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Finite Element Analysis of Adhesively Bonded Lap Joints

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Abstract

Adhesive bonding is a preferred method of joining aerospace structural components, since it provides fewer points of stress concentration compared to fastener joints. Geometrically non-linear analysis of adhesively bonded lap joints is presented in this paper using both linear and non-linear material properties of the adhesive. The numerical results show beneficial effects of material non-linear behaviour of the adhesive which decrease the stress concentration at the ends of the lap length. This paper also presents the estimation of strain-energy-release rate components in the presence of debond in the adhesive. The studies have relevance in structural integrity assessment of the joints.

Keywords: Adhesively bonded joints, Finite element analysis, metal adherends, debond

1. Introduction

Joints are inevitable in aerospace structures where the primary components are often made in parts due to operational requirements and they are assembled using various types of joints. These joints are sources of stress concentration (or elastic singularities) and are often potential sites for failure initiation. Adhesively bonded joints are preferred wherever possible over conventional fastener joints since they lead to fewer points of stress concentration. In particular, with the increased use of composite structures, adhesive bonding is the more favoured method of joining whereas the structural integrity of composites with fastener joints is suspect.

The subject matter of analysis of adhesively bonded joints has been extensively investigated in the literature[1] in the past. Lap joint is one of the simplest bonded joint configuration which has been analysed by several in the past. It is recognized that the eccentricity in load path in these joints requires a geometrically non-linear analysis. The properties of the materials of adherend and adhesive significantly affect the load transfer in these joints. Further, the geometric parameters of the joint such as adherend configuration, adhesive thickness, lap length etc., have considerable influence on the performance of these joints. In spite of considerable extent of literature, there are still several aspects, which need detailed investigation.

In the present work, a geometrically non-linear analysis of a typical lap joint between metal-metal adherends is conducted using NASTRAN and an in house GAMNAS software package. Analysis of plane stress and plane strain two-dimensional configuration of these joints is presented in this paper. For certain configurations, the results of the present study are compared with the results available in literature. A parametric study is conducted, but typical results are presented in this paper including the effect of material non-linear properties of the adhesive and the presence of debonds. These studies are valuable for structural integrity analysis of the joints.

2. Numerical Modelling and Analysis

2.1. Problem Statement

An adhesively bonded lap joint between aluminum-aluminum adherends is shown in Fig. 1. Adherends are considered to be bonded using araldite adhesive. The properties of the adherends and adhesive (including yield stress) is shown in Table 1. The joint is considered to be supported at the left end as shown in Fig. 1. A uniform stress of 1423 psi is applied on the right hand side of the adherend. The two dimensional joint is considered in both the states of plane stress and plane strain. However, the numerical results are given only for the state of plane stress. These geometric parameters and the applied loading match the configuration analyzed in Ref. [2] and the same are also used in the current analysis, so that the numerical results can be compared.

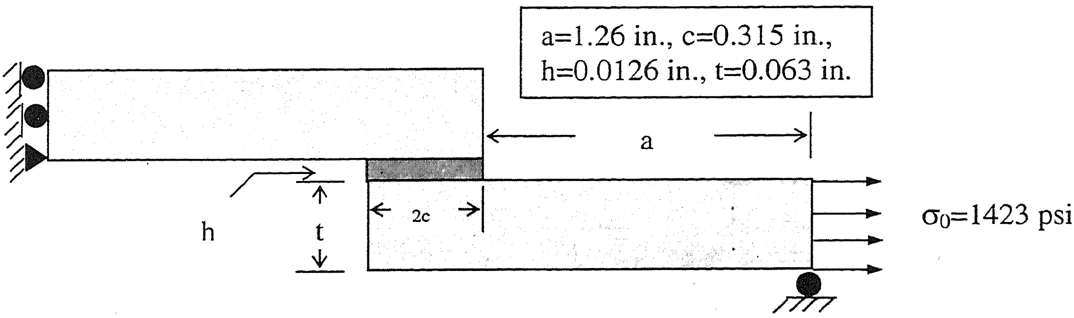


Fig. 1. Geometric configuration of the adhesively bonded lap joint

Table 1. Material properties of adherends and adhesives used in FEM analyses

Properties / Components	Adherend (Aluminum)	Adhesive (Araldite)
E	10.3 E6 psi	8.19E6 psi
ν	0.3	0.33
σy, yield stress	-	1500 psi

2.2. Finite Element Modelling and Analysis

The finite element analysis is conducted using MSC.NASTRAN software [3]. The eccentricity in the load transfer path requires a geometrically non-linear analysis, since the joint undergoes large deformations. The software uses the standard method of geometrically non-linear FE analysis [4-5]. The geometrically non-linear analysis is conducted using NASTRAN software using 4-noded quadrilateral elements. The finite element model used in the analysis is shown in Fig. 2.

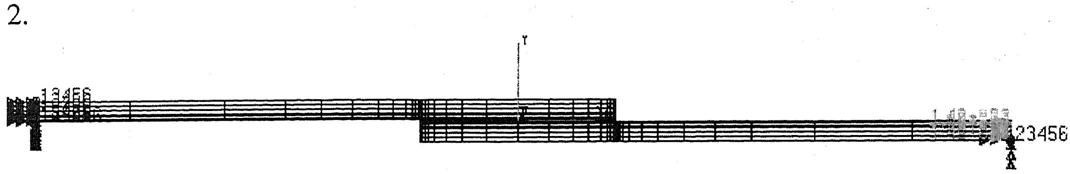


Fig.2. Finite element model of the joint

The details of the mesh are as follows:

Total number of Elements=408; Total number of nodes = 467; Total number of degrees of freedom = 934.

The material non-linear analysis assumes non-linear properties only for the adhesive. The material of the adhesive is assumed to be elastic-perfectly plastic with the yield stress of the material as shown in Table 1. The FE analysis is conducted with both linear and non-linear properties of the adhesive.

3. Discussion of Numerical Results

3.1. Model Validation

The finite element analysis is conducted with few different model sizes and convergence of the FEM was established. For the sake of brevity these are not presented in this short paper. In order to ensure the correctness of the results are compared with those of Reddy and Roy [2]. The peel stress variation along the mid bondline and shear stress variation along the lower bondline are shown in Fig. 3. The peel stress distribution is nearly symmetric as expected. The symmetry is disturbed marginally because of the way of imposing the boundary conditions. The shear stress distribution along the lower bondline has a large peak on the right end of the lap because of the load transfer path. The results of the present analysis and that of the Ref. [2] compared very well.

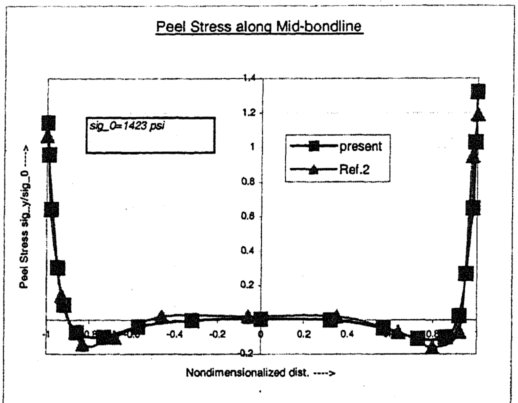


Fig. 3. Peel & shear stress variation along the bond line with geometrically non-linear analysis

3.2. Effect of Material Nonlinearity on Stress Distribution

The effect of material non-linearity on the peel and shear stress distribution is shown in Figs. 4 and 5. As anticipated the material non-linearity decreases the stress concentration because of yielding in peak stress regions. The stress distributions are redistributed on account of this.

3.3. SERR Components at Debonds

One of the failure mechanisms in the bonded joints is the debonding of the adhesives and its growth. This can be studied using the principle of the fracture mechanics [6]. The finite element model follows on the same line as in the Fig. 2. At the tip of the lap, debonds are introduced along the mid bondline. The number of nodes used in the debond analysis is 471, since there are additional nodes along the debond line. The important parameters to be determined are the stress intensity factors or strain energy release rate components in mode I and mode II.

Following the work of Ref. [7], Modified Virtual Crack closure integral is used for this purpose. This is shown in Fig. 6, where SERR components are obtained from the crack tip forces and crack opening and shearing displacements. The results of the FEM analysis is shown in Table 2. The mode I SERR component decreases as anticipated due to material non-linearity.

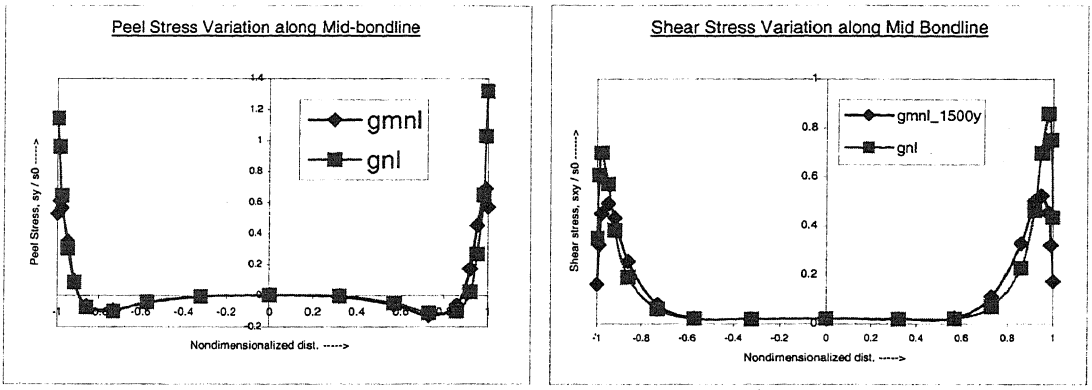


Fig. 4. Peel and shear stress variations along the mid bond line with linear and non-linear material properties

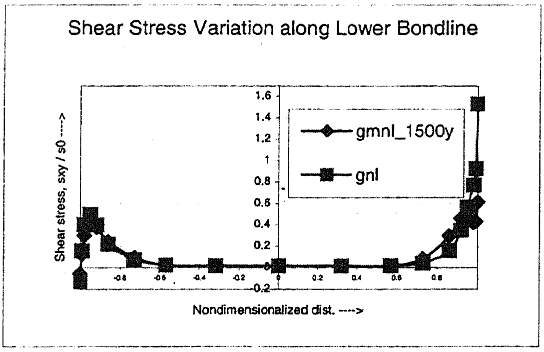
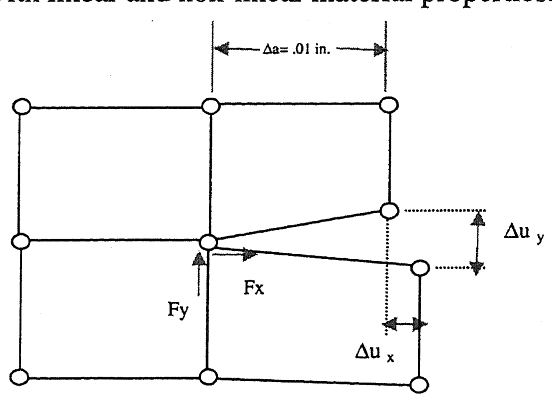


Fig. 5. Shear stress variations along the lower bond line with linear and non-linear material properties.



$$G_I = 1/(2\Delta a)\, F_y \Delta u_y$$
$$G_{II} = 1/(2\Delta a)\, F_x \Delta u_x$$

Fig. 6. Post-processing FEM data to estimate SERR componentsTable 2. SEER components estimated from non-linear FEM analyses

Analysis	Δu_x(in.)	Δu_y(in.)	F_x(lb/in.)	F_y(lb/in.)	G_I(lb-in/in^2)	G_{II}(lb-in/in^2)	G_T(lb-in/in^2)
Geometric Nonlinear	0.09e-4	0.01e-3	21.39	17.4	0.87e-2	0.97e-2	1.74e-2
Combined Nonlinear	0.17e-4	0.01e-3	14.87	15.425	0.77e-2	1.26e-2	2.03e-2

4. Concluding Remarks

A combined material and geometric non-linear analysis is conducted on adhesively bonded lap joint considering elastic-perfectly plastic adhesive. The analysis is validated by comparing the results available in the literature. The material non-linearity leads to beneficial effect by decreasing the stress concentration factors at the ends of the lap length. Also, FEM analysis is used to estimate SERR components at the tip of possible debonds. The studies presented are useful for the structural integrity assessment of the joints.

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