Experimental and numerical investigations on adhesively bonded joints

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Abstract. Two types of adhesively bonded joints were experimental and numerical investigated. Firstly, the adhesives were characterized through a set of tests and the main elastic and mechanical properties were obtained. After that, the stress distributions at interface and middle of adhesive layer were determined using a linear elastic FEA. The numerical data were fitted by a power law in order to determine the critical values of intensity of stress singularity.

1. Introduction
Adhesively bonded joints are used in many engineering applications (automotive and aerospace industries) as an alternative to the conventional riveted and bolted joints. Several advantages characterize the adhesive bonding including: good stiffness and strength, reduced weight and cost, capacity to join dissimilar materials. Delicate joining technology (surface preparation, curing procedure etc.) and environmental sensitivity represent real disadvantages [1]. As a new trend, the hybrid joints (bonded/riveted [2]) are of great interest. However, the joint’s strength evaluation represents a major challenge.

The geometries of the single- and double-lap tested joints were established according to the ASTM D1002-10 and ASTM D3528-96 recommendations (figure 1, width of 25.4 mm). Aluminium alloy 7075 T651 adherents and two types of adhesives (araldite AV138M-1 with hardener HV 998 and araldite AW106 with hardener HV 953U) were used.

Figure 1. Geometries of adhesive-bonded joints, single-lap (up) and double-lap (down)
2. Experimental investigations

After the mechanical treatment of the surfaces, the adherents were cleaned in an acetone bath. The adhesives were cured at room temperature for 24 hours, under constant pressure applied through weights. The thickness of adhesive layer was carefully controlled at 0.25 (mm), but no attempts were made to control the fillet geometry.

| Materials          | E (MPa)
|--------------------|---------|
| Al 7075 T651       | 70198   |
| Araldite AV138M-1  | 3384    |
| Araldite AW106     | 2585    |

Table 1. The elastic and strength properties of bonded materials

\[^{a}\text{Determined by impulse excitation technique, ASTM E1876-09}\]

\[^{b}\text{Obtained through tensile tests}\]

| Joint type       | Adhesive | t (mm) | Fmax (kN) | \(\tau\) (MPa) |
|------------------|----------|--------|-----------|---------------|
| Double-lap       | AW106    | 3; 6   | 12.956±1.270 | 10.04±0.98    |
| Single-lap       | AW106    | 3      | 4.522±0.570  | 7.01±0.88     |
| Single-lap       | AV138M-1 | 3      | 3.301±0.216  | 5.12±0.33     |

Table 2. The apparent shear strength of adhesively bonded joints

The tests were carried out on an universal testing machine under displacement control at 1.3 (mm/min) speed. The stress-strain curves (figure 2) and the tensile strength \(\sigma_u\) for adherent and adhesives were experimentally obtained (table 1). Also, the elastic properties were determined using a Resonant Frequency and Damping Analyzer device based on impulse excitation technique, ASTM E1876-09 (table 2). A brittle behaviour was observed for AV138M-1 adhesive and a nonlinear one for AW106 adhesive.

3. Analytical solution for stress singularity

As a consequence of changes in geometry and in elastic properties, singular stress fields occur at the edge of interface between the adhesive and the adherent. An investigation in determining how the order of the stress field singularity depends on the material elastic constants and corner angles was conducted by Bogy and Wang [3]. For the free edge geometry presented in figure 4, the stress singularity could be expressed in the form:

\[
\sigma_{\alpha\nu} = H r^{x-1} f_{\alpha\nu}(\alpha, \beta, \lambda, \theta) \tag{1}
\]

\[
\sigma_{ij} = \frac{H r^\lambda}{2a_j} g_{ij}(\alpha, \beta, \lambda, \theta) \tag{2}
\]
where: $H$ represents the stress intensity factor at joint; $i, k$ are the polar coordinates $(r, \theta)$; $j$ is the material number; $G_j$ represents the shear modulus of material $j$; $\lambda$ is the stress singularity; $f_{ik}$ and $g_{ij}$ are non-dimensional functions of $\lambda$, $\theta$ and Dundurs parameter $\alpha$ and $\beta$.

Figure 4. Bonded dissimilar materials

Expressing the stresses and displacements through two complex functions $\Phi(z)$ and $\Omega(z)$ and imposing the appropriate boundary conditions (i.e. the continuity for stresses and displacements on the interface, the values of stresses on the free edges) the problem is reduced to a linear homogeneous system (Sinenscu et al. [4]). Because a non-trivial solution is searched, the stress singularity was found by imposing to have null determinant of the coefficients matrix. For computing the stress singularity a Mathcad routine was developed and the results for bonded joints were obtained (table 3).

Table 3. The stress singularity values for investigated adhesive bonded joints

| Joints             | 01 (rad) | 02 (rad) | $\lambda -1$ (-) |
|--------------------|---------|---------|------------------|
| Al 7075 T651 / AV138M-1 | $\pi/2$ | $\pi/2$ | -0.2714          |
|                    | $\pi$   | $\pi/2$ | -0.1951          |
| Al 7075 T651 / AW106 | $\pi/2$ | $\pi/2$ | -0.3127          |
|                    | $\pi$   | $\pi/2$ | -0.2084          |

4. Numerical analysis of bonded joints

A 2D linear elastic FEA was conducted using commercial Abaqus package. The bonded joints were meshed using 8 nodes isoparametric plane strain quadrilateral elements. A progressive mesh towards the overlap ends was adopted, in order to take into account the stress gradient and the singularities. The minimum size of the element at the overlap ends is 0.008 (mm) with 8 elements in the adhesive thickness and the maximum aspect ratio reaching the maximum value 10:1. The model was clamped at one adherent end and allowed to move only in the longitudinal direction at the other end. The applied load represents the average load obtained experimentally for joints failure.

The results plotted in figure 5 in terms of maximum principal stress $\sigma_1$ (log axes used for distance, in order to highlights the stress distributions at overlap ends) show that the stresses are almost constant across the overlap length excepting the ends, due to the joint singularity. The stress peaks are higher in the case of the single-lap bonded joint. As expected, for the stress distributions through the middle of the adhesive layer the singularity effect is not present, but it is obvious at adherent-adhesive interface.

A method for debonding strength evaluation using two stress singularity parameters $H$ and $\lambda -1$ was proposed by Hattori et al. [5,6]. Expressing the maximum principal stress $\sigma_1$ distribution near the bonding edge, in the dominant stress singularity zone, as follows (Sawa [7]):

$$\sigma_1(r) = HCr^{-1/2}$$  \hspace{1cm} (3)

the critical values of intensity of stress singularity $HC$ were determined by fitting equation (3) to the stress distributions obtained through FEA, near the bonded edge.
Considering the single-lap bonded joints, the critical values of $H_C$ were calculated for these two different used adhesives (in this case $\theta_1=\pi$ and $\theta_2=\pi/2$) by fitting the numerical data through a power law in the singularity predominant area, resulting the values presented in figure 6.

![Figure 5](image.png)

**Figure 5.** Maximum principal stress $\sigma_1$ vs. distance from ends to middle of overlap (adhesive AW106, double-lap in blue and single-lap in black)

**Figure 6.** Numerical data fitted by the power law in the case of single-lap bonded joints

5. Conclusions

This paper presents the mechanical characterization of two types of adhesives through tensile and tensile-shear tests (with single- and double-lap bonded joints). The determined properties were applied to the linear-elastic FEA of bonded joints and the stress distributions at the adhesive-adherent interface were studied. Numerical data were fitted by a power law and the critical values $H_C$ of intensity of stress singularity were determined for used adhesives.

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