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Three-dimensional modeling of carbon/epoxy to titanium single-lap joints with variable adhesive recess length

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ABSTRACT

The objective of this paper was to investigate the performance of recessed single-lap joints with dissimilar adherends through the finite element method. The influence of material and geometric nonlinearity of the adhesive as well as the impact of the recess length was examined in terms of maximum principal stresses. The strength of the joint was obtained as the load to initiate the crack propagation. Results suggested that either adding a spew fillet or considering the adhesive plasticity led to reduced peak stresses at the edge of the adhesive layer. The presence of a spew fillet in the single-lap joint with a recess length of 50% of the overlap length reduced the peak stress concentrations in the adhesive layer by 45.2% and subsequently improved the strength of the joint by 36.3%. Mitigation of stress concentration was observed in cases of an adhesive layer with a smaller recess length. The strength of recessed joints with a gap less than 50% of the overlap length decreased slightly. For the recess length as 70% and 90% of the total overlap length, the strength of the joints reduced 36.4% and 66.3%, respectively. This study suggested a recess of less than 50% of the overlap length may be beneficial for the performance of the joints.

1. Introduction

Adhesively bonded structure joints have emerged as one of the primary means of bonding in response to the demand for lightweight, high-strength, low-cost products, especially in the automotive and aerospace industries. Recessed adhesive joints, i.e. a gap in the center portion of the adhesive within the overlap, were proposed as one of the bonding techniques with the same performance as the continuous joint [1]. Although continuous adhesive joints have been extensively studied [2–6], the analysis of recessed adhesive joints is lacking in the literature. For example, Rossettos and his co-workers [7,8] have shown that the shear stresses were hardly affected by a central void size up to 70% of the overlap length for single-lap joints. If the void was located closer to the overlap ends, 20% variations of maximum shear stresses were observed. Olia and Rossettos [9] performed an analytical study on the effects of gaps in single-lap joints subjected to combined axial and bending loads. Their results showed that the presence of a gap led to high peel stresses at the free edges. However, if the gap was centrally located, the peel stresses at the outside edges increased only slightly as compared to the case without the gap. The shear stresses remained essentially unaffected at distances far from the gap. Mazumdar and Mallick [10] conducted static tensile tests on single-lap joints with varied degrees of recess, which showed that the average failure load did not change with increased recessing. Lang and Mallick [1] numerically studied recessed bonded joints with a spew fillet. Their results showed that the maximum stress remained near the adhesive spew terminus and increased only slightly with an increased level of recessing. The existing numerical studies in the recessed adhesive joints focused on the stress analysis in the two-dimensional (2D) case. However, the in-plane tension on the single-lap joint would develop complicated three-dimensional (3D) stresses, such as out-of-plane bending, which could not be captured in the 2D modeling.

In this work, 3D finite element models of recessed single-lap joints were developed. 3D stress distributions in the adhesive were obtained. The influence of material and geometrical properties of the adhesive as well as the impact of the recess length was examined in terms of maximum principal stresses. The crack initiation load predicted by extended finite element method (XFEM) [11,12] was used to evaluate the strength of the recessed joints.

2. Finite element modeling

A 3D model of the recessed single-lap joint was developed using commercial finite element software ABAQUS (Dassault Systems Simulia Corp., RI, USA). Fig. 1 presented the dimensions

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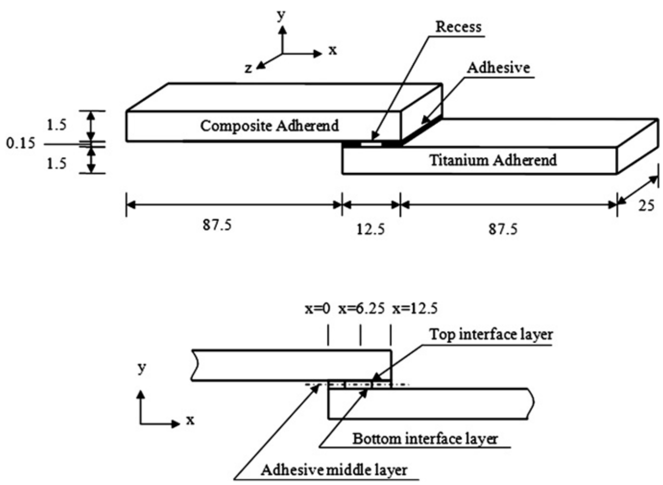

Fig. 1. Recessed single-lap dissimilar joint with dimensions in mm.

and material properties of the single-lap joint with the recess length as 50% of the overlap length. The overlap length between two adherends is fixed as 12.5 mm in this work. The carbon/epoxy adherend (0/+45/−45/0) was characterized by orthogonal elastic moduli $E_1=147$ GPa, $E_2=E_3=10.3$ GPa, shear moduli $G_{12}=G_{13}=7$ GPa, $G_{23}=3.7$ GPa, and Poisson's ratio $v_{13}=v_{23}=0.27$, $v_{12}=0.54$. The material properties for the titanium adherend were $E=116$ GPa and $v=0.33$. The FM73 adhesive cured at 120 °C [13] was used for bonding with isotropic properties $E=1100$ MPa, $G=382$ MPa and $v=0.44$.

The model was meshed with reduced 8-node hexahedral elements (C3D8R). A fine mesh was used at both the overlap ends. A mesh convergence test has been conducted and the minimum mesh size was chosen as 0.05 mm. The left end of the composite adherend was constrained in all degrees of freedom while a 120 MPa tensile load was applied along the *x*-direction on the opposite edge of the titanium adherend. Perfect adhesion was assumed on the interfaces between adhesive layer and adherends. Furthermore, the extended finite element method (XFEM) coupled with the cohesive traction separation law [12–14] has been used to evaluate the strength of the recessed joints.

3. Results and discussions

3.1. FE model validation

A continuous titanium–titanium joint subjected to 10 MPa tensile load was used to validate the numerical model against the analytical solutions obtained from both the Volkersen shear lag equation [15] and the classical Goland and Reissner (G–R) solution [16]. The shear stress in a single-lap joint can be calculated from the Volkersen equation as follows:

$$\tau=\frac{F\omega\cosh(\omega x)}{2b\sinh(\omega_l/2)}+\frac{F\omega\sinh(\omega x)}{2b\cosh(\omega_l/2)}\left[\frac{E_2t_2-E_1t_1}{E_2t_2+E_1t_1}\right] \tag{1}$$

$$\omega=\sqrt{\frac{G}{\eta}\left[\frac{E_2t_2+E_1t}{E_2t_2E_1t}\right]} \tag{2}$$

where F is the applied tensile force, b is the width of the adhesive, l is the length of the overlap, G is the shear modulus of the adhesive, η is the thickness of the adhesive layer, and E_1,E_2,t_1,t_2 are the Young's modulus and thickness of the top and bottom adherends, respectively. It is worth noting that if the thickness and Youngs modulus for the adherends are equal (as in this case) then the above expression simplified greatly. While the Volkersen solution is relatively easy to calculate it is not of very much practical use. This methodology does not take into account adherend bending and also this analytic solution makes the assumption that the adhesive will deform in shear and offer no axial stiffness [17,18]. These restrictions lead to a drastic underestimation of the actual shear stress in the joint, especially at the edges of longer joints, which was demonstrated in Fig. 2.

A G–R solution which gives the shear stress for a single-lap joint in tensile loading via the following equation:

$$\tau=\frac{pt}{8c}\left\{\frac{\beta c}{t}(1+3k)\frac{\cos\frac{\beta c}{t}\cdot\frac{x}{c}}{\sin\frac{\beta c}{t}}+3(1-k)\right\} \tag{3}$$

$$\beta^2=8\frac{G}{E}\frac{t}{\eta} \tag{4}$$

where p is the applied tensile pressure, c is the half length of the overlap, k is the moment factor and all other parameters are as before. This moment factor is found through tables given by Goland and Reissner [16] that correlate k with the following quantity:

$$\frac{c}{t}\sqrt{\frac{P}{E}} \tag{5}$$

k was obtained as 0.9033 for the applied tensile load of 10 MPa, and 0.7024 for that of 120 MPa.

The numerical model was developed following the specifications described in Section 2 for the case of a continuous titanium–titanium joint subjected to 10 MPa tensile load. The obtained shear stress along the center of the adhesive bottom interface was plotted in Fig. 2. It is clear that the numerical solution fitted the G–R solution much better than the Volkersen solution. As expected the Volkersen equation only predicted about 50% of the peak stress at the end of the adhesive layer obtained by Goland and Reissner. The predicted shear stress in the numerical model deviated from the G–R solution up to 14%. This was due to the fact that the G–R equation assumed constant stress along the thickness and width, as well as constant flexural stiffness in the adhesive [17,18], which did not capture the 3D, unsymmetrical effects, found in adhesive joints with square edges. More confined boundary conditions could lead to symmetrical behavior and thus reduced error between analytic solutions and the simulation.

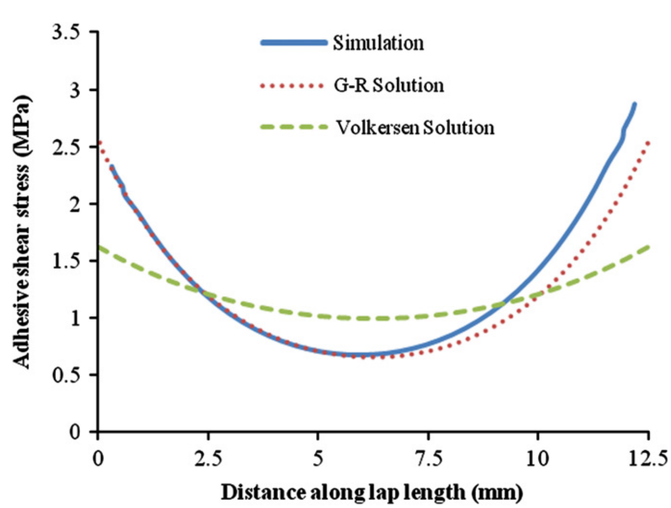

Fig. 2. Comparison of adhesive shear stress for a titanium–titanium continuous joint subjected to 10 MPa tension.