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Evaluation of bonding strength and fracture criterion for aluminum alloy–woven composite adhesive joint based on cohesive zone model

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ABSTRACT

In this paper, the bonding strength between aluminum alloy and woven composite joined by Araldite adhesive is evaluated. A fracture criterion for the joint subjected to mixed-mode loading is then proposed. For this work, specimens consisting of aluminum alloys adhered to woven composites by Araldite® Standard were fabricated and tested under normal and shear loadings by using the double-cantilever beam test and the shear-lap joint test, respectively. The fracture behavior of the adhesive joint was investigated by monitoring cracks formed at the adherend surfaces. The results indicate that cracks propagate into the woven composite bulk rather than into the aluminum alloy bulk. Furthermore, finite-element simulations of these tests suggest that the fracture behavior of adhesive joints is well described by the cohesive zone model. Bonding strengths under opening- and shearing-fracture modes are evaluated by comparing experimentally applied loads with simulated loads. This study reveals characteristics of the aluminum alloy–woven composite adhesive joint that differ from those of adhesive joints between similar adherends. Finally, a locus of fracture criterion for the adhesive joint based on the bonding strength of the joint is presented.

1. Introduction

Designing reliable joint between aluminum alloy and woven composite for load-bearing structures is an important issue that must be addressed [1]. Reliable joint technology is urgently needed, together with better composite performance, because they offer superior strength-to-weight ratio and corrosion resistance compared with metal-based components [2]. For several decades, rivets have been the conventional choice for joining structures made of different materials. Although rivets theoretically concentrate stress, engineers have confidently used rivet joints to join metals because of the numerous studies that allow the failure of such joints to be accurately predicted [3]. However, the use of rivet joints to join woven composites that serve as primary load-bearing structures leads to technical problems as reported by Saleem et al. [4]. Rivet joints require drilling a hole through the composites, which is problematic because microcracks can be created at the hole surfaces. Because holes naturally concentrate stress, such microcracks can easily propagate and lead to delamination at any time, which increases the possibility of structural failure.

To overcome these problems, adhesive joints have been introduced and have great promise for replacing rivet joints, especially for joining aluminum alloys and woven composites. From a numerical study conducted by Yamaguchi et al. [5], adhesive joints relatively do not concentrate stress because the stress is distributed over the entire contact area. This is the main reason why adhesive joints provide good resistant to fatigue and impact loadings as reviewed by Machado et al. [6] and Abdel Wahab et al. [7], respectively. Furthermore, no hole need be drilled through the composite when using adhesive joints, which decreases the likelihood of crack generation and propagation. In addition, self-healing technology may also be applied to adhesive joints [8]. However, countering these advantages and the potential they represent is the reliability of adhesive joints, which remains questionable, and the bonding quality, which remains relatively difficult to control.

Fracture behavior in adhesive joints is relatively complicated and follows uncertain patterns, especially as concerns aluminum alloys joined with woven composites. In fact, the bonding behavior produced by an adhesive material is complicated and difficult to evaluate because they depend on many parameters in the adhesive process. The bond is a complex mechanism that combines chemical bonding [9], electrostatic bonding [10], and mechanical bonding [11]. The properties of the bond are also affected by microcracks generated during the adhesion process. Thus, predicting the strength of an adhesive joint remains a challenging

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task.

The fracture behavior is also affected by the properties of adherends. Budhe et al. [12] stated that bonding strength depends on the roughness of adherend surfaces. Reis et al. [13] confirmed that the adhesive material of Araldite® 420A/B generates different bonding strength for adherends of composite–composite, steel–composite, and steel–steel materials. This occurs because the adhesive materials are usually designed to be used for specific adherend only. Further, the behavior might also be influenced by load transfer characteristic from adherend surface to adhesive materials. It causes the investigation of the fracture behavior for anisotropic adherend such as woven composite becomes more complicated. Load transfer is highly influenced by stress distribution on the adherend surface which depends on fiber orientation as reported by Saleh et al. [14]. Thus, fracture behavior must be carefully investigated considering adherend materials.

To avoid the complexity of evaluating adhesive bonds, a cohesive zone model was introduced in previous work to predict such fracture behavior [15]. The model is a phenomenological model which represents the adhesive region as a spring system with parameters such as adhesive stiffness and bonding strength. In most studies, simulations of such models can accurately predict the interaction between the two surfaces of similar or different adherends [16]. However, the physical meaning of these parameters remains debatable [17]. In particular, the relationship between experimental results and the results of simulations must be more clearly explained.

In the present work, the bonding strength of aluminum alloy–woven composite adhesive joints with respect to opening- and shearing-fracture modes are evaluated through experimentation and finite-element simulations. The opening- and shearing-fracture modes are tested by using double-cantilever beam (DCB) and shear-lap joint (SLJ) tests, respectively. Second, the applied forces and displacements are recorded while monitoring and analyzing the fracture behavior. Third, adhesive joints are simulated by modeling them as a spring system with a cohesive zone in a finite-element simulation model for studying fracture behavior. Fourth, the simulation is tuned until it gives the same force-displacement curves as obtained experimentally, which allows the bonding strength to be predicted. Finally, from the opening and shearing bonding strengths, a fracture criterion for mixed-mode loading is proposed.

2. Evaluation of bonding strength

2.1. Double-cantilever beam and shear-lap joint tests

To evaluate bonding strength, the standard tests DCB for the opening-fracture mode and SLJ for the shearing-fracture mode are used. Fig. 1(a) and (b) show schematic illustrations of the specimens for the DCB test and SLJ test, respectively. Five specimens containing aluminum alloys and composites were glued together using Araldite® Standard adhesive produced by Huntsman Advanced Material (Europe) BVBA, as detailed in Table 1. The original color of the Araldite is pale yellow. However, a drop black ink was mixed for each 30 mL mixture of the Araldite to made fractures easy to monitor for both cohesive and adhesive debonding. The addition of the black ink might slightly alter the Araldite properties. However, the focus on this study is to evaluate the bonding strength of the adhesive joint, not the Araldite properties. Thus, small alteration of the Araldite properties might not be problem as long as it will not increase the properties variance. To assure small alteration and prevent the increasing variance of the properties, the black ink is added in the Araldite with small and identic dosage for all specimens. Moreover, fine stirring process is also conducted to create uniform Araldite properties. Note that specimens in which two aluminum alloys were bonded together and in which two woven composites were bonded together were also created and tested for comparison.

The tests were done using a commercial copper aluminum alloy with an elastic modulus of 70 GPa and a Poisson's ratio of 0.33. The composite was manufactured by hand using the lay-up method with 30% fiber by volume [18]. The composite contained six layers of plain-woven fabric glass fiber EW-200 bound by epoxy Resin Yukalac 157 BQTN-EX cured at room temperature for 1 day. The composite was then cut by an automated cutter machine to ensure that the fiber orientations of the specimen were 0° and 45° with respect to the load direction.

Tensile tests were first conducted on the woven composite by using the tensile machine TENSILON RTF-1310 with a crosshead velocity of 2 mm/s. Tensile testing serves to evaluate the elastic modulus of the woven composite, which can be used at input data for the simulation. Fig. 2(a) and (b) show stress-strain (σ-ε) curves for the woven composites obtained from the tensile tests for fiber orientations of 0° and 45°, respectively, with respect to the tensile load direction. The stress-strain curves are different for different fiber orientations. For the fiber orientation of 0°, the stress-strain curves are linear and reflect high strength because the load is mostly borne by the fiber. In contrast, for the fiber orientation of 45°, the epoxy endures the brunt of the load, resulting in nonlinear stress-strain curves typical of low strength. Table 2 details the mechanical properties of the adherends and the adhesive. These properties are used for simulation as input data. Note that the elastic modulus and Poison's ratio of the adhesive are assumed to be identic with the Araldite® AV138 produced by the same manufacturer, because from a preliminary study of the Araldite® Standard properties, a brittle behavior, which is similar with the Araldite® AV138, was observed. This assumption is acceptable because the focus in this study is to investigate the bonding strength which is no correlation with the elastic modulus and Poison's ratio, as they are considered as independent parameters. Thus, the exact values of these properties might not be required.

For the DCB test, loading blocks from steel were made to transfer the force from the tensile machine and installed the blocks onto the specimens to avoid drilling through the composite. For the SLJ test, a tab was fixed to each adherend to ensure good alignment and thereby obtain a pure shearing force in the adhesive during tensile testing. The tab was made of material similar to the adherends. The adhesive thickness for both tests was about 0.76 mm, as recommended by ASTM D5868. Note that the adhesive process must be strictly controlled to ensure uniform adhesion properties over the entire adhesive region. In fact, the adhesive properties are difficult to evaluate because the complex physical parameters involved depend strongly on the adhesive process, such as the process of mixing resin and hardener, the spreading of the adhesive, or its curing temperature.

The tests were implemented by applying a tensile force to specimens by using a tensile testing machine TENSILON RTF-1310 with a crosshead velocity of 0.1 mm/s. Force-displacement (F-d) curves were recorded simultaneously for each specimen. The strong correlation is investigated between maximum applied force $F_{\max}$ and bonding strength.

2.2. Modeling the adhesive joint

The bonding between the aluminum alloy and the woven composite involves a complex mechanism. The fracture behavior of the adhesive joint can be divided into three cases such as cohesive failure of the adhesive, double-surface of adhesive failure, or single-surface of adhesive failure. Those can be seen in Fig. 3a. Physically modeling the adhesive bond is of almost no use because the parameters are so complex that the simulation time becomes excessive. Moreover, a complex model is not guaranteed to give accurate results because of the numerous parameters that must be considered and validated in many experiments. To tackle these problems, a cohesive zone model is defined in which the adhesive bond is modeled as a spring system (see Fig. 3b). This model is a phenomenological model that considers the bonding process more than the physical properties of the adhesive. It drastically reduces the time required for the simulation because it involves far fewer parameters than the physical model. The various