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Measurement-based evaluation of interfacial polymer layer inserted in sound deadening laminated sheet

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Abstract. Mixed mode bending (MMB) test associated with measurement of crack tip opening displacement (CTOD) is a practical method to experimentally evaluate mixed-mode cohesive zone model (CZM) properties of polymer layers in various mixed-mode ratios. However, it has an obvious limitation that does not allow for plastic bending of adherends during the tests, making it difficult to evaluate the polymer layer inserted in the sound deadening laminated sheet (SDLS) comprising thin metal sheets which are vulnerable to the plastic bending. This paper provides an experimental technique to suppress the plastic bending of the thin metal sheets during the MMB test. Supporting tools were designed, and bonded to the both outer surfaces of the SDLS. Until delamination occurred, the evolution of fracture toughness (G) was evaluated, and the CTOD was measured in the stereo image using a digital image correlation system. Finally, the mixed-mode CZM properties was successfully established based on the differentiation of the relation between the evolution of G and CTOD.

1. Introduction

Sound deadening laminated sheet (SDLS) is a composite material with three-layered sandwich structure manufactured by bonding two metal sheets with interfacial polymer layer having excellent sounddeadening characteristics. Its applications to automotive parts that experience bending or drawing processes are still limited, because interfacial slip of the polymer layer that usually occurs upon the manufacturing processes can cause delamination defects without failure of the bonded metal sheets. In order to analysis the delamination behaviour of the polymer layer, mixed mode cohesive zone model (CZM), which can deal with mixed mode loading, is increasingly used [1]. It is defined by the tractionseparation law, which represents the constitutive behavior of interfacial bonding traction (T) as function of the separation (δ) between two bonded points, with respect to loading directions (i.e. normal, shear, mixed). The δ can be obtained by the measurement of crack tip opening displacement (CTOD). The under area of $T-\delta$ law represents critical fracture toughness (G^c), and the elastic energy based calculation during the beam bending delamination tests is the well-known method to evaluate G^c . Moreover, to experimentally characterize the $T - \delta$ law, a differentiation concept has been developed between the energy based calculation and the measurement of CTOD [2].

Mixed mode bending (MMB) test is one of the beam bending delamination tests standardized in ASTM for establishing various mixed mode ratios, and Khoramishad et al. [3] firstly introduced the MMB test linked with the differentiation concept. However, the beam bending delamination tests were originally designed to target composite adherends, which allows only elastic deformation; therefore,

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they are not suitable for the evaluation of the ductile adhesive layer inserted in the SDLS comprising thin metal sheets that are vulnerable to plastic bending [4,5].

This paper provides an experimental technique to suppress the plastic bending of the thin metal adherends during the MMB test. The thicker supporting tools were designed, and bonded to the both outer side of the SDLS using a stiff and brittle adhesive. Then, the SDLS and supporting tools behave like a single body, and the plastic bending of the thin metal adherends is suppressed during the test. Until delamination occurred, the evolution of G was evaluated, and the CTOD was measured in the stereo image using a digital image correlation (DIC) system. The $T-\delta$ law was established based on the differentiation of the relation between the evolution of fracture toughness and CTOD. Finally, the mixed mode CZM properties were obtained from the bilinear fitted $T-\delta$ law.

2. Experimental procedure

2.1. Materials

The base material is dual phase (DP) 590 MPa grade high strength steel sheets with 0.7 mm thickness. In order to investigate the mechanical properties of the steel sheets, a uniaxial tensile test along the rolling direction was carried out on ASTM-E8 standard specimens with a universal testing machine (UTM) using the quasi-static rate of 0.001/s [6]. The SDLS was fabricated by passing through roller after inserting the acrylic-based adhesive layer between two adherend metal sheets having size of 300 mm x 300 mm.

Elastic modulus (GPa)	Yield stress (MPa)	Ultimate tensile stress (MPa)	Uniform elongation (%)	Total elongation (%)	Lankford value
210.3	347.6	635.9	18.5	27.0	0.84

2.2. Design of supporting tools

To suppress the plastic bending of the thin metal sheets during the MMB test, the supporting tools were designed and made of the ion-nitrided SM45C structural carbon steel as shown in Fig. 1. They were bonded to the both outer surfaces of the SDLS using the epoxy-based strong adhesive (S/N: 3M 460NS). During the test the hinge for opening mode is fixed on the supporting tools through the bolt holes.



Fig. 1 Detailed geometry of the SDLS specimen with supporting tools

2.3. Mixed mode bending test

MMB test was performed using UTM to experimentally evaluate mixed mode CZM properties, and detailed apparatus is shown in Fig. 2. The arm length (c) can be changed to vary the ratio of the opening force (mode I) at the end of the adherend to the flexure force (mode II) at the middle, and the mixed mode ratio ($\eta = G^c$ of mode II / G^c of mode I+II) of 0.4 was utilized in the test. On the specimen prior to tests, a stochastic pattern was applied to the surface of side wall using white and black spray. Until delamination occurred, the applied load (P) and loading point displacement (U) were measured from the UTM, and synchronized with CTOD measured in the stereo image using the DIC system.

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Fig. 2 Apparatus of MMB test

3. Adhesive characterization

During the MMB test, the evolution of fracture toughness (G) can be evaluated by the Irwin-Kies equation as follows [7]:

$$G = \frac{P^2}{2b} \frac{dC}{da} \tag{1}$$

where *P*, *b*, and *a* are the applied load, specimen width, and crack propagation length, respectively. *C* is the compliance, and defined by:

$$C = \frac{U}{P} \tag{2}$$

where U is the vertical displacement at the loading point. According to the Ducept et al [8], it was not easy to visually define the horizontal crack propagation length due to the unstable propagation, the equivalent crack (a_{eq}) concept based on the Timoshenko beam theory was utilized as follows:

$$a_{eq} = \left(\frac{8bh^3 E_{eq}l^2 C - 2L^3 (c+l)^2}{4(3c-l)^2 + 3(c+l)^2}\right)^{\frac{3}{2}}$$
(3)

where b, h, and l are the width, thickness, actual half length of the specimen, respectively. E_{eq} is the equivalent elastic modulus, and given by:

$$E_{eq} = \frac{(3c-l)^2 8a_0^3 + (c+l)^2 (6a_0^3 + 4l^3)}{16l^2 bh^3 C_0}$$
(4)

where a_0 and C_0 are the pre-crack length and initial compliance obtained from the early linear part in Eq. (2). By introducing Eq. (3) into Eq. (1), the *G* can be derived as follows:

$$G = \frac{3P^2 a_{eq}^2}{16b^2 E_{eq} h^3 l^2} \Big[4(3c-l)^2 + 3(c+l)^2 \Big]$$
(5)

Because *G* is determined as a function of *P*, the δ -*P* curve measured during the MMB test can be converted to the *G*- δ curve, then the *T*- δ law can be established by differentiating the *G*- δ curve against δ as follows:

$$T(\delta) = \frac{dG}{d\delta} \tag{6}$$

4. Results and discussion

The MMB tests were performed under the elastic deformation of the adherend sheets. Fig. 3 shows the established $T-\delta$ law of the ductile adhesive inserted in the SDLS during the MMB test. The separation (δ) was obtained from monitoring the CTOD, and the equivalent crack concept described in section 3 was applied to the test results in order to evaluate the evolution of *G*. The $G-\delta$ curve and its derivative, $T-\delta$ law, are shown in Fig. 3(a) and (b), respectively. The mixed mode CZM properties were extracted from the bilinear-fitted $T-\delta$ law (see the red line in Fig. 3(b)), as listed in Table 2.

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Fig. 3 Established T- δ law of polymer layer inserted in SDLS: (a) G- δ curve and (b) T- δ law

5. Summary

This study provided an experimental technique to evaluate mixed mode CZM properties of the polymer layer inserted in the SDLS. To suppress the plastic bending of the thin adherend sheets during the MMB test, the supporting tools were designed and bonded to the both outer surfaces of the SDLS. As a results, the mixed mode $T-\delta$ law was successfully established based on the differentiation of the relation between the evolution of *G* and CTOD. Finally, the mixed mode CZM properties ($\eta = 0.4$) were extracted from the bilinear-fitted $T-\delta$ law.

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