Spring Element for modelling of 2-D adhesively bonded lap joints

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Abstract

A geometrically linear, two-dimensional (2D) finite element analysis has been performed to study the stress distribution in adhesive layer of the lap joints. Including the degradation of the joints due to cracks in adhesive layer is needed for better understanding. The primary purpose of this research is to use spring elements existing in ABAQUS (Finite Element Commercial Software) to study the effect of crack-length extension on the joint stiffness and the stresses distribution in adhesive layer. The panels are represented by 2-D plane strain solid elements while spring element are used to replace the adhesive layer with normal and shear spring elements connecting between contacting surfaces. To evaluate the capability of this method, the existing results will be compared. There is a good agreement for the normal stress distribution in adhesive layer, however there is a discrepancy at the ends zone of adhesive layer for the shear stress distribution. The second purpose of this study is to predict the joint distortion and stiffness loss in adhesive lap joint due to cracks in adhesive layer. The stiffness and rotational angle of the joint are reduced about 14% and 34% respectively, when the bonding area is reduced about 40%.

1. Introduction

In recent years, high modulus adhesives have been widely used to bond metallic-to-metallic and metallic-to-composite structural members. Particularly in aircraft and automobile structures, several kinds of adhesives, e.g., high modulus adhesives such as epoxy [1-6] have been used for joining the structural members in order to minimize weight, stress concentrations, and increase durability by lap joint. When the lap joint is subjected to applied load, the joint strength may be degraded by cracking in adhesive layer. The degradation of the joints due to cracks in adhesive layer on the joint stiffness, as well as the stress distribution in adhesive layer, becomes very important in joint design and material selection for structural engineering.

In this paper, the adhesive lap joint bonding similar materials previously modeled and studied by Raul, David, and Siegfried [7] is selected in order to study two important tasks. Firstly, TALA (Thin Adhesive Layer Analysis which is spring element method as shown in Figure 1.) is used for validation on 2-D finite element model. Secondly, the previous model and TALA method is further used to investigate the stress distribution, joint distortion, and stiffness in adhesive lap joint due to cracks in adhesive layer by removing the spring to represent crack-length extension in the model.

2. TALA Method

Figure 1 presents the general idea of TALA. Each pair of coincident nodes between two contacting surfaces in the finite element models is connected by spring elements.

In this study, the thin adhesive layer (thickness, h) is assumed to be very thin. Thus, the effects of stresses (σ_x, σ_y, τ_{xz}, τ_{xy}, τ_{yz}, τ_{yx}), strains (γ_{xz}, γ_{xy}, γ_{yz}, γ_{yx}) and poisson's ratio are neglected. There are only σ_z, τ_{zx}, τ_{zy} and acting area A_i connecting between the two nodes (a and b). The normal stress (σ_z) is changed to normal force, while the shear stresses (τ_{zx}, τ_{zy}) are changed to shear force in each spring element when the small contacting area and thickness of the layer are known. The normal and shear strains (ε_z, γ_{zy}, γ_{zx}) are changed to normal and shear relative displacements in spring i. The equations used for converting the stresses and strains in the solid element to forces and displacements to define the properties of the spring element are presented below.

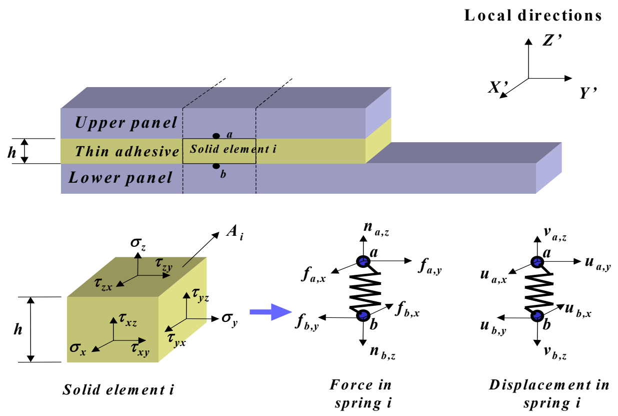

Figure 1. Schematic of spring representation of solid adhesive element.

In the normal direction of tension and compression spring. By Hooke's law

$$\sigma_z = E^*(\varepsilon_z) \tag{1}$$

$$n_{a,z} + n_{b,z} = E^*(A_i / h)^*(v_{a,z} + v_{b,z}) \tag{2}$$

$$n_{a,z} + n_{b,z} = K_{n,i}^*(v_{a,z} + v_{b,z}) \tag{3}$$

$$F_{n,i} = K_{n,i}^* v_{n,i} \tag{4}$$

$$K_{n,i} = E^*(A_i / h) \tag{5}$$

Where $F_{n,i}$ is the normal force transmitted in spring element i, $v_{n,i}$ is the relative displacement of spring element i in the normal direction, $K_{n,i}$ is the local stiffness of spring element i in the local normal direction, and E is the secant elastic modulus of the adhesive. In the shear direction (shear spring) in x'-y' plane τ_{zx} and τ_{zy} are equal in magnitude because the material is isotropic;

$$\tau_{zx} = G^*(\gamma_{zx}) \tag{6}$$

$$f_{a,x} + f_{b,x} = G^*(A_i/h)^*(u_{a,x} + u_{b,x}) \tag{7}$$

$$f_{a,x} + f_{b,x} = K_{f,i}^*(u_{a,x} + u_{b,x}) \tag{8}$$

$$F_{f,i} = K_{f,i}^* u_{f,i} \tag{9}$$

$$K_{f,i} = G^*(A_i/h) \tag{10}$$

Where $F_{f,i}$ is the shear force transmitted in spring element i, $u_{f,i}$ is the relative displacement of spring element i in the shear direction, $K_{f,i}$ is the local stiffness of spring element i in the local shear direction, and G is the secant shear modulus of the adhesive.

For the case of a linear material, the values of $K_{n,i}$ and $K_{f,i}$ can be defined directly for spring element i in the normal and shear directions. However, for a nonlinear material $K_{n,i}$ and $K_{f,i}$ vary. Then, in order to define the nonlinear behavior for spring element i, pairs of force-relative displacement values are required over a sufficiently wide range of relative displacement values. The more information about defining spring properties shown in ABAQUS manual [8].

3. Analysis

3.1 Finite element model for TALA validation

A two dimensional finite element model of adhesive lap joint bonding similar materials in Raul, David and Siegfried's research [7] is created as shown in Figure 2. The adhesive layer bonds two similar material panels. They are treated as linear elastic two dimensional plane strain finite element analysis. There are 66 elements for each panel (all CPE8, 8-node biquadratic solid element). The lap joint is subjected to tensile load (P_0) and constrained in y-direction at the edge of the upper panel, while the edge of the lower panel is constrained in the x and y-direction. The properties of the materials are E_{panel} = 68.3 GPa, ν_{panel} = 0.3, $E_{adhesive}$ = 2.5 GPa, $\nu_{adhesive}$ = 0.3 and the applied tensile load P_0 = 100 MPa.

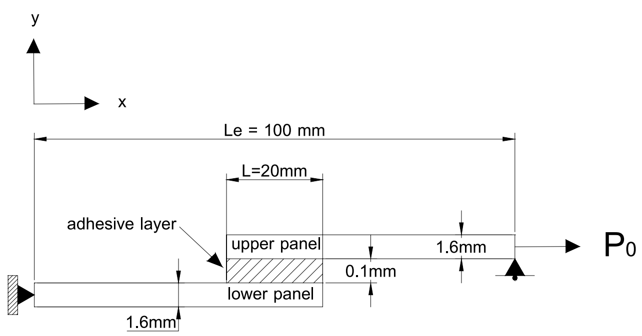

Figure 2. Single lap joint specimen

The adhesive layer is transformed to 28 linear normal and shear spring elements connecting the lower surface and the upper surface of panels by TALA method. Stress distributions along the adhesive layer for thickness of 0.1 mm are obtained for validation.

3.2 Finite Element Model of crack-length extension in adhesive layer

The finite element model previously verified is used in order to study the crack-length extension affecting on the stiffness of lap joint. It is assumed that the crack starts at both ends and then propagates equally into the central region of the adhesive layer. The normal and shear spring elements are removed in the finite element model in order to represent the extension of crack-length in adhesive layer. The additional number of normal and shear spring elements is removed from the left and right ends while total overlapping length (L) is constant as shown in Figure 3. To obtain stiffness, the slope of the plot between tensile load P and the magnitude of joint displacement at the edge of the upper panel in the loading direction is calculated. In this study, the crack-length is varied from no crack to 12 mm while the load is varied from 0 to 640 N. Rotational angle is calculated from bending angle of panels at tensile loading (P_0) of 100 MPa while the crack-length is varied from no-crack to 12 mm.

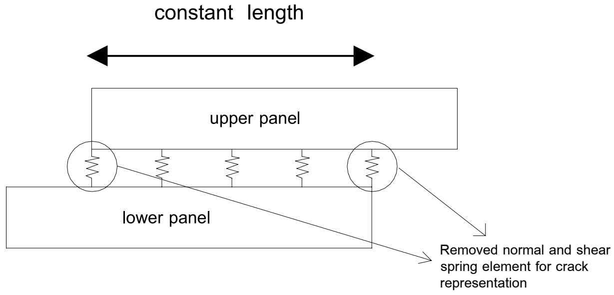

Figure 3. The schematic of removed spring element to represent crack in adhesive layer

4. Results

4.1 The validation of TALA

To validate TALA method on 2-D adhesive lap joint, the stress distributions in adhesive layer obtained by TALA are compared with Raul, David, and Siegfried's calculation as shown in Figure 4 and 5. The normal and shear stress in each spring are divided by the average panel stress (T) to represent the stress distribution in the vertical axis. The horizontal axis represents overlapping distance. The results from the spring element method (TALA) analysis agree with Raul, David, and Siegfried's method. The shape of normal stress curves are almost the same, there is a small discrepancy in the magnitudes at 0 to 5 mm from the ends and getting closer to zero at 5 mm from the ends. For the shear stress distribution, there is discrepancy near the ends zone of overlapping.

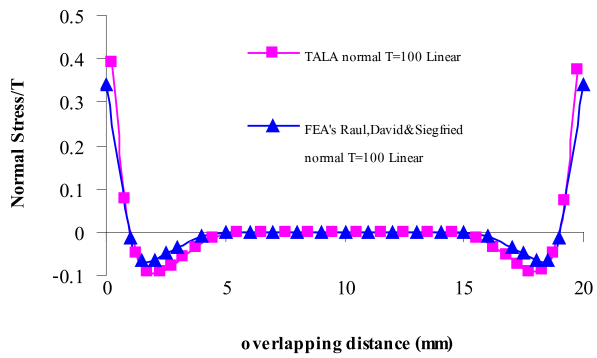

Figure 4. Normal stress distribution in adhesive layer for a single lap joint.

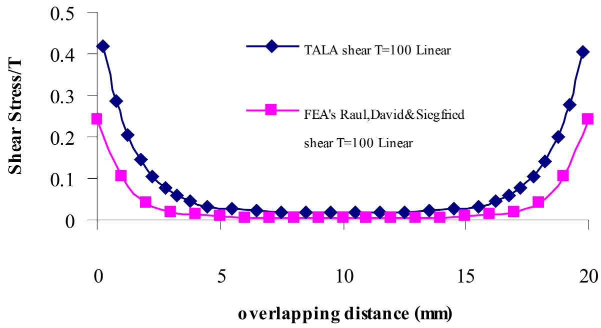

Figure 5. Shear stress distribution in adhesive layer for a single lap joint.

4.2 The effects of crack-length on adhesive lap joint

The spring elements are removed to characterize the crack-length extension in the adhesive layer. The parametric plot between ratio of stiffness and ratio of crack-length is shown in figure 6. It shows that the longer crack-length decreases the stiffness of the joint linearly. The stiffness is maximum when there is no crack at the ends. The stiffness is reduced about 14% when the bonding area is reduced (due to the crack) about 40%. Figure 7 and 8 represent the stress distributions in the half-length of adhesive layer when the joint is subjected to the same tensile loading (P) of 160 N for each crack-length. The maximum normal and shear stress for each crack-length are still located at the end of adhesive layer. The increase of maximum normal and shear stress is about 12% and 14% respectively, when the bonding area is reduced about 40%. Comparing between crack-length, it is found that the curves of shear stress in the adhesive are elevated when the crack-length is increased. The average shear stress is also increased, while the average normal stress is being zero.

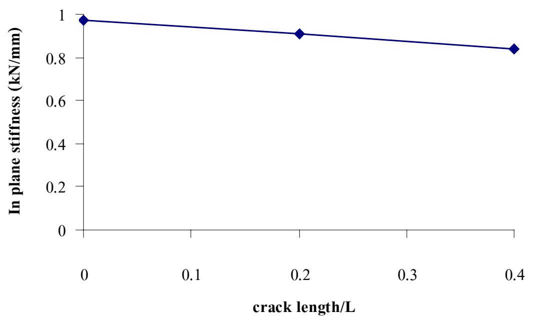

Figure 6. Plot of stiffness and crack-length extension.

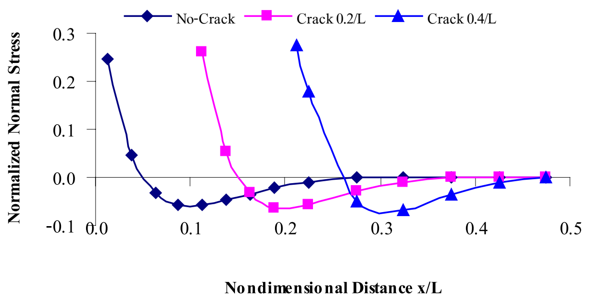

Figure 7. The effect of crack-length on normal stress.

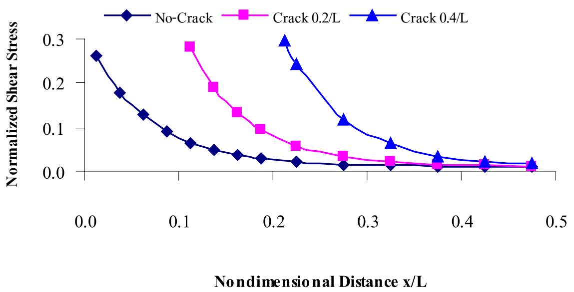

Figure 8. The effect of crack-length on shear stress.

Figure 9 represents the angle of joint distortion for each crack-length. It shows that the longer crack-length decreases the angle of joint distortion linearly. The maximum angle of joint distortion is 0.0106 radian (0.61^0) when there is no crack at the ends. The minimum angle of joint distortion is 0.007 radian (0.4^0) when the crack-length is 12 mm from the ends. The angle of joint distortion is reduced about 34% when the bonding area is reduced about 40%.

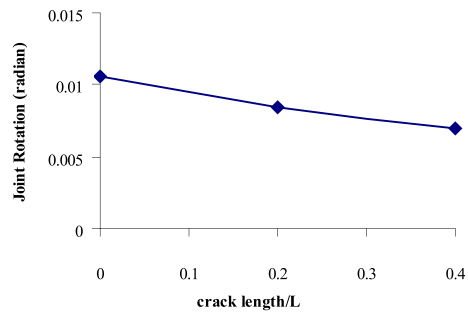

Figure 9. The effect of crack-length on distortion joints.

5. Discussion and Conclusions

The using of spring method (TALA) on adhesive lap joint has been validated by stress distributions in adhesive layer obtained by Raul, David, and Siegfried's work [7]. There is a good agreement for the normal stress distribution in adhesive layer. For shear stress, there is not good agreement at the end zone. The discrepancy at the end zone of adhesive layer for shear stress is necessary to improve by increasing the number of spring element at the end zone. Further, this method is used to study the effect of crack-length extension on the joint stiffness, joint distortion and stress distribution. It is found that the stiffness of joint is reduced linearly about 14% due to crack-length extension. While the crack-length extension reduces about 40% bonding area of adhesive layer, it increases the noninterfacing length of upper and lower panels. When this length is increased, it seems to reduce the total stiffness concurrently. The rotational angle of the joint are also reduced about 34% when the bonding area is reduced about 40%. It seems to reduce the panel bending when there is more crack-extension in adhesive layer. Considering at the same load, the adhesive layer is subjected to the higher stress while the bonding area is reduced because the load is transferring in adhesive constantly. The maximum stresses are still located at the ends of adhesive layer because there is discontinuous in geometry and material properties at the ends zone of adhesive layer.

From this study, it is not taken into account for material property variation. To extend this work, the parameter of material property and also the debonding stress of adhesive layer should be taken into account for joint design.

6. Acknowledgement

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