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Strain-rate dependent micromechanical method to investigate the strength properties of glass/epoxy composites

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ABSTRACT

The mechanical properties of glass/epoxy composites are sensitive to applied loading rates. In the present research, a strain-rate dependent micromechanical (*SRDM*) method is developed to predict the strength of unidirectional (*UD*) polymeric composites under various loading rates. In this paper, the Goldberg et al. model, as a strain rate dependent constitutive equation of polymers, has been combined with a micromechanics model (the bridging matrix method) to predict the strength of *UD* composites at arbitrary strain rates. In addition, the bridging matrix method is modified by using strain concentration factor to determine the transverse tensile and in-plane shear strengths of *UD* composites. To verify the proposed model, first the dynamic mechanical behavior of glass fibers and epoxy matrix were studied experimentally. Then, the predicted results are compared with the available experimental data of glass/epoxy composites. A comparison between predicted results and available experimental data for longitudinal tensile, transverse tensile and in-plane shear strengths of *UD* glass/epoxy composites under various strain rates shows the capability of the proposed novel model.

1. Introduction

In the many applications, composites structures are under dynamic loadings. Furthermore, polymers and polymeric composites are sensitive to the applied loading rates. Therefore, it is not reasonable to design these composites structures based on static mechanical properties. However, dynamic characterization of composites as a transversely isotropic material is expensive, time consuming and needs special apparatuses. Thus, it is required to develop a micromechanics method to predict the dynamic mechanical properties of composites.

Shokrieh and Omidi [1-3] studied the mechanical properties of glass/epoxy composites under intermediate strain rates up to 100 s^{-1} and compared the results with statics tests. They have investigated that the longitudinal tensile strength increased significantly by increasing the strain rate [1]. Similar to the longitudinal tensile strength, they have found that the transverse tensile and shear strengths are increased by increasing the applied strain-rate [2,3].

Okoli and Smith [4,5] have shown that the tensile strength of glass/epoxy laminate increased by increasing the applied loading rate. Similar results achieved by Staab and Gilat [6] in investigation of glass/epoxy angle ply laminates. Harding and Welsh [7] introduced a dynamic tensile technique (over the range 10^{-4} to 10 s^{-1}) and verified it by test on glass/epoxy composites. The dynamic tensile strength for the glass/epoxy composite was about twice the static value. Kawata et al. [8] studied various composite materials such as glass/polyester and glass/epoxy under tension from 10^{-3} to 2000 s^{-1}. Their results showed that the strength clearly increased with the strain rate. Davies and Magee [9,10] studied the effect of strain rates on the glass/polyester composites. They reported that the tensile strength increased over the strain rate change.

The transverse tensile properties of unidirectional (*UD*) carbon/epoxy laminate composites at strain rates up to 500 s^{-1} are investigated by Daniel et al. [11,12]. They reported that the transverse tensile strength had a significantly increase in comparison with the static value. These results are similar with experiments were conducted by Chamis and Smith [13]. Al-Salehi et al. [14] investigated that transverse tensile properties of glass/epoxy and kevlar/epoxy at various strain rates has noticeably increase over the static value.

The in-plane shear properties of carbon/epoxy composites under the strain rate up to 500 s^{-1} were characterized by Daniel et al. [12]. The results of tests indicated that the dynamic in-plane shear strength increased approximately 30% over static values. Harding and Welsh [7] studied the effect of high loading rate on the in-plane shear behavior of glass/epoxy composites. They

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showed that the shear strength increased sensibly with increasing of applied strain rate. The in-plane shear behavior of unidirectional carbon/epoxy composites at strain rate up to 1200 s^{-1} was investigated by Hsiao et al. [15]. It was shown that the dynamic shear strength increased sharply with strain rate in comparison with quasi-static value. Tsai and Sun [16,17] studied the strain rate effect on the in-plane shear strength of unidirectional glass/epoxy laminate composites using split Hopkinson pressure bar. Their experimental results exhibited the quite sensitivity of shear strength of the composites to the applied strain rate.

Experimental dynamic characterization of composites is a tedious task, so it is necessary to develop a micromechanical method to predict dynamic mechanical properties of composites. Micromechanics is a theory to study the mechanical properties of a unidirectional composites based on properties and the geometrical occupations of its constituent materials [18]. Chamis [19] presented semi-empirical relations to determine the static strength of composites based on its constituents. The Chamis model assumes that the tensile strength of a unidirectional composite is only a function of the strength of the reinforcement. This model is validated when the fiber is remarkably stiffer and stronger than the matrix [20]. Aboudi [21] presented the method of cells for predicting static mechanical properties of composites. The implementation of his method is complicated and sometimes needs modified values instead of real values of mechanical properties of neat constituents. Huang [22] developed a micromechanical model based on his bridging matrix method to predict the strength of composites at static conditions. Although his model is simple to use but it also needs modified values of mechanical properties of composites.

To the best knowledge of present authors, the strain-rate dependent strength of fibrous composites is not predicted yet by micromechanics models. In the present study, a novel micromechanics method is proposed to predict the strength of composites under different dynamic loading rates. First, a modified constitutive equation, presented by Goldberg et al. [23] is selected to represent the strain-rate dependent mechanical behavior of pure polymers. Furthermore, dynamic strength of fibers is studied and an empirical equation is presented. Then, the bridging matrix method [22] is modified to combine with the constitutive equation of polymers and the proposed empirical equation of fibers. The developed model is called as the strain-rate dependent micromechanics (*SRDM*) method. To verify the model, the results obtained by the model are compared with available experimental data.

2. Problem statement and modeling strategy

The fibrous composites are sensitive to the loading rate, so it is necessary to investigate their mechanical properties in different loading rates. Determination the trend of these properties at quasi-static and dynamic strain rates requires different types of characterization tests at several loading rates. In addition, there are various test methods which have different advantages and limitations and should be chosen appropriately to produce good experimental results [24]. Furthermore, characterization of composite materials at dynamic loading rates is expensive and difficult. However, it should be mentioned that any change in the constituents 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 rate [22]. To the best knowledge of the present authors, in most of the micromechanical models static properties of composites are predicted based on mechanical properties of its constituent materials (reinforcement and matrix). Therefore, in the present research, a strain-rate dependent micromechanics (*SRDM*) method is developed to predict the strain-rate dependent strength of composite materials. The presented method (*SRDM*) is able to predict the strain-rate dependent mechanical strength of *UD* composites by using the strain-rate dependent properties of the constituent materials. Fig. 1 shows a diagram of the *SRDM* method.

According to the flowchart, a strain-rate dependent mechanical properties of composites ingredients (fibers and matrix) are combined with a modified micromechanics model (bridging micromechanical model [22]). The bridging micromechanical model [22] is able to predict the static mechanical properties of fibrous composites. The nonlinear rate dependent mechanical behavior of pure polymers is represented by a strain-rate dependent constitutive equation (Goldberg et al. model [23]). Furthermore, rate dependent mechanical properties of the reinforcement are studied and expressed as an empirical equation. Moreover, Then the influence of the applied strain-rate on the strength properties of composites is predicted by the present method. Finally, to verify the proposed method, the predicted results are compared with the available experimental data at various strain rates. In the following sections, components and details of the *SRDM* method are explained.

3. Strain-rate dependent micromechanical (*SRDM*) method

In this section, the required steps for modeling of mechanical behavior of fibrous composites under dynamic loading have been discussed. First, the strain rate dependent mechanical properties of matrix and fibers as the main ingredients of fibrous polymeric composites are studied. Then bridging matrix micromechanics model is modified. For this reason, the share of each constituent from total applied loading rate is calculated to determine the rate dependent mechanical properties of each constituent. Furthermore, the strain concentration factor is studied and considered in the *SRDM* method. Finally, strength properties of composites at arbitrary loading rate are predicted.

3.1. Strain-rate dependent mechanical properties of composites constituents

The polymeric matrix and some fibers such as glass fibers are sensitive to the applied loading rates, so it is necessary to investigate dynamic mechanical properties of each constituent of composites at applied loading rate. In the present study, dynamic

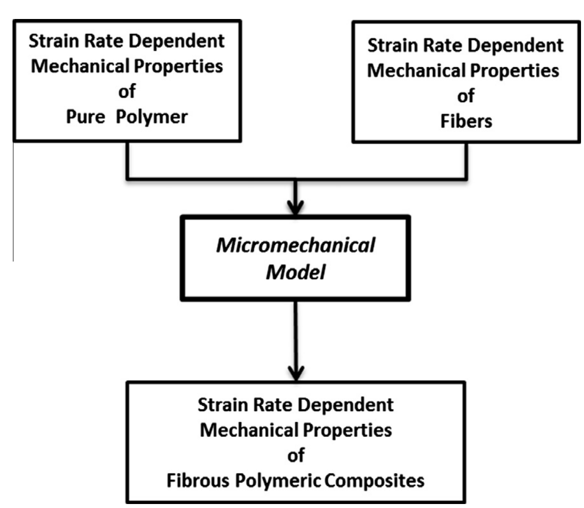

Fig. 1. Schematic flowchart of *SRDM* method to predict the strain-rate dependent strength of fibrous composites.