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The strength of the adhesively bonded step-lap joints for different step numbers

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ABSTRACT

Peel stresses developing at the edges of the overlap area of the adhesively bonded single lap joints subjected to static tensile loading have a profound effect on the damage of the joint. The reduction in the stress values formed at the edges of the overlap area or the transfer of these stresses to the middle part of the overlap area increase the strength of the joint. In this study, mechanical properties of the single lap joint (SLJ), one step lap joint (OSLJ) and three step lap joint (TSLJ) subjected to tensile loading were examined experimentally and numerically by keeping the bonding area same for all samples examined. In the samples produced for experimental study, AA2024-T3 aluminum alloy was used as adherent, while a flexible adhesive SBT9244 and a stiff adhesive DP460 were applied separately. After experimental studies on the three different joint types were conducted, stress analyses in the joints were performed with a three-dimensional finite element method by considering the geometrical non-linearity and the material non-linearities of the adhesive and adherend. As a result, it was observed that one-step lap geometry reduces the stress concentration developing at the edges of the overlap area while the highest decrease occurred in the three-step lap geometry. Additionally, the amount of reduction in the stress values supports the increase in the experimentally obtained load carrying capacity of the joint.

1. Introduction

Adhesively bonded joints are preferred due to their advantages such as formation of uniform stress distributions, ability to join different materials, high fatigue resistance and impermeability [1,2]. However, in the adhesively bonded joints, extreme levels of stress concentration form at the edges of the overlap area, which significantly influences the strength of the joint. In order to use the adhesive bonding technique and to increase the load carrying capacity of the joint, the effect of these stresses forming at the free edges of the bonding area should be reduced.

When the literature is surveyed, it can be seen that there are various types of the joints bonded with adhesives. The single-lap joint is the most commonly because of the simple geometry. Meanwhile, this type of joint has been frequently used for joining composite materials [3–10]. The analyses conducted for this type of joint demonstrated that peel stresses developing at the edges of the overlap area reduces the load carrying capacity of the joint [11,12].

There are many methods to increase the strength of the adhesively bonded joints by reducing the effect of these peeling stresses [13–19]. One of these methods is spew fillet technique, which was shown to reduce the effect of these peeling stresses and increase the strength of the joint [20,21,16,22–26]. Crocombe and Adams [20] included the effect of additional parameters such as material and geometric properties. They found that triangular spews reduce the stress levels from those predicted for square-ended joints without spews.

Another method is the use of a bi-adhesive in the overlap area of the adhesively bonded joints and it was observed that this method increases the load carrying capacity of the joint [27–31]. In a study performed by da Silva and Lopes [31], the behavior of SLJ geometry, which was obtained by using mixed-adhesive technique in the overlap area, under tensile loading was investigated. Silva and Lopes concluded that stress concentration at the overlap ends decreased by applying the flexible adhesive towards the edges of the overlap.

In a study conducted by Temiz et al. [32], mechanical behaviors of the two different single lap joint geometries, i.e., SLJ with flat edges of the adherent and SLJ with curved overlap length of the adherent, subjected to tensile loading, were examined experimentally. These resulting compressive residual stresses decreased the

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effect of the peel stresses normally present at the overlap termini and increased the load-carrying capacity and displacement capacity of the adhesive joint [33].

In the literature, there are different studies investigating the effect of adhesively bonded stepped-lap joints on the strength of joint [34–39]. However in this type of joint, composite were commonly used as adherend [34–37]. In a study performed by Ichikawa et al. [38], behavior of a stepped-lap adhesive joint, in which steel was used as adherent, under tensile loading was examined experimentally and three dimensional finite analysis. As a result of the investigation, the maximum value of the maximum principal stress occurs at the edge of the adhesive interfaces. Reduction of the thickness of the adhesive, increasing the Young's modulus of the adhesive and the number of steps decrease the ultimate stress value [39].

In the present study, mechanical properties of three different joints subjected to tensile loading having the same bonding area, namely, single lap joint (SLJ), one step lap joint (OSLJ) obtained by machining a single step and three step lap joint (TSLJ) obtained by machining three steps were studied experimentally and numerically. In the production of experimental samples, an aluminum alloy of AA2024-T3 was used as an adherend and flexible adhesive SBT9244 and stiff adhesive DP460 were employed as adhesives. After experimental studies on the three different joint types were conducted, stress analyses in the joints were performed with a three-dimensional finite element method by considering the geometrical non-linearity and the material non-linearities of the adhesive and adherend. Experimental studies were also performed in order to validate the results of finite element analysis.

2. Experimental program

2.1. Material and specimens

In this study, DP460, a two-part paste stiff adhesive produced by 3 M, and SBT 9244, a film type flexible adhesive, were used as adhesives. AA2024-T3 aluminum alloy, a well-known material used in the aerospace and automotive industry due to its low density, high machinability and corrosion resistance as well as reasonable mechanical and physical properties, was used as adherent. The stress-strain behaviors of adhesives and adherend are necessary for elasto-plastic stress analysis via non-linear finite element method (FEM). The mechanical properties of both adhesives (DP460 and SBT9244) and the adherend given in Table 1 were taken from a study carried out by Akpinar et al. [40]. A full discussion can be found in that study.

In this study, mechanical properties of six different samples prepared by bonding of three joints with both flexible and stiff adhesives were studied experimentally and numerically. The joints with different geometries but with the same adherend thickness, width and overlap length were employed. The experimental and geometrical parameters of these samples are given in Table 2 and Fig. 1.

The strength of the adhesively bonded joints depends on the preparation method of the surface used [41–46]. For this reason before bonding, aluminum adherend parts (AA2024-T3), which were used in the production of samples, were degreased with acetone, sand blasted, etched with $H_2SO_4 + Na_2Cr_2O_7{\cdot}2H_2O$, washed in running tap water, and dried in an oven at 60 °C for 15 min. In order to produce proper adhesively bonded joint samples, to adjust the thickness of the adhesive thickness and to apply uniform pressure, the mold shown in Fig. 2b was used. In order to obtain an adhesive layer thickness of 0.15 mm after curing, metal shims (see Fig. 2) were placed into the mold. In order to obtain adhesively bonded Type-I, Type II and Type III joint samples, SBT 9244 and DP 460 were separately applied as shown in Fig. 3b before curing to the aluminum adherend parts. The specimen was then placed into the mold displayed in Fig. 2b. There exist some different curing conditions for the adhesives SBT 9244 and DP 460 depending on temperature, pressure and time, while, in this study, curing was performed under a pressure of 0.15 MPa for 60 min at 140 °C for both. For each type of joint 3 samples were produced making up 18 samples in total (Fig. 2c).

Table 1
Material properties of the adherend and adhesives used in the study [40].

	AA2024-T3	SBT 9244	DP 460
E (MPa)	72,400 ± 530	82 ± 4	2077 ± 47
ν	0.33	0.35	0.38
σ_t (MPa)	482 ± 12	20.9 ± 0.7	44.6 ± 1.2
ε_t (mm/mm)	0.1587	0.945	0.0428

E: Young's modulus; ν: Poisson's ratio; σ_t: ultimate tensile strength; ε_t: ultimate tensile strain.

2.2. Experimental procedure

All experiments were conducted by using Shimadzu AG-I (Tokyo, Japan) universal tensile testing machine at 16 °C and 28% humidity with a speed of 1 mm/min. For each type of samples (Type-I, Type-II and Type-III) boundary conditions and the applied force were the same as shown in Fig. 3.

Samples were closely observed during the course of the experiments and after the failure, damaged area was investigated. At the same time, ultimate load carried by the samples and the failure type observed were recorded. Additionally, force–displacement curves were obtained for each type of joint.

3. Three-dimensional finite-element modeling (3-D FEM)

Samples of three different joint types (Type-I, Type-II and Type-III) used in the experimental studies were modeled three dimensionally by using ANSYS 14 [47] package software (Fig. 4). The stress analyses in the adhesively bonded joints using a non-linear finite element method were performed by considering both the geometrical non-linearity and non-linear material behaviors of both adhesives (SBT9244 and DP460) and adherend (AA2024-T3). The dimensions of the samples (Fig. 1) and boundary conditions (Fig. 4) used in the finite element analyses were the same as those used in the experimental works.

In the 3D analysis, the adherend and adhesive of the adhesively bonded joint were modeled by using three degrees of freedom and elements with 20 nodes via solid 186. Apart from this, smaller meshes were used in zones where the stress distribution is critical (Fig. 4). The used material model is Multilinear Isotropic Hardening-von Mises plasticity (MISO). Also, for stress analysis the von Mises yield criterion was used to calculate the equivalent stress (σ_{eq}) and strain (ε_{eq}) distributions in the adhesive layers and adher-

Table 2
Experimental parameters for adhesively-bonded joints.

Specimen	Joint type	Adhesive area (mm^2)
SBT9244-adhesively bonded single lap joint	Type I a	625
DP460-adhesively bonded single lap joint	Type I b	625
SBT9244-adhesively bonded one-step lap joint	Type II a	625
DP460-adhesively bonded one-step lap joint	Type II b	625
SBT9244-adhesively bonded three-step lap joint	Type III a	625
DP460-adhesively bonded three-step lap joint	Type III b	625