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Fracture toughness for mixed mode I/II of epoxy resin

Wakako Araki *, Kentaro Nemoto, Tadaharu Adachi, Akihiko Yamaji

Department of Mechanical Sciences and Engineering, Tokyo Institute of Technology, 2-12-1-I6-5 Ookayama, Meguro-ku, Tokyo 152-8552, Japan

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Abstract

We investigated the fracture locus and the direction of the crack initiation under mixed mode I/II for epoxy resin at room temperature. In order to obtain them over a whole mode mixity, we conducted asymmetric bending tests. We examined four common fracture criteria to compare them with the experimental results. Based on our experimental results, we concluded that the relaxation effect on fracture toughness varies with the mode mixity, so the common fracture criteria for mixed mode could not be applied to the epoxy resin. In contrast, the crack initiation angle can possibly be determined independently of the relaxation effect.

Keywords: Mixed mode; Fracture toughness; Polymers

1. Introduction

The use of thermo-viscoelastic materials, such as polymers and their composites, in various environments has been on the increase in recent years. Ascertaining the fracture behaviors of these materials in practical use has therefore become important.

It is widely recognized that fractures generally initiate at preexisting flaws oriented at arbitrary angles to the farfield loading direction, so that the flaws in material of practical structures are seldom subjected to pure mode I or II loading. Clarifying fracture criteria under multiaxial loading condition is a very important issue. Many different theoretical criteria have been suggested for mixed-mode fractures to determine fracture onset and the direction of crack initiation [1–7]. The validity of the criteria has been discussed for various materials [8–11]. Most criteria predict that a crack will propagate in the direction along which stress [1,2], strain [3], energy [4,5], and so on, have (or will have) a maximum value, when the parameter attains its inherent critical value.

The purpose of this study is to make clear a fracture criterion of the epoxy resin for the mixed mode I/II at the room temperature. In particular, epoxy resins with different glass transition temperatures were used in order to investigate the effect of the glass transition temperature on the mixed mode fracture toughness. Also four common fracture criteria, namely maximum hoop stress criterion [1], minimum strain energy density criterion [6], maximum stress release rate criterion [4], and Richard's empirical criterion [12], were examined in order to compare them with experimental results. Based on these analyses, we discuss the onset of fracture and the direction of crack initiation of the epoxy resin with different glass transition temperatures.

2. Experimental procedure

2.1. Specimen

The epoxy resin used in the experiment was a blend of bisphenol-A type epoxide resin (Japan Epoxy Resins

* Corresponding author. Tel.: +81 3 5734 2175; fax: +81 3 5734 2893.
E-mail address: araki@mech.titech.ac.jp (W. Araki).

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Co. Ltd, Epikote 828) with metyl-tetrahydro-phthalic anhydride as a curing agent (Hitachi Chem., HN-2200R), and 2,4,6-tris (dimethylaminomethyl) phenol as an accelerator (Daitocurar HD-Acc43, Daito Sangyo). The weight ratio of the resin, curing agent and accelerator was 100:80:0.5. The mixture of raw materials was cast in a mold after it was agitated and degassed in vacuum, then cured in a thermostatic oven. The curing was performed in two steps. First, for pre-curing, the material was kept at 353 K for 3 h to gel the matrix resin [13,14]. Then, for post-curing, which affects the cross-linking reaction of the resin, the specimen was kept under various conditions: at 393–433 K, for 3–15 h.

Specimens were taken from cured plates using a diamond-cutter. Then, the thermo-viscoelasticity test was conducted with a dynamic viscoelastometer (Orientec, Rheovibron DDV-III-EA) to investigate glass transition temperatures, T_g of the materials.

2.2. Fracture toughness test

We conducted a three-point bending test (3PBT) of an asymmetric pre-cracked specimen to measure mixed mode I/II fracture toughness [8,10,15,16]. The geometry and the size of the specimen are shown in Fig. 1 and Table 1, respectively. The stress field around the crack tip can be changed by the distance d from the center to the crack as shown in Table 2. In the case of a symmetric pre-crack, namely $d = 0$, the crack is subject to pure tension (mode I) [17].

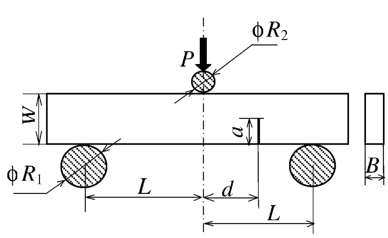

Fig. 1. Three-point bending test (3PBT) of asymmetric pre-cracked specimen. (Shaded area represents stainless steel; white area represents epoxy specimen.)

We also conducted an asymmetric four-point bending test (4PBT) of a pre-cracked specimen [16,18,19]. The geometry and the size are shown in Fig. 2 and Table 1, respectively. The stress field near the crack tip can be changed by the pre-crack length a. In the case of $a/W \approx 0.75$, a pre-crack is subject to pure shearing (mode II) [19].

Each fracture test was conducted using a universal material testing machine (8501, Instron) at room temperature (298 K) under a constant displacement rate of 3 μm/s at the loading point. The histories of the load and displacement at the loading point were measured. The displacement was calibrated based on measured local deformations of the epoxy specimen at supporting and loading points. Deformation of the stainless steel jig could be neglected since the stiffness of the jig was sufficiently larger than that of the specimen.

If the load–displacement curve of the specimen is almost linear until breaking, stress field near the crack tip is small scale yielding. Therefore, linear elastic fracture mechanics can be applicable in order to determine the mixed mode I/II fracture toughness. The stress intensity factors for each mode, K_I and K_{II} are given by [15,16,18]:

$$K_I = \sigma_0 F_I \sqrt{\pi a}, \tag{1}$$

$$K_{II} = \sigma_0 F_{II} \sqrt{\pi a}, \tag{2}$$

and F_I, F_{II} for 3PBT are different from ones for 4PBT. For 3PBT

$$\sigma_0 = \frac{3PL}{W^2 B},$$

$$F_I = F_{I3} \cdot \left(1 - \frac{a}{W}\right)^{-3/2},$$

$$F_{II} = F_{II3} \cdot \left(1 - \frac{a}{W}\right)^{-1/2},$$

And for 4PBT

$$\sigma_0 = \frac{P}{BW},$$

Table 1
Sizes for 3PBT and 4PBT (in mm)

	L	W	B	d	a	R_1	R_2
3PBT	25	12	5	0–22.5	6	10	5
4PBT	30	12	5	6	2–8	10	5

Table 2
Glass transition temperature and fracture toughness for pure modes

	Post-cure	T_g (K)	K_{Ic} (MPa m$^{1/2}$)	K_{IIc} (MPa m$^{1/2}$)	K_{IIc}/K_{Ic}
Epoxy A	433 K, 3 h	385	1.94	1.52^{*1}	0.78
Epoxy B	433 K, 15 h	399	1.99	2.77^{*2}	1.40

(*1. $\phi = 0.97$, *2. $\phi = 0.99$).