Composite Structures 121 (2015) 37–45

Contents lists available at ScienceDirect

Composite Structures

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

A strain-rate dependent micromechanical constitutive model for glass/epoxy composites

Mahmood M. Shokrieh [a,*], Reza Mosalmani [a], Majid Jamal Omidi [b]

[a] Composites Research Laboratory, Center of Excellence in Experimental Solid Mechanics and Dynamics, School of Mechanical Engineering, Iran University of Science and Technology, Narmak, Tehran 16846-13114, Iran

[b] Department of Aerospace Engineering, MUT, Tehran, Iran

ARTICLE INFO

Article history:
Available online 7 November 2014

Keywords:
Glass fibers
Micro-mechanics
Analytical modeling
Mechanical testing
Strain rates

ABSTRACT

The mechanical behavior of polymeric fibrous composites under dynamic loading is not completely investigated. Therefore, in the preset research, a strain-rate dependent micromechanical constitutive model is developed to predict the dynamic mechanical behavior and elastic properties of fibrous composites under arbitrary loading rates. First, strain rate dependent mechanical behavior of matrix and fibers are experimentally characterized and for each constituent a dynamic empirical material equation is presented. Then, the bridging matrix micromechanical model in combination with a constitutive equation for polymers is utilized to predict the elastic properties and mechanical behavior of fiber-reinforced polymeric composites under arbitrary applied strain rates. Moreover, the strain rate sharing of each constituent of composites (matrix and fiber) is calculated. In order to validate the present method, results predicted by the model are compared with the experimental data. It is shown that the present micromechanical method is able to simulate the rate dependent elastic behavior of fiber-reinforced composites with a good accuracy.

1. Introduction

The mechanical response of fiber reinforced polymeric composite materials varies significantly under the strain rate at which they are loading as compared with the static loading conditions. Since mechanical properties of composites vary significantly with the strain rate, the use of static properties in the analysis and design of structures under dynamic loadings can lead to a conservative design or designs with unexpected and untimely fail [1]. In addition, the dynamic mechanical response of composites is needed for modeling and analyzing the dynamic phenomena like impact, crashworthiness, dynamic fracture, etc. However, Characterization of composite materials under different strain rates is expensive and needs special test apparatus. In addition, it is required to test a large number of specimens under different strain rates to investigate the trend of the mechanical behavior of composites.

The unidirectional (*UD*) composites are considered as transversely isotropic materials, so it is necessary to investigate the longitudinal, transverse and in-plane shear properties of composites. Shokrieh and Omidi [2–5] investigated mechanical properties of *UD* glass/epoxy composites under different strain rates up to 100 s^{-1} and compared them with results obtained by static loading. They have shown that the tensile strength increased significantly by increasing the strain rate while the tensile modulus increased slightly [2]. Considering transverse properties of composites, they have found that the elastic modulus and strength increased by increasing the strain rate [3]. In-plane shear tests under different strain rates show that although shear strength of composites increased by increasing the strain rate, but the shear modulus decreased slightly [4].

Rotem and Lifshitz [6] investigated the tensile behavior of *UD* glass fiber/epoxy composites over a wide range of strain rates from 10^{-6} to 30 s^{-1} and found that the dynamic modulus is 50% higher than the static modulus. The effects of rate sensitivity in the range of loading speeds from 0.008 mm/s to 4 m/s on the tensile, shear and flexural properties of glass/epoxy laminate were investigated by Okoli and Smith [7–9]. They have reported that the tensile and shear mechanical properties increased by increasing the applied strain rate [8]. A similar observation was presented by Armenakas and Sciamarella [10] at various rates of strain (0.0265–30,000 min^{-1}), and suggested a linear variation of elastic tensile modulus of *UD* glass/epoxy composites with the log of the

* Corresponding author. Tel.: +98 (21) 7720 8127.
E-mail address: Shokreih@iust.ac.ir (M.M. Shokrieh).

http://dx.doi.org/10.1016/j.compstruct.2014.10.035
0263-8223/

strain rate. Harding and Welsh [11] validated a dynamic tensile technique by performing tests (over a range of 10^{-4} to $10^{3}\ s^{-1}$) on carbon/epoxy, glass/epoxy, glass/polyester, carbon/polyester and Kevlar/polyester composites. It is found that the dynamic modulus for the glass/epoxy composites was about twice the static modulus. Experimental studies on effects of strain rate from 3×10^{-5} to $8 \times 10^{-3}\ s^{-1}$ on tensile properties of glass-bead/high density polyethylene composites were conducted by Bai et al. [12]. The Young's modulus of the glass bead/HDPE composite was found to increase with the strain rate. The influence of strain rate from 0.1 to $10\ s^{-1}$ on the tensile properties of glass/phenolic resin and glass/polyester resin composites was studied by Barre et al. [13]. They found that the elastic modulus increases with the strain rate.

The in-plane shear behavior of composite materials is controlled by the matrix of composites. Polymeric matrices have rate dependent mechanical behavior, so the shear modulus of polymeric composites is sensitive to the loading rate [4]. Daniel et al. [14] attempted to characterize the effect of strain rate up to $500\ s^{-1}$ on in-plane shear properties of carbon/epoxy composites using the 10° off-axis rings under internal pressure. The results obtained from tension tests of rings indicated that the in-plane dynamic shear modulus and strength increased significantly over static values. Hsiao et al. [15] investigated the in-plane shear behavior of 45° off-axis *UD* carbon/epoxy specimens at strain rate up to $1200\ s^{-1}$ using a split Hopkinson pressure bar and found that the initial shear modulus increased with the strain rate from the quasi-static value by up to 18%. In addition, it was found that the shear strength increased sharply by increasing the applied strain rate. Papadakis et al. [16] studied the effects of strain rate on in-plane shear properties of ±45° glass/polypropylene composite specimens. The experimental results indicated that the shear modulus had a decrease by increasing the strain rate. Daniel and Liber [17] characterized different fibrous composites whereas epoxy is the matrix, under strain rate up to $20\ s^{-1}$. Based on the obtained results from intra-laminar shear experiments, the shear modulus of Boron/epoxy and Carbon/epoxy increased by increasing the strain rate significantly; while no significant increase of in-plane shear modulus were noticed for S-glass/epoxy and Kevlar 49/epoxy.

Micromechanics is a method to study the macroscopic response or the mechanical properties of reinforced composites based on the properties and the geometrical occupations of its constituent materials [18]. There are several researches which attempt to simulate the dynamic mechanical behavior of fibrous composites micromechanically [19–23]. While, there are more material models presented in the literature which are empirical [24]. Goldberg [23] presented a strain rate dependent micromechanical model for neat polymers and then extended it for fibrous composites. In his model, the unit cell method is implemented to predict the mechanical properties of fibrous composites. However, he assumed that fiber is strain rate independent and there is no difference between the total applied strain rate and strain rate sharing of each constituents. Tabiei et al. [19–22] developed a finite element method to consider the nonlinearity and dynamic sensitivity in calculating mechanical properties of fibrous composites by using the Goldberg model for polymers [25]. Koyanagi et al. [26] studied the strain rate dependent transverse tensile of *UD* composites numerically. Although the fiber, matrix and interface have been modeled individually, but the aim of their study was investigating the failure modes of *UD* composites under strain rate dependent transverse tensile loadings.

In the present research, the strain rate dependent mechanical properties of constituent materials of composites (fibers and matrix) have been considered to develop a strain rate dependent micromechanical constitutive model. The present micromechanical constitutive model is able to simulate the stress–strain behavior and the elastic properties of *UD* composites under various strain rates. Therefore, dynamic mechanical properties of fibers and matrix are presented by an empirical material equation. Furthermore, the strain rate sharing of fibers and matrix in the fibrous composites are determined based on the loading type and rate. Finally, the results predicted by the model are compared with the available experimental data at quasi-static and intermediates strain-rates, ranging from 0.001 to $100\ s^{-1}$.

2. Problem statement and modeling strategy

Determination the stress–strain constitutive equation and these mechanical properties at quasi-static and dynamic strain rates requires different types of characterization tests at several loading rates. In addition, there are various characterization test methods which have different advantages and limitations and should be chosen appropriately to produce good experimental results [27]. Also, characterization of composite materials at dynamic loading rates is expensive and difficult. Moreover, it should be mentioned that any change in the constituent of composite materials and their volume fractions, requires the repetition of all mentioned tests.

Several micromechanics methods have been developed to understand the elastic, inelastic and failure behaviors of composites by using their constituent properties and geometric parameters at static loading condition [28]. In the present research, in order to use a micromechanics method to predict the strain-rate behavior of composites, the strain rate dependent mechanical properties of its constituent materials are used in a micromechanical equation. Fig. 1 shows a schematic diagram of the modified micromechanical model to predict the strain rate depended stress–strain constitutive model of fibrous composites. According to this diagram, a micromechanics model such as bridging matrix micromechanical model [29,30] is selected and developed to predict the rate dependent mechanical behavior of fibrous composites. The strain rate sensitivity of polymeric matrix is also considered by using a strain rate dependent constitutive equation developed by Goldberg et al. [25]. Furthermore, the rate dependent mechanical behavior of the matrix material and reinforcement are studied experimentally. Also, the sharing of applied total strain rate between the constituents (fiber and matrix) is considered.

3. Strain-rate dependent micromechanical constitutive model

In this section, required steps to model the mechanical behavior of fibrous composites under dynamic loading conditions, based on the strain rate dependent micromechanical approach are

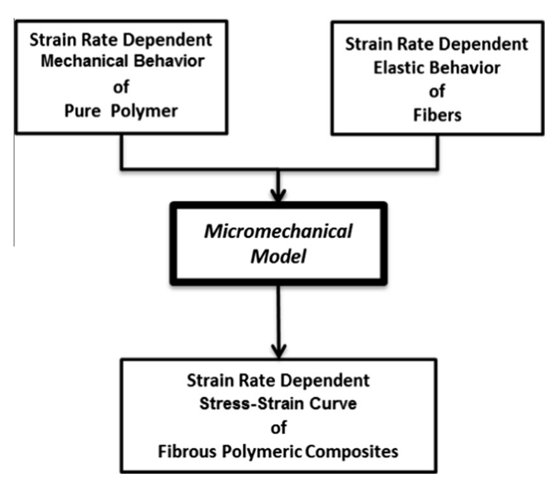

Fig. 1. Schematic diagram of the present method to predict the strain rate dependent stress–strain curve of composites.