FAILURE MODE TRANSITION IN FIBER REINFORCED COMPOSITES UNDER DYNAMIC MULTIAXIAL COMPRESSION

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SUMMARY: Results for an unidirectionally reinforced polymer composite, E-glass/vinylester, loaded in the fiber direction using a servo-hydraulic material testing system for low strain rates and a Kolsky (split Hopkinson) pressure bar for high strain rates, up to 3000 s^{-1} are presented. The results indicate that the compressive strength of the composite increases with increasing levels of confinement and increasing strain rates. Post-test optical and scanning electron microscopy is used to identify the failure modes. The failure mode that is observed in unconfined specimen is axial splitting followed by fiber kink band formation. At high levels of confinement, the failure mode transitions from axial splitting to kink band formation and fiber failure.

KEYWORDS: multiaxial compression, E-glass/vinylester, high-strain-rate, Kolsky (split Hopkinson) bar, axial splitting, kink banding, compressive strength, failure mode transition.

INTRODUCTION

Deformation and fracture behavior of fiber reinforced composites have received considerable attention because of their importance in structural applications. Composites are finding increased use in impact-related applications such as marine structures, turbine blades, automotive and others. Of particular interest for marine composite structures subjected to impact are their high-strain-rate properties, resistance to crack initiation and propagation as well as their strength under multiaxial loading conditions. Hence, there is a need to understand the dynamic deformation and fracture behavior of fiber reinforced composites in order to develop a mechanistic understanding of their behavior. Also, in general, the loading in most applications is multiaxial, and even under uniaxial loading of a composite laminate the stress state is multi-dimensional. Such an understanding will aid in the development of constitutive and failure models for analysis and design of composite structures subjected to impact [1,2]. Relatively little is known concerning dynamic behavior of fiber reinforced composites [3.4].

The limiting factor in the design of composite structures is their compressive strength. The compressive strength of unidirectionally reinforced composites is found to be roughly one-half of their tensile strength. Also, their compressive strength has been consistently and considerably lower than theoretical predictions. Extensive studies have been carried out on unidirectional fiber composites under uniaxial compression [5]. In general, the loading in most applications such as pressure vessels and submersibles is multiaxial. Even under uniaxial loading, due to shear coupling the stress state in a laminate is multi-dimensional. However, little is known concerning the multiaxial behavior of fiber reinforced composites [3,6,7]. The limited work concerning behavior of composites under multiaxial compression has been performed under hydrostatic pressure. In many applications involving composites, e.g. laminates, the loading path is proportional, i.e. stress components change in proportion to one another.

A major objective of this paper is to present a new experimental technique for studying the dynamic behavior of fiber reinforced composites using a modified Kolsky (split Hopkinson) pressure bar. This technique is used to study the high-strain-rate behavior of an unidirectionally reinforced E-glass/vinyl ester polymeric composite under multiaxial compression. The deformation and failure response of the composite over a wide range of strain rates and stress states are presented and discussed. A new energy based analytic model for studying axial splitting phenomenon in unidirectionally fiber-reinforced composites is presented.

EXPERIMENTAL

Modified Kolsky Pressure Bar

Kolsky (Split Hopkinson) pressure bar is a well-established apparatus commonly utilized in the high-strain-rate testing of materials. Originally developed by Kolsky [8], the concept has found widespread applications in testing ductile materials at strain rates up to 10^4 s^{-1}. However, the application of this technique without adequate modifications for testing composite materials has serious limitations. As will be discussed below, modifications must be made to the conventional split Hopkinson pressure bar to reliably obtain properties at small strains as well as to avoid repeated loading of the specimen thus enabling specimen recovery. The modified Kolsky (Split Hopkinson) bar is shown in Fig. 1.

The conventional Kolsky pressure bar consists of a striker bar, an incident bar and a transmission bar. A specimen made of the material under investigation is placed between the incident bar and the transmission bar. When the striker bar impacts the incident bar, an elastic compressive stress pulse, referred to as the incident pulse, is generated and propagates along the incident bar towards the specimen. The pulse duration equals the round-trip time of a longitudinal elastic bar wave in the striker bar. When the incident pulse reaches the specimen, part of the pulse is reflected back in the incident bar due to impedance mismatch at the bar/specimen interface, and the remaining part is transmitted through the specimen into the transmission bar. The strain gages mounted on the bars provide time-resolved measures of the pulses in the incident and the transmission bars. For a specimen that is under mechanical equilibrium, Kolsky [8] showed that the nominal strain rate $\dot{\varepsilon}(t)$ in the specimen could be calculated using the relation

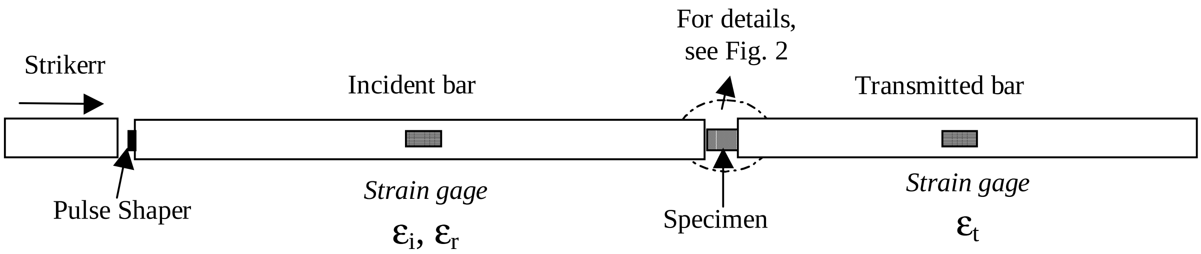


Fig. 1: Schematic of a modified Kolsky (split Hopkinson) pressure bar

$$\dot{\varepsilon}(t) = -\frac{2c_o}{l}\varepsilon_r(t) \quad (1)$$

where l is the original length of the specimen, $\varepsilon_r(t)$ is the time-resolved reflected strain measured in the incident bar, and c_o $\left(\sqrt{E/\rho}\right)$ is the longitudinal bar wave speed in the bar material. E and ρ are the Young's modulus and the mass density respectively. Integration of Eqn 1 with respect to time gives the time-resolved axial strain of the specimen.

The nominal axial stress σ in the specimen is determined using the equation

$$\sigma(t) = E\frac{A_o}{A_s}\varepsilon_t(t) \quad (2)$$

where A_s is the cross-sectional area of the specimen, and $\varepsilon_t(t)$ is the time-resolved strain in the transmission bar of area A_o. All the foregoing calculations are based on the assumption that the specimen undergoes homogeneous deformation. In the derivation of Eqns 1 and 2, the incident and transmission bars are assumed to be of the same material, remain elastic and of identical and uniform cross-sectional area.

When nominally brittle materials such as composites are tested in the conventional split Hopkinson pressure bar, the limitations of the technique must be recognized. In order to obtain reliable and consistent experimental data when testing these materials with the Kolsky bar, appropriate modifications must be incorporated in both the experimental technique and the design of specimen geometry. For example, shaping of the loading pulse by a thin soft disc, called a pulse shaper, placed at the impact end of the incident bar has been used to prevent brittle high strength materials from failing before equilibrium is attained in the specimen. In addition to pulse shaping, reliable strain data at small strains (<1%) has been obtained during testing of brittle materials by mounting strain gages on the specimen surface [9]. The limiting strain rate below which reliable deformation and failure data for a brittle material can be obtained using the split Hopkinson pressure bar technique has been established [10]. The stress in the specimen is computed from the transmitted pulse (Eqn 2) and has been shown to be in close agreement with the stress in the specimen [11].

Using the conventional split Hopkinson pressure technique, it is possible for the specimen to be loaded multiple times due to subsequent wave reflections in the incident bar. In the investigation, the transmission bar was made to be shorter than the incident bar [12] as shown in Fig. 1. With this modification, the shorter transmission bar will act as a momentum trap, thereby moving the transmission bar away from the specimen before a second compressive pulse due to reflected tensile pulse in the incident bar reloading the specimen. Thus, the specimen having been subjected to a single known loading pulse can be recovered for microstructural characterization and unambiguous interpretation of failure modes.

Experimental Setup

The dimensions of the bars in the Kolsky pressure bar setup used in this study are 1220 and 580 mm in length for the incident and transmission bar respectively, with a common diameter of 19 mm. The striker bars are also of 19 mm diameter varied in their lengths from 50 to 100 mm to achieve the desired loading pulse duration. All the bars are made of high strength maraging steel (C-350, Rockwell hardness, Rc=60) with an yield strength of 2.7 GPa. A thin, half-hardened copper disc of 3 mm diameter and 0.85 mm in thickness is typically used as a pulse shaper. The material as well as the diameter and the thickness of the pulse shaper are varied to control the rise time of the incident pulse. The rise time and shape of the pulse are tailored to ensure stress equilibration within the specimen [10]. High resistance (1000 Ω) strain gages (Micro-measurements WK-06-250BF-10C) with excitation voltage of 30 volts are used to measure the surface strain on the specimen as well as on the bars. Raw strain gage signals without any pre-amplifiers that may distort the signals are recorded using a high-speed 12-bit digital oscilloscope, Nicolet model 440.

Lateral Confinement

A schematic for imposing proportional lateral confinement on a specimen that is axially loaded are shown in Figs. 2 a and b. The experimental set-up consists of a cylindrical specimen placed in a hollow cylinder with a sliding/running fit and is axially loaded using platens. The hollow cylinder and the loading platens are designed to remain elastic during the experiments. The confining cylinder and the platens are made of high strength alloys. Proportional loading is achieved by proper choice of the geometry (the inner and outer radii, a and b respectively) and the material properties for the hollow cylinder. The lateral confinement σ_c, in the elastic regime is a function of the axial stress σ, the cylinder geometry (Fig. 2b) and the elastic properties of the composite specimen and the confining cylinder,

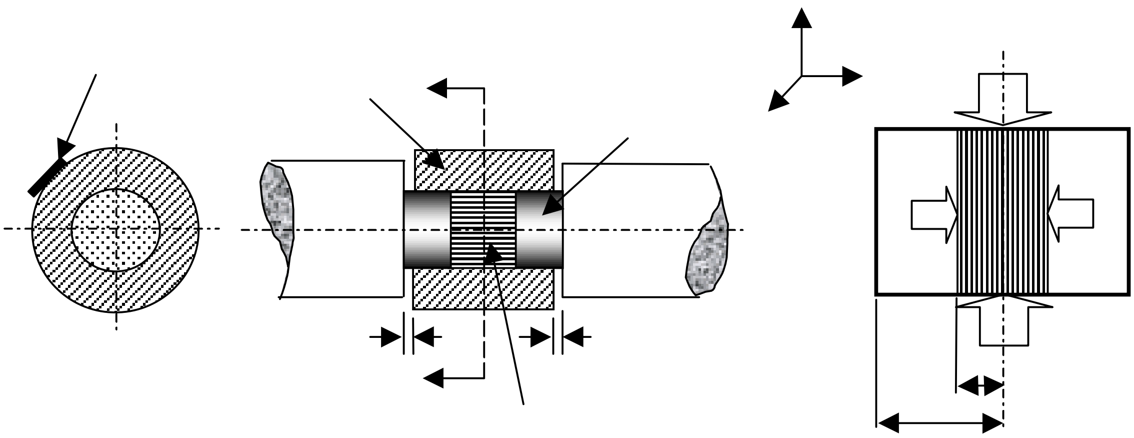


Fig. 2: (a) Schematic of a composite specimen surrounded by a metallic sleeve and loadedthrough hardened platens; (b) Geometry and stress state of an ideally confined composite specimen

$$\sigma_c = \frac{\sigma}{\left[\frac{(1-\nu)E_{22}a^2}{\nu_{12}E(b^2-a^2)}\left\{1+\frac{(1+\nu)}{(1-\nu)}\frac{b^2}{a^2}\right\}+\frac{(1-\nu_{32})}{\nu_{12}}\right]} \qquad (3)$$

where E and ν are the Young's modulus and Poisson's ratio of the sleeve material and E_{22}, ν_{12} and ν_{32} are the elastic properties for the composite.

With the guidance from Eqn 3 and proper material choice, desired lateral confinement can be attained using the hollow cylinder configuration in Fig. 2. A strain gage mounted on the external surface of the confining cylinder is used to measure the circumferential or hoop strain (ε_c) and to ascertain the confining stress, $\sigma_c=E\varepsilon_c$. Such a configuration to apply proportional confinement loading can be used both under quasistatic and dynamic loading conditions.

Materials

A unidirectional fiber reinforced composite with 50% volume fraction E-glass/vinyl ester is investigated in the present study. This material is finding increasing applications in marine structures because of the relatively low cost in manufacturing using techniques such as resin transfer molding (RTM). Continuos E-glass (Certainteed R099-625) fibers of 24.1 μm in diameter are aligned in a glass tube and are impregnated with vinyl ester resin (Dow Derakane 411-C50). Following curing, specimens of desired length (6.25 mm) are sectioned using a low speed diamond saw and are sized to desired diameter (6.25 mm) using low speed machining. The ends of the specimen are made parallel and polished using diamond paste. The details of the material and specimen preparation can be found elsewhere [4].

The confinement sleeve (Fig. 2a) is typically made of a 7075 aluminum alloy and the dimensions are chosen to provide the desired confinement level (Eqn 3). The inner diameter is carefully machined to provide smooth sliding fit on the specimen as well as the hardened sleeves. The inner and outer diameters of a typical sleeve used in the experiments are 6.25 mm and 30 mm respectively. The loading platens are made of hard tool steel, Rockwell hardness Rc=60 and dimensions 6.25 mm in diameter and 2.5 mm in length. The lengths of the sleeve and the platens are chosen to provide a predetermined clearance (δ) used to control the extent of deformation imposed on the specimen.

RESULTS

Experiments on the unidirectionally fiber reinforced E-Glass/vinyl ester composite material were performed at low stain rates using a servo hydraulic materials testing system and at high strain rates using the modified Kolsky (Split Hopkinson) pressure bar. Experiments were conducted in the strain rate range of 0.001 to 3,000/s. Experiments were also performed on the pure matrix material, vinyl ester (Dow Derakane 411-C50).

Stress-Strain Response

The stress-strain curves obtained from experiments for the unconfined composite specimens loaded in the fiber direction are presented here for nominal axial strain rates of 0.001and 3,000/s in Fig. 3. The stress-strain curves are linear up to a maximum prior to catastrophic load drop and are followed by deformation at a nearly constant stress. The peak stress increased from 470 MPa at a strain rate of 0.001/s to 600 MPa at a strain rate of 3,000/s. All the specimens in the above uniaxial experiments failed by axial splitting. The multiaxial compression experiments were designed for the stress ratio σ_c/σ of 0.3 (Eqn 3). The axial stress-strain curves for the multiaxial compression experiments loaded in the fiber direction and confined laterally (Fig. 2) are shown in Fig. 3 for the strain rates of 0.001 and 3,000/s. The experiments were stopped at a strain of 0.05 to enable the failure mode characterization of the specimens. The maximum stress attained during the experiments on confined specimens increased with increasing strain rate from 600 MPa at 0.001/s to 1,000 MPa at 3,000/s. At low strain rate (0.001/s), the material exhibited a linear response up to 400 MPa followed by load drops and degradation of modulus. Extensive acoustic emission activity was observed during these load drops. At a given strain rate, the maximum stress that the material appears to sustain under multiaxial compression is greater than its unconfined strength. Following the deformation, the confined specimens were sectioned and all the specimens appeared to be intact without any signs of visible failure.

The response of the matrix under unconfined conditions was highly non-linear with yielding at approximately 50 MPa and exhibits a relatively low hardening [4]. When the matrix was subjected to multiaxial compression under lateral confinement, the matrix exhibited a strongly pressure sensitive behavior. Under these conditions, the matrix did not yield even at 600 MPa and the axial modulus remained unchanged with confinement.

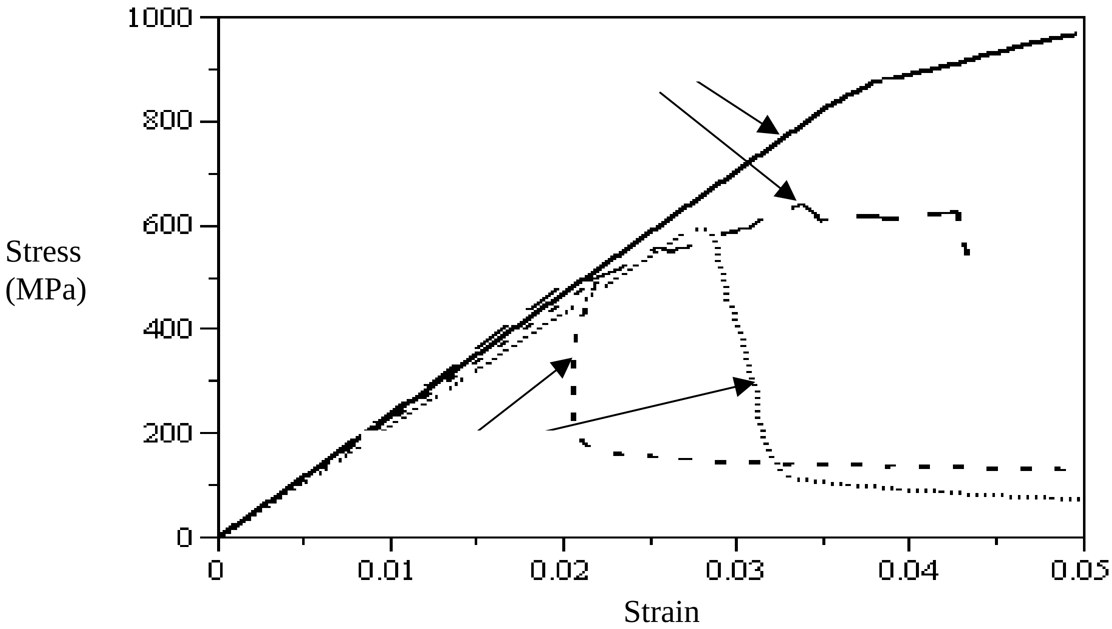
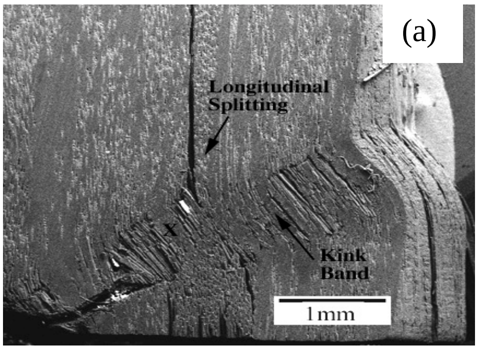


Fig. 3: Stress-strain curves for unconfined and confined 50% V_f E-glass/vinylester composite

Failure Modes

The failure surfaces of the specimen from the uniaxial experiments and the sectioned surfaces of the specimen from the multiaxial experiments were examined using optical and scanning electron microscopy. The failure surfaces of the unconfined specimens revealed axial splitting induced kink banding as shown in Fig. 4a. The specimen splitting appeared to have preceded by debonding of the fiber leading to local stiffness reduction. The local softening lead to transverse tension causing the specimen to split. The splitting resulted in relaxation of the stress state in the surrounding matrix leading to microbuckling and kink band formation and subsequent fiber failure. The axial splitting is manifested as a catastrophic drop in the stress as seen from the stress-strain response of the unconfined composite. The post failure modes of the kink band formation results in sustaining a lower level of resistance observed in the stress-strain curve as seen in Fig. 3.

In the confined specimens, multiple or conjugate kink bands are observed on the sectioned surface. The kink banding eventually lead to fiber failure at the ends of the kink bands. The acoustic emission activity observed during the quasistatic experiments in confined specimens corresponds to fiber failure from the kink band formation. The multiple load drops observed in the stress-strain curve are related to the transfer of axial loading in the transverse direction due to the kink band geometry. With increasing confinement, the axial splitting mode of failure in the unidirectional fiber reinforced composite is suppressed and transitions to kink band formation is shown in Fig. 4b. Due to lateral confinement, the axial splitting mode is suppressed and the micro buckling leading to kink band is favored. To accommodate applied axial deformation, multiple (conjugate) kink bands are formed which eventually leads to a limiting strength which is related to the crushing of the composite as observed from the leveling of the stress-strain curve for the confined specimens. The observed failure modes and their transition is a function of the strength and toughness of fiber and matrix and their interface, elastic and inelastic properties of the constituents and the applied stress state.



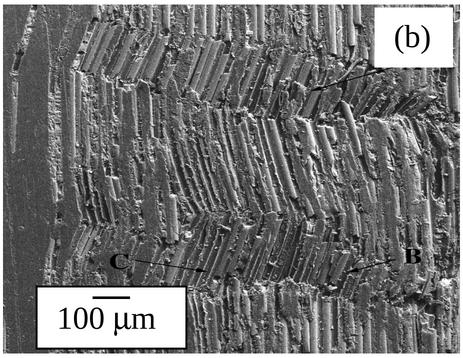


Fig. 4: Failure mode transition in E-glass/vinylester composite, (a) axial splitting followed by kink banding (unconfined); (b) Kink banding followed by fiber fracture (laterally confined)

MODELING

Micromechanics based models have been developed to explain the failure mode transition and the observed trends in compressive strength. An energy-based model together with a failure criterion is used to simulate axial splitting [13]. For a given lateral confinement, the compressive strength can be computed as a function of the effective properties of the unsplit and the split composite as well as the fracture energy. The results from the analysis indicate that the effect of confinement on compressive strength is relatively small in comparison to the effect of fiber volume fraction. The rate of increase in compressive strength with increasing confinement is shown less than or equal to unity. An elastic column supported by an elastic foundation subjected to end loads is used to simulate the formation of observed instability, i.e., kink-band formation. The resulting solution shows an increase in compressive strength with increasing lateral confinement. The splitting and buckling analyses are able to capture the essential features of experimental data [6,7,14] for unidirectional fiber reinforced composites. Insights gained from the modeling regarding the influence various material parameters and length scales on the strength of composites are useful in designing marine and other structures with composites.

SUMMARY

A new experimental technique using a modified Kolsky (split Hopkinson) pressure bar has been developed to investigate materials at high strain rates and under multiaxial compression. Methods for proportional radial confinement, pulse shaping, specimen recovery and controlling specimen deformation have been outlined. Experiments on a 50% by volume E-glass/vinyl ester composite at various strain rates of up to 3,000/s revealed an increase in compressive strength with increasing strain rate. Results from proportional loading multiaxial compression experiments on the composite showed an increase in strength in comparison to its unconfined compressive strength at a given strain rate. The experimental data is currently being used to develop high-strain rate constitutive models for fiber reinforced composites as a function of stress-state.

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