Strain Rate Effects on the Mechanical Properties of Polymer Composite Materials

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ABSTRACT: This paper is a detailed review of the strain rate dependence of some mechanical properties of polymer composite materials. An attempt is made to present and summarize much of the published work relating to the effect of strain rate studies done in the past on the tensile, shear, compressive, and flexural properties of composite materials to better understand the strain rate effects on these mechanical properties of fiber-reinforced polymer composite materials. © 2004 Wiley Periodicals, Inc.* J Appl Polym Sci 94: 296–301, 2004

Key words: composites; fibers; resins; mechanical properties

INTRODUCTION

Composites in the past were mainly used for savings in secondary structures. With several advances made in understanding the behavior of composite materials, many fiber-reinforced polymer composite materials are finding increasing use as primary load-bearing structures and also in a wide range of high technology engineering applications. The ability to tailor composites, in addition to their attributes of high stiffness-to-weight and strength-to-weight ratios, fatigue resistance, corrosion resistance, and lower manufacturing costs, makes them very attractive when compared with conventional metals for use in many naval, aerospace, and automotive structural components.

High strain rate loading is probable in many of the applications where fiber-reinforced polymer composites find use as candidate materials. It has always been a cause for concern that the mechanical properties of composite materials may be poor at high rates of strain. Hence, study of how the mechanical properties of these composites would change with strain rate is warranted to be able to design structures that would not fail prematurely and unexpectedly at high loading rates. Determination of dynamic mechanical properties of these composites would also ensure the design of composite structures that are weight efficient and structurally sound when they are subjected to higher dynamic loads. The above argument reinforces the need for dynamic characterization of fiber-reinforced polymer composite materials to understand the strain rate effects on their mechanical properties. In this paper an attempt is made to review much of the work published in the literature that investigates the strain rate effects on the tensile, shear, compressive, and flexural properties of fiber-reinforced polymer composite materials (Table I).

Inertial effects prevalent at elevated rates of strain are an experimental difficulty encountered by scientists investigating the effects of strain rate on performance properties of a composite material. For example, test fixtures can be subject to inertial disturbances at medium to high rates of strain. These disturbances are due to the phenomenon of mechanical resonance that the test equipment acquires at higher speeds. Inertial responses of test systems increase with test speed and obscure test data, causing the analysis of the test data to be difficult and inaccurate. Therefore, it is important for investigators to overcome the inertial problems while studying strain rate effects on composites.

Various test methods have different advantages and limitations and must be chosen appropriately to pro-

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TABLE I
Summary of Published Data on the Effects of Loading Rate on Tensile, Compressive, Shear, and Flexural Properties

Reference	Materials studied	Range of rates investigated	Observations
Davies and Magee[1,2]	Glass/polyester	10^{-3}–10^{3} s	Increase in ultimate tensile strength with increasing loading rate
Rotem and Lifshitz[3]	Glass/epoxy	10^{-6}–30 s	Tensile strength and modulus increased with increasing loading rate for unidirectional glass/epoxy composites
Lifshitz[4]	Glass/epoxy	Static–4.2 m/s	Tensile modulus and failure stress were strain rate independent for the angle ply glass/epoxy laminate
Melin and Asp[5]	Carbon/epoxy	10^{-3}–10^{3} s	Transverse tensile properties only exhibited a weak dependence on strain rate
Okoli and Smith[6,8,9]	Glass/epoxy	0.008, mm/s–4 m/s	Tensile strength, tensile modulus, shear strength, and shear modulus increased with increasing loading rate; increase in tensile, shear, and flexural energy with increase in loading rate
Armenakas and Sciamarella[10]	Glass/epoxy	0.0265 min^{-1}–30,000 min^{-1}	Tensile modulus increased with increasing loading rate while ultimate tensile strain and stress decreased with increasing loading rate
Vashchenko et al.[11]	Glass/polyamide	3.3×10^{-5}–12 m/sec	Tensile strength increased with increasing loading rate
Staab and Gilat[12,13]	Glass/epoxy	10^{-5}–10^{3} s	Maximum tensile stress and strain increased with increasing loading rate
Harding and Welsh[14,15]	Graphite/epoxy, glass/epoxy, glass/polyester, graphite/polyester, Kevlar/polyester	10^{-4}–10^{3} s^{-1}	Tensile modulus and failure stress for graphite/epoxy were strain rate insensitive; tensile modulus for glass/epoxy, glass/polyester, graphite/polyester, and Kevlar/polyester increased with increasing loading rate
Roberts and Harding[16]	Glass/phenolic resin	1–20,000 mm/sec	Increase in tensile strength, stiffness, and displacement with increasing loading rate
Bai et al.[18]	Glass bead/HDPE	3×10^{-5}–8×10^{-3} s^{-1}	Tensile modulus and strength increased with increasing loading rate
Daniel et al.[19]	Carbon/epoxy	1×10^{-4}–500 s^{-1}	Longitudinal tensile and compression modulus increased with increasing loading rate; longitudinal tensile and compression strength and strain were loading rate insensitive; transverse tensile and compression modulus and strength increased with increasing loading rate while the tensile strain was loading rate insensitive
Hayes and Adams[20]	Glass/epoxy and graphite/epoxy	1.7–4.9 m/s	Tensile modulus and strength of glass/epoxy was strain rate insensitive while that of graphite/epoxy decreased with increasing loading rate
Daniel and Liber[21,22]	Boron/epoxy, glass/epoxy, Kevlar/epoxy, graphite/epoxy	1.4×10^{-4}–27 s^{-1}	Increase in tensile modulus and failure strength of Kevlar/epoxy with increasing loading rate while that of boron/epoxy, glass/epoxy, and graphite/epoxy remained strain rate insensitive
Chamis and Smith[23]	Graphite/epoxy	Static–381 s^{-1}	Longitudinal tensile strength for graphite/epoxy was loading rate insensitive; transverse tensile and shear properties increased with increasing loading rate
Daniel et al.[24]	Graphite/epoxy	100 s–500 s^{-1}	Longitudinal tensile strength for graphite/epoxy was loading rate insensitive; transverse tensile and shear properties increased with increasing loading rate
Kawata et al.[25,26]	Glass/polyester, glass/epoxy, graphite/epoxy, short graphite fiber/nylon 6,6	0.001–2000 s^{-1}	Tensile strength for graphite/epoxy and graphite/nylon 6,6 increased while that of glass/epoxy and glass/polyester decreased with increasing loading rate

TABLE I *Continued*

Reference	Materials studied	Range of rates investigated	Observations
Barre et al.[27]	Glass/polyester and glass/phenolic resin	0.1–10 s^{-1}	Tensile modulus and strength increased with increasing loading rate
Paterson et al.[28]	Chopped glass fiber in styrene/maleic anhydride resin	1.67×10^{-3}–6 s^{-1}	Tensile modulus and strength increased with increasing loading rate
Groves et al.[29]	Carbon/epoxy	0–3000 s^{-1}	Compressive and tensile properties (strength and modulus) increased with increasing loading rate
Powers et al.[30,31]	Graphite/epoxy and graphite/polyimide	49–1430 s^{-1}	Compression yield stress and elastic strain energy increased with increasing loading rate for the graphite/epoxy composite while the ultimate strength and modulus of elasticity were strain rate insensitive for both composites
Li et al.[32]	Short glass fiber/ liquid crystalline polymer	10^{-4}–350 s^{-1}	Compression modulus and strength increased with increase in loading rate
Takeda and Wan[33]	Glass/polyester	10^{-3}–750 s^{-1}	Compression strength increased with increasing loading rate
Tzeng and Abrahamian[34–36]	Graphite/epoxy	10–100 in/s	Compression strength and strain increased with increasing loading rate
Amijima and Fuji[37]	Glass/polyester	10^{-3}–10^{3} s^{-1}	Compression strength increased with increasing loading rate
Cazeneuve and Maile[38]	Graphite/epoxy	10^{-3}–600 s^{-1}	Longitudinal and transverse compression strength increased with increasing loading rate
Sims et al.[39]	Glass mat/polyester	10^{-6}–10^{-1} m/s	Increase in flexural strength with increasing loading rate

duce good and comparable results. The drop weight impact test allows easy variation of strain rate and is inexpensive. However, it is difficult to increase the maximum limit of strain rate since the speed is directly related to drop height. The use of hydraulic machines is convenient and accurate but they are expensive and the strain rate is limited. Hopkinson bars are used for dynamic characterization above 1000 s^{-1}. However, the system is very sensitive to contact surface conditions. The use of thin ring specimens under internal or external pressure can also be used for high rate dynamic testing but it is expensive and complex.

LITERATURE SURVEY

Davies and Magee[1,2] studied the effect of strain rate on the ultimate tensile strength of glass/polyester composites. They reported the glass/polyester composites to be rate sensitive with the magnitude of the ultimate tensile strength increasing by 55% over the strain rate change. Rotem and Lifshitz[3] investigated the effect of strain rate on the tensile properties of unidirectional glass fiber/epoxy composites and found that the dynamic strength is three times the static value and the dynamic modulus is 50% higher than the static value. However, while investigating angle ply glass/epoxy laminates Lifshitz[4] found that the elastic modulus was independent of strain rate and the dynamic failure stress was only moderately higher than the static value (20–30% higher). The dependence of the transverse tensile properties on strain rate of a high performance carbon/epoxy composite loaded in transverse tension was investigated by Melin and Asp.[5] Dogbone-shape specimens were tested 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 slightly with increased strain rate. Thus, when loaded in the transverse direction it was concluded that the carbon/epoxy composite exhibited a weak dependence on strain rate.

Tensile tests were performed on a glass epoxy laminate at different rates (1.7×10^{-2}-2000 mm/s) by Okoli and Smith[6,7] to determine the effects of strain rate on Poisson's ratio (ratio of transverse strain to the corresponding axial strain below the proportional limit) of the material. Poisson's ratio was found to be rate insensitive. It was suggested that the rate insensitivity in Poisson's ratio of the laminates tested is due to the presence of fibers in the composites. The effect of strain rate on the tensile properties of a glass/epoxy composite was investigated by Okoli and Smith.[8] The tensile strength of the composite was found to increase with strain rate. This increase in tensile strength with strain rate was attributed to the increased strength of the glass fibers with strain rate. In other studies the effects of strain rate on the tensile, shear, and flexural properties of glass/epoxy laminate was investigated by Okoli and Smith.[6,9] Tensile modulus increased by 1.82%, tensile strength increased by 9.3%, shear strength increased by 7.06%, and shear modulus increased by 11.06% per decade increase in log of strain rate.[6] The above observation was in agreement with the results of the investigation conducted by Armenakas and Sciamarella[10] that suggested a linear variation of the tensile modulus of elasticity of unidirectional glass/epoxy composites with the log of strain rate. However, the ultimate tensile strain and stress of the composite decreased with the increase in strain rate. An increase in tensile, shear, and flexural energy of 17, 5.9, and 8.5%, respectively, per decade of increase in the log of strain rate was observed.[9] The study indicated that it is a change in failure modes as strain rate is increased, which brought about the increase in energy observed.

Work done by Vashchenko et al.[11] on glass/polyamide composites also suggested a linear relationship between the tensile strength characteristics of the composite and the log of strain rate. A systematic study of the strain rate effects on the mechanical behavior of glass/epoxy angle ply laminates was done by Staab and Gilat[12,13] using a direction tension split Hopkinson bar apparatus for the high strain rate tests and a servo hydraulic testing machine for the quasi-static tests. The tensile tests at higher strain rates (in the order of 1000 s^{-1}) showed a marked increase in the maximum normal stress and strain when compared to the values obtained in the quasi-static tests. Although both fibers and matrix are strain rate sensitive, the fibers were thought to influence laminate rate sensitivity more than the matrix. Harding and Welsh validated a dynamic tensile technique by performing tests (over the range 10^{-4} to 1000 s^{-1}) on graphite/epoxy, glass/epoxy, glass/polyester, graphite/polyester, and Kevlar/polyester composites.[14,15] The modulus, failure stress, and failure mode of the graphite/epoxy composite were found to be strain rate insensitive. The dynamic modulus and strength for the glass/epoxy composite were about twice the static value. This increase in failure strength was explained on the basis of the observed change in failure mode. Similarly, the elastic tensile modulus of the glass/polyester, graphite/polyester, and Kevlar/polyester composites increased with strain rate and the strain rate dependence of the elastic modulus was suggested to be derived from the elastic interaction between the reinforcement and the matrix and was determined by the strain rate dependence of the matrix strength. Tensile tests were performed at up to five displacement rates, from about 1 to 30,000 mm/s, by Roberts and Harding[16] to determine the effect of strain rate on the tensile properties of a glass/phenolic resin composite. A significant increase in the tensile strength, stiffness, and displacement at failure was observed at higher displacement rates. This was attributed to the rate dependence of the resistance of the resin matrix to fiber straightening and of the fracture strength of the glass fibers.

The tensile mechanical behavior of a short carbon fiber-filled liquid crystalline polymer composite, Vectra A320, was examined under static loading (10^{-2} s^{-1}) and dynamic loading (400 s^{-1}) by Shim et al.[17] A pendulum-type tensile split Hopkinson bar device was used to apply dynamic tension. The fracture strain and Young's modulus of the composite were found to be noticeably influenced by changes in the strain rate. Experimental studies on the effects of strain rate on the tensile properties of glass bead/HDPE composites were conducted by Bai et al.[18] Both Young's modulus and the tensile strength of the glass bead/HDPE composite were found to increase with strain rate. Daniel et al.[19] 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 longitudinal, transverse, and in-plane shear loading at strain rates up to 500 s^{-1}. In the longitudinal direction the modulus increased moderately with strain rate (up to 20% over the static value) but the strength and ultimate strain did not vary significantly. The modulus and strength increased sharply over static values in the transverse (to the fiber) direction but the ultimate strain only increased slightly. There was a 30% increase in the in-plane shear modulus and strength. In the second test method used for dynamic testing of thin laminates in compression, longitudinal properties were obtained up to a strain rate of 90 s^{-1}. 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 static values. 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. There was a 30% increase in the in-plane shear modulus and strength. 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 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.

Hayes and Adams constructed a specialized pendulum impactor to investigate the strain rate effects on the tensile properties of unidirectional glass/epoxy and graphite/epoxy composites.[20] The modulus and strength of the glass/epoxy composites were concluded to be rate insensitive at impact speeds in the range of 2.7 to 4.9 m/s. However, the modulus and strength of the graphite/epoxy composites decreased with increasing impact speeds. Daniel and Liber[21,22] attempted to characterize the effect of strain rate on the mechanical properties of unidirectional boron/epoxy, glass/epoxy, graphite/epoxy, and Kevlar/epoxy composites. While the Kevlar/epoxy composite showed a 20% increase in tensile modulus and failure strength in the fiber direction with increasing strain rate from 10^{-4} to 27 s^{-1}, the tensile modulus and failure strength of the boron/epoxy, glass/epoxy, and graphite/epoxy composites were found be rate insensitive. The increase in modulus and failure strength of the Kevlar/epoxy composite was 40 and 60%, respectively, during transverse and shear (off-axis) loading.

Work done by Chamis and Smith[23] and further investigations by Daniel et al.[24] on unidirectional graphite/epoxy laminates yielded similar results wherein the tensile strength in the fiber direction did not change with strain rate. However, there was an increase in the transverse tensile properties and shear properties with increasing loading rate.

The effect of strain rate (10^{-3} to 2000 s^{-1}) on the tensile properties of glass/polyester, glass/epoxy, graphite/epoxy, and graphite short fiber-reinforced nylon 6,6 composites was investigated by Kawata et al.[25,26] The strength of the graphite/epoxy and graphite/nylon 6,6 composites increased with strain rate while that of the glass/epoxy and glass/polyester composites decreased. The influence of strain rate on the tensile properties of glass/phenolic resin and glass/polyester resin composites was studied by Barre et al.[27] The elastic modulus and strength were found to increase with strain rate. Peterson et al.[28] studied the tensile response of chopped glass fiber-reinforced styrene/maleic anhydride materials in the range 10^{-3} to 10 s^{-1} and observed a 50 to 70% increase in the elastic modulus and strength with increase in strain rate.

Groves et al. attempted to characterize the high strain rate response (in tension and compression) of continuous carbon/epoxy composites.[29] Strain rates from 0 to 100 s^{-1} were generated using conventional and high-speed hydraulic test machines, those from 10 to 1000 s^{-1} were generated using a high energy drop tower, and those from 1000 to 3000 s^{-1} were generated using a split Hopkinson bar. The experimental results indicated an increase in both the compression and the tensile properties (strength and modulus) with increasing strain rate. Powers et al.[30] 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.[31] 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 strain rate.

Li et al.[32] investigated the effect of strain rate on the compression stress strain characteristics of a short glass fiber-reinforced thermotropic liquid crystalline polymer (an aromatic copolyester consisting of *p*-hydroxybenzoic acid and 2,6-hydroxy-naphthoic acid) over a wide range of strain rates (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} to 10^{-2} s^{-1}) but it increased more rapidly with strain rate at higher strain rates. The compression strength changed linearly with log(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[33] studied the effects of strain rate 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[34–36] 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 $[(0/45/\text{-}45/0)_4]$ 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.

Amijima and Fujii[37] investigated the strain rate effects 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, with the increase being higher in the case of the woven composite. Study of the effect of strain rate (over the range 10^{-3} to 600 s^{-1}) on the compressive strength of unidirectional graphite/epoxy composite specimens by Cazeneuve and Maile[38] highlighted a 50% increase in the longitudinal strength and a 30% increase in the transverse strength.

Sims et al.[39] investigated the effect of strain rate on the flexural strength of glass mat/polyester laminates and reported increasing flexural strengths over a wide range of displacement rates from 10^{-6} to 10^{-1} m/s.

CONCLUSION

It can be inferred from this detailed review that the effect of varying loading rate on the tensile, compressive, shear, and flexural properties of fiber-reinforced composite materials has been investigated by a number of workers and a variety of contradictory observations and conclusions have resulted. Hence, more work must be done in the pursuit of eliminating all disagreements that currently exist regarding the effect of loading rate on the tensile, compressive, shear, and flexural properties of fiber-reinforced polymer composite material. There is also not much literature available on the effect of strain rate on the tensile, compressive, and shear properties of random chopped fiber-reinforced composite materials that can find extensive use in a wide range of load-bearing engineering and industrial process applications primarily due to the low costs involved in their manufacture in addition to the ease of manufacture. Hence, the need for investigating and characterizing in detail the strain rate effects on the tensile, compressive, shear, and other mechanical properties of random chopped fiber composites is suggested.

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