INVERSION ANALYSIS FOR INTERFACIAL STRESS OF COMPOSITE SINGLE-LAP JOINT BASED ON FULL-FIELD DEFORMATION AND FEM

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ABSTRACT

A hybrid inversion method combining the finite element method (FEM) and full-field displacement data was proposed to analyze the adhesive interface stress at a composite single-lap bonded joint. The displacement field distribution on the outer surface of the overlapped composite plate was measured through the two-dimensional digital image correlation method (2D-DIC) at different times by performing a tensile test. Then, the external surface displacements were linearly interpolated into the finite element node displacement data of the lapped plates. At the same time, the structure was simulated by the eight-node plate elements and the sixteen-node adhesive elements, then a finite element model (FEM) of the composite single-lap joints was established, in which the external surface nodal displacement of two bonded composite plates was applied as a loading condition to calculate the inner surface nodal displacements, which are regarded as the surface displacement loading condition of an adhesive layer FEM model. At last, the shear stress distribution of the adhesive layer was calculated by the inversion analysis model. The validity of the hybrid inversion method was proved by FEM analysis and experiments.

1 INTRODUCTION

Composite material is the ideal material for large-scale integrated structure, can maximize the potential of composite materials, not only can reduce the number of fasteners and structure of the discontinuous state, improve the overall structure of the function, but also reduce the manufacturing process and assembly cycle, thereby reducing costs. In the integrated design, the interface between the adhesive interface and the composite layer is an important design element. The experimental study on the actual structural failure mode and the bearing capacity shows that the interface defects and expansion are easy to cause the early failure of the structure [1-2]. In practical application, master the stress distribution of composite joints can better rational design of cemented joints, improve the carrying capacity.

There have been a lot of researches on the stress distribution of the composite adhesive bonded joints [3-5]. Finite element analysis is the main way of understanding the full field stress distribution of adhesive joints, but the input information, such as material parameters and applied loads, boundary conditions in the numerical simulation is too idealization, thus the numerical model can not be completely consistent with the actual structure. Moreover, all kinds of unknown manufacturing defects and damage which are easily appeared in the actual structure of the composite material are not considered, which leads to the deviation between the predicted results and the actual results. Raos et al studied the mechanical behavior of the single lap joint under tensile load by experiment and finite element method, and the best lap length is obtained [6]. Nunes et al. studied the shear deformation of single lap joint by using digital image correlation method [7]. Both the electrical measuring method

and the optical measuring technique are more mature to the structural surface strain measurement, but can not get the strain distribution of the inner adhesive layer [8-9].

In this paper, a hybrid inversion method for adhesive stress analysis for composite adhesive joint has been carried out. The displacement field distribution on the outer surface of the overlapped composite plate was measured through the two-dimensional digital image correlation method, and then the nodal displacements of the corresponding finite element model were obtained by discrete and interpolation methods. The finite element model for the composite single-lap joint was established, and the inner surface nodal displacements of two bonded composite plates were calculated by applying the nodal displacements at outer surface as loading condition which were obtained by experiment measurement. At last, the shear stress distribution of the adhesive layer was calculated by substituting the inner surface nodal displacements into the inversion analysis model.

2 PRINCIPLES OF EXPERIMENT/NUMERICAL HYBRID INVERSION METHOD

2.1 Laminated plate element

According to the plate deformation theory, the displacement of the laminated plate can be expressed by the displacement in the middle plane as follows

$$\begin{cases} u(x,y,z) = u_0(x,y) + z\theta_y(x,y) \\ v(x,y,z) = v_0(x,y) - z\theta_x(x,y) \\ w(x,y,z) = w_0(x,y) \end{cases} \tag{1}$$

where, (u_0, v_0, w_0) is the displacement in the middle plane along the direction of x, y, z, θ_x and θ_y are the rotation angles of the normal plane around x and y axis, respectively. The eight-node plate element is used to simulate the bonded two laminated plates. By using the experimental optical measurement data of the displacement (u, v, w) in the outer surface of the two bonded laminated plates as driving force for the numerical single-lap bonded joint single lap model, the displacement of the upper and lower surface of the adhesive layer can be obtained by calculation.

2.2 Adhesive element

The sixteen-node adhesive element is shown in Fig. 1, in which the 1-8 node and the 9-16 number node correspond to the 8 nodes of the laminated plate element at the glued upper and lower composite laminated plates respectively.

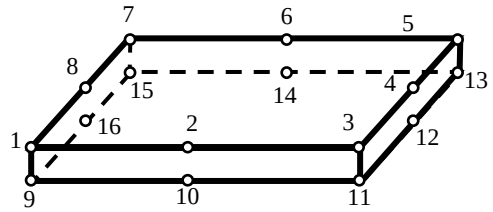


Figure 1: Sketch of sixteen-node adhesive element.

In finite element analysis, the displacement of the adhesive element (u', v', w') can be obtained by the mid plane displacements (u_0, v_0, w_0), then the strain of the adhesive element can be calculated by

$$\begin{cases} \gamma_{xz} = \left(u_0^1 - u_0^2 - h_1\theta_y^1 - h_2\theta_y^2\right)/t \\ \gamma_{yz} = \left(v_0^1 - v_0^2 + h_1\theta_x^1 + h_2\theta_x^2\right)/t \\ \varepsilon_z = \left(w_0^1 - w_0^2\right)/t \end{cases} \tag{2}$$

where, superscript 1 and 2 represent the upper and lower plates, respectively, and h_1=0.5(t_1+t), h_2=0.5(t_2+t), t is the thickness of the adhesive layer, t_1 and t_2 are the thickness of the upper and lower plates, respectively.

2.3 Experiment/ numerical hybrid inversion

The surface displacement field of the composite adhesive joint can be obtained by optical measurement only for the outer surface zone of laminated plates at different continuous moments, and when the corresponding inner surface displacement field of laminated plates was calculated according to that of the outer surface zone, then the stress field of the layer can be accurately calculated. The principle and procedure of experimental/numerical hybrid inversion analysis of the interfacial stress are shown in Fig. 2.

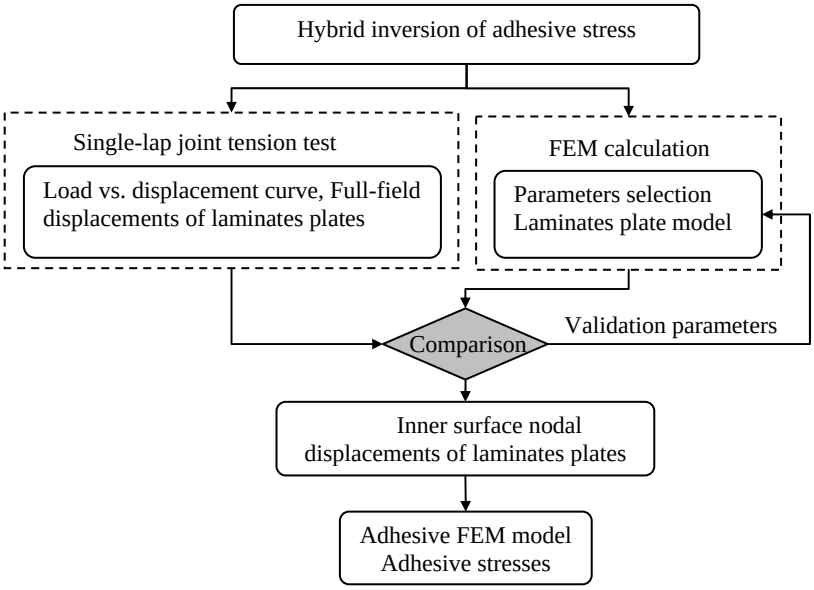


Figure 2: The flowchart of experimental and numerical hybrid-inverse method.

First, the tensile shear experiment by using digital image correlation optical system is carried out in order to obtain displacement field of composite plate structure at the outer surface, and then the displacement information of all the key points is extracted from optical experimental data, at the same time the load displacement curve is also need to be recorded and analyzed.

Next, the initial finite element model for numerical analysis is established, and the experimental results can provide a reference for the parameter setting in the finite element model. Furthermore, the corresponding relationship between the displacement of the inner and outer surfaces is obtained.

Then, the corresponding finite element nodal displacement information from the experimental data on the outer surface of the plate is extracted, and such nodal displacement data will be applied as displacement load for the finite element model to calculate the relative displacement of the inner surface of the lap joint by further finite element analysis.

In the end, the displacement of the inner surface of the overlap joint will be applied to the finite element inversion model of the adhesive layer, and the final adhesive stress field can be obtained.

3 EXPERIMENT

3.1 Specimen preparation

The glued two composite laminated plates of single-lap bonded joint specimen were made of carbon fiber epoxy resin composite material (T300/QY8911), and the specimen geometry is depicted in Fig. 3. The dimensions of the model are L=100 mm , L_0=12.5 mm , L_1 =50 mm , and B=25 mm. The stacking sequence of is $[0_2/90_2]_{2S}$, and the thickness of each layer is 0.125 mm. The material parameters of the composite laminates are shown in Table 1.

At first, the bonding interface of the composite laminates was cleaned with absolute alcohol and dried. Then, the treated surface of the specimen was spread with epoxy resin adhesive equably, which was produced in the Optical Laboratory of Dalian University of Technology. In order to control and guarantee the adhesive thickness, 2 copper wires of 0.2mm diameter were placed along the direction of

applying force. A little pressure was applied after bonding to fix the experimental specimen and prevent sliding. The applied cure cycle was 24h at room temperature. Two glass fiber reinforced plastics strengthening plates were bonded at the end of the two composite laminates, which are used as the clamping end of the testing machine. The surface of the specimen was covered with artificial painted speckles in shear zone, which is aiming to analyze the deformation of the surface of lapped plates by DIC method.

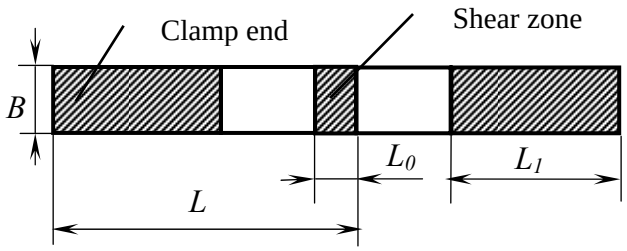


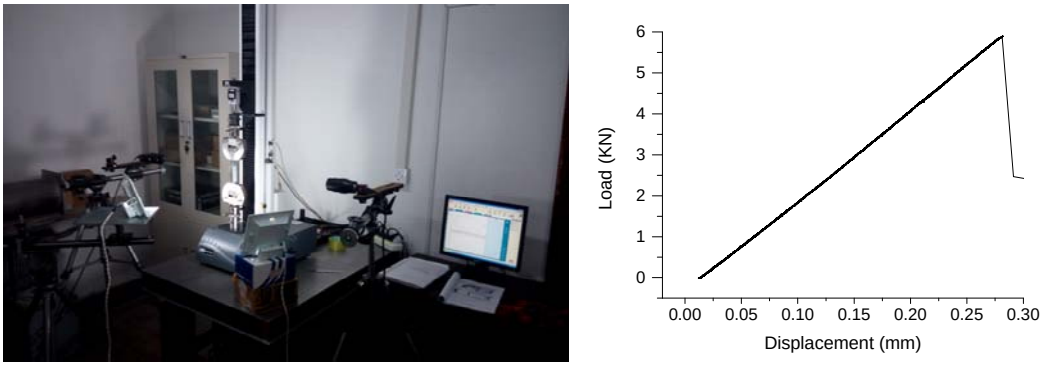
Figure 3: Schematic of single-lap composite specimen.

Elastic Parameter [GPa]				Poisson's ratio	
E_1	E_2=E_3	G_{12}=G_{13}	G_{23}	v_{12}=v_{13}	v_{23}
126	10.7	4.47	3.57	0.33	0.38

Table 1: Properties of T300/QY8911.

3.2 Tensile test

The experimental system of composite single-lap joint tensile test is shown in Fig. 4, where, basic optical path of two dimensional digital image correlation (2D-DIC) method is presented in Fig. 4(a), two CCD cameras were used to collect the deformation pictures of the front and rear surfaces of the specimen in shear zone real-timely. The resolution of the two CCD cameras (Guppy F080b) is 1024×768 pixels, and the real-time collecting frequency is 2 fps. A single arm micro force testing machine (Instron 3345) was used to perform tensile loading. Before loading, it is necessary to ensure that the loading axis coincides with the central line of the experiment, so as to avoid the influence of eccentricity on the experiment.



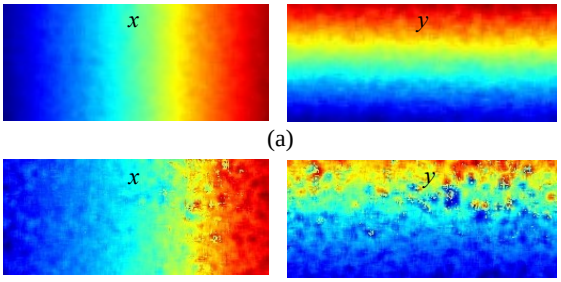
(a) (b)

Figure 4: (a) Schematic diagram of experimental setup and (b) load and displacement curve.

4 RESULT AND DISCUSSION

4.1 Optical measurement

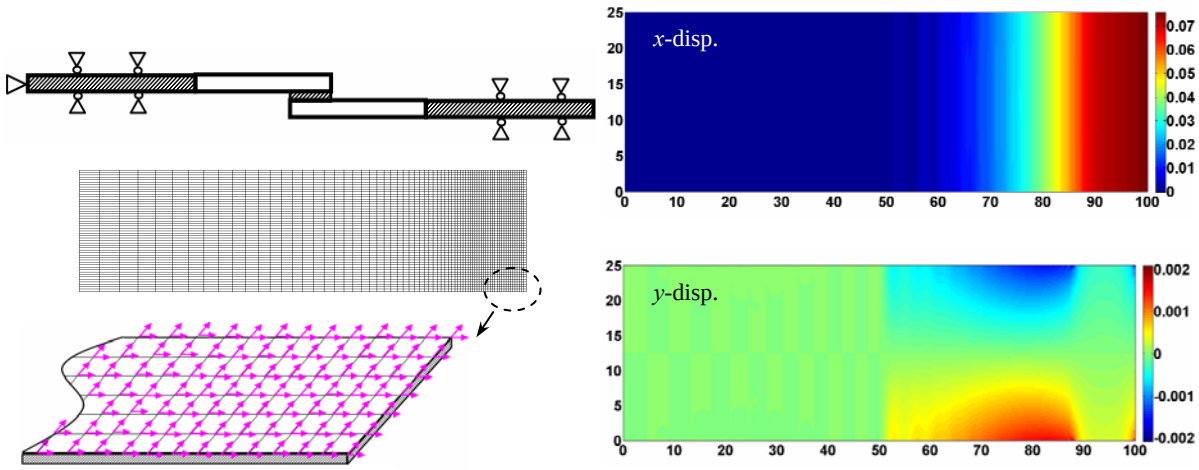
During the whole tensile loading process, the sequential images of the outer laminate surface in bonded area have been collected in real-time by using CCD camera, and calculated through the two-dimensional digital image correlation method to get the displacement and strain data corresponding to the pixel position. The displacement of the outer surface for the overlapped plates under the loading of 4000N, are shown in Fig. 5. It can be seen that although the local noise and stress concentration will cause the discontinuity of the displacement field, the local noise should be avoided in the linear interpolation. But the global displacements along the longitudinal (x) and transverse (y) are continuous.



(a)

(b)

Figure 5: (a) X-directional and y-directional displacement fields of the lower laminate and (b) the upper laminate.



(a) (b)

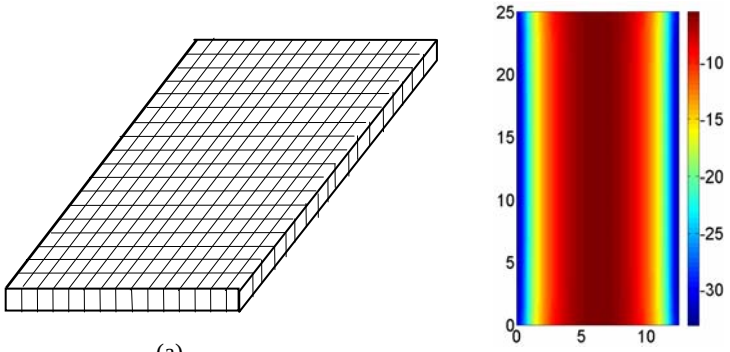
Figure 6: Schematic of displacement loading of single-lap joint (a) and (b) displacements of the inner surface of upper laminated plate.

4.2 Inverse calculation

When calculating the whole field displacement of the outer surface of the overlapped plate with DIC, the calculated area is smaller than the actual shear zone of the overlapped plate, so the displacement out of the calculation area should be obtained by linear interpolation. In addition, the optical measurement data after discretization was converted into the nodal displacement by using linear interpolation method. Applying the nodal displacements at outer surface as loading condition shown in Fig. 6(a), the inner surface nodal displacements of two bonded composite plates were calculated, and then the shear stress distribution of the adhesive layer was calculated by substituting the inner surface nodal displacements into the inversion analysis model.

Fig. 6(b) shows the displacement of the inner surface of the upper lap plate when the tensile load is 4000N. It can be seen that the transverse displacement has the obvious effect of lateral contraction Poisson effect, while the longitudinal displacement distribution is even. For a further processing, the nodal displacements were extracted from the displacement field of the inner surface of the upper and the lower plates, which were applied to the inversion model as a driving load in node displacement form, as shown in Fig. 7(a). The boundary condition, the normal displacement of nodes was fixed, and the solved shear stress distribution of the adhesive layer is shown in Fig. 7(b).

It can be seen from Fig. 7(b) that the shear stress (S13) of the adhesive layer is symmetrically distributed, and the shear stress concentration exists on the edge of the adhesive joint. From the shear stress distribution along adhesive layer as shown in Fig. 8, it can be seen that the shear stress of adhesive layer at the edges of is much higher than that at the center, with a difference of about 7 times. It is worth noting that the single lap finite element model used in this paper is suitable for thin plate, the thickness of t is much smaller than the minimum size of B in the middle surface, this hybrid-inverse has high accuracy when the t is less than $B/8$. While for thick plate and medium thickness plate, other finite element models and corresponding analysis methods should be developed.



(a) (b)

Figure 7: (a) FEM inverse model and (b) S13 shear stress of the adhesive layer.

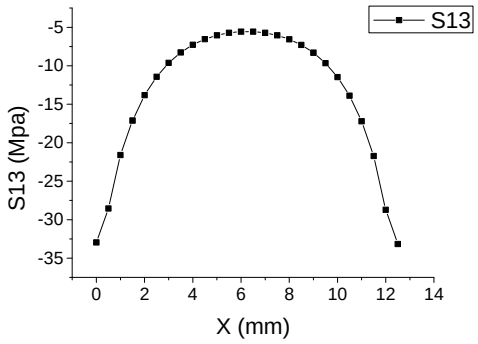


Figure 8: Stress distribution along adhesive layer.

5 CONCLUSIONS

By means of the finite element model and the experimental displacement data, this paper proposes a hybrid inversion analysis method to determine the interfacial stress of the single-lap bonded joint. Considering the plate deformation theory, the displacement relationship of inside and outside surface was established for single-lap composite plate joint in the finite element model. The present model has high calculation accuracy and efficiency when plate thickness is far less than the minimum size of middle plane. The deformation of the composite single lap joint under tensile shear test was measured, and the full field displacement data was discretized into the nodal displacement on the outer surface of the two bonded laminated plate. The nodal displacement data of the inner surface for both bonded

laminated plate was calculated by the finite element model, thus the strain and stress distribution was obtained when the nodal displacement was applied as driving force in the numerical inversion model. The shear stress distribution obtained by inversion analysis is consistent with the results of pure finite element analysis, while the results obtained by inversion calculation are more in line with the actual mechanical properties than the pure finite element calculation results. The results show that the shear stress S13 of the adhesive layer is symmetrically distributed, and the shear stress concentration exists on the edge of the adhesive joint.

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