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Strength of cylindrical butt joints bonded with epoxy adhesives under combined static or high-rate loading

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ABSTRACT

The influence of loading rates and the combined stress states of tension and shearing on the strength, strain, and absorbed energy of an adhesively bonded joint was experimentally investigated. Cylindrical butt joint specimens were prepared and strength tests were performed on the specimens with a servo-controlled hydraulic testing machine that combined tension and torsion loading. Two types of epoxy adhesives, ductile and brittle, were applied to the specimens. The tests were performed under a quasi-static condition of 6.67×10^{-2} MPa/s and a high-rate loading condition of 1.00×10^{3} MPa/s. The results of the combined loading tests showed that the states of the fractured surfaces were not affected by the loading rates. As for the ratio of tensile and shear loading, adhesive failure tended to partially occur when the ratio of shear loading was very high. The strength points for the specimens bonded with each adhesive were distributed in a stress plane of tension and shearing and could be fitted with a curve that was described by an equation with exponential parameters that were not influenced by the strain rate; however, other parameters that described the intercepts were influenced. The failure strains and absorbed energies for the brittle adhesive were slightly dependent on the strain rate, but this dependency was unclear for the ductile adhesive.

1. Introduction

The reduction of CO_2 emissions is an important environmental protection issue, and reducing the weight of vehicles is an effective and versatile method for resolving this problem. Automobile and aircraft components are consequently being constructed of lighter and higher-strength materials such as high-strength steel, aluminum alloys and carbon fiber reinforced plastics [1–3]. In addition, it has been predicted that the use of different materials within a structure, i.e., multi-materials, will increase in the future. Adhesive bonding is a suitable method for attaching joints in a multi-material structure. Compared with mechanically fastened or welded joints, adhesively bonded joints can reduce the product weight and increase productivity in terms of costs and production time. The adhesives used for bonding structural members are typically called structural adhesives. Richard reported on the properties and usage of structural adhesives [4].

Adhesively bonded joints in a structure may be subjected to a combination of tensile and shear loads. It is thus important to investigate the effects of combined loading states on the strength of these joints. It is possible to apply combined loading to a specimen through various test methods. For instance, combined loading tests were performed with an Arcan apparatus [5–7] on cylindrical butt-joint specimens [8–10]. Although an Arcan apparatus is convenient to use with a universal testing machine, it possesses an inherent problem of stress concentration. The use of cylindrical butt-joint specimens can precisely measure the strength of a joint under combined loading conditions.

The strength of an adhesively bonded joint at a high strain rate is crucial to automotive applications because car structures are subjected to impact loadings in crash scenarios. There has been significant research conducted on adhesive properties in high-rate loading using various methods [11–19]. The most popular method to measure the impact strength of a material is the Split Hopkinson Bar Test [20–22]. This method, however, does not easily measure the strength of an adhesively bonded joint under combined loading conditions, as few studies have been conducted for these loading conditions [23].

The energy absorbed by an adhesively bonded joint is important because it is closely related to the ductility of the joint. Adams et al. investigated the strengths of block impact specimens and measured their energy absorption [24]. In terms of joint fracture, a

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critical energy release rate is another important value because it also characterizes the ductility of a joint, i.e., the absorbed energy per adhesion area. Adhesive layers are often represented by a cohesive zone model (CZM) to simulate crack propagation [25,26]. In these cases, the critical energy release rate of a joint is an essential parameter for the simulation. Various methods have been proposed to determine the critical energy release rate of an adhesively bonded joint [27–32], but these methods still have difficulties with complicated situations such as high-rate loadings in either mode II or a combined mode.

This paper presents a novel experimental method for measuring the strength of an adhesively bonded joint subjected to high-rate combined loading of tension and sharing using a servo-controlled hydraulic testing machine and a cylindrical butt-joint specimen bonded with adhesive. Through this method, uniformly-distributed tensile and shear stresses can be simultaneously applied to the joint in the specimen. The loading rate can be specified from a quasi-static to high-rate state because the hydraulic testing machine is specifically designed to work appropriately at a high speed. The deformation of the adhesive layer in the specimen was measured with an extensometer and the energy absorbed in the layer was calculated from the experimentally obtained load–displacement curve.

2. Experiment

2.1. Materials

The adherends in the joint specimen are made of S45C carbon steel. Two types of adhesive—one-component ductile epoxy adhesive (XA7416, 3 M Japan Ltd., Tokyo, Japan) and a two-component brittle epoxy adhesive (DENATITE2204, Nagase ChemteX Co., Ltd., Osaka, Japan)—were selected for use in this study.

2.2. Specimen preparation

2.2.1. Bulk adhesive specimens

The mechanical properties of the adhesives were experimentally investigated through tensile tests of the bulk specimens. The geometry of the bulk specimens comprising the adhesives is shown in Fig. 1. The tensile tests were conducted with a mechanical testing machine (Autograph AGS-500A, Shimadzu Co., Ltd., Kyoto, Japan) at a crosshead speed of 0.5 mm/min.

2.2.2. Cylindrical butt-joint specimens

The geometry of a cylindrical butt-joint specimen is shown in Fig. 2. The adhesion surface for the adherend was treated with #600 sandpaper and degreased with acetone. An adhesive was applied to the adherends and they were bonded with the specially made jig shown in Fig. 3. A micrometer was installed at the upper part of the jig that was temporally fixed to the upper adherend with adhesive tape. The spindle of the micrometer met the lower part of the jig so that a proper thickness of the gap between the adherends could be obtained. The mechanism enabled us to control the thickness of the adhesive layer at an objective value of 0.3 mm. After bonding, XA7416 was cured at 140 °C for 20 min. and DENATITE2204 was cured 100 °C for 30 min. while being supported by the jig in a temperature chamber. The adherends and the thickness control jig were made from the same material—S45C. For this reason, any differences of bonding space between the adherends during heat curing would be minimal. Spew fillets around the joints were removed with an ultrasonic knife to control the stress concentration [33].

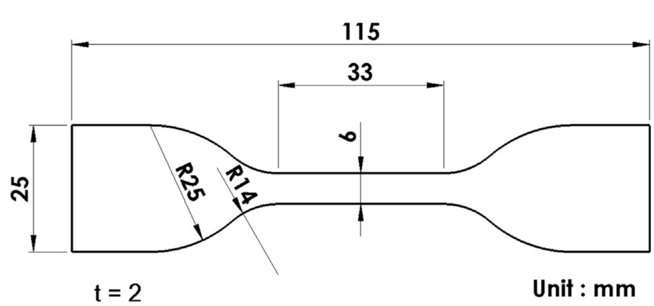

Fig. 1. Configuration and dimensions of bulk specimen made of adhesive.

2.3. Testing

Schematic illustrations of the hydraulic testing machine used for the study are shown in Figs. 4 and 5. The testing machine was originally developed by Shindo et al. [34] and based on a machine invented by Lindholm [35] that was modified by the authors. The machine has a hydraulic actuator with two oil chambers—one for tensile loading and the other for shear loading. The actuator is controlled with a pair of closed-loop feedback systems comprising a load cell, strain amplifiers, displacement sensors, electric circuits, and servo valves. The feedback control systems were only used for quasi-static tests because displacement control was possible when considering the response time. Because the control systems were not able to be utilized because of the slow response during high-rate loading, an open-loop control was employed. The increments of the actuator displacement rate were determined by preliminary tests aimed at objectively identifying the stress increment rate. The advantage of this testing machine is that both oil chambers in the actuator begin simultaneous loading when one of the loads exceeds the static friction; as a result, the synchronization of the tensile and torsional loading can be established, even for high-rate loading.

The loads applied to a specimen were measured with a specially made load cell from which tensile and torsional loads could be simultaneously measured. The deformation of the adhesive layer in a specimen was measured with the biaxial extensometer shown in Fig. 6, which utilized a pair of eddy current gap sensors placed in the axial and circumferential directions.

The specimens were tested under combined loading conditions in which two stress rates were selected: 6.67×10^{-2} MPa/s for the quasi-static condition and 1.00×10^{3} MPa/s for the high-rate condition. The tensile stress σ and shear stress τ in the adhesive layer were calculated by

$$\sigma = \frac{F}{\frac{\pi}{4}\left(d_o^2 - d_i^2\right)}, \quad \tau = \frac{T}{\frac{\pi}{16}\frac{d_o^4 - d_i^4}{d_o}}, \tag{1}$$

where F is the tensile load, T is the torque, d_o is the outer diameter (= 26 mm) and d_i is the inner diameter (=20 mm) of the specimen. The tensile strain ε and shear strain γ were calculated from measured displacements with the biaxial extensometer by

$$\varepsilon = \frac{l_1}{t}, \quad \gamma = \frac{l_2}{t}, \tag{2}$$

where l_1 is the axial displacement, l_2 is the circumferential displacement at the outer diameter of the adherents, and t is the thickness of the adhesive layer. Absorbed energies, W_1 for tension and W_2 for shearing, were calculated by integrating each stress–displacement curve to the maximum displacements l_{1f} and l_{2f} with the following equations:

$$W_1 = \int_0^{l_{1f}} \sigma(x)dx, \quad W_2 = \int_0^{l_{2f}} \tau(x)dx. \tag{3}$$