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Investigating the transverse behavior of Glass–Epoxy composites under intermediate strain rates

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ABSTRACT

In this study, the strain rate effects on transverse tensile and compressive properties of unidirectional Glass fiber reinforced polymeric composites are investigated. To demonstrate strain rate effects, the tensile and compressive composite specimens with identical configuration are fabricated and tested to failure in the transverse direction at quasi-static strain rate of approximately 0.001 s^{-1} and intermediate strain rates of 1–100 s^{-1}. The tensile and compressive tests are performed using a servo-hydraulic testing apparatus equipped with strain rate increasing mechanisms. For performing the practical tests, a jig and a fixture and other test supplies are designed and manufactured. The performance of the test jig is evaluated and showed that it is adequate for composites testing under tension and compression loads. The effects of strain rate on mechanical properties (maximum strength, modulus, and strain to failure) are considered. The characteristic results for the transverse properties indicate that damage evolution is strain-rate-dependent for the examined material. Also, a strain-rate-dependent empirical material model associated with different regression constants is proposed based on the experimental results obtained to characterize the rate dependent behavior of Glass/Epoxy composite material.

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1. Introduction

By considering the wide applications of composite materials, it is essential to have a proper knowledge and understanding of the response of these materials to increasing strain rate loading conditions. The mechanical responses of fiber reinforced polymeric composite materials vary significantly under such loading as compared to the static loading. On the other hand, for these materials, damage progress is quite sensitive to strain rate. 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 conservative estimates. Therefore, reliable design of the composite components under dynamic loading requires the detailed characteristics of these materials at varying strain rates.

Most of the researches in this field are focused on applying real loading and gripping boundary conditions on the testing specimens. Also, few studies exist that describe the changes in the transverse properties of polymeric composites as functions of the strain rate. Daniel and Liber [1] investigated the tensile strain rate effects up to 10 s^{-1} on the transverse properties of unidirectional Carbon/Epoxy coupons and reported small effects of strain rate on the mechanical properties. For coupons, the transverse tensile modulus and strength were found to increase slightly with an increase in strain rate, whereas the strain to failure was found to be strain rate insensitive. Daniel et al. [2] also Chamis and Smith [3] studied the transverse tensile properties of unidirectional Carbon/Epoxy laminate composites at strain rates up to 500 s^{-1}. The results of their investigations indicated that the transverse tensile modulus and strength had an increase of two to four times higher as compared to the static value. Al-Salehi et al. [4] extracted the lamina transverse tensile properties at various rates of strain from the results of burst tests on Glass/Epoxy and Kevlar/Epoxy filament wound tubes with winding angle of ±25° under internal hoop loading. The results of their investigation showed that for Kevlar/Epoxy at a strain rate of 70 s^{-1}, there was an increase of almost six times in modulus and ten times in strength over the static value. The corresponding increases for Glass/Epoxy were three and half times and six times for transverse modulus and strength, respectively. The dependence of the transverse tensile properties on strain rate of a high performance Carbon fiber/Epoxy composite loaded in transverse tension was investigated by Melin and Asp [5]. They tested dog-bone shape specimens under quasi-static and dynamic loading conditions (10^{-3}–10^{3} s^{-1}). The average transverse modulus was observed to be independent of strain rate while the initial transverse modulus was found to decrease slightly with increased strain rate. The strain to and stress at failure was found to increase

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slightly with increased strain rate. Thus, when loaded in the transverse direction it was concluded that Carbon/Epoxy composites exhibited a weak dependence on the strain rate. Daniel et al. [6] investigated the dynamic response of Carbon/Epoxy composites at high strain rates using three different test methods. In the first test method, used for dynamic testing of thin laminates in tension, a Carbon/Epoxy laminate was characterized under transverse loading at strain rates up to 153 s^{-1}. In the transverse direction, the tensile modulus and strength increased sharply over static values but the ultimate strain only increased slightly. In the second test method, used for dynamic testing of thin laminates in compression, transverse compressive properties were obtained up to a strain rate of 210 s^{-1} and found that the transverse dynamic modulus and strength increased much higher than the static values while the dynamic ultimate strain was lower than the static one. In the third test method, used for dynamic testing of thick laminates in compression, transverse properties were obtained up to a strain rate of 80 s^{-1}. The transverse compressive modulus moderately increased with strain rate (up to 18% over the static value) but the strength and ultimate strain increased by 50% and 30% over corresponding static values.

Also there are few studies on transverse properties of unidirectional plies under high strain compression loading. Lowe [7] performed transverse compression tests on T300/914 Carbon/Epoxy unidirectional composites at various strain rates. The experimental results indicated an increase in both transverse compressive strength and modulus with increasing strain rate. Hsiao et al. [8] characterized the dynamic transverse behavior of unidirectional Carbon/Epoxy composites at strain rate up to 1800 s^{-1} using a split Hopkinson pressure bar. The results of the investigations indicated that the transverse compressive strength had an increase of nearly two times higher as compared to the static value. The transverse modulus followed a similar trend with an increase of up to 37%. Vural and Ravichandran [9] investigated the transverse failure behavior of thick unidirectional S2-Glass/Epoxy fiber reinforced composites with varying degrees of lateral confinement at strain rates from 10^{-4} to 10^{4} s^{-1}. Their experimental results indicated that the compressive strength increased with the application of the lateral confinement as well as the increment of the strain rate. A study of the effect of strain rate from 10^{-3} to 600 s^{-1} on the compressive strength of unidirectional Carbon/Epoxy composite specimens by Cazeneuve and Maile [10] highlighted a 50% increase in the longitudinal strength and a 30% increase in the transverse strength. Hall and Guden [11] conducted low-to-high strain rate testing of unidirectionally reinforced Graphite/Epoxy composites. High strain rate testes were performed using a split Hopkinson pressure bar at various strain rates up to 2000 s^{-1}. The results of their investigation indicated that in the transverse direction, the failure strength increased noticeably from 215 MPa at quasi-static strain rate to an approximately constant value of 360 MPa at high strain rate. The failure strain was almost constant at 5 ± 0.3%, and no significant change was also noted in Young's modulus over the strain rate range investigated. Hosur et al. [12] investigated the dynamic response of unidirectional Carbon/Epoxy laminated composites under transverse loading using a modified split Hopkinson pressure bar set-up at three different strain rates of 82, 164 and 817 s^{-1}. Their experimental results indicated a 0.6–25% increase in transverse strength and a 25–50% increase in the modulus under dynamic loading as compared to static values. Tsai and Kuo [13] investigated the effect of strain rate from 10^{-4} to 500 s^{-1} on the transverse compressive strength of Glass/Epoxy and Carbon/Epoxy composites using a hydraulic MTS machine and a split Hopkinson pressure bar. For both composites, the transverse compressive strength was found to increase with increasing strain rates. Inspection of the compression failed specimens using the scanning electro microscope (SEM) indicated that for the Glass/Epoxy composites, the main failure mode was due to the matrix shear failure, however, for the Carbon/Epoxy composites, it became the fiber and matrix interface de-bonding which might dramatically reduce the transverse compressive strength of the fibrous composites.

The aim of the present paper is an experimental study of strain-rate-dependent behavior of unidirectional Glass/Epoxy composites under different strain rates. For this reason, a servo-hydraulic testing apparatus is used to characterize the transverse behavior of composite material at quasi-static strain rate to intermediate strain rate of approximately 100 s^{-1}. Based on the quasi-static and dynamic test results, the effects of strain rate on the transverse properties of Glass/Epoxy composites are analyzed and evaluated. In addition, constitutive equation of this material as a function of strain rate, based on experimental results is proposed.

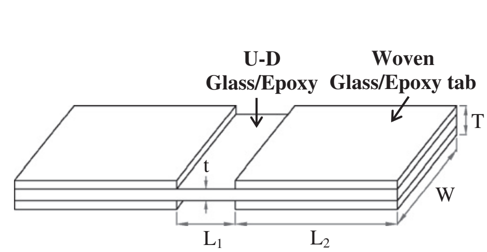
2. Material, equipment and experimental procedure

2.1. Material selection and preparation of specimens

Unidirectional glass fiber reinforced epoxy is studied in this paper. Two different thin plates are used to manufacture the transverse specimens. For the transverse tensile behavior characterization of material system, thin laminate composed of nine plies of reinforcement with epoxy resin are fabricated, giving a laminate approximately 1.82 mm in thickness. In addition, 15 plies of reinforcement with epoxy resin are fabricated for characterization of transverse compressive properties and the thickness of the laminate is approximately 3.1 mm. The composite laminates are manufactured by the hand lay-up and cured under recommended process. The specimens are cut from the panels using a low speed diamond saw in perpendicular direction to fibers axis from laminates coincide with the transverse loading direction. Then, the specimens are polished using sanding rotor equipped with a fine sand paper (grit #800). Fig. 1 shows the specimen equipped with tabs bonded to the ends for the tests. The end tabs are manufactured of woven glass fiber reinforced epoxy and adhesively bonded on both sides of the specimens. These tabs allow a smooth load transfer from the grip to the specimen. They can reduce stress concentration and thus the shock wave stress effects. The gauge lengths of both the tensile and compressive specimens are 12.7 mm. The fiber volume fraction of the composite material is 50%. For design and manufacturing of test specimens, the available recommendations provided by Broughton [14] are utilized.

2.2. Testing machine

Various test methods have different advantages and limitations and must be chosen appropriately to produce good and comparable results. There are many review articles on strain rate dynamic response of composites [15,16], which describe various testing



Dimensions, *mm*	L_1	L_2	W	t	T
Matrix in tension	12.7	35	20	1.82	6
Matrix in compression	12.7	35	20	3.1	6

Fig. 1. Geometry and dimensions of the test specimens.

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