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Quasi-static and dynamic tensile properties of fiberglass/epoxy laminate sheet

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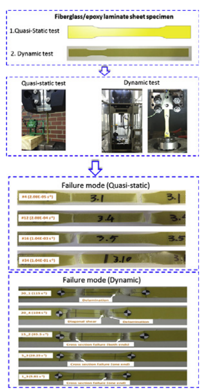
HIGHLIGHTS

- Quasi-static and dynamic tensile tests on fiberglass/epoxy laminate were conducted.
- Stress-strain curves were plotted with strain rate up to 115 s^{-1}.
- The material properties of fiberglass/epoxy laminate were sensitive to strain rate.
- Empirical formulae for the tensile material properties were derived.

GRAPHICAL ABSTRACT



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ABSTRACT

Fiberglass/epoxy laminate or structures strengthened by fiberglass/epoxy laminate might be subjected to dynamic loadings such as impact and blast. Understanding the dynamic material properties of the fiberglass/epoxy laminate is important to predict the behavior of fiberglass/epoxy laminate or its strengthened structure against dynamic loading. In this study, unidirectional quasi-static and dynamic tensile tests on fiberglass/epoxy laminate were carried out to investigate its dynamic material properties. The strain rate for quasi-static and low velocity test varied from 2.08E-05 to 1.04E-01 s^{-1}. The high speed dynamic tests were conducted by INSTRON® VHS 160/100-20 machine at the strain rate from 2.75 to 115 s^{-1}. The strain rate effects on the tensile strength, failure strain and Young's Modulus of fiberglass/epoxy laminate were investigated. Based on the testing data, empirical formulae were derived to predict the dynamic enhancement of tensile material properties of fiberglass/epoxy laminate as a function of strain rates, which can be used to model the dynamic material properties in the numerical simulation of structural responses.

1. Introduction

Fiber composite as a high-performance engineering material has been widely used due to its high stiffness and strength. The glass fiber laminate composite can be made from different glass fiber reinforcements in the forms of unidirectional, woven, multi-axial and chopped strand mat in various matrices such as epoxy, polyester or phenolic [1]. Thermo-laminated woven fiberglass/epoxy material, as one of glass fiber laminate materials, is made from woven glass fiber fabric impregnated with epoxy resin binder, which is manufactured under pressure and heat. The glass fiber

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laminate has the advantages of high mechanical strength, good corrosion resistance, sound flame resistance and humidity resistance etc. This type of laminate composite can be used in a variety of applications including insulating structural parts in electrical equipment, vehicle and boat structure, marine structure, pressure vessel, container, gas pipe, aerospace structure, and civil engineering structure etc. [2]. During the service life, fiberglass/epoxy laminate or structures strengthened by fiberglass/epoxy laminate might be subjected to dynamic loadings such as impact and blast. For instance, the fiberglass/epoxy laminate material was applied as an interlayer of structural insulated panel for improving the structural performance against windborne debris impact [3]. As reported in [1], an impact with the velocity of $1 \sim 10$ m/s on a structure can generate a strain rate of between $100\,s^{-1}$ and $1000\,s^{-1}$ near the impacted location. Therefore, understanding the dynamic behaviors of fiberglass/epoxy laminate material under different strain rates is of significance for reliable predictions of its responses subjected to dynamic loadings.

G10 and FR-4 (FR represents Fire Retardant) laminate materials are two commonly used fiberglass/epoxy laminate materials. The commercially available laminate sheet has the thickness in the range of 0.1 mm to 76 mm. G10 and FR-4 laminates have almost the same mechanical properties except that the epoxy resin of FR-4 contains flame retardant. G10/FR-4 fiberglass/epoxy composite can be manufactured into sheet, tube and rod. Some studies have been carried out to investigate the mechanical properties of the fiberglass/epoxy laminate (G10/FR-4). Naderi et al. [4] experimentally investigated the energy dissipation and damage evolution of woven fiberglass/epoxy (G10/FR-4) laminate by conducting fully reversed bending fatigue tests. The degradation progression and damage process were estimated by using two non-intrusive techniques, i.e. infrared thermography and acoustic emission. Naderi and Khonsari [5] investigated the fatigue failure of fiberglass/epoxy (G10/FR-4) laminate by conducting tension–tension and bending fatigue tests. The finding can be used to assess the severity of degradation of the specimen and predict fatigue life. Liakat and Khonsari [6] applied thermographic approach to study the fatigue behavior of fiberglass/epoxy (G10/FR-4) composite laminate by conducting uniaxial tension–compression and fully-reversed bending fatigue tests at different stress levels and loading ratios. Whisler and Kim [7] investigated the effect of impactor radius on the low velocity impact resistance of plain weave fiberglass/epoxy (G10/FR-4) composite panels. It was found that the impactor radius significantly affected the damage. Herranena et al. [8] assumed the FR-4 glass fiber laminate as an isotropic and linear material in the numerical simulation. It can be concluded that the study on the dynamic mechanical properties of G10/FR-4 fiberglass/epoxy laminate sheet material is still lacking in the literature. However, some studies have been conducted with regard to the strain rate effect on the mechanical properties of glass fiber laminate material, which can be used as references.

In the previous studies, contradictory results were reported with respect to the strain rate effect on the mechanical properties such as strength, failure strain and Young's Modulus. For example, some studies [1,2,9–15] reported the existence of strain rate effect on the material while others [16–21] presented that strain rate has marginal effect on the material properties. Barre et al. [1] studied the strain rate effect on the tensile dynamic mechanical properties of glass fiber reinforced phenolic and polyester resins. It was found that the elastic modulus and the strength were strain rate dependent. Reis et al. [2] found that glass fiber reinforced polymer was strongly affected by strain rate with the strain rate between 0 and 1.6E-03 s^{-1}. Ochola et al. [9] found that glass fiber reinforced polymer had strain rate effect on the compressive strength when the strain rate was between 10^{-3} and $450\,s^{-1}$. Davies and Magee [10] reported that the glass Fiber reinforced plastic was sensitive to strain rate and the dynamic increase factor was 1.55 over the strain rate from 10^{-3} to $10^{3}\,s^{-1}$. Staab and Gilat [11] studied the ply fiberglass/epoxy and found that the mechanical response characteristics were strain rate sensitive. Welsh and Harding [12] studied the laminates properties at strain rate up to $700\,s^{-1}$, and found an increase of both the tensile strength and elastic modulus. Schoßig et al. [13] studied the glass fiber reinforced plastics and revealed the positive correlation between the tensile stress and the strain rate. Harding and Welsh [14] tested the woven glass fiber/epoxy composite at strain rate from quasi-static to $1000\,s^{-1}$. It was found that the dynamic modulus and strength were 2.5 times of the static values in the 0 degree direction (with tensile axis parallel to the principle reinforced direction) and 1.7 times of the static values in the 45 degree to the principle reinforced direction. The increase of material strength was related to the different failure modes. It was also found that strain rate effect was influenced by fiber reinforcement architecture. The dynamic elastic modulus was 2.5 and 2 times of the static modulus for the plain-weave and satin-weave fiberglass/epoxy laminate, respectively. The mechanical properties were also affected by the fiber reinforcement orientation and the specimen size. Landel and Nielsen [22] reviewed and summarized previous researches on some polymer and composite material. Unlike the isotropic material, the mechanical properties of glass fiber laminate were depended on the woven orientation of the fibers. Wisnom [23] investigated the effects of specimen size on the mechanical properties of unidirectional glass fiber/epoxy material. The size effect on tensile failure was found in both tensile and flexural tests. The strength of laminates decreased with the increase in specimen size. Harding [24] reported two types of woven fiberglass/epoxy materials in compression up to $860\,s^{-1}$ using cylindrical and thin strip specimens. It was revealed that there was a significant increase in the initial modulus, strength and ultimate strain with increasing strain rate for woven fiberglass/epoxy composites. Shokrieh and Omidi [25] investigated tensile properties of unidirectional fiberglass/epoxy composites under different strain rate of $0.001–100\,s^{-1}$. The results revealed that the tensile strength increased significantly with the strain rate but the tensile modulus and the failure strain increased gently with the strain rate.

However, other studies found the strain rate has marginal effect on dynamic properties of glass fiber laminate. Daniel and Liber [16] found that strain rate had no influence on the material properties such as the longitudinal elastic modulus of fiberglass/epoxy laminate. Lifshitz [17] reported that the initial modulus and failure strain of the angle ply fiberglass/epoxy laminates were insensitive to the strain rate but the dynamic strength was $20\% \sim 30\%$ higher than the static value. Armenakas and Sciammarella [18] presented that the ultimate strength of unidirectional fiberglass/epoxy specimens had a decreased trend with the increasing strain rate. Hou and Ruiz [19] found that the tensile strength and modulus of woven carbon fiber reinforced laminate were independent of strain rate. Belingardi and Vadori [20] carried out the low speed impact test on the glass fiber composite, no sensitivity between the mechanical characteristics and strain rate was found. Okoli and Smith [21] found that Poisson's ratio of fiberglass/epoxy laminate was insensitive to strain rate when the strain rate is between $10.6 * 10^{-3}$ and $2.72\,s^{-1}$. It was inferred that the absence of strain rate sensitivity on Poisson's ratio was due to the presence of fibers in the laminate. Ou and Zhu [26] studied the tensile behaviors of glass fiber/epoxy laminate composite at different strain rates from quasi-static up to $160\,s^{-1}$. The results revealed that tensile strength, maximum strain and toughness of the material were sensitive to strain rate while Young's Modulus was insensitive to strain rate. The above reviews reveal that there is no general consensus yet on the strain rate effects on fiber materials. The difference on strain rate effects observed by different researchers