

Impact tensile properties and strength development mechanism of glass for reinforcement fiber

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Abstract. In this study, impact tensile properties of E-glass were investigated by fiber bundle testing under a high strain rate. The impact tests were performed employing two types of experiments. One is the tension-type split Hopkinson pressure bar system, and the other is the universal high-speed tensile-testing machine. As the results, it was found that not only the tensile strength but also the fracture strain of E-glass fiber improved with the strain rate. The absorbed strain energy of this material significantly increased. It was also found that the degree of the strain rate dependency of E-glass fibers on the tensile strength was varied according to fiber diameter. As for the strain rate dependency of the glass fiber under tensile loading condition, change of the small crack-propagation behaviour was considered to clarify the development of the fiber strength. The tensile fiber strength was estimated by employing the numerical simulation based on the slow crack-growth model (SCG). Through the parametric study against the coefficient of the crack propagation rate, the numerical estimation value was obtained for the various testing conditions. It was concluded that the slow crack-growth behaviour in the glass fiber was an essential for the increase in the strength of this material.

1. Introduction

In recent years, an application of the fiber-reinforced plastics (FRP) is growing, and the introduction rate in the fields of the aerospace and the automobile is higher than in other industries. Designing a structural member in these industries, the crashworthiness subjected to an impact load is an important design factor. Therefore, when applying FRP to a structural member, it is important to fully understand the characteristics under impact loading conditions. It has been reported that FRP has different strain-rate dependencies according to the reinforcements [1-3].

In previous studies, Taniguchi et al. investigated the influence of the strain rate on the tensile properties of FRP based on the thermoplastic epoxy resin. They found that strain rate has very small effect on tensile properties in case that the carbon fiber is employed as reinforcement, on the other hand, glass fiber composite was obviously affected by the strain rate [4]. They concluded the fiberglass contributed more significantly to the strain rate dependency of FRP than the matrix. Xia et al. studied about impact properties of glass fiber [5-6]. From the result of the impact tensile test, they established a statistical model for the strain rate dependency and determined the constitutive equation of the glass fibers. Although the proposed model are in good agreement with the experimental results, it is not enough shows experimental data necessary for the material design such as the influence of fiber



diameter and fiber glass composition.

In this study, impact tensile properties of glass fibers were investigated in order to obtain useful knowledge for material and structural design. First, the impact tensile test was performed about the fiber bundle of E-glass, and the strain rate dependencies on the mechanical properties were investigated. Then, impact tensile tests were performed on of the glass fibers having different diameters, and the effect of fiber diameter on the impact properties was investigated. Furthermore, the tensile fiber strength was estimated by employing the numerical simulation based on the slow crack-growth model (SCG).

2. Experiment

Figure 1 shows the geometry of the specimen used for impact tensile tests. E-glass fiber bundle (the fiber diameter is $17\mu\text{m}$, the number of fibers is 1000) was used as the specimen, and the aluminum tabs were bonded at both ends. The impact tests were performed employing two types of experiments. One is the tension-type split Hopkinson pressure bar (SHPB) system, and the other is the universal high-speed tensile-testing machine (Shimadzu Hydro Shot, HITS-T10). Figure 2 shows schematics of the SHPB apparatus. It consists of an input bar with a flange, an output bar, and a cylindrical striker.

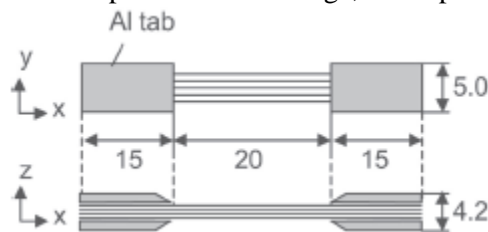


Figure 1. Geometry of the specimen used for impact tensile test.

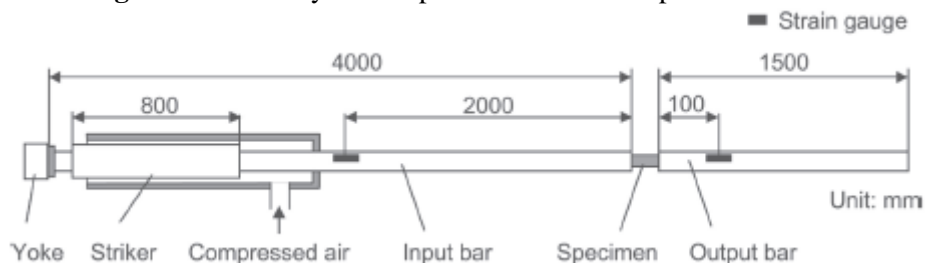


Figure 2. Tension-type SHPB apparatus

It is observed that a tensile incident wave is produced after the striker hits the yoke. In the SHPB system, the stress, strain and strain rate of a specimen can be calculated using the strain gauge outputs from the input and output bars on the basis of the one-dimensional wave propagation theory.

3. Experimental result and Discussion

3.1. Effect of strain rate on mechanical properties

Figure 3 shows the comparison of stress-strain curves of E-glass under quasi-static loading condition and strain rate of 250s^{-1} . In Figure 3, the initial slope of the stress strain curve is not changed. In other words, there is no change in Young's modulus. On the other hand, with respect to the maximum stress and maximum strain, it can be seen that increasing has occurred in strain rate of 250s^{-1} compared to under quasi-static loading.

Figure 4 (a) - (c) shows the relationships between Young's modulus, tensile strength, fracture strain and strain rate, respectively. In addition, since the universal high-speed tensile-testing machine only measures the load history, strain rate dependency of the initial Young's modulus and fracture strain are

examined only in the results of Hopkinson bar method. Figure 4 (a) shows the strain rate have very small effect on the initial Young's modulus. It is estimated that this is because E-glass fiber exhibits little viscoelasticity. Figure 4 (b) also shows the tensile strength of E-glass is improved with the strain rate. The tensile strength increases up to the strain rate of 50s^{-1} , and after that the rate of increase becomes gradual. As a result, it increases by 60% compared to the quasi static condition in the strain rate of 250s^{-1} . This is the same trend with the study by Xia et al [6].

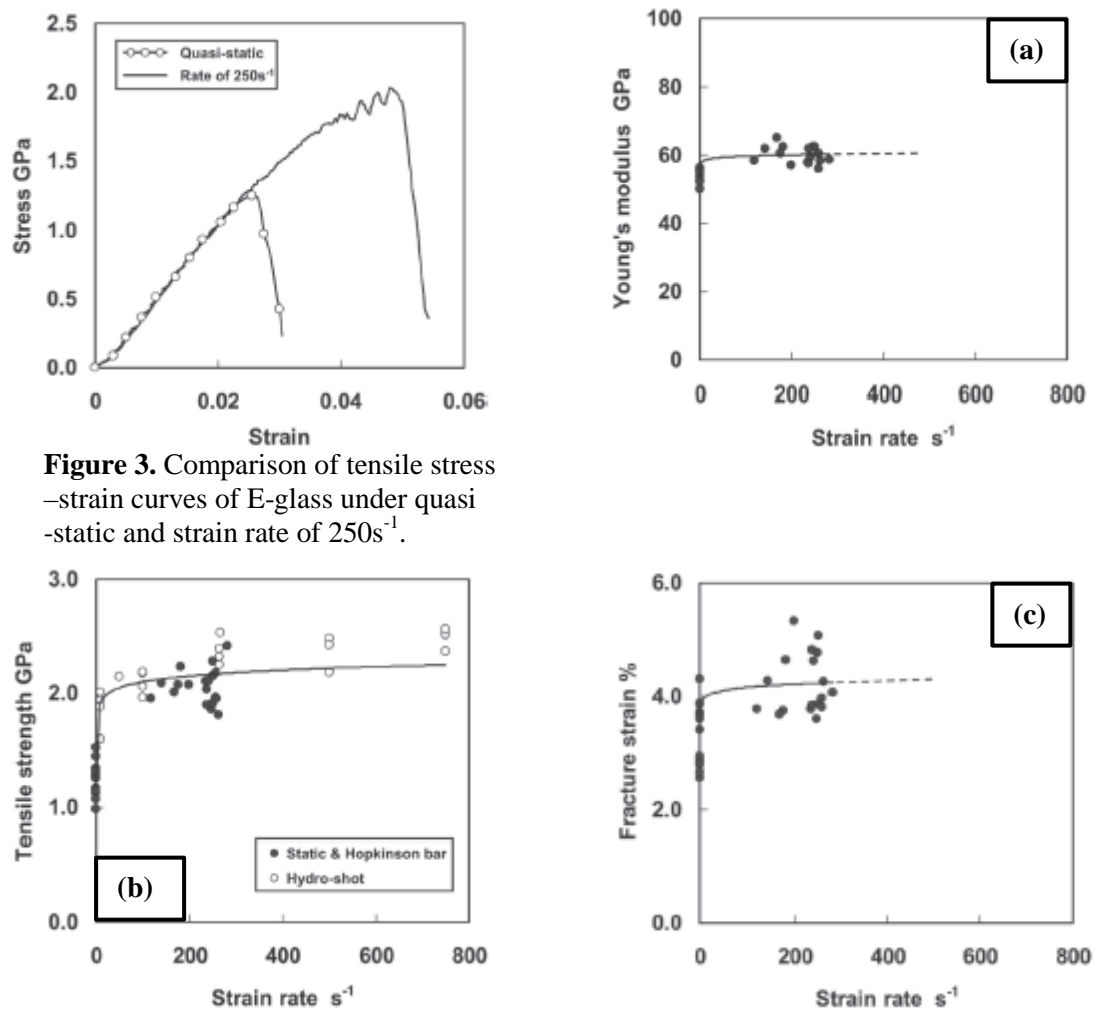


Figure 3. Comparison of tensile stress–strain curves of E-glass under quasi-static and strain rate of 250s^{-1} .

Figure 4. Dependence of strain rate on (a) Young's modulus, (b) tensile strength and (c) fracture strain in E-glass

One of the factors that tensile strength is improved by the strain rate is the slow crack-growth behavior which is the characteristic phenomenon of glass fracture. In general, the strength of the glass, σ_f is represented by the following formula in linear fracture mechanics.

$$\sigma_f = \frac{K_{IC}}{Y(a) \cdot \sqrt{\pi a(t)}} \quad (3.1)$$

where K_{IC} denotes the fracture toughness of glass, $a(t)$, the length of crack; and $Y(a)$, the shape factor.

Suratwala et al. and Freiman et al. reported that there is the slow crack-growth behavior, where the crack has grown slowly at a rate that depends on the stress intensity factor, before reaching the fracture toughness [7-8]. In equation (3.1), as the crack length is a function of time, it is possible that the crack length before reaching the fracture toughness is different under quasi-static loading and high strain rate.

For this reason, the tensile strength of the glass might be improved under high strain rates. The relationships between the slow crack-growth behavior and the strain rate dependency of E-glass on the tensile strength.

3.2. Effect of fiber diameter on the strain rate dependency

The tensile strength of glass fiber is generally dominated by micro-cracks present in the surface of the fiber. When varying fiber diameter of glass fiber, the surface properties of the fibers might change, and it is possible that the tensile strength of glass fiber significantly changes. It is also possible to change the strain rate dependency as well. Therefore, E-glass fiber bundles having five types different fiber diameter were prepared and evaluated the strain rate dependency of the tensile strength by Hopkinson bar method. Table 1 shows the specification of E-glass used in this study. The fiber diameter was varied by adjusting the winding speed of the glass fibers after the melting step.

Table 1. Specification of E-glass fiber

Specimen	EG17	EG13.8	EG9.2	EG7.5	EG5.3	EG3.2
Average diameter μm	17.0	13.8	9.2	7.5	5.3	3.2
Number of fiber	1000	906	200	200	200	1600

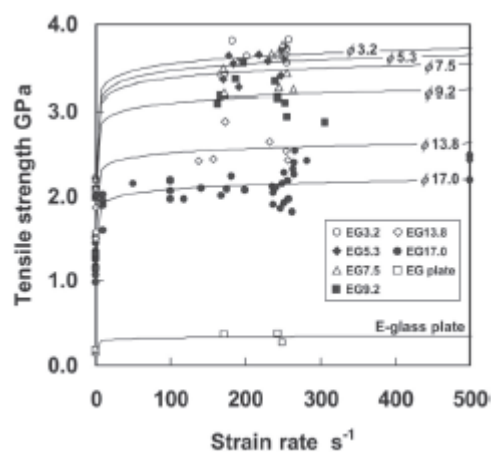


Figure 5. Relationships between tensile strength and strain rate obtained for each specimen

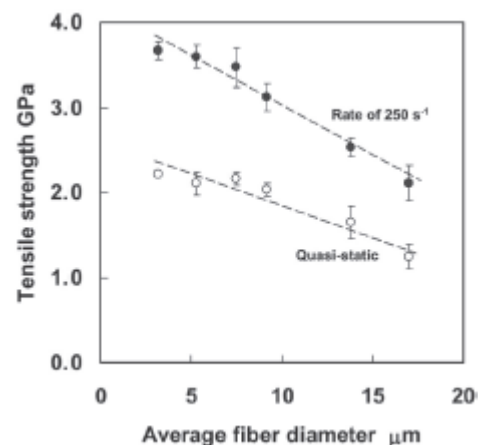


Figure 6. Relationships between tensile stress and the fiber diameter under quasi-static loading condition and strain rate of 250s^{-1}

Figure 5 shows the relationships between tensile strength and strain rate obtained for each specimen. In all specimens, the tensile strength increased with increasing strain rate. Further, it was confirmed that E-glass fiber with smaller diameter tends to exhibit higher strength. Therefore, E-glass with smaller diameter should be less affected by micro-cracks present in the surface of the fiber. In addition, Figure 5 also shows the results of impact tensile test of the flat glass plate (the gage length, the width and the thickness of the specimen is 20mm, 5.0mm and 0.5mm. the aluminium tabs were bonded at both ends of the specimen) having same component with E-glass fiber. Although strain rate dependency of tensile strength can be confirmed in the flat glass plate specimen, the strength is very low value compared to the glass fiber specimens.

Figure 6 shows the relationships between tensile stress and the fiber diameter under quasi-static loading condition and strain rate of 250s^{-1} . It was confirmed that E-glass fiber with smaller diameter exhibits higher strength, and E-glass fiber under strain rate of 250s^{-1} exhibits higher strength than under quasi-static loading condition. As a result, it is concluded that the size of the fiber diameter is a factor which affect the strain rate dependency of the tensile strength on E-glass. In addition, the surface properties of the fibers might change when varying diameter of glass fiber. So, the surface properties might have some influence on the strain rate dependency of the tensile strength.

4. Prediction of glass fiber strength

The tensile strength of glass fiber was estimated by employing the numerical simulation based on the slow crack-growth model (SCG) and using material values obtained in the double cleavage drilled compression (DCDC) test. In prediction of glass fiber strength, following assumptions were applied.

- (1) The material constants of the glass fibers are not changed by the test environment.
- (2) The glass fiber is treated as an elastic body.
- (3) The glass fiber is cylindrical and has a penny shaped crack.
- (4) The strength of the glass fiber dominated by the crack length.

First, using assumptions (1) and (2), the applied stress $\sigma_{app}(t)$ is calculated by multiplying the Young's modulus E (72.6GPa (Silica glass, E-glass), 84.5GPa (T-glass)) in the strain $\varepsilon(t)$.

$$\sigma_{app}(t) = E\varepsilon(t) \quad (4.1)$$

Then, the stress intensity factor $K_I(t)$ at any given time t is calculated by the following equation,

$$K_I(t) = Y(a(t))\sigma_{app}(t)\sqrt{\pi a(t)} \quad (4.2)$$

where, Y denotes the shape correction factor, $a(t)$, the length of crack. The shape correction factor Y is calculated by the following equation using assumption (3) [9].

$$Y(a(t)) = 0.661 - 0.011 \left[\frac{a(t)}{r} \right] + 0.415 \left[\frac{a(t)}{r} \right]^2 \quad (4.3)$$

When the stress intensity factor K_I is greater than the lower limit of the stress intensity factor K_S and crack growth rate V is calculated from the following empirical formula.

$$V(t) = \frac{da(t)}{dt} = A[K_I(t)]^n \quad (4.4)$$

The crack length a is obtained by time integrating the crack growth rate V .

$$a(t) = \int_0^t V(\tau) d\tau \quad (4.5)$$

Further, the apparent fiber strength $\sigma_{as}(t)$ for load time can be obtained by using the fracture toughness K_{IC} .

$$\sigma_{as}(t) = \frac{K_{IC}}{Y(a(t))\sqrt{\pi a(t)}} \quad (4.6)$$

The fiber is assumed to break when the applied stress σ_{as} reaches the apparent fiber strength σ_{app} , and then, the applied stress σ_{as} denotes the fiber strength σ_b .

Table 2 shows the calculated fiber strength σ_b . It is confirmed that the strength is T-glass > E-glass > Silica glass in the same environment. In addition, there is a tendency that the glass fiber in lower humidity environment has higher strength. However, the tensile strength of each glass fiber is at least 5GPa in silica glass (fiber diameter 125 μ m), 3.43GPa in E-glass (13 μ m), 4.65GPa in T-glass (13 μ m), so it is significantly different from the result of strength prediction. These are the strength of the glass with small defects immediately after manufacture. Therefore, it is necessary to consider the initial defect a_0 . Figure 7 shows the relationship between calculated strength and initial crack length using the results of DCDC tests (Relative humidity (RH) = 2%). From Figure 7, in order to obtain the fiber strength immediately after manufacture, it is necessary that the initial defects in Silica glass, E-glass and T-glass is less than 6nm, 14nm and 9nm, respectively. Although these values may be as initial

defect, its validity must be investigated further. Thus, the single fiber tensile test of E-glass was performed at normal temperature and humidity, and the validity of the strength prediction was investigated. As the result, the breaking stress σ_0 of 522MPa was obtained. In addition, observing the fracture surface (Figure 8) by the optical microscope, the initial defect size a_0 was measured to be 500nm. Strength prediction was performed using the data in DCDC test of E-glass (RH = 65%) and the initial defect size a_0 . The calculated strength σ_b was 595MPa, and almost coincide with the value of the breaking stress σ_0 of 522MPa. Therefore, the validity of this strength prediction model was confirmed.

Comparing the result of the strength prediction with $V-K_I$ diagram, to indicate low crack growth rate and high stress intensity factor is a key of high strength glass fiber. In other words, it is concluded that the slow crack-growth behaviour in the glass fiber was an essential for the increase in the strength of this material.

Table 2. Calculated fiber strength σ_b

Glass	S	E	T	S	E	T	S	E	T
σ_b GPa	1.51	1.74	1.98	1.62	1.82	2.04	1.82	1.80	2.04
RH %	65 ± 5			25 ± 5			2 ± 2		
Environment	In air						In Ar(g)		

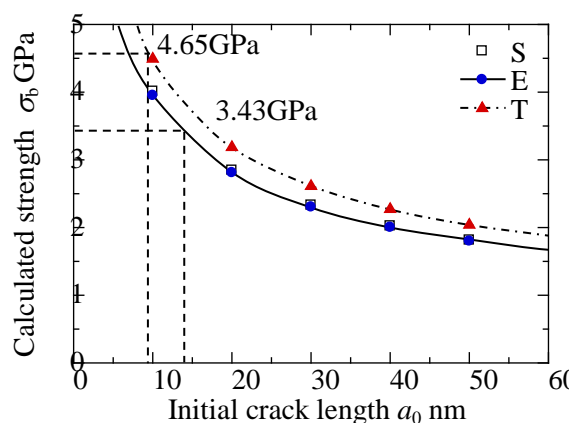


Figure 7. Relationship between calculated strength and initial crack length

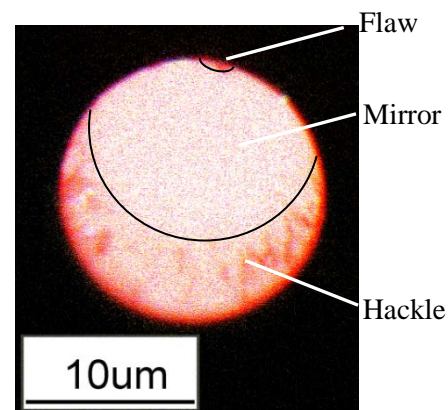


Figure 8. Fracture surface of E-glass fiber

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