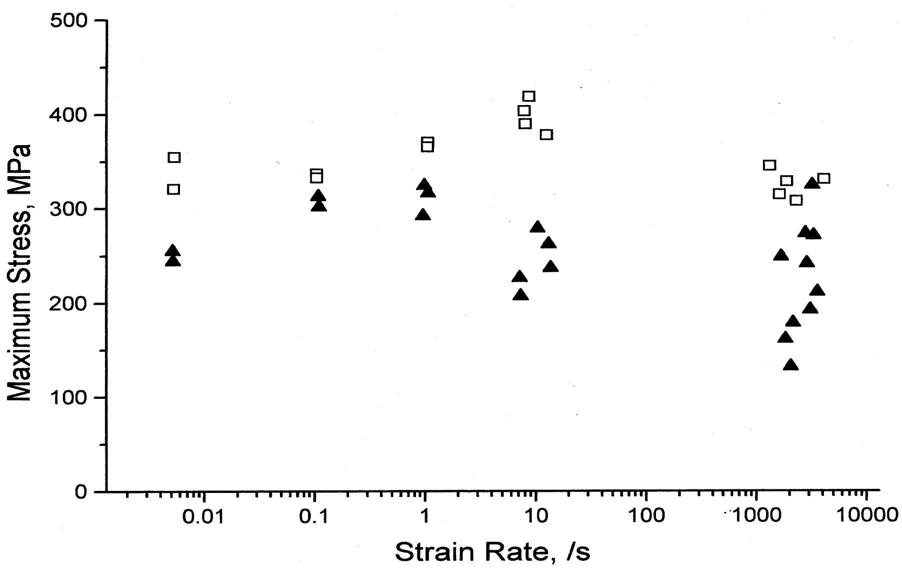
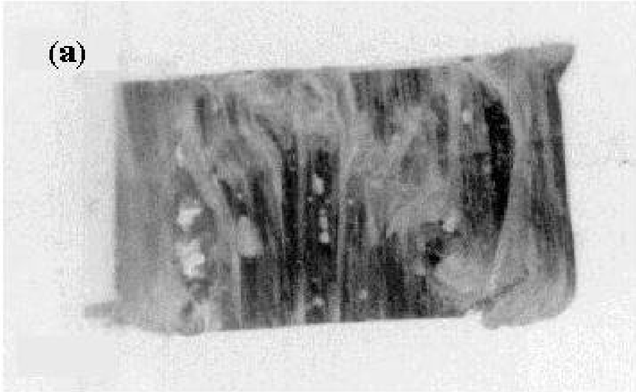



Fig. 2 The variation in the strength of woven GRP composite with strain rate; (▲) in-plane and (□) normal directions of loading. Estimated strain levels up to $11s^{-1}$ were 3.7%-6.8% (▲) and 9%-10.5% (□); above $1000s^{-1}$, estimated strain levels were 4%-6% (▲) and 10%-12.5% (□).



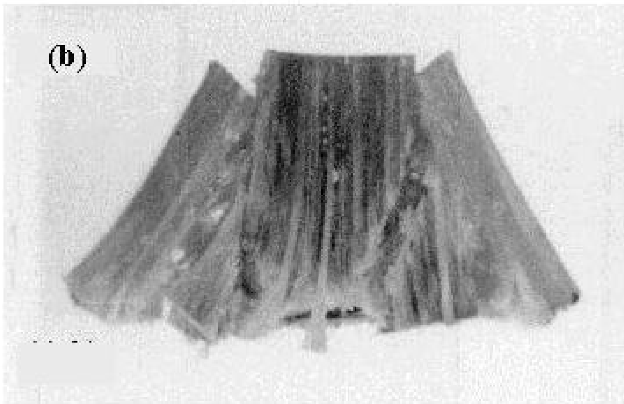




Fig. 3. Optical micrographs taken of specimens after failure at 0.1s$^{-1}$ (a) and 11s$^{-1}$ (b) in the in-plane direction. Micrographs enlarged 4x from original magnification of 4x.

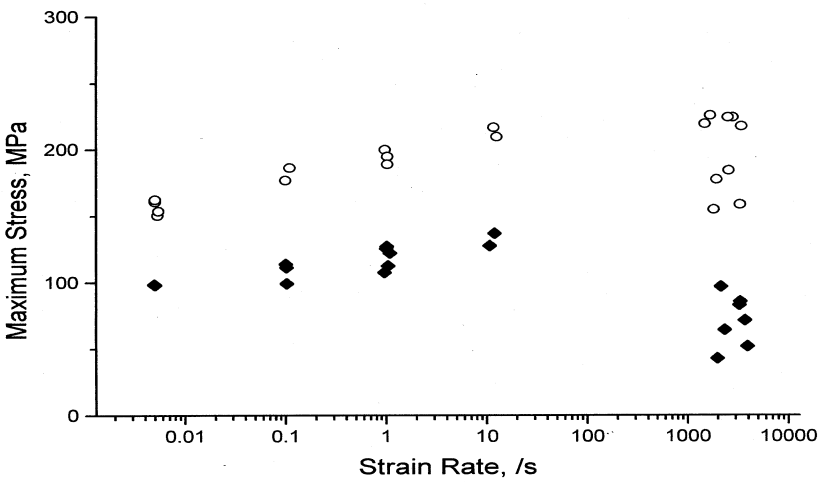



Fig. 4. The variation in the strength of short fibre composites with strain rate; (o) polyester and (♦) vinylester resins. Estimated strain levels up to 11s$^{-1}$ were 4%-6% (♦) and 4%-7% (o); above 1000s$^{-1}$, estimated strain levels were 5%-6% (♦) and 4%-6% (o).

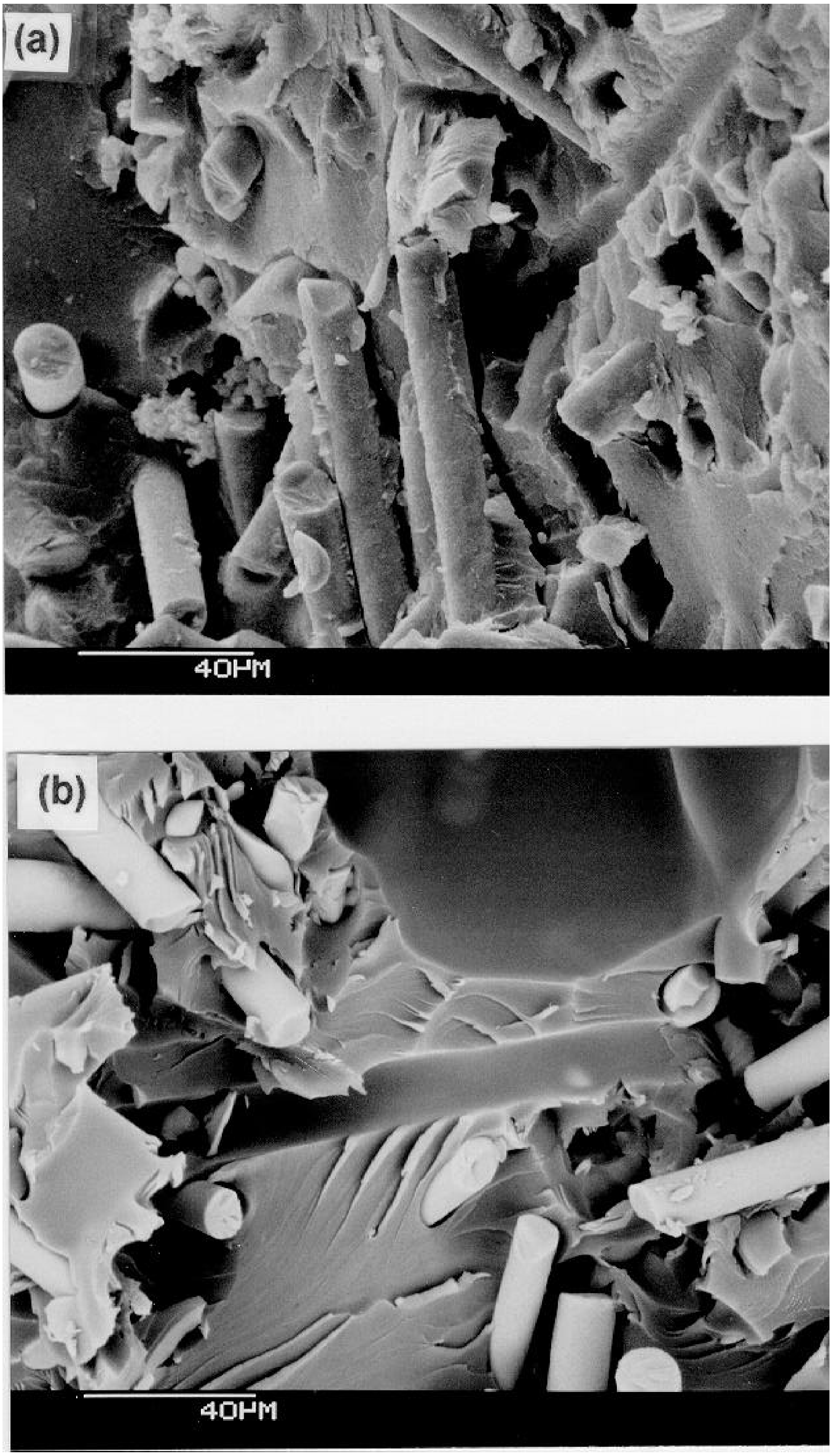



Fig. 5. Scanning electron micrographs of fracture surfaces of short fibre composite specimens tested at $10s^{-1}$; (a) polyester resin and (b) vinylester resin.