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Investigation of strain rate effects on in-plane shear properties of glass/epoxy composites

Mahmood M. Shokrieh *, Majid Jamal Omidi

Composites Research Laboratory, Mechanical Engineering Department, Iran University of Science and Technology, Tehran 16846-13114, Iran

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ABSTRACT

Fiber-reinforced polymeric composites exhibit excellent mechanical properties over conventional engineering materials especially due to their great weight saving. Therefore, by considering the specific attributes of these materials, having a proper knowledge of dynamic behavior as well as static behavior of them is necessary. In order to study the effects of strain rate on the behavior of the materials, special testing machines are needed. Most of the researches in this field are focused on applying real loading and gripping boundary conditions on the testing specimens. This paper discusses the experimental study on the in-plane shear behavior of unidirectional glass fiber-reinforced polymeric composite under quasi-static and intermediate strain rate loading conditions. The symmetric and balanced ±45° composite laminates are manufactured for characterization of the in-plane shear properties (modulus and strength) at various strain rates. Specimens are tested under uni-axial tensile loading using a servo-hydraulic testing apparatus. For performing the practical tests, jig and fixture are designed and manufactured. The performance of the test jig is evaluated and found to be adequate for composites testing. Dynamic tests results are compared with static tests carried out on specimens with identical geometry. The experimental results show that the mechanical shear properties are quite sensitive to strain rate. Under dynamic loading, the failure shear strength increased with increasing the strain rate but the shear modulus decreased. Based on the results obtained from the experiments, empirical functions for expressing the mechanical shear properties are proposed in terms of shear strain rate.

1. Introduction

Fiber-reinforced polymeric composites due to their specific attributes such as high stiffness and strength-to-weight ratios, fatigue and corrosion resistance, high damping capability and lower manufacturing costs, are attractive when compared with conventional metals. In many practical situations, structures are under dynamic loading conditions. The mechanical responses of greater materials vary significantly under such loading as compared to static loading. In the absence of the proper understanding of strain rates effects on the composite materials behavior, the response of a structure designed with static properties might lead to a very conservative overweight design or designs that fail prematurely and unexpectedly. The use of dynamic mechanical properties of fibrous composites would ensure the design of composite structures that are weight efficient and structurally sound when they are under dynamic loads.

Unidirectional composite materials generally exhibit lower in-plane shear strength than longitudinal tensile and compressive strengths. This behavior is attributed to the fact that in-plane shear deformation and failure are controlled by the matrix of the composite. For polymeric composites, this indicates that the shear modulus and strength may be sensitive to loading rate. Shear properties of a variety of fibrous composites under static loading are well studied, while their shear behavior under dynamic loading is not yet clearly understood. The static shear behavior of composite materials has been extensively investigated and developed experimentally using different test methods [1–4].

The above argument indicates the need for dynamic characterization of fiber-reinforced polymer composite materials to understand the strain rate effects on their mechanical properties. Strain rate effects on the tensile and compressive behavior of fiber-reinforced polymeric composite materials has studied experimentally by many researches while a few investigation have developed and experimentally validated for characterize of shear behavior of composites under dynamic load conditions. Daniel et al. [5] 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 of rings indicated that the in-plane dynamic shear modulus and shear strength increased approximately 30% over static values. However, the dynamic ultimate shear strain was lower than the static one. The results of the researches by

* Corresponding author.
E-mail address: Shokrieh@iust.ac.ir (M.M. Shokrieh).

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Harding and Welsh [6] on the −45° glass/epoxy composite specimens using a modified version of the tension split Hopkinson's pressure bar apparatus and Staab and Gilat's researches [7] on the ±45° glass/epoxy composite specimens using a direction tension split Hopkinson bar apparatus showed a sensible increase of laminate strength with strain rate of the order of 1000 s^{-1}. The increase in laminate strength reflects to a large increase in the shear strength. Chiem and Liu [8] investigated the dynamic behavior of woven carbon/epoxy composite under shear impact loading in the orthogonal direction using a torsional split Hopkinson bar at various shear strain rate, ranging from 1000 to 5500 s^{-1}. The results obtained from torsion tests on the carbon/epoxy composite specimens showed an increase in shear strength with increasing strain rate.

Daniel et al. [9] investigated the dynamic response of unidirectional carbon/epoxy composites at high strain rates using an internal pressure pulse produced explosively through a liquid medium. In the test method used for dynamic testing of thin laminates in tension, a carbon/epoxy laminate was characterized under in-plane shear loading at strain rates up to 500 s^{-1} and found that the in-plane shear properties (modulus and strength) of composite increased by up to 30% over the static value. Al-Salehi et al. [10] extracted the lamina in-plane shear properties at various rates of strain from the results of burst tests on glass/epoxy and Kevlar/epoxy filament wound tubes with winding angles ±55° and ±65°, for both, under internal hoop loading. The results obtained from ±55° specimens showed that with increasing shear strain rate from 0 to 400 s^{-1}, the shear strength increased by 70% and 115% for glass/epoxy and Kevlar/epoxy materials, respectively. The results extracted from ±65° specimens were lower than the last ones. Hsiao et al. [11] investigated the in-plane shear behavior of 45° off-axis unidirectional carbon/epoxy specimens at strain rate up to 1200 s^{-1} using a split Hopkinson pressure bar and found that the dynamic shear strength increased sharply with strain rate from the quasi-static value by up to 80%. The initial modulus also followed a similar trend with an increase up to 18%.

Tsai and Sun [12,13] investigated the strain rate effect (up to 700 s^{-1}) on the in-plane shear strength of unidirectional off-axis S2/8552 glass/epoxy laminate composites using split Hopkinson pressure bar. The specimens were tested at orientations of 15°, 30°, 45°, and 60°. They modeled stress–strain curves based on a viscoplasticity model established at the lower strain rate data and then extended this model to high strain rates up to 700 s^{-1} [12]. The shear strain rate was also obtained from the axial strain rate by relating the effective plastic strain rate to the plastic shear strain rate with the aid of a viscoplasticity model [13]. The experimental results showed that, in all cases, the shear strength of the composite was quite sensitive to strain rate and the shear strength increased as strain rate increases.

Tensile tests were performed at 5, 50 and 500 mm/min crosshead displacement rates by Papadakis et al. [14] to determine the effects of strain rate on the in-plane shear properties of ±45° glass/polypropylene composite specimens. The specimens were loaded uniaxially in tension using a universal testing machine. The experimental results indicated that the shear modulus had a decrease with increasing strain rate while the shear stress at failure increased with strain rate. The shear strain to failure was also strain rate independent. Raju et al. [15] investigated experimentally the in-plane shear responses of carbon fabric/epoxy and fiber glass/epoxy composites using a servo-hydraulic testing machine at nominal stroke rates ranging between 2.5×10^{-5} and 12.7 m/s. The V-notch rail shear configuration was used for characterizing the in-plane shear properties of material systems. A maximum estimated shear strain rate of 500 s^{-1} was achieved up to shear strain levels of 0.08 radians, during the tests. The stress–strain behavior of both material systems exhibited contrasting behavior with increasing stroke rates. The experimental results showed that at the highest test rate, the shear strengths increased by a factor of three relative to that of the quasi-static rate, and were independent of the reinforcement type.

The aim of the present research is to investigate the in-plane shear properties of unidirectional glass/epoxy composite materials at various strain rates. The servo-hydraulic testing apparatus is used to develop the quasi-static stroke rate of approximately 0.0216 mm/s and the intermediate stroke rates range from 12.7 to 1270 mm/s. The symmetric and balanced ±45° composite specimens with identical geometry are used for determining the in-plane shear characteristics (modulus and strength) in all the tests. The results of the dynamic tests are subsequently compared to quasi-static tests. Under dynamic loading, the failure shear stress increased with increasing strain rate while shear modulus and strain to failure decreased.

2. Materials, equipments and experimental procedure

2.1. Materials and preparation of test specimens

Full characterization of the shear properties of a composite lamina or laminate requires the measurement of shear modulus and shear strength in the 1–2, 1–3 and 2–3 planes which coordinate system conform to lamina coordinate system. Because in-plane and through-thickness shear properties are not necessarily equal, test methods have been developed to induce both in-plane and through-thickness shear loading. In this study, we are only concerned for determining the in-plane shear characteristics (modulus and strength) at various strain rates.

The composite material used in this study is a unidirectional E-glass fiber/ML-506 epoxy resin system. Thin laminates with a configuration of $[\pm 45°]_{3s}$ with twelve plies are fabricated, giving the laminate an approximately 2.3 mm thickness. The composite laminates are manufactured by hand lay-up and cured under recommended process. Then, the ±45° tensile specimens with 82.7 mm length and 20 mm width are cut from the panels using a low speed diamond saw. Specimens are polished using sanding rotor equipped with a fine sand paper (grit #800). All of the specimens have constant cross sections with tabs bonded to the ends. End tabs are manufactured of glass fiber reinforced epoxy, with the fiber axis of the fabric set at ±45° to the specimen axis. The preparation and manufacturing stages of the tabs is like the production of the specimens. The end tabs are adhesively bonded to the specimen with 1.85 mm thick, 35 mm length and tab angle of 90°. The selection of the tab sequence and its angle is based on the recommendation available in [16] for determining the in-plane shear characteristics (modulus and strength) of the ±45° tensile specimen. These tabs allow a smooth load transfer from the grip to the specimen. Tabs can reduce stress concentration and thus the shock wave stress effects. The gauge lengths of the specimens are 12.7 mm. The fiber volume fraction of the composite layers is 50%. The tensile load is applied causes the in-plane shear stress in the specimen. The specimen configuration and dimensions are shown in Fig. 1.

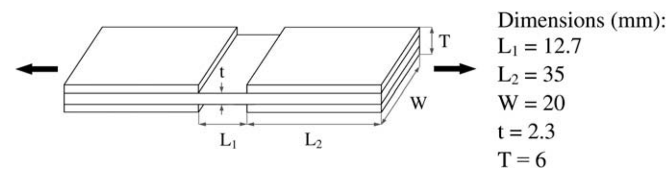

Fig. 1. Geometry and dimensions of symmetric and balanced ±45° composite specimens under tensile loading.