Materials and Design 49 (2013) 566–574

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Technical Report

Modeling quasi-static and high strain rate deformation and failure behavior of a (±45) symmetric E-glass/polyester composite under compressive loading

A. Kara, A. Tasdemirci [*], M. Guden

Dynamic Testing and Modeling Laboratory and Department of Mechanical Engineering, Izmir Institute of Technology, Gulbahce, Urla, Izmir 35430, Turkey

ARTICLE INFO

Article history:
Received 7 August 2012
Accepted 2 January 2013
Available online 23 January 2013

ABSTRACT

Quasi-static (1×10^{-3}–1×10^{-2} s^{-1}) and high strain rate ($\sim$1000 s^{-1}) compressive mechanical response and fracture/failure of a (±45) symmetric E-glass/polyester composite along three perpendicular directions were determined experimentally and numerically. A numerical model in LS-DYNA 971 using material model MAT_162 was developed to investigate the compression deformation and fracture of the composite at quasi-static and high strain rates. The compressive stress–strain behaviors of the composite along three directions were found strain rate sensitive. The modulus and maximum stress of the composite increased with increasing strain rate, while the strain rate sensitivity in in-plane direction was higher than that in through-thickness direction. The damage progression determined by high speed camera in the specimens well agreed with that of numerical model. The numerical model successfully predicted the damage initiation and progression as well as the failure modes of the composite.

1. Introduction

Polymer matrix composites have been increasingly used in airplanes, spacecraft, light weight structures, medical prosthesis and sandwich structures. In these applications, the deformation rate in composites structures may exceed the quasi-static strain rate range particularly under high velocity impact loading. Hydraulic driven and/or drop weight impact test systems are widely used to test composites at intermediate strain rate levels, ranging from 50 s^{-1} to 150 s^{-1}. On the other hand, the Split Hopkinson Pressure Bar (SHPB) is frequently used, in the testing of composite materials, to achieve the strain rates higher than 200–300 s^{-1}. The SHPB testing can suffice nearly the uniaxial stress state and also be used as a tool to validate the determined constitutive relations. The compressive dynamic behavior of various composites has been previously investigated [1–5] using hydraulic testing machines (strain rates up to $\sim$100 s^{-1}) and the SHPB apparatus for higher strain rates (strain rates of 500–2000 s^{-1}). These studies were mainly focused on the determination of damage modes and strain rate sensitivity of composites experimentally. Gary and Zhao [6] investigated the compressive impact loading of polymer matrix composites using a so-called anti buckling device to prevent undesirable modes of composite buckling. Several studies also focused on the high strain rate tensile testing of the composites [7–9], using a tension SHPB apparatus and high speed tensile testing machine in the range of $\sim$100–1000 s^{-1}. The strain rate dependent strength of the composites was reported to vary with the testing direction and the fracture mode of the composites was shown to be affected by the strain rate. Few studies were on the modeling the compression, tension and shear deformation of composites at high and quasi-static strain rates [10–12]. In these studies, the specimens recovered through interrupted tests were examined microscopically in order to explore the differences in the sequences of damage initiation between quasi-static and high strain rate loadings. The effect of sample size on the measured mechanical properties of the composites was also analyzed numerically. The quasi-static and high strain rate behavior of glass fiber reinforced polymer composites were previously investigated experimentally and numerically [13–15] and Brown et al. [16] simulated the deformation of the thermoplastic composites using material model MAT_162 in LS-DYNA 971.

The present study is an extension of the modeling efforts, simply to incorporate the material deformation and failure models together to determine both deformation and fracture of the composite at varying strain rates based on the quasi-static and high strain rate stress–strain behaviors. For that, a (±45) symmetric E-glass/polyester composite along with three perpendicular directions were compression tested at quasi-static (1×10^{-3}–1×10^{-2} s^{-1}) and high strain rates ($\sim$1000 s^{-1}). The compressive mechanical behavior of the composite was then modeled numerically using MAT_162 of LS-DYNA 971 explicit commercial finite element code. Finally, the operative failure modes of the composite in SHPB and the measured stress waves in SHPB were used to validate the developed models.

2. Experimental details

E-glass fiber woven fabric (0.6 kg/m^2)/Crystic PAX 702 polyester composite plates of ±45 laminate configuration and 12 mm in

---

[*] Corresponding author. Tel.: +90 232 7506780; fax: +90 232 7506701.
E-mail address: alpertasdemirci@iyte.edu.tr (A. Tasdemirci).

0261-3069/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2013.01.002

thickness were prepared using a vacuum assisted resin transfer molding process. The specimen dimensions are very critical in the SHPB testing. It was previously reported that the length to diameter ratio of cylindrical specimens should be between 0.5 and 2.0 in order to achieve dynamic equilibrium in the specimen during testing [1,17]. Cylindrical specimens with length to diameter ratio of one were core-drilled from the prepared plate in longitudinal, long transverse, and through-thickness directions. The core drilled cylindrical specimens (Fig. 1a–c) were quasi-statically tested at quasi-static strain rates, 1×10^{-3} and 1×10^{-2} s^{-1}, using a Shimadzu AG-I testing machine. High strain rate compression tests were conducted using a compression SHPB test apparatus. The used SHPB apparatus is made of 20.35 mm diameter CPM Rex76™ steel bar and consisted of a 350 mm long striker bar, a 3600 mm incident bar and an 1800 mm transmitter bar. The strain rate ($\dot{\varepsilon}$), the strain (ε), and the stress (σ) of the tested samples were calculated using the following equations:

$$\dot{\varepsilon}(t) = -\frac{2C_b}{L_s}\varepsilon_r(t) \tag{1}$$

$$\varepsilon(t) = -\frac{2C_b}{L_s}\int_0^t \varepsilon_r(t)dt \tag{2}$$

$$\sigma(t) = \frac{E_b A_b}{A_s}\varepsilon_t(t) \tag{3}$$

in which C_b is the elastic wave velocity of the bar, L_s is the sample length and A_s and A_b are the sample and bar cross-sectional area, respectively. ε_i, ε_r, and ε_t are, respectively, the incident, reflected and transmitted strains measured from strain gages on the bar. The above equations are derived based on the assumption that the forces at sample-bar interfaces are equal. The force equilibrium in the specimens may be checked by the use of dimensionless number R given as [17]

$$R = -\frac{2(F_1 - F_2)}{F_1 + F_2} \tag{4}$$

where F_1 and F_2 are, respectively, the front and back surface forces on the SHPB sample. The number R is a measure of the deviation from stress equilibrium in the specimen. When the value of R reaches 0, the stress equilibrium in the sample is reached.

3. Modeling

Finite element simulations of the quasi-static and high strain rate compression tests were performed using MAT_162 material model in LS-DYNA 971. In order to simulate quasi-static experiments using explicit LS-DYNA 971 code in a reasonable computational time, mass scaling was applied by defining a positive time step in *CONTROL_TIMESTEP card. The positive time step of 0.002 was used in the quasi-static simulations. The model included three parts: upper moving compression plate, composite specimen and bottom supporting plate. The plates and specimen were modeled using eight-node solid elements. The sizes of the elements used in plates were 2.62 mm and in the specimen 0.26 mm. The number of elements used in plates and specimen were 33280 and 53760, respectively. An eroding single surface contact was defined between composite layers. Two eroding surface to surface contacts were defined between bottom plate and specimen and between upper plate and specimen. The displacements and rotations of the bottom plate were prevented throughout the simulations and a velocity was defined for the upper plate, the same with the crosshead speed of the experiments.

A full (no symmetry definitions) numerical model was used to simulate SHPB tests. The model had three components: the incident and transmitter bars, each of these 1520 mm in length and the specimen. For each SHPB test modeled, the output was displayed at several locations within the sample as well as at the location of the strain gages on the incident and transmitter bars of the SHPB set-up. The desired result, then, is that data calculated from the numerical model closely match output from the strain gages on the incident and transmitter bars. If these conditions are met, the model can accurately capture the wave propagation behavior inside the sample and bars. The numerical model can then be further used to determine local conditions at any point within the sample: for example, to predict fracture initiation sites and the local stress gradients. In numerical simulations, shorter bars were used in order to decrease the computational time. It was previously shown that this had the effect of decreasing the transit time between successive waves and shortening the wave duration slightly: however, it did not affect the basic wave-shapes or amplitudes [12]. Trial computations were carried out using full-length bars, but apart from the slightly smaller time window, no significant differences were found and the shorter bars were used in numerical models henceforth. Experimentally measured stress pulse was provided as an input to the face of the incident bar in the simulations and all other boundaries were traction-free. In separate SHPB tests, the stresses in the incident bar as function of time were recorded for two different striker bar velocities. The time window for the striker bar length of 350 mm is ~150 microseconds. The recorded incident wave stress as function of time was used input for the simulations of SHPB tests for a certain striker bar velocity. By this way a more accurate stress profile exposed to the specimen could be modeled. The finite element model of a composite specimen between incident and transmitter bars is shown in Fig. 2. The bars and specimen were modeled using

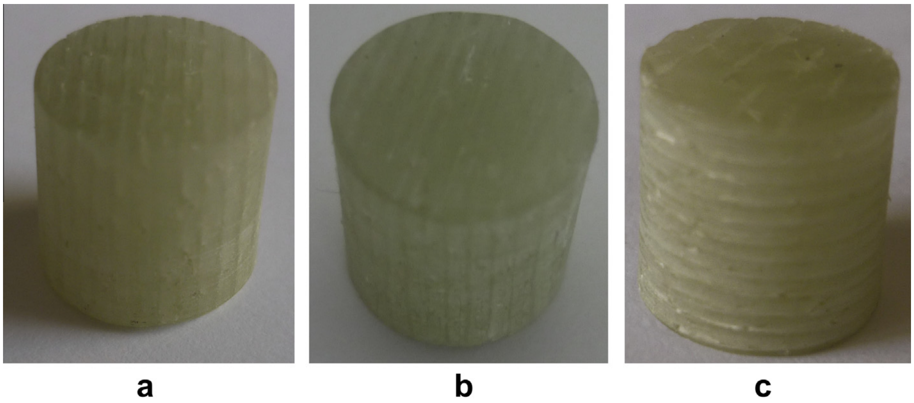

Fig. 1. Cylindrical composite samples were cut in (a) longitudinal, (b) long transverse, and (c) through-thickness directions.