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Effect of the cohesive law shape on the modelling of adhesive joints bonded with brittle and ductile adhesives

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ABSTRACT

Cohesive Zone Models (CZMs) have been increasingly used for the fracture prediction of adhesively bonded joints. In order to better understand the relation between the fracture behaviors of the different geometry/adhesive combinations and the shape of CZMs, the butt-joint uniaxial tension, shear and the double cantilever beam (DCB) fracture experiments were conducted using two distinct adhesives, an epoxy-based brittle adhesive and a VHB^{TM} tape ductile adhesive. Three shapes of CZMs were adopted, including the exponential, bilinear, and trapezoidal models, to numerically predict the experimental performance. The comparisons between the numerical predictions and the experiments results demonstrated that the bilinear CZM is suitable for modelling the brittle adhesive bonding butt-joints in the uniaxial tensile and shear fracture processes, and the exponential CZM is suitable for modelling the ductile adhesive bonding ones. The critical stresses, the fracture energy and the shape of the CZMs have significant effects on the numerical results of the butt-joints uniaxial tension and shear for the two types of adhesives. In addition, for the DCB specimen fracture processes, it is shown that the bilinear CZM and the trapezoidal CZM predicted the brittle adhesive bonding joints better, and the trapezoidal CZM fitted the experimental data best for the two types of adhesives bonding joints. The overall results demonstrate that the selection of the shapes of CZM depend on the properties of the adhesive to obtain an accurate fracture processes prediction.

1. Introduction

Adhesive bonding is very widely employed in many industrial applications such as automotive, aerospace, construction, microelectronic, etc. [1]. It offers quite a few major advantages, such as the simplicity of application, time and cost saving, high corrosion and fatigue resistance, crack retardance and good damping characteristics. However, if the applications of the adhesives are to be extended, it must be clearly demonstrated that the failure processes of adhesively bonded joints can be predicted accurately.

To develop predictive models to simulate crack initiation and propagation of adhesively bonded joints with sufficient accuracy, the numerical approaches based on fracture and damage mechanics have been frequently employed [2,3]. Cohesive zone models (CZMs), which were originally introduced by Barenblatt [4] and Dugdale [5], have been attracted much attention to model the fracture behaviors in adhesively bonded joints. In this approach, the entire fracture process is lumped into the crack line and is characterized by a cohesive model which associates with tractions and displacement jumps across the cohesive surface. With separation increasing the traction increases, reaches a maximum stresses (cohesive strength) and then, governed by a softening curve, decreases and eventually vanishes, allowing for traction-free crack surface creation. Needleman [6] used polynomial and exponential (non-linear) types of cohesive laws to simulate particle debonding in metal matrices. Xu and Needleman [7] adopted these models to study void nucleation at the interface between the particle and matrix, and dynamic fracture growth at bi-material interfaces. Tvergaard and Hutchinson [8] proposed a trilinear type of CZM to determine crack growth resistance. Camacho and Ortiz [9] utilized a linear type of CZM to simulate multiple cracking along arbitrary paths under impact damage in brittle materials. Geubelle and Baylor [10] employed a bilinear CZM to simulate initiation and propagation of transverse matrix cracks and delamination in a thin composite plate due to low-velocity impacts. These CZMs differ in shape and other factors that describe the different traction-displacement relationships for the adhesively bonded joints separation. The parameters that principally define the traction–separation response are the cohesive fracture energy and the critical stresses of the adhesive in each CZM [11]. Some experiments that are commonly used to determine these adhesive parameters are the double cantilever beam test, the end-notched flexure

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test, the mixed-mode flexure test, and the notched coating adhesion test [12]. Owing to the difficulties associated with the direct measurement of the main parameters, very often there are obtained simply by comparing a measured fracture property with numerical predictions based on an idealized cohesive model.

These CZMs have been widely used to describe fracture and failure in metals, ceramics, polymers, and composite materials, and have successfully interpreted a variety of problems such as crack tip plasticity and creep, crazing in polymers, failures in adhesively bonded joints, and interface cracking in bi-materials [13]. Yan et al. [14] used the CZMs to carry out numerical prediction to check the fracture behavior of the interfacial delamination in PZT thin films. The simulation results showed that the bilinear CZM is suitable to describe the brittle interfacial delamination. Sarrado et al. [15] investigated the effect of the cohesive law on the adhesive and adherend thicknesses. The results showed that the impact of the two latest parameters was to be minor which mainly defines the cohesive law shape. Campilho et al. [16] investigation results showed that the single-lap joints bonded with ductile adhesives were highly influenced by the CZMs shape, and that the trapezoidal shape CZM fit the experimental data best. Recently, some researchers have paid attention to the effects of the CZMs shape and the key parameters on the strength prediction of adhesively bonded joints for the different adhesives [17]. However, Blackman et al. [18] employed the two-parameter CZM approach to simulate the DCB specimen fracture and 90° peel test. The results suggested that the detailed form of the traction versus separation curve is less important than the values of the fracture energy and the critical stress. Therefore, it is significant to employ suitable types of CZMs allowing an accurate strength prediction which is of interests in the adhesively bonded joints engineering designs.

Using the epoxy-based adhesive and a VHB tape adhesive bonding joints, the butt-joints uniaxial tensile, shear and the DCB fracture experiments were conducted. Combined with finite-element analysis (FEA) methods, three types of cohesive zone models (the exponential, bilinear, and trapezoidal) are adopted to simulate the butt-joints uniaxial tension, shear and the DCB fracture processes. The main parameters of the CZMs for the two adhesives were extracted from the tensile and shear experimental results. The comparisons between numerical predictions and experimental results are conducted to make accurate predictions for the fracture process of the different adhesively bonded joints and adhesives.

2. Experimental procedures

2.1. Materials and specimens

The ductile adhesive used in this study is G16F VHB^{TM} Tape, one of Pressure Sensitive Adhesive (PSA), which are made with acrylic foam, provided by 3 M Company. It is 25.4 mm wide and 1.5 mm thick. The brittle adhesive is a commercially available epoxy resins adhesive, LORD 320/322, which is grey paste; two-component epoxy adhesive mixed together using the manual dispensing gun and mixing tip, provided by LORD Corporation.

A typical aluminum extrusion was used as the butt-joints specimen adherend which is made by Alpco (Aluminum Line Products Company, Westlake, OH). It has an I-beam geometry and is formed from 6061-T6 aluminum. The aluminum extrusion was experimentally examined and analyzed showed that it was sufficiently stiff, sufficiently strong, and easily constrained. The use of the particular geometry of the I-beam Aluminum extrusion for the adherend strongly reduces the contribution of the stresses singularities due to edge effects. It was cut to 50 mm length. The configuration of the specimen and the aluminum extrusions dimensions are shown in Fig. 1.

The adherend of DCB specimen is made of T6061 aluminum alloy. The DCB specimens bonded by the brittle and ductile adhesives respectively were prepared according to the dimensions suggested in ASTM standard [19], as shown in Fig. 2. The experimental verification has been done before to ensure that no adherend yielding was occurred during the experiment. Here, a = 50 mm, l = 250 mm, h = 12.75 mm, d = 1 mm, and the width of the DCB specimen is 25.4 mm.

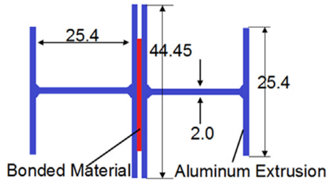

Fig. 1. Configuration of specimen and Aluminum extrusion dimensions.

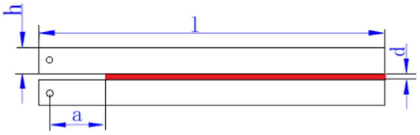

Fig. 2. Configuration and dimensions of the DCB specimen.

The adherend bonding surfaces of the butt-joints and DCB specimen were polished prior to bonding using Milwaukee Sander (PAS14.4PP, Midvale, UT 84047, USA), which can ensure a uniform surface roughness. Before bonding, the adherends were chemically pretreated by placing them in a 10% (wt) NaOH solution for 10 minutes, rinsing with DI water, and then placing them in a solution of HNO_3: H_2O = 1:1 (v) for 2 to 3 minutes or until the gray surfaces regained a white metallic appearance. The adherends were rinsed again with DI water, and then placed in an oven heated to 110 °C for at least 1 hour. For the epoxy resins bonding, the Teflon shims were placed at the two ends of the specimen to control bond line thickness at 1 mm. A stable pressure was imposed on the specimen bonded with VHB^{TM} tape to obtain a perfect cohesive strength. All the specimens were cured at room temperature for 16 hours to guarantee the full development of the crosslinks prior to experiments.

2.2. Butt-joint specimen assemblies

A modified Arcan fixture with the balance weight was employed in the butt-joints tensile and shear tests [20]. A clamping system was built for the specified aluminum extrusion used in a typical semi-trailer construction. A particular clamp was proposed by taking account of fixing the Aluminum extrusion and connecting to the modified Arcan fixture. Fig. 3 shows the particular clamp and the assembly of the specimen in the Arcan fixture, respectively.

2.3. Experiment procedure

The experiments were conducted on a hydraulic tensile machine of Instron 5800 with a maximum load of 5kN and 30kN for the two adhesives, respectively. The machine cross-head speed was controlled at 0.5 mm/min. An extensometer was used to obtain the actual displacement of the butt-joint bonded with the brittle adhesive when the tensile and shear tests were conducted, as shown in Fig. 4. However, owing to the bonding strength of VHB^{TM} tape being low, the aluminum adherends deformation can be ignored. The assembly of specimens followed a rigorous and identical procedure. Due to the influence of bubbles in the adhesive, the mixing uniformity of two adhesive, the surface treatment of adherend and the link of the experimental device, each test was repeated five times using new specimens, with at least three valid results.

3. Brief review of CZMs and simulation method

The potential based exponential model [7], the trapezoidal model [9] and the bilinear model [10] are the most widely adopted CZMs. In