Interlaminar fracture toughness analysis of fiber reinforced metal laminates based on APDL

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Abstract. Fiber Reinforced Metal Laminates (FRMLs) are widely used in modern industry because of excellent comprehensive properties. However, due to the existence of the interface, there will be delamination damage in their use process. Interface is the weakest part of fiber reinforced metal laminates. The bonding strength at the interface is determined by the fracture toughness of the interface. It is an important mechanical property index of fiber reinforced metal laminates. It is usually measured by a single cantilever beam test. In this paper, the finite element model of fiber reinforced metal laminate was constructed based parametric design language APDL of ANSYS to simulate the fracture toughness tests of FRMLs using element birth-death technology. The results show that the numerical simulation is very close to the experimental results. The numerical simulation is a very effective method to determine the interlaminar fracture toughness of fiber reinforced metal laminates.

1. Introduction

The metal alloy sheets are bonded to the fiber/resin composite layer by alternating lamination, thus forming Fiber Reinforced Metal laminated plates(FRMLs). FRMLs combines the advantages of metal alloy and fiber/resin composite materials while overcoming their respective disadvantages:FRMLs has inherited the excellent impact resistance, corrosion resistance and mechanical processing performance of metal alloy, and at the same time, it has excellent fatigue resistance characteristics of fiber/resin composite materials due to the "bridging" effect [1-3]. Therefore, fiber-reinforced metal laminates are widely used in modern industry.

However, due to the unique structure of FRMLs itself, i.e. interface between the sheet metal and the composite material layer, the properties of materials on both sides of the interface are usually different. The essence of interface is a kind of internal restraint of material on one side of interface to material on the other side. Moreover, there are usually various defects at the interface, and stress concentration exists at the interface. Therefore, FRMLs is often damaged from their interfaces. when
the stress in the thickness direction exceeds its strength limit, delamination fracture is initiated at the laminate interface [4]. However, after the initiation of delamination fracture, the crack propagation is not controlled by the strength limit along the thickness direction of the laminates, but depends on the interfacial fracture toughness of the laminates. Therefore, interfacial fracture toughness is a very important mechanical property index of FRMLs.

Usually, the fracture toughness of the interface is determined by experiments. In this paper, based on the experiments, the parametric design language APDL of ANSYS is used to establish the model and the birth-death element technique is used to simulate the delamination fracture process of Carbon Fiber Reinforced Magnesium Laminates (CFRL/Mg), and finally determine the interfacial fracture toughness.

2 Experimental determination of interfacial fracture toughness

The fracture toughness of CFRL/Mg interface was measured by single Cantilever Beam (SCB) structure. The SCB structure is shown in Figure 1. The loading rate is 0.5 mm/s, and the crack propagation starts from the pre-crack and propagates along the interface between magnesium alloy and carbon fiber/resin composite plate.

![Figure 1 Schematic diagram of a single cantilever beam](image1)

![Figure 2 Material coordinate system of CFRL/Mg](image2)

Loads, displacements and crack lengths were recorded during the tests, and the interfacial fracture energy ($K_c$) was calculated by using the following equations.

$$K_c = \frac{P^2}{2B} \frac{dC}{da}$$

(1)

where

$P$: the applied force
$B$: the width of the specimen
$C$: the specimen compliance
$\alpha$: the crack length.

The specimen compliance is expressed by:

$$C = C_0 + ma^3$$

(2)

where

$m$ is the slope of $C – \alpha^3$ straight line, $C_0$ is the constant of the given specimen, and it is determined by the ordinate of the intersection point of the straight line and the longitudinal axis.

Using equation (1) and (2), fracture energy $K_c$ can be determined:

$$K_c = \frac{3P^2ma^2}{2B}$$

(3)

The material coordinate system of CFRL/Mg is shown in Figure 2.
The preparation of the specimen, mechanical properties of magnesium alloys and carbon fibers/resins and the detailed test process are referred to in the references [5].

3 Failure criteria

During the CFRL/Mg fracture toughness test, the delamination failure of CFRL/Mg along the interface occurs as the crack propagates at the interface.

There are two main damage modes: matrix cracking of composite layers and interlaminar delamination (interlaminar damage).

3.1 Failure Criteria for Matrix of Composite Layer

The modified Hashin [6] matrix failure criterion is adopted here. The failure degree of the matrix of the fiber/composite layer is determined by the matrix cracking failure factor $e_m$.

$$e_m^2 = \left(\frac{\sigma_{22}}{Y}\right)^2 + \left(\frac{\sigma_{33}}{Y}\right)^2 + \left(\frac{\tau_{23}}{S}\right)^2$$

$$Y = Y_c, \quad \sigma_{22} < 0$$

$$Y = Y_t, \quad \sigma_{22} \geq 0$$

where:

$Y$: the tensile and compressive strength of the laminate

$S$: the interlaminar shear strength of the laminate

$Y_c$: the compressive strength of the laminate

When $e_m \geq 1$, the matrix of the pavement is damaged.

3.2 Interface Layering Criterion

The degree of interfacial delamination failure is determined by the interfacial delamination failure factor $e_d$.

$$e_d^2 = \left(\frac{\tau_{23}}{mS}\right)^2 + \left(\frac{\tau_{13}}{rS}\right)^2 + \left(\frac{\sigma_{22}}{rY}\right)^2$$

$$Y = Y_c, \quad \sigma_{22} < 0$$

$$Y = Y_t, \quad \sigma_{22} \geq 0$$

where:

The superscript $M$ indicates magnesium alloy, $F$ indicates carbon fiber/resin composite layer.

When $e_d \geq 1$, the interface is damaged.

3.3 The numerical simulation

The model of CFRL/Mg was established by APDL. The thickness of magnesium alloy plate and carbon fiber/resin layer was 5mm, and the width of the specimen was 20mm. In order to reduce the workload, according to the symmetry of the model and load, half of the entity is taken to build the model. The length of pre-crack is 10 mm. The SOLID92 entity unit is used to mesh the model. The tensile strength, shear strength and elastic modulus of magnesium alloy sheet are 174.3 MPa, 133.8 MPa and 42.1 GPa respectively. The tensile strength, compressive strength, shear strength and elastic modulus of carbon fiber/resin along the fiber direction are 630.2 MPa, 516 MPa, 42.2 MPa and 48.4 GPa.

Before the solution, the upper surface of magnesium alloy and the right end of the specimen are restrained. In the process of solving the problem, the load is divided into two stages. In the first stage, the load starts from zero and increases monotonously with the increase of head displacement. The load step is 1N. At the same time, the displacement and the magnitude of the load after the end of each load step were recorded and the matrix cracking failure factors $e_m$ of each matrix element and the interface stratification failure factors $e_d$ of the element at the interface were calculated. If $e_m \geq 1$, the single
stiffness matrix is multiplied by a small number before the total stiffness matrix is introduced by using the element birth-death technology, so that the stiffness of the element is set to zero. If $e_d \geq 1$, the same method is used to set the stiffness of the failure element to zero. The appearance of CFRL/Mg delamination means the end of the first stage. In the second stage, the load does not increase monotonously with the increase of displacement. The load increases from zero, and the load step size is also set to 1N. Unlike the first step, it is not necessary to record the displacement of the head and the magnitude of the load at each load step. Displacement, load and crack length are recorded only when $e_d \geq 1$. The load increases from zero until the crack length reaches 55 mm, and the solution is completed. The meshing of the model and the shape of the deformed model are shown in figure 3.

![Figure 3 Mesh generation, lamination and deformation of CFRL/Mg](image)

The calculation flow diagram is shown in figure 4.

![Figure 4 Schematic diagram of calculation process](image)

The calculation flow diagram is shown in figure 4.

where

$P$: the applied force

$\delta$: the displacement of head

$a$: the crack length

4 Comparison between numerical simulation and experimental results
The comparison of load-displacement curves between numerical simulation and test is shown in figure 5. It is very clear from the graph that the two curves are very close. Overall, the numerical simulation curve is slightly lower than the experimental curve. Moreover, the curve of numerical simulation is smoother than that of experiment. The reason for this result lies in the difference between the two constraints. The stiffness of the specimens is increased by using 45 # steel stiffener in the test, while the upper surface of the magnesium alloy plate is completely restrained while in the numerical simulation, which is equivalent to infinite stiffness. Therefore, the stiffness of the test specimen is less than that of the numerical simulation. As a result, the numerical simulation curve is slightly lower than the experimental curve, but there is little difference between them.

Figure 5 Comparison of load-displacement curves between numerical simulation and test

Figure 6 is the comparison of numerical simulation and experimental $C-a^3$ curves. It can be seen from the figure that the relationship between the compliance $C$ of numerical simulation and test and the cubic of crack length $a$ is approximately linear. This is completely consistent with the conclusion (equation (2)) obtained by theoretical deduction.

The compliance of the test specimen is slightly greater than that of the numerical

Figure 7 shows the comparison of numerical simulation and experimental $K_c-a$ curves. It can be seen that before the crack length reaches 65 mm, the $K_c$ of numerical simulation and test increases with the increase of the crack length, and both curves are relatively smooth. When the crack length exceeds 65 mm, the simulated curve approaches the level and remains smooth, while the experimental curve fluctuates. Overall, the two curves are very close.

Figure 7 Comparison of numerical simulation and experimental $K_c-a$ curves
5 Conclusion

Based on the platform provided by ANSYS, the finite element model of CFRL/Mg is established by using APDL, and the program is written. The growth process of interface crack is simulated by using birth-death element technology. Finally, the interface fracture toughness of laminates is determined. The results show that the load-displacement curves, $C-a^3$ curves and $K_c-a$ curves obtained by numerical simulation are very close to those obtained by experiments. It is proved that the simulation of fracture delamination process of fiber reinforced metal alloy laminates based on APDL and life-and-death elements technology is an effective way to determine the interfacial fracture toughness.

6 Reference

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