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Static and dynamic material properties of CFRP/epoxy laminates

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HIGHLIGHTS

- Quasi-static and dynamic direct tensile tests were performed on CFRP/epoxy laminates.
- Stress-strain curves were derived from quasi-static state to about 240 s^{-1}.
- Dynamic amplification effect to tensile strength and stiffness were discussed.
- Dynamic Increase Factor (DIF) for CFRP was formulated with testing data.

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ABSTRACT

Carbon fiber reinforced polymer (CFRP) has been extensively used to strengthen structures owing to its outstanding mechanical properties. With an increasing threat from terrorist bombing attacks and accidental explosions, the application of CFRP has been extended to mitigate the effect of blast loading on structures. A better understanding of the dynamic material properties of CFRP/epoxy laminates at high strain rates is therefore needed for more reliable analysis and design of CFRP strengthened structures under dynamic loadings. In this study, the unidirectional tensile properties of CFRP (SikaWrap®-230C) and epoxy resin (Sikadur®-330) laminates is investigated experimentally over a wide range of strain rates. Quasi-static and low-speed tensile tests are conducted at strain rates varying from $7 \times 10^{-5}\ s^{-1}$ to $0.07\ s^{-1}$. Then, high-speed tensile tests are performed using a high-speed servo-hydraulic testing machine at strain rate from about $10\ s^{-1}$ to $240\ s^{-1}$. The testing results show that both the tensile strength and the stiffness of the CFRP/epoxy laminates are insensitive to loading speed when the strain rate is less than $50\ s^{-1}$. However, when strain rate is over $50\ s^{-1}$, both the tensile strength and the coupon stiffness increase with the increase of strain rate. High-speed camera images are used to assist inspecting the failure modes of CFRP/epoxy laminates. It is found that under high-strain rate tension CFRP/epoxy laminates fail differently from that at low-strain rate. The different failure mode is believed to contribute to the increment of laminate strength. The testing data are analyzed together with available testing results on CFRP/epoxy laminates at various strain rates. Empirical formulas of dynamic increase factor for CFRP material are derived for better prediction of material strength at various strain rates.

1. Introduction

CFRP, short for carbon fiber reinforced polymer, is a high strength and light weight material which has become notable in construction ever since its successful employments in aerospace, automotive, and marine areas. Owing to its outstanding performance in conventional building construction, the application of CFRP has been extended to structure retrofit against blast and impact loadings. The high strength and lightweight features enables CFRP to significantly increase the flexural resistance capacities of slabs and beams, enhance the axial load bearing capability of columns (as a result of lateral confinement), as well as reduce ejecting fragments of structures subjected to blast and impact loads since it is generally applied as an external layer.

In application, CFRP is normally impregnated in epoxy resin matrix to form CFRP/epoxy laminate. The CFRP/epoxy laminate is a composite material, which consists of a resin matrix and a reinforcement– carbon fiber. The latter governs the composite strength and rigidity. Considerable amount of studies have been carried out to investigate the mechanical properties of various types of CFRP materials. Jacob et al. [1] reviewed and summarized previous

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testing on FRP composites including not only carbon but also glass, graphite and Kevlar etc. Different techniques including drop weight tube, servo-hydraulic machine, pendulum impact system, Split-Hopkinson Pressure bar (SHPB) etc. are utilized to investigate the behavior of FPR material at different strain rates [2]. Unlike isotropic materials such as steel, the mechanical properties of CFRP depend on its direction. Both the layout and the proportion of fibers significantly influence CFRP/epoxy laminate properties. Hou and Ruiz [3] performed tensile test, compressive test and in-plane shear tests on woven CFRP/epoxy laminates with fiber directions in 0°, 45° and 90° against the loading direction. It was found that specimens show linear elastic properties in both 0° and 90° directions, while tensile test on 45° specimens give non-linear stress-strain curves. Through reviewing available experimental data, Wisnom [4] observed a tendency of laminate strength to decrease with higher volume of fibers. In addition, size effects were found among different sized specimens primarily in flexural tests [4]. This can probably be attributed to the existence of more defects such as fiber waviness in larger specimens.

Despite a large amount of tests undertaken to examine the dynamic material properties of CFRP material of various types, contradicted testing results are reported. As a result there is no consensus on the significance or even existence of strain rate effect on FRP materials, and the degree of its sensitivity. For instance, Welsh and Harding [5] carried out quasi-static and dynamic tensile tests on T300 carbon/epoxy laminates at strain rate from $1.5 \times 10^{-4}\,\mathrm{s}^{-1}$ to $700\,\mathrm{s}^{-1}$. The testing results showed an increase in both the tensile strength and elastic modulus of the coupon. Dynamic tensile tests on type T300 carbon/epoxy composite were also conducted by Zhao et al. [6] and Chen et al. [7] respectively using SHPB technique. Both testing results indicated that the tensile strength and the initial modulus increase with the strain rate. Similarly, Gilat et al. [8] utilized SHPB technique on IM7/977 carbon/epoxy composite. The results showed significant strain rate effect on material response. Recently, Al-Zubaidy et al. [9] tested CF130 carbon/epoxy laminates in the strain rate range of $0.000242\,\mathrm{s}^{-1}$ to $87.4\,\mathrm{s}^{-1}$. The increased strain rate was found to lead to increase in material tensile strength and modulus. On the other hand, some opposite conclusions on the effect of strain rate were given based on dynamic testing results on CFRP/epoxy laminates. For example, with dynamic tests on T300 carbon/epoxy laminates, Hou and Ruiz [3] observed insignificant strain rate effect in material tensile strength and modulus, while the shear properties were found to be strain rate dependent. Similar conclusions were made by Taniguchi et al. [10] through their dynamic testing on type T700 carbon/epoxy laminates.

In this paper, unidirectional tensile tests on SikaWrap®-230c with Sikadur®-330 carbon/epoxy laminates are carried out at both quasi-static and dynamic states. The dynamic material properties of the CFRP material and the laminates are investigated experimentally. The strain rate effects on the tensile strength, failure strain, and elastic modulus are studied. Dynamic increase factors (DIF) are derived based on the testing results.

2. Methodology and theory

2.1. Testing systems

Commonly used techniques to investigate material tensile properties include conventional screw driven load frame, servo-hydraulic machine, pendulum impactor, drop weight impact system, high-speed servo-hydraulic machine, and Split-Hopkinson Pressure Bar system. Conventional systems like screw driven frame and servo-hydraulic machine normally can achieve a testing strain rate from quasi-static state to $1\,\mathrm{s}^{-1}$ in the specimen. Split-Hopkinson Pressure Bar (SHPB) is commonly used to determine material strength at strain rates over $100\,\mathrm{s}^{-1}$ [6,7]. The pendulum impactor, drop weight impactor and the high-speed servo-hydraulic machine are widely used to determine material strength at strain rate above $1\,\mathrm{s}^{-1}$. Dog-bone shaped specimens or straight coupons are most commonly adopted for the dynamic tensile tests. Due to inherit difficulties, the strain rates that can be achieved by a drop weight impact machine or the pendulum impactor is normally limited to below $100\,\mathrm{s}^{-1}$. Moreover, during a test the velocity of the actuator varies due to interaction with the response of the specimen. It is therefore difficult for the drop weigh impactor or the pendulum impactor to maintain a constant velocity. In this study, servo-hydraulic and high-speed servo-hydraulic machines are used to perform the quasi-static and dynamic tensile tests. The testing setups and machine information are described in detail in section three.

2.2. Testing requirements for dynamic tensile tests

Ensuring a state of stress equilibrium through the tested specimen is essential for the validity of testing data in dynamic tests. For quasi-static and low-speed tests, comparing with the loading duration there is more than sufficient time for an elastic wave to travel back and forth many times inside the specimen. The specimens are therefore under quasi-static equilibrium, and generally further validation of stress equilibrium is not necessary. However, for high-speed tests to achieve the state of stress equilibrium is much more difficult since the loading time can be very short. In a dynamic test, a state of dynamic equilibrium is usually pursued, where a minimum number of elastic waves are required to propagate through the specimen [11,12]. To estimate the time for one stress wave to travel a round trip in the specimen the following equation can be used

$$\mathrm{t} = \frac{2\mathrm{L}}{\mathrm{c}} \tag{1}$$

where L is the gauge length of the specimen between the clamping grips; and c is the one-dimensional longitudinal elastic stress wave velocity in the testing material, which can be estimated by the relation in Eq. (2)

$$c = \sqrt{\frac{E}{\rho}} \tag{2}$$

where ρ is the density of the material, and E is the Young's modulus.

To achieve dynamic equilibrium, in a SHPB test it normally requires at least three reverberations of the loading wave in the specimen [13,14]. Based on dynamic tensile tests using a high-speed servo-hydraulic machine, Xiao verified that the criterion for a valid SHPB test is also applicable to dynamic direct tensile test [15]. It should be noted that there is no quantitative criterion in the literature yet to define the exact number of stress wave reverberation in the specimen to achieve dynamic equilibrium for a uniaxial tensile test. More theoretical and analytical studies therefore need be conducted to define a proper testing criterion. In the present study the conclusion drawn in [15] is adopted to determine the validation of testing data.

3. Experiment setup

3.1. Specimen

The carbon fiber SikaWrap®-230C (manufactured by Sika Australia Pty Limited) is a woven unidirectional carbon fiber fabric designed for structural strengthening applications. It is a mid-range strength CFRP material in its family with a dry fiber