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A numerical study of failure of an adhesive joint influenced by a void in the adhesive

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ABSTRACT

This study examines the effect of manufacturing induced voids on failure of adhesive joints. A single lap joint with preexisting crack between the adherend and the adhesive is considered and the crack growth behavior is studied in the presence of a void in the adhesive. The analysis conducted is numerical using finite elements and a revised virtual crack closure technique for calculating the energy release rate of the interface crack. After verifying the numerical model for a case where analytical solution exists, it is used to gain insight into the failure of the adhesive joint by conducting a parametric study where the size, shape and location of the void with respect to the crack tip are varied. The case of two preexisting cracks on opposite interfaces in the presence of a void is also examined.

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1. Introduction

Adhesively bonded joints are commonly used in aerospace, automotive and wind energy industries, in particular if polymer matrix composites are used. Among the different types of adhesive joints are the single lap joints, the double lap joints and the tapered lap joints [1]. The choice between different types of joints depends on the application as well as the manufacturing cost. Single lap joints have a lower manufacturing cost when compared to double lap joints. However, their failure modes determine their capacity to transfer loads between the adherends [2].

Volkersen [3] was the first to develop an analytical model to determine the shear stress distribution in a single lap joint. Goland and Reissner [4] took into account the eccentric load path, which leads to a normal stress. Hart-Smith [5] conducted an elastic–plastic analysis to determine the shear and normal stress distributions in the adhesive film. Ojalvo and Eidinoff [6] assumed that the stresses vary across the adhesive thickness. All the cited analytical models predict that both the maximum shear stress and the maximum normal stress occur at the end of the interface between the adhesive and the adherend, suggesting that this is a favorable location for cracks to form. The growth of such a crack along the interface has been studied analytically and numerically. A recent study by Thouless and Kafkalidis [7] reviews the failure mechanics of shear-lap joints that also includes the unbalanced joints.

Manufacturing induced defects, such as voids, are usually present in the adhesives of the joint as shown in Fig. 1 [8]. These voids can result from volatile impurities that evaporate during the curing process [9]. Another source of voids is the entrapment of air between the adherend and the adhesive during manufacturing of joints [9]. Rossettos et al. [10] showed that the presence of a void in the adhesive increases the shear stress at the ends of adhesive. Chadegani and Batra [11] investigated the effect of a void on the energy release rate of an interface crack. The void in their work was modeled simply as a gap in the adhesive. This did not allow studying the effects of void shape and location within the adhesive. Talreja [12] proposed a broader strategy for performance evaluation of composite structures where manufacturing induced defects are an integral part of damage and failure analysis. Among different examples for illustrating the proposed strategy is the case of crack growth affected by voids ahead of the crack front, studied by Ricotta et al. [13]. This case considered a double cantilever beam with voids in the mid-plane and calculated the effects of the void size, shape and location ahead of the crack front on the Mode I energy release rate of the crack.

One of the main issues in failure analysis of adhesive joints is whether the failure occurs by unstable crack growth in the interface between the adhesive and the adherend or whether the interface crack kinks out into the adhesive before growing unstably. The role of the manufacturing induced voids in the adhesive on the kinking process of the interfacial cracks has never before been studied to the best of the authors' knowledge. To gain insight into this process, a single lap joint with a pre-existing interfacial

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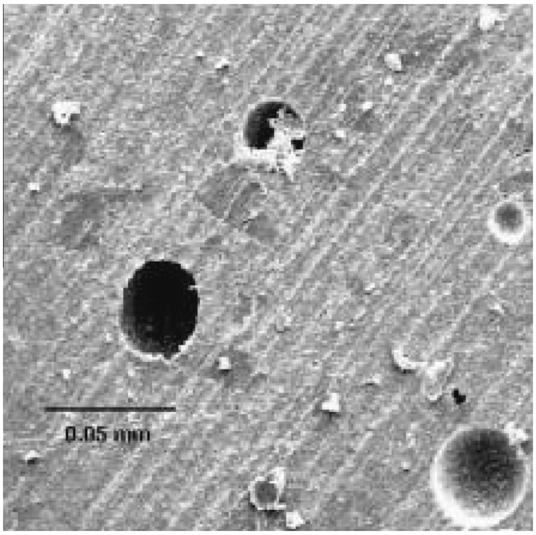

Fig. 1. Voids in the adhesive of a single lap Joint [8].

crack is considered in the present work. Using finite elements for stress analysis of the joint, the energy release rate of the crack is calculated by employing the recently proposed revised virtual crack closure technique (RVCCT) by Valvo [14]. This technique is more suited for asymmetrical cracks where the nodes on the upper crack face do not match the nodes on the lower crack face. After verifying the energy release rate of the crack against an analytical model [7], a parametric study of this quantity is conducted to study the influences of the size and shape of the void and its location in the adhesive. The crack kinking process is also studied for cracks in the two opposite interfaces of the joint in the presence of a void.

2. Finite elements model description

Fig. 2 shows the geometry and the boundary conditions of the studied single lap joint. The geometrical parameters shown are the unbonded adherened length l, the length a of the initial crack in the interface between the upper adherend and the adhesive, the adhesive bond length $2C$, the adhesive thickness t_a, and the adherend thickness t. The specific values of these parameters used in the numerical model are, $l = 50$ mm, $a = 12.5$ mm, $2C = 50$ mm, $t_a = 0.3$ mm and $t = 1.5$ mm. The material properties used are shown in Table 1 and are typical of composite adherends and epoxy adhesives. For the adherend, the orthotropic elastic properties as listed in the table are defined by the Young's modulus E, the Poisson's ratio ν, and the shear modulus G, with index 1 to these properties referring to the longitudinal direction, and indices 2 and 3 corresponding to the two orthogonal directions in the cross-sectional plane of the adherend. The adhesive is assumed isotropic.

Table 1
Material properties.

Material	E_{11}	$E_{22} = E_{33}$	$\nu_{12} = \nu_{13}$	ν_{23}	$G_{12} = G_{13}$	G_{23}
Adherend	130 GPa	11.2 GPa	0.306	0.48	5.3 GPa	3.78 GPa
Adhesive	2.07 GPa	2.07 GPa	0.345	0.345	0.76 GPa	0.76 GPa

The stress analysis problem is treated as a 2D plane strain linear elastic problem. The stress field is determined with a 2D finite elements model using the commercial software ABAQUS. The single lap joint is clamped at the left end, while the motion at the right end is restricted only in the vertical direction and a force boundary condition is applied there (Fig. 2). A geometrical nonlinear 2D plane strain finite elements mesh is used with a uniform fine square mesh near the crack tip.

3. Model verification

The calculation of the energy release rate of the interface crack by the finite element model was verified for the no-void case. For this case, an analytical model by Kafkalidis and Thouless [7] provides the total energy release rate, given by

$$G_T = \frac{P^2}{2Et} + \frac{6M_0^2}{Et^3} - \left[\frac{P^2}{4Et} - \frac{12(M_0 - kPt)^2}{16Et^3}\right] \tag{1}$$

where M_0 is the moment at the transition from the adherend to the adhesive induced by the applied axial force P and k is a geometry- and load-dependent parameter.

As stated above, the RVCCT developed by Valvo [14] was shown to be more accurate than VCCT for asymmetrical crack face separation. These techniques can calculate the Mode I and Mode II energy release rates separately. However, the analytical model [7] provides only the total energy release rate, as stated above. In Fig. 3 the sum of the energy release rates of the two modes calculated by RVCCT is compared with the total energy release rate by the analytical model. To additionally verify the RVCCT calculation, the J-integral method was used in the finite element model. The total energy release rate calculated by the J-integral is also shown in Fig. 3. The geometry of the no-void single lap joint used for these calculations was modified slightly from that shown in Fig. 2 to

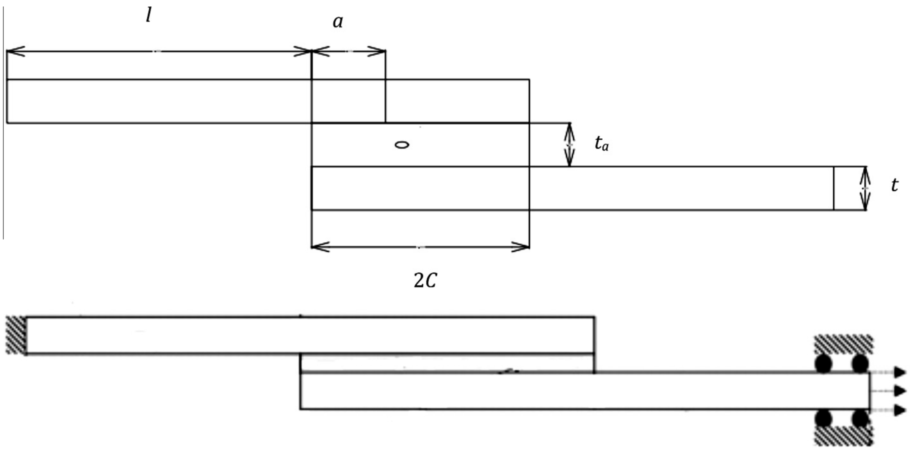

Fig. 2. Geometry and boundary conditions of the studied single lap Joint.

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