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Compressive response of glass–fiber reinforced polymeric composites to increasing compressive strain rates

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ABSTRACT

The utilization of composite materials instead of traditional materials in structural high-speed applications has induced the need for a proper knowledge of dynamic behavior as well as static behavior of them. The material and structural response vary significantly under dynamic loading as compared to static loading conditions. In order to investigate the dynamic responses of composite materials under dynamic loading at various strain rates, 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.

The present study is carried out in order to characterize the compressive properties of unidirectional glass–fiber reinforced polymeric composites using a servo-hydraulic testing apparatus at varying strain rates, ranging from 0.001 to 100 s^{-1}. For performing practical tests, a jig and a fixture are designed and manufactured, which could insure the alignment of axial loads on the specimens. During of tests, the performance of the test jig is evaluated. It is found that the designed jig and the fixture perform very well during the test process. The results of the dynamic tests are compared with the results of the static tests carried out on specimens with identical geometry. Based on the experimental results obtained from the tests, empirical functions for the mechanical properties are proposed in terms of strain rates. The results of the study indicate that strain rate has a significant effect on the material response. It is found that the compressive strength and modulus both increased with increasing the strain rate. Also, the results show that the compressive strain to failure is generally insensitive to strain rate.

1. Introduction

Fiber reinforced polymeric composites are used as candidate materials where dynamic loading is a major concern. It has always been a question that the dynamic properties of most composite materials may be poor as compared to their static properties. Since material response vary significantly with strain rate, the use of static properties in the analysis and design of structures under dynamic loadings can lead to a very conservative overweight design or designs that fail prematurely and unexpectedly. Hence, it is essential to characterize the responses of fibrous composites to varying strain rate loading.

Various researchers have attempted to characterize the rate-dependent behavior of composite under compressive loading. Sierakowski et al. [1] investigated the compressive strength and failure of steel reinforced epoxy composites by mechanical testing at strain rates ranging from 10^{-5} to 10^{4} s^{-1}. The experimental results for the composites tested were showed that strain rate effects depend upon composite constituent properties, geometric arrangement, volume fraction of reinforcement and size of the reinforcing fibers. The dynamic strength increased by 100% over corresponding static values. They reported very different failure modes in static and dynamic compressive tests on specimens. They also introduced a simple energy criterion for composite systems with a brittle matrix for predicting delamination. Work done by Sierakowski et al. showed that the high strain rate or impact failure characteristics are often distinctly different from failure observed at low strain rate testing.

Amijima and Fujii [2] studied the effects of strain rate from 10^{-3} to 10^{3} s^{-1} on the compressive strength of unidirectional glass/polyester and woven glass/polyester composites and found that the compressive strength of both composites increased with strain rate. The increase in strength was also shown to be higher for the woven composites than for the unidirectional ones. Daniel and LaBedz [3] developed a test method utilizing a thin graphite/epoxy ring (6–8 plies thick) composite specimen loaded by an external pressure pulse applied explosively through a liquid. They obtained compressive properties at strain rates up to 500 s^{-1}. The 0° properties show some increase in initial modulus over the static values but no change in strength. The 90° properties show much higher than static modulus and strength. In all cases the dynamic

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ultimate strains were lower than the static values by 33%. Study of the effect of strain rate (over the range 10^{-3}–600 s^{-1}) on the compressive strength of unidirectional graphite/epoxy composite specimens by Cazeneuve and Maile [4] highlighted a 50% increase in the longitudinal strength and a 30% increase in the transverse strength.

The dynamic compressive behavior of unidirectional and transversely isotropic glass–epoxy composites were determined by Kumar et al. [5], using the Kolsky pressure bar technique for fiber orientations of 0°, 10°, 30°, 45°, 60° and 90° at an average strain rate of 265 s^{-1}. Studies were carried out on cylindrical specimens of varying lengths and diameters. Quasi-static stress–strain curves at strain rates of 2×10^{-4} s^{-1} were compared to corresponding dynamic curves. The compressive behavior of glass epoxy composites was found to be strain rate sensitive for all fiber orientations. Compared to quasi-static, the dynamic ultimate strength increased almost 100% for 0°, 80% for 10° fiber orientations and about 45% for all other orientations. Specimens of 0° orientation fractured along the fibers by tensile splitting, due to the compressive loads causing transverse tensile strains because of Poisson's effect. Therefore, as the transverse tensile strain exceeded the transverse ultimate strain, failure occur by tensile splitting. Specimens of 10°, 30° and 45° orientation fractured along the fiber predominantly by interlaminar shear, although cracks caused by a degree of tensile splitting were also seen on the surface of some of the specimens. Their study indicated that that the dynamic stress–strain curves are linear up to fracture for angles of 0° and 10°, and nonlinear for orientations greater than 10°. El-Habak [6] investigated the compressive behavior of woven glass–fiber reinforced composites at failure strain rates ranging from 100 to 10^3 s^{-1}. The results illustrated a slight increase in the compressive strength for all composite variables such as fiber orientation and fiber volume fraction. The research was concentrated on the comparison of selected matrix systems, namely vinyl ester, polyester and epoxy. The highest strength was obtained from the composite based on vinyl ester matrix.

Montiel and Williams [7] used an instrumented drop tower to determine compressive mechanical properties of AS4 graphite/PEEK cross-plied composite laminates for strain rates up to 8 s^{-1}. The results indicated that at strain rates of the order of 8 s^{-1}, the strength increased by 42% over the static values and strain to failure increased by 25%. Only a small strain rate effect on the initial modulus was observed. Harding [8] studied two woven glass/epoxy material systems in compression up to 860 s^{-1} using cylindrical and thin strip specimens. The results for both specimen geometries indicated a significant increase in the initial modulus, strength and strain to failure with increasing strain rate.

An investigation into the effect of strain rate on cross-woven glass–fiber reinforced epoxy and pure epoxy resin under compressive loading was investigated by Tay et al. [9]. Quasi-static and low strain rate tests were conducted on a hydraulic tester while a split Hopkinson pressure bar was used for tests at dynamic strain rates. The range of strain rates was between 5×10^{-4} s^{-1} and 2500 s^{-1}. The experimental results on the behavior of pure epoxy and GFRP revealed that both are strain rate sensitive, especially in the low strain rate. A significant increase in the dynamic modulus was also observed with increasing strain rate. It was found that the stress-strain response under dynamic loading is a function of strain rate and the strain state. Daniel et al. [10] investigated the dynamic compression 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 compression, a carbon/epoxy laminate was characterized under longitudinal and transverse loading. Longitudinal properties were obtained up to a strain rate of 90 s^{-1} and found that the longitudinal modulus increased with strain rate (up to 30% over the static value) but the strength and ultimate strain were equal to or a little lower than the static values. Also, the dynamic modulus and strength at 210 s^{-1} increased sharply over static values in the transverse (to the fiber) direction while the ultimate strain was lower than the static one.

Powers et al. [11] used a split Hopkinson pressure bar to obtain compressive mechanical properties of a unidirectional graphite epoxy composite at different strain rates varying from 49 to 1430 s^{-1}. For each of the three principled directions, the yield stress increased with strain rate and so did the elastic strain energy. However, the ultimate strength, modulus of elasticity, and strain energy density to failure were found to be strain rate insensitive. In another study, a split Hopkinson pressure bar was used by Powers et al. [12] to obtain compressive mechanical properties of graphite/epoxy composites and graphite/polyimide composites. For both composites, in all three directions, the modulus of elasticity, strain to failure, and mean ultimate strength did not change with the strain rate.

Li et al. [13] investigated the effect of strain rate on the compression stress–strain characteristics of a short glass–fiber reinforced thermotropic liquid crystalline polymer over a wide range of strain rates from 10^{-4} to 350 s^{-1}. The low strain rate compression tests were conducted using a Instron universal tester while the high strain rate tests were carried out using a split Hopkinson pressure bar technique. The compression modulus was found to be insensitive to strain rate in the low strain rate regime (10^{-4}–10^{-2} s^{-1}), but it increased more rapidly with strain rate at higher strain rates. The compression strength changed linearly with log-scalled strain rate over the entire strain rate range. Macroscopic inspection of the compression failed specimens indicated that the strain rate had a strong influence on the failure mode. Takeda and Wan [14] studied the effects of strain rate from 10^{-3} to 750 s^{-1} on the compression strength of unidirectional glass–fiber reinforced polyester resin composites using the compression-type improved split Hopkinson pressure bar apparatus, where the impact loading can be stopped at any moment in the impact process so that the specimen can be recovered at various levels of loading. The compressive strength was found to increase with increasing strain rates.

Tzeng and Abrahamian [15–17] attempted to characterize the dynamic responses of composite materials for ballistic engineering applications. An experimental setup had been developed to investigate the dynamic effects on graphite/epoxy composite materials at strain rates typically found during launching of a projectile. An air gun system and a test fixture with a designed crashing mechanism were used to simulate a loading condition resulting from gun firing. Strain rate effects on the compressive strength of graphite/epoxy composites with lay up construction of $[(0/45/-45/0)_4]$ were determined at strain rates of 10–100 in/s. A 10% increase in the compressive strength was observed with increasing strain rate. A 1.5% strain was measured under impact failure, which is greater than the ultimate strain of 1.1% under a static loading condition.

The compressive behavior of unidirectional and cross-ply carbon/epoxy composite materials was investigated at strain rates up to several hundred per second by Hsiao and Daniel [18]. A hydraulic testing machine was used for strain rates below 10 s^{-1} and a drop tower apparatus developed was used for other ones above 10 s^{-1}. The transverse compressive strength of unidirectional composite increased sharply with strain rate to nearly double the quasi-static value at the highest rate. The initial modulus showed a similar trend with an increase up to 37% while the ultimate strain was found to be strain rate insensitive. In the longitudinal direction the initial modulus increased only slightly with strain rate but the strength and ultimate strain were significantly higher than the static values by up to 79% and 74%, respectively. Compressive properties of a cross-ply composite were also