Effect of Loading Conditions on the Fracture Behavior of Epoxy Resin

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(Received 13 December 2010; received in revised form 31 March 2011; accepted 5 June 2011)

Abstract
We studied the fracture behavior of a glassy polymer, epoxy resin, under the effect of static and impact tensile loading using single-edge-cracked specimens. The static and dynamic loads were determined using a load cell and a piezo sensor, respectively, and the displacement of the specimen was measured using a high-speed extensometer. From the load-displacement diagram, the external work (Uex) applied to the specimen was used to evaluate the elastic energy (Ee) and nonelastic energy (En) due to viscoelastic and plastic deformation, and the fracture energy (Ef) for creating a new fracture surface (Af). The energy release rate was then estimated using \[ G_f = \frac{E_f}{A_f} \]
and the values of \( G_f \) were correlated with the fracture load \( P_f \). The result indicated that although \( G_f \) increased with \( P_f \) for both tests, the impact test showed much lower values than the static test.

Key words

1. Introduction
Polymeric materials are widely used for many engineering applications such as lightweight structures due to their low densities. However, compared to metals, they are not as suitable in mechanical properties such as strength and fracture toughness. Hence, developing stronger and more reliable polymers through material processing is necessary. In addition, the precise evaluation of their mechanical properties is needed to ensure that these materials remain safe in real-life applications. The fracture behavior of polymers has been investigated under various loading conditions to determine their mechanical reliability. The concept of fracture toughness plays an essential role in understanding the initiation of crack extension in brittle or quasi-brittle materials. Under a static load, the fracture toughness is usually determined using elastic fracture mechanics theory by measuring the crack length and the load or external work applied to a tensile or bending specimen. In addition, the fracture toughness is measured under impact loading to estimate its dynamic value using various experimental techniques [1,2]. Most polymers generally exhibit some nonelastic effect due to viscoelastic and plastic deformation [3]. An impact load causes both inertia effects or kinetic effects and brittle fracture since a crack generally propagates dynamically within the specimen [4-23]. Hence, these two effects should be considered when evaluating the fracture toughness of a polymer. However, quantitative analysis of these two effects on the fracture toughness has been rare due to the difficulty of the experimental techniques that are currently available.

In this study, we examined the effects of the static load and the impact load in the brittle fracture of epoxy using special static and impact tensile loading devices that we developed [24-26]. The nonelastic energy \( (E_n) \) due to viscoelastic and plastic deformation was measured using a high-speed extensometer, which consisted of an optical fiber and a position-sensing detector (PSD). The elastic energy \( (E_e) \) in the static test was evaluated from the kinetic energy of the split specimen by measuring its flying height after fracture, while \( E_f \) in the impact test was estimated from the oscillation of the split specimen using the PSD. The external work \( (U_{ex}) \) applied to the specimen was determined from the static and impact load using a load cell and a piezo sensor, respectively, and the displacement of the specimen was measured using the PSD. By subtracting \( E_e \) and \( E_n \) from \( U_{ex} \), we obtain the fracture energy \( (E_f) \) for creating a new fracture surface. For the fracture surface \( (A_f) \), the energy release rate is evaluated using \[ G_f = \frac{E_f}{A_f} \]
correlated with the fracture load of the specimen. This paper presents the results and discusses the effect of loading conditions.

2. Experimental Methods
2.1 Specimen
Experiments were performed on single-edge-cracked tensile specimens made of 3-mm-thick epoxy plates. The specimen geometry is shown in Fig. 1. The specimens were 190 mm in length and 20 mm in width. To change the fracture initiation load of the specimens, various pre-crack lengths from 1 to 5.5 mm were generated using a momentum-controlled chisel-impact into a pre-machined saw-cut on one edge of the specimen.

2.2 Static tensile test
Figure 2 shows a schematic diagram of the experimental setup for static loading and displacement measurement, conducted with a high-speed extensometer consisting of an optical fiber and a PSD [24,26]. The lower part of the specimen was clamped rigidly. The upper part was also clamped tightly using steel plate grips and a pin-shaped bolt and nut to satisfy the symmetry requirements of the specimen, and loaded at the pin. The load was introduced using a special loading jig consisting of four steel bars. The shape of the jig enabled the split specimen to fly in the loading direction after fracture.

To estimate the elastic energy in the specimen, the flying height was recorded with a thin flexible paper pipe (0.3 g) inserted between the bars. As it flies, the split specimen (30 g) pushes the pipe, and the pipe stops at the highest position achieved by the upper part of the specimen. In this study, the elastic energy in the jig was disregarded.
since it has a stiffness that is much larger than the specimen. All the specimens were tested under displacement-controlled conditions using a tensile-testing machine, and the load was measured with the load-cell of the machine. Tests were performed at room temperature and at a constant crosshead rate of 1 mm/min.

Figure 2 also shows the configuration for measuring the displacement of the loading point and the region underneath the pre-crack position located at the center of the specimen. The displacement of the loading point is determined with the tensile-testing machine, while the displacement near the pre-crack is measured using an optical fiber and a PSD (SiTek Electro Optics). Ideally, the fiber should be attached as close as possible to the pre-crack. However, in this experiment, the fiber was attached at a point 2 mm away from the pre-crack to avoid damage due to the crack propagation. Nevertheless, the errors resulting from this placement can be disregarded, as the measured value would only be a few percent smaller than what would have been obtained on the centerline of the specimen. A laser diode was used as a light source, and an amplifier and a digital wave memory were employed for recording the output signals from the PSD. Since the PSD is an optoelectronic device that converts an incident light spot into continuous position data due to the lateral photo effect and has a frequency response of 100 kHz, it enables both static and dynamic displacement measurements [24,26].

2.3 Impact tensile test

Figure 3 shows a schematic diagram of a special impact-loading device that utilizes the free-fall of a weight [25]. This device consists of an electromagnet that holds the weight at an arbitrary height, loading axes for mounting the specimen, a metal frame for converting the impulse force into tension, and a piezo sensor for measuring the impact load. The specimen was clamped rigidly at its lower and upper parts to satisfy the requirements for specimen symmetry. A 3-mm-thick rubber sheet was mounted on the upper end of the frame to attenuate high-frequency vibrations caused by the impact [25].

All specimens were loaded by dropping a 10-kg weight from a height of 300 mm, resulting in an impact velocity of about 2.4 m/s. The piezo sensor has a frequency response of 45 kHz, permitting dynamic measurements [25]. The load \( P \) applied to each specimen was partitioned into an initial static load \( P_o \) due to the metal frame’s dead weight and a dynamic load \( P' \) due to the impact (see Fig. 3). The deformation of the loading axis was disregarded because it was much stiffer than the specimen. The displacement \( \delta \) at the specimen’s centerline was also evaluated and partitioned into an initial static value \( \delta_o \) and a dynamic value \( \delta' \) (see Fig. 3). In the impact test, \( \delta' \) was measured using an optical fiber and PSD. Similar to the static test, the fiber was attached to a point 2 mm from the pre-crack to avoid damage caused by the crack propagation. Again, the errors on \( \delta' \) resulting from this placement can be disregarded because measurements would only be a few percent smaller than what would have been obtained on the centerline of the specimen.

3. Results and Discussion

3.1 Static \( P-\delta \) relationship

Figure 4 plots the relationship between \( P \) and \( \delta \) under static loading. The \( P_o \) and \( \delta_o \) indicate the critical values at the onset of fracture. To examine a residual displacement \( \delta_n \) after fracture, the relationship between \( \delta \) and time \( t \) was recorded with a sampling rate of \( \Delta t = 1 \mu s \). Figure 5 shows that after fracture, \( \delta \) exhibits a damped oscillation behavior, fluctuating about \( \delta_o \). The \( P-\delta \) diagram is partitioned into three regions and this will be discussed in subsequent sections.

3.2 Dynamic \( P'-\delta' \) relationship

The dynamic load \( P' \) applied to the specimen was measured using the piezo sensor (see Fig. 3). Figure 6 plots the value of \( P' \) as a function of \( t \). The dynamic load \( P' \)
increases with \( t \), and then falls abruptly at the critical value \( (P'_c) \) as the crack starts to propagate. No high-frequency vibration was seen due to attenuation by the rubber sheet mounted on the upper end of the frame.

Figure 7 shows \( \delta' \) measured using the high-speed extensometer (see Fig. 3). \( \delta' \) increases with \( t \), and then falls abruptly as the fracture initiates at the critical value \( (\delta'_c) \). After fracture, \( \delta' \) exhibits damped oscillation, fluctuating about \( \delta_n \). \( \delta_n \) is almost equivalent to the initial static displacement \( (\delta_n = 0.05 \text{ mm}) \), which implies that no large residual displacement occurred due to viscoelastic or plastic deformation. This was the typical impact tensile fracture behavior seen in the specimen material used.

Figure 8 plots the relationship between \( P' \) and \( \delta' \) determined from Figs. 6 and 7. For specimens with almost identical initial crack lengths, the impact test yielded smaller critical values than the static test, especially in the critical displacement (see Fig. 4), suggesting the dynamic effect on material properties.

### 3.3 Definition of fracture energy

Figure 9 illustrates a \( P-\delta \) relationship for the frame’s dead weight (see Fig. 3). In this figure, \( P_o \) and \( \delta_o \) indicate initial static values due to the dead weight, and \( P' \) and \( \delta' \) denote dynamic values due to the impact loading. Although \( P-\delta \) relationships generally differ between static and dynamic loads, to simplify the analysis, the assumption was made that they are identical. External work \( (U_{ex}) \) applied to half the specimen is given by

\[
U_{ex} = \frac{P_o \delta_o}{2} = \frac{\delta'_c (P_c + P'_c)^2}{2P'_c^2},
\]

where \( P_c = P_o + P' \). and \( \delta_o = \delta'_c P_c / P'_c \). Eq. (1) is valid when \( P_o \) and \( \delta_o \) are much smaller than the critical values \( P_c \) and \( \delta'_c \), and when nonlinearity due to the material’s viscoelastic and plastic deformation is not significant.

This analysis also assumes that \( U_{ex} \) can be partitioned into three regions, as shown in Fig. 9 [24, 26]:

\[
U_{ex} = E_{el} + E_{el} + E_{ne},
\]

where \( E_{el} \) is the fracture energy created for half the new surfaces \((2A_o)\), \( E_{el} \) is the specimen’s elastic energy, and \( E_{ne} \) is the nonelastic energy due to the specimen’s viscoelastic and plastic deformation [24, 26].
under static loading.

Japan, i.e., $H = \frac{P'}{g}$, suggesting that the increased fracture energy $E_e$ shows the flying height ($\delta mgH E_e$) is increased with the fracture load $P_c$.

3.4 Nonelastic energy $E_e$

To evaluate $E_e$ in Eqs. (2) and (3), $\delta_n$ must first be determined under the following assumptions. First, $E_e$ is converted into the kinetic energy of the split specimen after fracture. Then, as the material’s viscosity can be neglected during dynamic crack propagation [19], the change from $P_c$ to $\delta_n$ or $\delta_c$ is elastic (see Fig. 9). Thus, the following relationships are obtained:

$$E_e = \frac{(\delta_n - \delta_o)}{\delta_o}, \quad E_o = \frac{\delta_n}{\delta_c}. \quad (3)$$

3.5 Elastic energy $E_e$

Figure 11 shows the flying height ($H_e$) of the split specimen as a function of the critical load ($P_c$). $H_e$ increases with $P_c$, suggesting that the increased fracture load resulted in elastic energy in the specimen, which then increased the flying height. $E_e$ is evaluated using the following relationship:

$$E_e = mgH_e, \quad (4)$$

where $m$ is the total mass of half the specimen, loading pin, grip and paper pipe, and $g$ is the gravitational acceleration.

Since no measurement of $H_e$ is made in the impact test, $\delta_c$ in Eq. (3) is determined by measuring the displacement.

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$E_e$ and $E_o$ is determined under the following assumptions. First, $E_e$ is converted into the kinetic energy of the split specimen after fracture. Then, as the material’s viscosity can be neglected during dynamic crack propagation [19], the change from $P_c$ to $\delta_n$ or $\delta_c$ is elastic (see Fig. 9). Thus, the following relationships are obtained:

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Since no measurement of $H_e$ is made in the impact test, $\delta_c$ in Eq. (3) is determined by measuring the displacement.
3.6 Energy ratios $E_d/U_{ex}$, $E_n/U_{ex}$ and $E_f/U_{ex}$

$E_f$ is determined from Eq. (2) using $U_{ex}$, $E_n$ and $E_e$. Figure 12 shows the outcome of plotting $E_d/U_{ex}$, $E_n/U_{ex}$, and $E_f/U_{ex}$ as a function of $P_c$ for the static test. From these results, the following observations can be made. First, $E_f/U_{ex}$ remains nearly constant at 40% over a wide range of $P_c$. Second, $E_n/U_{ex}$ decreases slightly from about 19% in the region of small $P_c$ to about 13% in the region of large $P_c$. Finally, although a slight change occurs in $E_e/U_{ex}$ it remains almost constant at 42% over a wide range of $P_c$.

Figure 13 plots $E_d/U_{ex}$ and $E_f/U_{ex}$ for the impact test, assuming that $E_n = 0$. The two ratios remain nearly constant over a wide range of $P_c$, suggesting that they are not strongly influenced by fracture parameters such as $P_c$, $\delta_c$, or $U_{ex}$, similar to the observations from the static test. However, the impact test results in larger values of $E_f/U_{ex}$ compared to the static test. The values of $E_d/U_{ex}$ and $E_f/U_{ex}$ are about 60% and 40%, respectively, suggesting that the energy ratios are strongly influenced by the loading conditions.

3.7 Energy release rate $G_t$

The energy release rate, $G_t$, is estimated with the following equation:

$$G_t = \frac{E_f}{A_e}$$  \hspace{1cm} (6)

where $A_e$ is half the area of the total fracture surface. Figure 14 shows $G_t$ as a function of $P_c$. $G_t$ for the two loading conditions increases with $P_c$, and values of $G_t$ for the impact test are smaller than those of the static test. This indicates that the loading conditions also influence the energy release rate because the nonelastic energy due to the viscoelastic and plastic deformation of the material will be different under different conditions. To investigate this effect in more detail, future work should involve investigating the crack velocity during crack propagation because the energy release rate also depends on the velocity [5–23].
4. Conclusions
We studied the fracture behavior of a glassy polymer, epoxy resin, under the effect of static loading and examined impact tensile loading using single-edge-cracked specimens. From the load and displacement diagram, the external work ($U_e$) applied to the specimen was used to determine elastic energy ($E_e$), nonelastic energy ($E_N$) due to viscoelastic and plastic deformation, and fracture energy ($E_f$) for creating a new fracture surface ($A_f$). The energy release rate was then estimated using $G_f = E_f/A_e$. Energy ratios $E_e/U_e$, $E_N/U_e$, $E_f/U_e$, and $G_f$ were correlated with the fracture load $P_c$. The following results were obtained.

1. The ratios $E_e/U_e$, $E_N/U_e$, and $E_f/U_e$ were nearly constant over a wide range of $P_c$ tested, although they showed different values for the static test and the impact test.
2. $E_f/U_e$ was about 40% in the static test, while it was almost zero in the impact test.
3. The value of $E_f/U_e$ obtained from the impact test (60%) was larger than that obtained from the static test (17%).
4. In contrast, the value of $E_f/U_e$ obtained from the impact test (40%) was almost equivalent to that obtained from the static test (40%).
5. In both the static test and impact test, $G_f$ increased with $P_c$. However, the impact test showed lower levels of $G_f$ compared to those indicated by the static test.

References