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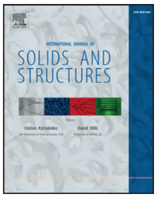

Mixed mode fracture toughness of adhesively bonded joints with residual stress

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ABSTRACT

Adhesively bonded double cantilever beam (DCB) test specimens with residual stress were manufactured. Deforming the adherends during the curing process caused the DCB specimens to curve due to the residual stress and shear load arose at the adhesive layer. Therefore, mixed mode fractures were generated by applying mode I loading to the specimens. The relation between the specimen curvature and the strain energy due to the residual stress was theoretically investigated and the mode II energy release rate for each specimen was calculated using measured specimen curvature. Because the mode I energy release rate for each specimen can be calculated with the DCB test result, the fracture toughness in mixed mode conditions was discussed. By manufacturing the specimens with different residual stresses, mixed mode fracture tests with various mixed mode ratios were conducted and the effect of the mixed mode ratio on the energy release rates was investigated.

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1. Introduction

Adhesive bonding has recently been used as a structural joining method for vehicles, aircrafts, ships, and so on. The fracture toughness and durability of adhesively bonded joints are essential in industrial uses and evaluation methods, such as for energy release rate, joint strength and creep resistance, have been widely discussed. Fracture modes, for instance mode I, mode II and mixed mode I/II, as shown in Fig. 1, change the energy release rate of the adhesively bonded joints. Therefore, methods to evaluate facture toughness have been derived for each mode. In the case of mode I fractures, double cantilever beam (DCB) and tapered-DCB tests have been standardized (ASTM D3433-99, 2012; ASTM D5528-01, 2007; ISO 15024, 2001). For mode II fractures, end notched flexure (ENF) (ASTM D7905-14, 2014; Banea et al., 2012; Chaves et al., 2014a; da Silva et al., 2010, 2012; Davies et al., 1999), four point ENF (4ENF) (Chaves et al., 2014a; da Silva et al., 2010; Davies et al., 1999; Martin and Davidson, 1999; Schuecker and Davidson, 2000) and end loaded split (ELS) tests (Blackman et al., 2005; Chaves et al., 2014a; da Silva et al., 2010, 2012; Davies et al., 1999) have been devised using DCB specimens. In addition, using DCB specimens, dual actuator loading (DAL) (Chaves et al., 2011, 2014a,b; Dillard et al., 2006; Singh et al., 2010), mixed mode bending (MMB) (ASTM D6671-06, 2006; Chaves et al., 2014a; Oliveira et al., 2007; Reeder and Rews Jr., 1990), and spelt loading jig (SPELT) tests (Fernlund and Spelt, 1994) have been devised for mixed mode fractures. These mixed mode test methods require the original loading jigs or original test machines to apply mixed mode loads, but a wide range of mixed mode ratios spanning mode I and mode II can be tested. Using the original specimens, asymmetric double cantilever beam (ADCB) (Xiao et al., 1993), single leg bending (SLB) (Davidson and Sundararaman, 1996; Yoon and Hong, 1990) and asymmetric tapered-DCB (ATDCB) tests (Park and Dillard, 2007) have also been devised for mixed mode fracture cases. Although only the opening load with a standard tensile testing machine is required for the ADCB and ATDCB tests, the mixed mode ratio is limited.

In many practical situations of joint failures, mixed mode fracture is dominant because the stress distribution at the joints is very complicated. Therefore, it is important to obtain energy release rates with a wide range of mixed mode ratios. One source of combined loads is the residual thermal stress at the joints. When different materials are jointed together, their different thermal expansion/contraction characteristics generate residual stress (Franco and Royer-Crafagni, 2016; Nairn, 2000; Shimamoto et al., 2016). Because the difference between the curing temperature and room temperature cannot be avoided with heat cure adhesives, residual thermal stress arises during the curing process. Residual stress is also generated when the adhesive is cured while the adherend is deformed such as bent lamination, which is well known for

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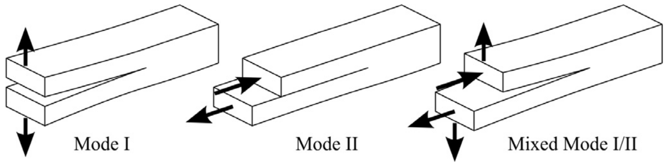

Fig. 1. Schematic illustration of Mode I, Mode II, and Mixed Mode I/II.

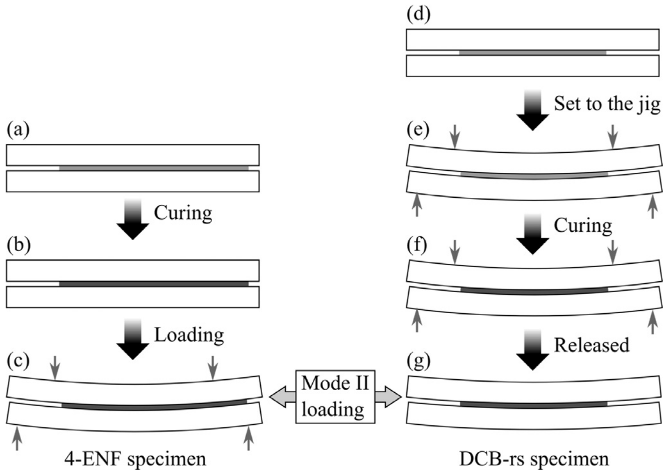

Fig. 2. Schematic illustration of (a)–(c) the four point end notched flexure test and (d)–(g) DCB-rs specimen manufacturing.

laminated glass or glue-laminated-timber (Galuppi and Royer-Carfagni, 2015a). With such cases, residual bending stress arises at the adherend and can be another factor of the mixed mode fractures.

In this paper, the manufacturing process of a DCB test specimen with a residual stress (DCB-rs) is investigated. The adherends are elastically deformed by an external load during the curing process. Shear stress arises at the adhesive layer when the load is removed. The residual stress was calculated by measuring the curvature of the DCB-rs specimens. The applied opening load caused mixed mode fracturing of the DCB-rs specimens. The residual stress can be arbitrarily changed by controlling the magnitude of the adherends' deformation during the curing process. Therefore, a wide range of mixed mode ratios can be tested with the DCB-rs specimens.

2. Description of a double cantilever beam specimen with residual stress

2.1. Manufacturing process of the DCB-rs specimens

The 4ENF test is a pure mode II fracture tests that is used to generate shear loads at the adhesive layer, as shown in Fig. 2(a)–(c). Conversely, when the specimen is kept bent during the curing process, as shown in Fig. 2(d)–(g), the specimen remains curved even after the external load is released. Hence, shear stress is generated at the adhesive layer. Specimens with different residual stress can be manufactured by changing the magnitude of the bend.

A four point bending jig, as shown in Fig. 3, was used to manufacture the DCB-rs specimens. The adherends were set to the jig after adhesive was applied and they were sandwiched together. They were then put into an electric furnace for curing. Then, the specimen was taken off of the jig. Because pure mode II loading was only generated between the inner load points of the four point bending jig, adhesive was pasted inside the inner load points.

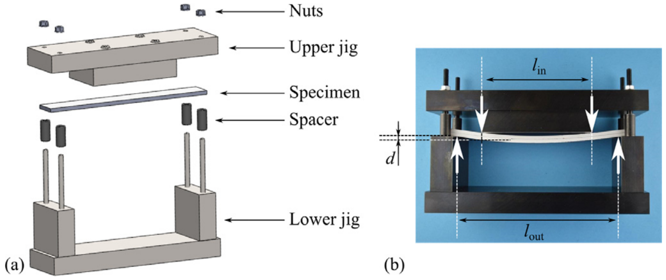

Fig. 3. Four point bending jig (a) schematic illustration with each part separated, (b) side view of the jig when the specimen is set.

2.2. Stress distribution of the adherends

The radius of curvature of a couple of beams bonded together has been derived in the case of bi-metal thermostats (Timoshenko 1925), where the bending moment is generated by the gap of the coefficient of expansion. During the manufacturing process of the DCB-rs specimens, a constant moment is applied to the adherends by fixing the specimen to the four-point bending jig. Using the same derivative method as Timoshenko (1925), the relation between the stress and the radius of curvature is investigated for the DCB-rs specimens in the assumption of Euler-Bernoulli beam theory. The radius of curvature of the adherends is constant, denoted as ρ'. The stress of each adherend before the release from the jig is given by

$$\sigma_{\text{before}} = -E\frac{\left(y - \frac{t+t_a}{2}\right)}{\rho'} \tag{1}$$

for the upper adherend and

$$\sigma_{\text{before}} = -E\frac{\left(y + \frac{t+t_a}{2}\right)}{\rho'} \tag{2}$$

for the lower adherend, where E is the Young's modulus of the adherend, y is the distance from the center of the adhesive layer, t is the thickness of the adherend, and t_a is the thickness of the adhesive layer. Conversely, the stress at the adhesive layer is zero because the adhesive is not cured and still liquid-like when the specimen is bent. When the specimen is released from the jig after the cure, the radius of the specimen curvature increased and the stress of the adherends due to the bending is changed to

$$\sigma_{\text{bend}} = -E\frac{\left(y - \frac{t+t_a}{2}\right)}{\rho} \tag{3}$$

for the upper adherend and

$$\sigma_{\text{bend}} = -E\frac{\left(y + \frac{t+t_a}{2}\right)}{\rho} \tag{4}$$

for the lower adherend, where ρ is the radius of the specimen curvature after the release. After the adhesive is cured, the adhesive layer inhibits the change of the strain at the interface and a stress arises in the longitudinal direction of the adherends. To constrain the interface, the upper adherend stress acts in tension and the lower one acts in compression with constant values. Denoting the magnitude of this stress as $\sigma_{\text{constraint}}$, the stress acting to the adherends after the release is expressed as

$$\sigma_{\text{after}} = \sigma_{\text{bend}} + \sigma_{\text{constraint}} \tag{5}$$

for the upper adherend and

$$\sigma_{\text{after}} = \sigma_{\text{bend}} - \sigma_{\text{constraint}} \tag{6}$$

for the lower adherend. Because no external force acts at the specimen after being manufactured, the moment acting on the

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