MACROSCOPIC AND MICROSCOPIC EVENTS OF DAMAGE UNDER A HIGH STRAIN RATE COMPRESSIVE LOADING

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Keywords: *naval applications, dynamic response, damage scenarios, fiber orientation effect*

Abstract

Material and structural response vary significantly under impact loading conditions as compared to static loading. The strain rate sensitivity of glass fibre reinforced polymer (GFRP) is studied by testing a single laminate configuration at strain rates of 200 s^{-1} to 2000 s^{-1}. The compressive material properties are determined by testing the laminate systems with different orientations at low to high strain rates. The laminates were fabricated from 40 layers of cross-ply glass fibre/epoxy matrix. Samples were tested in out of plane direction for seven fibre orientations; 0°, ±20°, ±30°, ±45°, ±60 °, ±70° and 90°. High-speed photography was used in association with optical techniques to check the damage scenarios. Preliminary compressive stress–strain vs. strain rates data obtained show that the dynamic material strength increases with increasing strain rates. Macrostructural and microstructural investigation have revealed that the sequence of damage events differs and depends on composite sequence lay-up. The tests show a strong material sensitivity to the dynamic loading. The failure and damage mechanisms are implicitly related to the rise in temperature during static and dynamic compression.

1 Introduction

The choice of composite materials as a substitute for metallic materials in high technological applications like marine field is becoming more pronounced especially due to the great weight savings these materials offer. In many of these practical situations, the structures are subjected to high impact loads like slamming, impact, underwater explosions or blast effect. Material and structural response vary significantly under impact loading conditions as compared to static loading. The mechanical characteristics of these materials are well known for static loading, they are likely to evolve with the strain rate [1-6].

The dynamic compressive behaviour of unidirectional and transversely isotropic glass/epoxy composite are determined by Kumar et al. [7], using the Kolsky pressure bar technique for six fibre orientations, 0°, 10°, 30°, 45°, 60° and 90° at a strain rate of 265(±50) s-1. Studies were carried out on cylindrical specimens of varying lengths 12-35 mm, and diameters 16-17 mm, respectively. Quasi-static stress–strain curves at strain rates of 2.10^{-1} s^{-1} are compared to corresponding dynamic curves. The results indicate that for all orientations of glass/epoxy there is a change in the failure modes, as well as an increase in strength at higher strain rates. Specimens of 0° orientation fracture along the fibres by tensile splitting, due to the compressive loads causing transverse tensile strains because of Poisson’s effect. Therefore, as the transverse tensile strain exceeds the transverse ultimate strain, failure occurs by tensile split-distinct points will shift. The ultimate stress increases and the point at which complete separation takes place are delayed. El-Habak [8] therefore shows a change in the failure mode at increasing strain rates.

Srikanth et al. [9] present a study of modelling the high strain rate response of the unidirectional S2Glass/8553-40 polymeric composite material system. They use a 3-D viscoplasticity model to describe the high strain rate response of the composite. A comparison of the analysis result with experimental data indicates that the viscoplasticity model determined using low strain rate testing could still be valid for modelling high strain rate responses. Gary and Zhao [10] employed the use of low impedance material such as nylon, for the incident and output bars of the split Hopkinson bar, to test the strain rate behaviour of glass epoxy composite panels. The failure strength of the glass epoxy panel tested by Gary and Zhao is reported to be strain rate sensitive.

In this study, specimens of glass/epoxy composite used in marine applications were subjected to a dynamic compression loading. The split-Hopkinson pressure bar (SHPB) is used for dynamic tests. Samples were tested in out of plane direction. The fibre orientations of the samples were 0°, ±20°, ±30°, ±45°, ±60°, ±70° and 90°. Stress-strain curves at increasing strain rates were obtained for different cases. However, no experimental data for the intermediate range of strain rates between ($80s^{-1}$ to $300s^{-1}$) was obtained, because the SHPB employed in the experimental tests are designed for high strain rates. Off-axis composites and angle ply laminates exhibited significant nonlinear and strain dependent behaviour. Finally experimental observations enable us to draw up the history of the dynamic damage in the specimens according the fibre orientation and load direction.

2 Material and Specimens

The material used in this study consists of 2400 Tex E-glass fibres impregnated with an epoxy matrix. The reinforcement consists of a plain weave fabric with 90% warp yarns and 10% weft yarns. Panels were made by infusion in ambient temperature and seven orientations are studied: 0°, ±20°, ±30°, ±45°, ±60°, ±70° and 90°. The square panels, 500×500 mm, were cut into samples, Table 1. The standard deviations are indicated in brackets.

Table 1. Materials

Panel	Thickness, (mm)	void fraction (%)	Stacking sequence	Fibre volume Fraction (%)
A	13.00 (0.1)	2.26	$[0]_{40}$	53.5 (0.5)
B	12.52 (0.3)	2.00	$[\pm 20]_{20}$	54.0 (0.5)
C	13.00 (0.1)	1.78	$[\pm 30]_{20}$	55.0 (0.5)
D	12.78 (0.2)	1.69	$[\pm 45]_{20}$	54.3 (0.5)

3 Dynamic Tests

The split Hopkinson bar test is the most commonly used method for determining material properties at high strain rates, Figure 1. This technique of characterization, based on the response of a material to wave propagation for high strain rate from $100s^{-1}$ to $5000s^{-1}$, was improved by Kolsky [11].

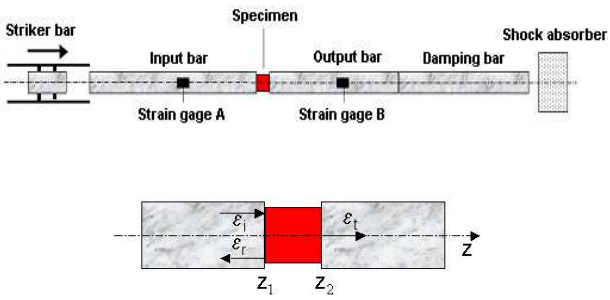


Fig. 1. Typical compressive SPHB apparatus

The dynamic tests carried out on the test set-up require a phase of preparation that consists of polishing the sample to guarantee a parallelism between the faces of supports with the bars. The sample is placed in a darkroom which is connected to the infra-red camera to follow the history of its heating with a dynamic compression. The camera recording is triggered with the incident signal. The dynamic compression test consists of placing a sample between two bars with a high elastic limit, called input bar and output bar. These bars are correctly aligned and are able to slide freely on their support. The composite specimen is not attached to the bar in order to prevent the perturbations of measurements due to additional interfaces [12]. The experimental set-up consists of (1) a stress generating system which is comprised of a split Hopkinson bars and the striker, (2) a specimen, (3) a stress measuring system made up of sensors (typically resistance strain gauges), and (4) a data acquisition and analysis system.

3.1 Data Processing Procedure

In order to express the signals recorded at the input bar/sample and sample/output bar interfaces, it is necessary to propagate the waves in the material. The case can be treated as one-dimension. In this situation, all the waves are propagated at the same velocity C_0 in the bar. The non-dispersive property of the propagation in the bars is roughly verified in experiment. However it is more realistic to consider the problem as bi-dimensional [13]. In this case the speed of each wave depends on its frequency w and the radius R of the bar. This theory works well for predicting the dispersive nature of waves. A typical set of incident, reflected, and transmitted signals resulting from gauges A and B recorded by the digital oscilloscope from a pulse-shaped SHPB experiment on the composite at the strain rate of 336 s^{-1} for 0° OP test is shown in figure 2.

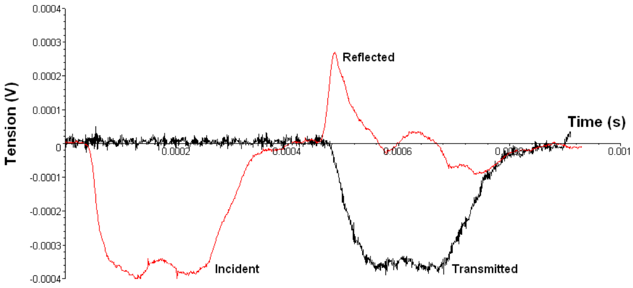


Fig. 2. Typical incident, reflected and transmitted pulse from the SHPB

3.2 Dependencies of Dynamic Properties

The out-of-plane (OP) direction of loading used in dynamic case is considered. Results for compressive strain rates between 200 s^{-1} and 2000 s^{-1} are obtained using SHPB.

Figure 3 shows the evolution of the strain rate versus time. The maximum value is considered for the analysis of the experimental results.

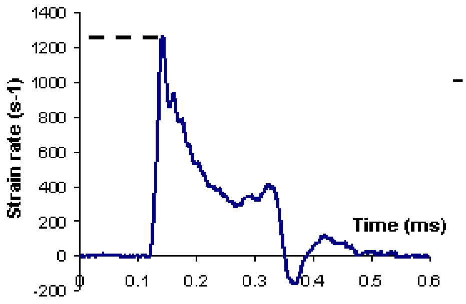


Fig. 3. Strain rate evolution, OP test of [±20/±70] P=1.4 bar

The strain rate evolution is sensitive to the entry pressure in the chamber of compressed air P (impact pressure of the striker on the input bar), the loading direction and the sample lay-up (angle θ). we will analyze that in detail in the following section.

The evolution of $\dot{\varepsilon}$ is approximated by a quadratic function, equation (1), Figure 4. Table 2 gives the coefficients of the function.

$$\dot{\varepsilon} = \alpha \cdot P^2 + \beta \cdot P + \gamma \qquad (1)$$

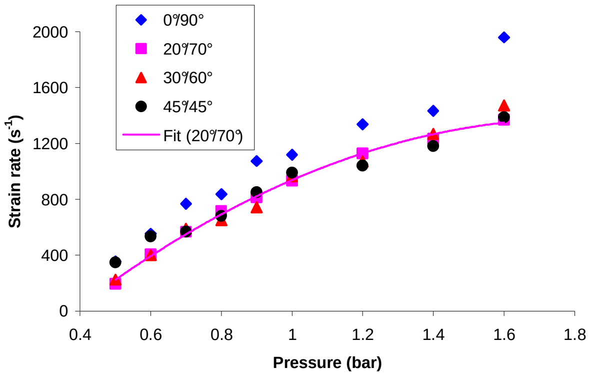


Fig. 4. Strain rate versus impact pressure for OP tests

Table 2. Coefficients of quadratic functions

IP Tests	0°/90°	20°/70°	30°/60°	45°/45°/
α	-135.5	-676.66	-341.17	-329.77
β	1581	2444.9	1801.9	1585.9
γ	-336.33	-830.42	-560.75	-34173

Figure 5 gives the experimental curves in blue and the envelope surface. The evolution of $\dot{\varepsilon}$ follows two phases: a first phase ($0.5 \le P \le 1.2\,\text{bar}$) where the increase is fast and the second phase where the variation is less marked. The fibre orientation has an effect on the strain rate evolution. Indeed, one notices on blue curves that the evolution of $\dot{\varepsilon}$ is relatively similar for samples 20/70, 30/60 and 45/45 whereas for samples 0/90 it is different.

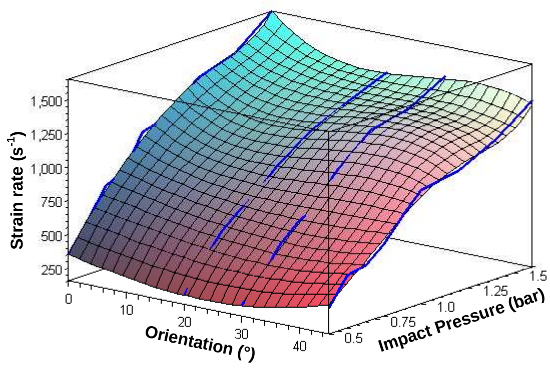
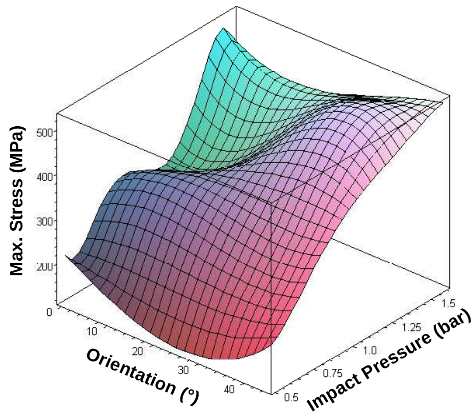


Fig. 5. Strain rate evolution versus fibre orientation and impact pressure

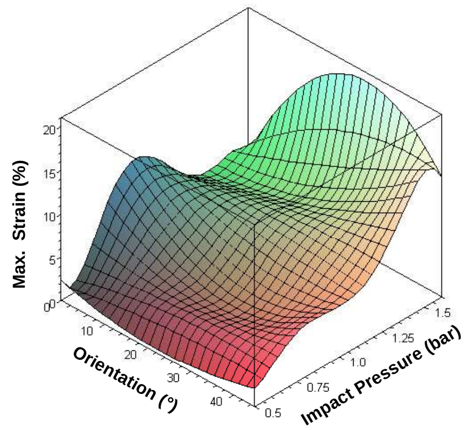
For the results analysis and exploitation, we will be interested in the evolution of:

- initial dynamic modulus ($E_{dynamic}$) witch is evaluated for the linear part of $\sigma = f(\varepsilon)$ curves for different ($\dot{\varepsilon}$),
- maximum stress (σ_{Max}),
- strain at maximum stress ($\varepsilon_{\sigma_{Max}}$),
- maximum strain (ε_{Max}).

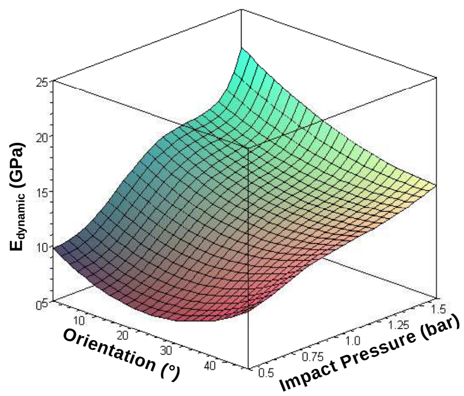
For OP tests, there is always an increase in $E_{dynamic}$, σ_{Max} and $\varepsilon_{\sigma_{Max}}$ with the increase in the impact pressure. There is not threshold effect for OP loading; the transitional pressure does not exist, Figure 6.



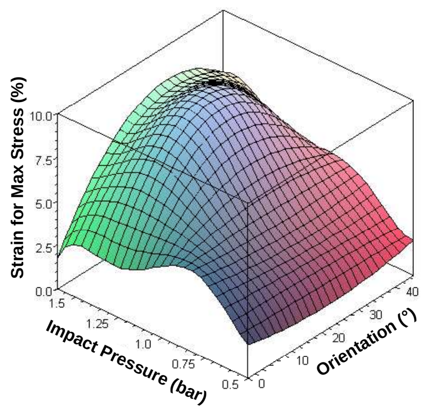
(a) Maximum Stress



(b) Maximum strain



(c) $E_{dynamic}$



(d) Strain at Max. stress

Fig. 6. $E_{dynamic}$, σ_{Max}, $\varepsilon_{\sigma_{Max}}$ and ε_{Max} versus P and θ for OP tests

4 Damage

Several techniques are used to examine the extent of damage. First, during the dynamic compression, High-speed photography and infrared camera were used to follow the damage in the samples. Frames taken in real time will be used for illustrating the evolution of the damage. Impacted samples were inspected by optical techniques and fluorescent dye was applied to improve damage visualization.

4.1 Macroscopic damage mechanisms

For OP tests, the laminates have a good dynamic compressive strength. The first phase of compression generates a layers crushing from where the plastic deformation appears. The multiplication of the microscopic cracks involves the catastrophic failure. The kinetics of damage for this direction of loading is strongly conditioned by the specimens fibre orientations. Figure 7 summarizes the damaging modes for the various laminates. The first observation that one can make, for out-of-plane tests, is that material shows a greater strength. The damage appear only for the great impact pressures:

- 0.8bar for $[0/90°]_{40}$
- 1.4 -1.6bar for $[20/70°]_{20}$ and $[30/60°]_{20}$
- 1.4bar for $[45/45°]_{20}$

For this lower range of pressure there were only plastic deformations with matrix cracks. One can also notice that the nature of the damage is strongly affected by the laminates orientation.

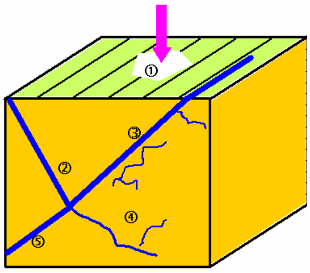
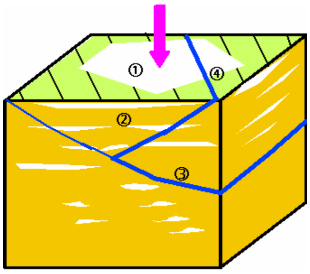
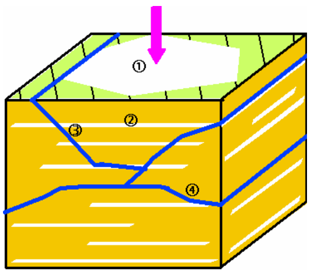
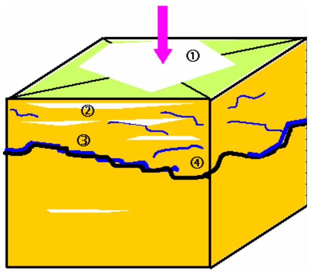
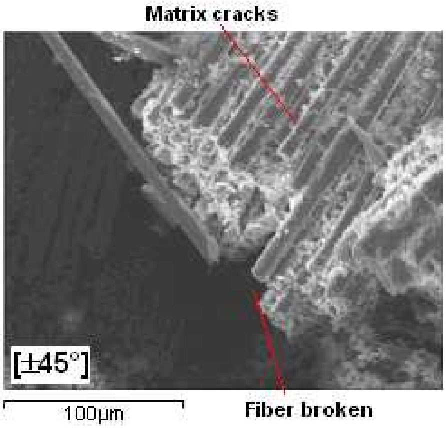
$[0/90]_{40}$		① : Crushing of the resin in contact with the incidental bar ② : Formation of damaged zone (V shape) ③ : “Macro”-cracks ④ : “Micro”-cracks ⑤ : Propagation of ② and ③ → Failure
$[\pm20/\pm70]_{20}$		① : Crushing of the resin in contact with the incidental bar ② : Layers crushing with plasticity (important crushing in the direction of the incidental bar - matrix cracks) ③ : Shearing through the layers – Macrocracks ④ : Cracks in the external layers → Failure
$[\pm30/\pm60]_{20}$		① : Crushing of the resin in contact with the incidental bar ② : Layers crushing with plasticity (important crushing in the direction of the incidental bar - matrix cracks) ③ : Shearing through the layers – Macrocracks ④ : Cracks in the external layers → Failure
$[\pm45/\pm45]_{20}$		① : Layers crushing with plasticity ② : Microcracks ③ : Macrocracks ④ : Propagation of ③ → Failure

Fig. 7. Damaging modes for OP tests

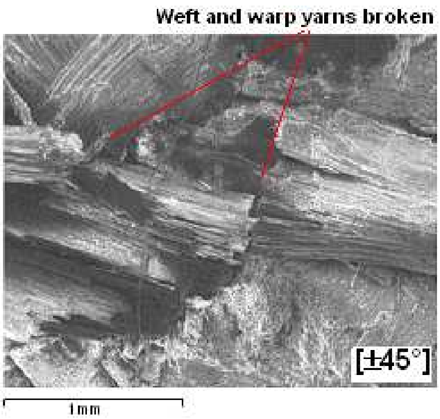
Laminated composites have a good dynamic compressive strength. The first phase of compression generates a layers crushing from where the plastic deformation appears. The multiplication of the microscopic cracks involves the catastrophic failure. The kinetics of damage for this direction of loading is strongly conditioned by the specimen's fibre orientations.

4.2 Microscopic damage mechanisms

In the preceding section we were interested in the macroscopic damage; for a more complete study one is interested now in the microscopic damage mechanisms.



(a)



(b)

Fig. 8. Microscopic damage

The material complexity introduces several types of damages on a microscopic scale. In short, the final failure of a composite is the result of the accumulation of various elementary mechanisms:

- fibres broken (weft and/or warp yarns),
- failure of the matrix/fibre interface,
- the shearing of the plies.

To see these mechanisms one had recourse to an electron microscope (MEB). The analysis of the stereotypes show these mechanisms well, Figure 8.

5 Conclusions

In this work, the high strain rate material response of $[0]_{40}$, $[\pm 20]_{20}$, $[\pm 30]_{20}$, $[\pm 45]_{20}$, $[\pm 60]_{20}$, $[\pm 70]_{20}$ and $[90]_{40}$ E-glass/epoxy composite material systems was investigated. Split Hopkinson pressure bars were used to conduct high strain rate experiments. Maximum strain rates around 2000s-1 were achieved. Samples were subjected to OP tests. the effects of fibre orientation and strain rates in a glass/epoxy composite material under compressive dynamic loading are examined. Moreover, a family of compressive stress–strain curves, as well as failure modes, at dynamic strain rates at a series of fibre orientation were determined. All of the stress–strain curves had similar shapes: an initial linear elastic portion followed by a nonlinear behaviour until failure. The stress–strain curves of the composite materials show that the material is strongly sensitive to fibre orientation at the same impact pressure: the initial modulus of elasticity, maximum failure stress, strain at maximum stress and the maximum strain are all dependent on fibre orientation and strain rates. The initiation and propagation of failure mechanisms at different strain rates have been examined. The most pronounced effect of increasing the strain rate results in changes in the failure modes. Specimen fails by fibre kinking at low strain rates, with delamination and interfacial separation dominating the high strain rate failure regime. Off-axis composites and angle ply laminates exhibited significant nonlinear and strain dependent behaviour.

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