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A study on the strength of adhesively bonded joints with different adherends

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ABSTRACT

In this study, mechanical properties of adhesively bonded single-lap joint (SLJ) geometry with different configurations of lower and upper adherends under tensile loading were investigated experimentally and numerically. The adherends were AA2024-T3 aluminum and carbon/epoxy composite with 16 laminates while, the adhesive was a two-part liquid, structural adhesive DP 460. In experimental studies, four different types of single-lap joints were produced and used namely; composite–composite (Type-I) with lower and upper adherends of the same thicknesses and four different stacking sequences, composite–aluminum (Type-II) with lower and upper adherends of the same thicknesses and four different stacking sequences, composite–aluminum (Type-III) with lower adherend (composite) of the same thickness but upper adherend of three different thicknesses, aluminum–aluminum (Type-IV) with lower adherend of the same thickness but upper adherend of three different thicknesses, composite–composite (Type-V) with $[0]_{16}$ stacking sequences and three different overlap length, aluminum–aluminum (Type-VI) with three different overlap length. In the numerical analysis, the composite adherends were assumed to behave as linearly elastic materials while the adhesive layer and aluminum adherend were assumed to be nonlinear. The results obtained from experimental and numerical analyses showed that composite adherends with different fiber orientation sequence, different adherend thicknesses and overlap length affected the failure load of the joint and stress distributions in the SLJ.

1. Introduction

Composite materials in advanced engineering structures have gained great popularity in the past decades because of their high strength/weight ratios and high damping capacity. Traditional methods of joining, such as riveting and screwing, became the first choice due to their relatively low cost and ease of assembly. However, as is already widely known, even when such joints are used with traditional materials, high stress concentrations can develop at the point of joining, and the joint can be brought to failure at far lower stress levels than expected [1]. One of these problems is the stress concentrations occurring in the free edges of the bonding area. Different methods, for example, tapering the adherend, forming an adhesive fillet or changing the lap joint geometry, exist to reduce these stresses and many studies have been conducted on this subject [2–8]. Therefore, adhesively bonded joints are more preferable to a mechanical joint in the joining of composite materials [9–13].

Unlike isotropic adherends, laminated composite adherends have relatively low transverse strength and shear stiffness compared to their in-plane material properties. In addition, laminates suffer from material non-homogeneity, residual stresses and free edge problems [14,15]. For adhesively bonded joints, these factors make the problem with the composite adherends more complicated than that with homogeneous isotropic adherends [16–19]. Thus, 3D analysis is essential to understand the joint stress fields as well as initiation and propagation of damage in practical applications. However, prediction of 3D stress and failure for bonded joints is a difficult analytical problem, owing to the fact that an adequate solution has to account for the step-wise geometry and material property variations such as anisotropy and laminated construction of the adherends, nonlinear behavior of adhesive [20–22].

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There are a number of different damage criteria that are used in damage load prediction of adhesive joined-connections [23–26]. However, recent studies have shown that making damage load prediction of the connection theoretically and numerically with cohesive zone model (CZM), gives more accurate results in adhesive joined-connections [27,28].

The singularity stress occurring at the ends of overlap area of adhesively bonded joints is important for failure load prediction. Russo and Zuccarello [29] using boundary element method (BEM) for prediction of failure load at metal-composite co-cured joints have evaluated the relation of Generalised Stress Intensity Factors (G-SIFs) at singular points.

The damage in adhesively bonded joints is mostly caused by peel stress in free ends of the overlap area. This stress is originated from the bending moment due to the eccentric structure of single-lap joints. Thus, in the formation of damage it is extremely important to examine the peel stress.

In the structures where both composite and aluminum are applied together in space, aviation, and automotive industry; the transition region where two different materials are joined, is considerably a critical region to be investigated. The idea of using single-lap joint (SLJ) types which is joined by adhesive and shows more uniform stress distribution with respect to conventional joining methods (such as riveting and screwing), will be more convenient in joining of this transition region; was developed. Therefore, in the present study, mechanical behaviors of tensile loaded single-lap joint (SLJ) types:

- Composite–composite (Type-I) with lower and upper adherends of the same thicknesses and four different stacking sequences.
- Composite–aluminum (Type-II) with lower and upper adherends of the same thicknesses and four different stacking sequences.
- Composite–aluminum (Type-III) with lower adherend (composite) of the same thickness but upper adherend of three different thicknesses.
- Aluminum–aluminum (Type-IV) with lower adherend of the same thickness but upper adherend of three different thicknesses.
- Composite–composite (Type-V) with $[0]_{16}$ stacking sequences and three different overlap length.
- Aluminum–aluminum (Type-VI) with three different overlap length were investigated experimentally and numerically. In the numerical analysis, the composite adherends were assumed to behave as linearly elastic materials while the adhesive layer and aluminum adherend were assumed to be nonlinear. Finite element analysis (FEA) results were compared with experimental results.

2. Experimental details

In this study, adherends material was either AA2024-T3 aluminum alloy or 16-ply laminate of T300/934 carbon/epoxy composite which was produced by Izoreel in İzmir, Turkey. For bonding, a two-part paste epoxy (DP460, produced by 3M Company, St. Paul, MN, USA) was used as adhesive. The stress–strain behaviors of adhesive and adherend (AA2024-T3) are necessary for elasto-plastic stress analysis via non-linear finite element method (FEM).

For this purpose, the specimens were manufactured in the bulk form which cured at 60 °C for 120 min and were tested in a Shimadzu Universal Testing Machine under a crosshead speed of 1 mm/min. Three specimens were tested for adhesive. A full discussion can be found elsewhere [30]. Typical tensile stress–strain ($\sigma - \varepsilon$) curves and the material properties for the adhesive (DP460) and adherend (AA2024-T3) which is obtained by averaging the results of three bulk specimens for adhesive and adherend are given in Table 1, while mechanical properties of carbon/epoxy composite are given in Table 2.

In this study, the mechanical behavior of SLJs subjected to tensile loadings was investigated experimentally and numerically. For this purpose, samples, i.e., SLJs of Types I–VI were designed in six main groups. The geometrical parameters of these samples are given in Fig. 1 and Table 3.

Before bonding, surfaces of adherends were degreased with acetone, sand blasted, washed under running tap water, and dried in an oven at 50 °C for 20 min. In order to obtain DSJ samples, DP460 liquid paste adhesive was applied on patches before curing and samples were placed into the mold displayed in Fig. 2 a. In order to obtain an adhesive layer thickness of 0.10 mm after curing, metal shims with a thickness of $h_1 + 0.10$ mm were placed into the mold, the upper cover of the mold was closed before putting into a hot press. Next, adhesive bonding with DP460 was achieved by curing at 60 °C for 120 min. Three samples for each joint type were produced, for a total of fifty-one samples. After curing, thicknesses of adhesive layers for all SLJs with DP460 were separately measured, and the mean thickness value was found to be 0.10 mm (Fig. 2b).

All experiments were conducted by Shimadzu AG-IS 100 (Tokyo, Japan) testing machine with a 100 kN load cell, under 1 mm/min crosshead speed, in a laboratory with 17 °C temperature and 33% relative humidity. For samples of four types (Type-I Type-II, Type-III, Type-IV, Type-V and Type-VI), the boundary conditions and applied load are the same, see Fig. 3.

The samples were closely observed during experiments and the deformation zone was examined after failure. Meanwhile, maximum load was recorded in the solutions of the finite element approach for further use.

3. Finite element modeling of the single-lap joint

The numerical analysis was performed in the commercial FEM package ANSYS® [32] (code version 12) to predict the three-dimensional effects (anti-clastic, free edge and bending–twisting coupling effects). Meanwhile, it was aimed to assess the effects of the fiber orientation angle of the laminates on stress distributions and failure prediction in SLJs subjected to tensile loading. In the analysis, the composite adherends (T300/934) with four different fiber orientation angles ($[0]_{16}$, $[0/90]_8$, $[45/-45]_8$ and $[0/\pm45/90]_4$) were assumed to behave linearly elastic, while both the adhesive layer (DP460) and the aluminum adherends (AA2024-T3) were assumed to be nonlinear. Also, the nonlinear geometric deformations of SLJ samples were taken into account [9].

Three-dimensional 8-node layered solid element (SOLID 185) associated with a shell section (SECTYPE) was used for composite adherend. The properties of the layered composite (including layer thickness, material, orientation and number of integration points through the thickness of the layer) are specified via shell section (SECDATA) commands. Three-dimensional 8-node structural solid element (SOLID 65) was used for both adhesive layer and aluminum adherend. Meanwhile, composite adherend were modeled with sixteen layers of SOLID 185 elements. The dimensions of the samples (Fig. 1), loading conditions and boundary conditions (Fig. 3) used in the finite element analyses are the same as those used in the experimental study. Smaller meshes were used in zones where the stress distribution was critical (Fig. 4).