Paper

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Humidity Aging Effect on Adhesive Strength of Composite Single-lap Joint

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Abstract

Because adhesively bonded joints are used in many structural systems, it is important to predict accurate adhesive strengths. Composite aircraft with many joints are easily exposed to low temperatures and high relative humidity. This paper presents a humidity aging effect on the adhesive strength of a composite single-lap joint (SLJ). The adhesive strength of the SLJ is predicted using a finite element analysis with a cohesive zone model (CZM) technique. The humidity aging effect is evaluated based on the adhesive strength and CZM parameters. A lap joint test is carried out on the composite SLJ specimens, which are exposed for four months of 100% R.H. at 25°C. The predicted strengths are in good agreement with experimental data, and the actual crack propagation is satisfactorily simulated using the local CZM technique.

Key words: Adhesively Bonded Joints, Adhesive Strength, Cohesive Zone Model, Single-lap Joint, Humidity Aging

1. Introduction

Adhesively bonded joints have been widely used in aircraft and space structures because they offer a number of advantages over conventional mechanical fastened joints. These advantages include lower structural weights, lower fabrication costs, more uniform stress fields at the bonding region, high fatigue resistance, and improved damage tolerance. Because an epoxy adhesive is used in the majority of adhesively bonded joints, the adhesive strength is greatly affected by environmental exposure conditions such as high humidity, temperature, and UV light. In particular, composite aircraft are easily exposed to low temperatures and high relative humidity. These environmental effects cause a strength reduction in the adhesively bonded joints. Accordingly, engineers need to design structures considering the strength reduction caused by environmental exposure since the structural integrity of composite structures is often determined by the strength and durability of their joints.

Much research has been carried out to predict the strength of adhesively bonded joints. In the adhesive strength prediction method, which is based on material strength, the strength is predicted by checking whether a maximum stress or strain at the edge of the adhesive exceeds an allowable value. Hart-Smith et al. [1] proposed a failure criterion based on the maximum strain at the adhesive joints. This criterion could be adopted for cases with pure shear in which the peel stress is not applied at the adhesive region. In addition, the failure strength of the single-lap joint (SLJ) was in good agreement with the experimental data. Recently, critical failure criteria values have been defined according to the equivalent stress or strain calculated using stress or strain analyses with the finite element method. However, failure criteria based on material strength are not appropriate for adhesive joints, which have large plastic deformations and crack propagation. Accordingly, methods based on linear elastic fracture mechanics (LEFM) have recently been applied to predict the strength and crack growth behavior of adhesively bonded joints. Anderson et al. [2] predicted the strength of highly brittle adhesive joints by using the strain energy release rate. Lee et al. [3] proposed

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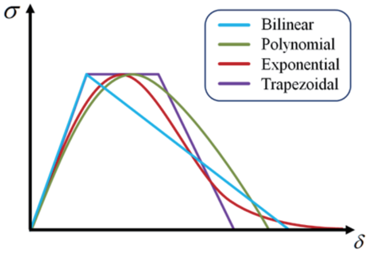
that failures depended on the plastic region at the crack tip in adhesive joints, and that fracture energy was related to the material properties of bulk adhesive. Groth [4] suggested a failure criterion based on stress concentration factors at the singularity point of the interface between the adhesive and the adherend where the high stress concentration occurred. In recent years, many studies have been carried out to predict the strength of adhesive joints by using fracture mechanics-based finite element methods such as the virtual crack closure technique (VCCT) and cohesive zone model (CZM). The VCCT was first suggested by Rybicki and Kanninen [5]. This method calculates the energy release rate and predicts crack propagation behavior with the assumption that the energy needed to separate a surface is the same as the energy needed to close the same surface. The CZM was first suggested by Dugdale [6] and Barenblatt [7], and it was applied to the finite element method provided by Alfano [9] and Needleman et al [10]. This method predicts the fracture behavior of cohesive elements by using the stresses and the energy release rates at the crack tip of the adhesive joints.

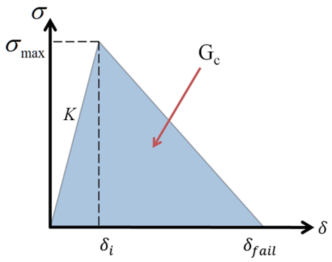
The major purpose of this study is to investigate the humidity aging effect on the adhesive strength of a composite SLJ. For this, a finite element analysis for the composite SLJ is performed to evaluate the adhesive strength and cohesive zone parameters reduced by exposure to high relative humidity for four months (100% R.H. and 15°C). In order to predict the adhesive strength, a CZM is determined from the test results of the composite SLJ specimens. The predicted strength and crack behavior are in good agreement with the experimental data. Also, the changes of strength and cohesive zone parameters are analyzed after exposure to the high relative humidity condition.

2. Cohesive zone model (CZM)

The cohesive zone model (CZM) defines the mechanical behavior of an element in an adhesive region by applying the critical energy release rate (G_C) and critical stress (σ_{max}) for the crack tip region in respect of the failure mode of the adhesively bonded joints. The CZM is determined by the traction-separation behavior, which is derived from the traction stress (σ) and relative displacement of interface (δ). The shapes of various CZMs are defined and shown in Fig. 1. The bilinear model is defined as a triangular shape, and the polynomial model is defined as a parabolic shape. The exponential and trapezoidal models are defined as an exponential function shape and a trapezoidal shape, respectively. The bilinear model is typically used because it can express the behavior of a cohesive element in simple form, and it prefers to determine a mixed mode using the linear superposition. The bilinear model is represented in Fig. 1(b).



(a) Various cohesive zone models



(b) Bilinear cohesive zone model

Fig. 1. Shapes of various cohesive zone models.

When performing a finite element analysis to obtain the strength of an adhesively bonded joint, a cohesive element can be used depending on the defined CZM. If the bilinear model is adopted, as shown in Fig. 1(b), the displacement and traction stress of the element increase linearly until they reach the critical stress (σ_{max}) from the transferred structural load. When the stress reaches its critical value, crack initiation and subsequent growth occur quite readily. Upon unloading, the nodes of the cohesive element start to separate. Finally, complete de-bonding occurs when the crack initiation displacement (δ_i) reaches the failure displacement (δ_{fail}). This bilinear cohesive zone model can be defined by using three parameters; critical stress (σ_{max}), penalty stiffness (K), and critical energy release rate (G_C). σ_{max} is the critical traction for each direction in the cohesive element, K is the slope of a straight line, and G_C is an area of the CZM.

The three parameters defining the bilinear CZM can be obtained using double cantilever beam (DCB), end notched flexure (ENF), and mixed mode flexure (MMF) tests. This enables a pure mode I test, a pure mode II test, and two mixed mode tests, respectively. An SLJ test can also be used to obtain the CZM parameters. From the finite element analysis for the SLJ specimen, three CZM parameters can be predicted via calibration with the experimental data. In this paper, CZMs of composite SLJ specimens are predicted using a test and finite element analysis. Two types of SLJ specimens are used in this paper – the reference specimen (unexposed) and a specimen exposed for four months of 100% R.H. at 25°C. Finally, the adhesive strength and crack propagation behavior are predicted using the predicted CZM parameters, and the effects of humidity aging on the adhesive strength and CZM are analyzed.

3. Parametric study of CZM

3.1 Finite element modeling of composite single-lap joint

The SLJ specimen in this paper uses the adherend of a carbon fiber reinforced plastic (CFRP) composite material and a brittle epoxy adhesive. A finite element model is generated to be equal to the shape and dimensions of the test specimen. The finite element modeling and analysis are performed with the commercial finite element program ABAQUS.

The finite element model of the SLJ is shown in Fig. 2. The two dimensional plain strain elements are used in the model. The adhesive is modeled as an isotropic material, and the adherend is modeled as a material with the equivalent stiffness of the composite laminate. ABAQUS provides the modeling technique for adhesive joints such as the 2-D and 3-D cohesive elements based on the CZM, as well as the surface-to-surface contact model. In this paper, the 2-D cohesive element technique is applied. The cohesive elements can be modeled in locations predicted to initiate and propagate the crack. Generally, the crack initiation and propagation occur in the interface between the adhesive and adherend (interfacial failure mode) or the inside of the adhesive (cohesive failure mode). As such, in this paper, the cohesive elements are modeled in the upper and lower interfaces, and in the centerline in the adhesive bondline (Fig. 3).

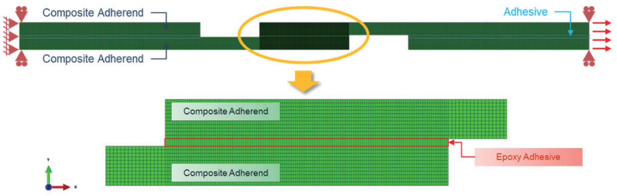


Fig. 2. Finite element model of composite single-lap joint specimen

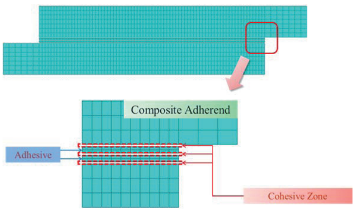
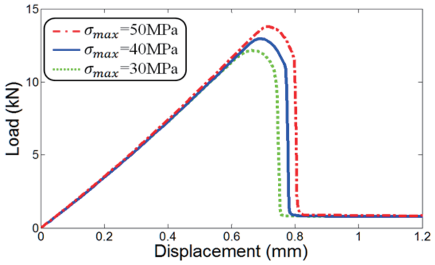


Fig. 3. Cohesive elements in the interface and centerline of adhesive

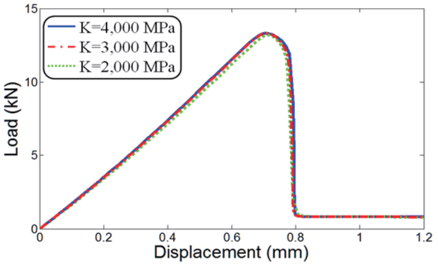
3.2 Parametric study of CZM via FEA

The crack initiation and propagation, as well as the mechanical behavior of the cohesive element, are determined according to the CZM characteristics, which are defined by three parameters – the critical stress ($\sigma_{\max}$), penalty stiffness (K), and critical energy release rate (G_C). In this paper, the parametric CZM study is performed using the finite element analysis for the composite SLJ specimen model. Through this study, the effects of the CZM parameters are investigated.

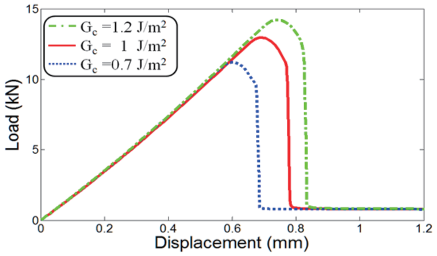
The CZM parameters are defined for each failure mode. First, it is assumed that the parameters of modes I and II are the same values. The mechanical behaviors of the SLJs are subsequently simulated with increases in critical stress, penalty stiffness, and the critical energy release



(a) The effect of maximum stress



(b) The effect of penalty stiffness



(c) The effect of critical energy release rate

Fig. 4. Mechanical behavior according to CZM parameters

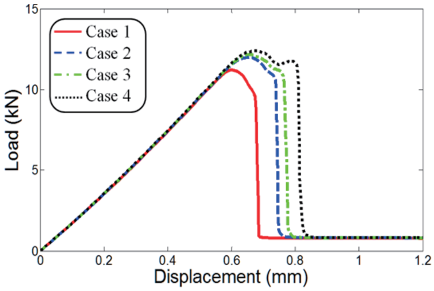


Fig. 5. Mechanical behavior according to interaction for each CZM failure mode

Table 1. CZM parameters for each failure mode

Failure Modes	K [N/mm^3]	σ_{max} [MPa]	G_C [J/m^2]
I	4,000	40	0.7
II-1	4,000	40	0.7
II-2	5,000	50	0.9
II-3	6,000	60	1.05
II-4	8,000	80	1.4

rate, respectively (Fig. 4). With the increase in critical stress, both the failure strength and displacement increase slightly. In addition, the strength and displacement increase significantly as the critical energy release rate increases. However, there is no change in the mechanical behavior due to the increase in penalty stiffness. From these results, it can be seen that the mechanical behavior of the adhesive joint is significantly affected by the critical energy release rate, also known as fracture toughness. In addition, there are no effects on the slope of the straight line because it is determined by the overall stiffness of the adhesive joint.

A variation of the mechanical behavior is also analyzed by changing the mode II parameters in four types while fixing the mode I parameters. The CZM parameters for each failure mode are shown in Table 1, and the load-displacement curve obtained from the finite element analysis is represented in Fig. 5. It can be seen that the fracture behavior is quite varied according to the ratio of mode I to mode II parameters. In addition, if mode I and II parameters are the same, rapid crack propagation occurs alongside the crack initiation in a location of maximum stress. As such, the load decreases rapidly as the displacement increases. However, when the mode II parameters are four times larger than mode I (case II-4 in Table 1), the crack propagates quite slowly, and complete de-bonding eventually occurs. The maximum load also increases as the mode II parameters increase. This is a result of the fracture toughness for each failure mode overlapping one another.

4. Strength prediction for composite single-lap joint

4.1 Single-lap joint test

The SLJ tests are carried out to determine the CZM parameters for each failure mode and predict the adhesive strength. Specimen manufacturing and testing are performed based on ASTM D3165, and the adhesive strengths are predicted for the reference specimens (not exposed) and the specimens exposed to four months of 100% R.H. at 25°C. The test results for the reference specimens are shown in Fig. 6. A crack is initiated at the first maximum load and propagates to the second maximum load, where total de-bonding occurs. Fig.7 represents the test results of the specimens exposed to four months of 100% R.H. at 25°C. As soon as the load

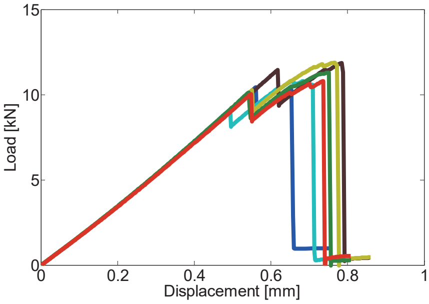


Fig. 6. Test results for reference specimens

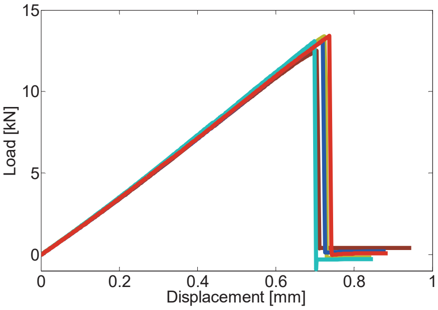


Fig. 7. Test results for specimens exposed to four months of 100% R.H. at 25°C

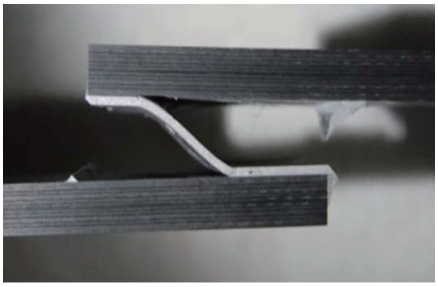


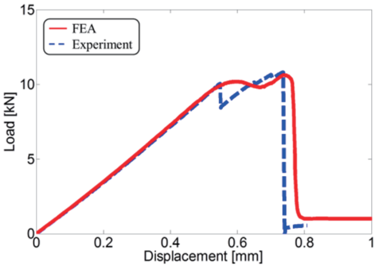
Fig. 8. De-bonding shape of failed single-lap joint specimen

reaches the first maximum value, total de-bonding occurs. This does not occur with the reference specimens. Fig. 8 is a picture of a failed SLJ specimen. It shows that an interfacial failure occurs in the same manner that it occurs with the general results of the SLJ test.

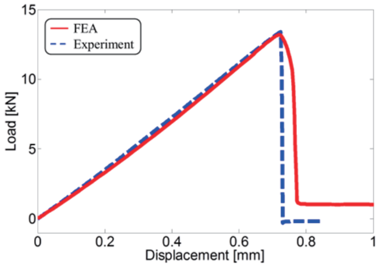
4.2 Finite element analysis for composite single-lap joint

In order to predict the adhesive strength of the composite SLJs, the CZM parameters are determined using a test and finite element analysis for the reference and exposed specimens. By comparing the load-displacement curves obtained from the test and analysis, the CZM parameters are predicted for each failure mode.

The CZM parameters, which are predicted using the FE analysis for the reference and exposed specimen models, are shown in Table 2. In addition, the load-displacement curves obtained from the FE analysis and test are represented in Fig. 9. It can be seen that the predicted mechanical behavior and adhesive strength are in good agreement with the experimental data. Fig. 10 shows the stress distribution and crack propagation behavior of the SLJ specimen model according to the step time. The failure configuration of the specimen is well predicted, adequately resembling the failed specimen in Fig. 10.



(a) Reference specimen

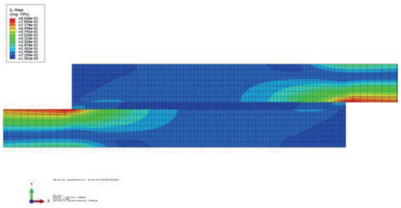


(b) Humidity aged specimen

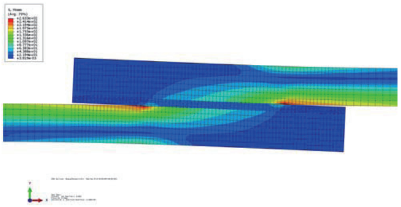
Fig. 9. Load-displacement curves of reference and exposed specimens

4.3 Effect of humidity exposure on adhesive strength and CZM

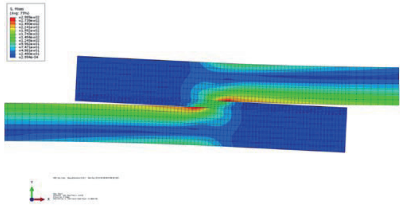
The adhesive strengths from the test and analysis for



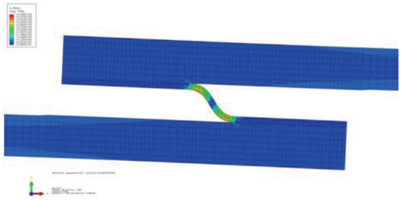
(a) Step time = 5.75E-03



(b) Step time = 0.32



(c) Step time = 0.38



(d) Step time = 1.00

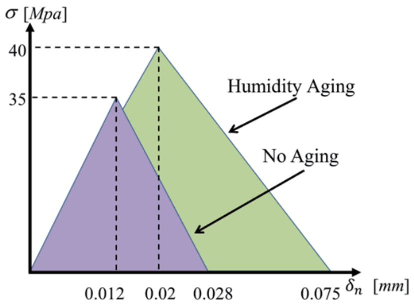
Fig. 10. Stress distribution and crack propagation behavior of single-lap joint specimen model

Table 2. CZM parameters according to humidity exposure

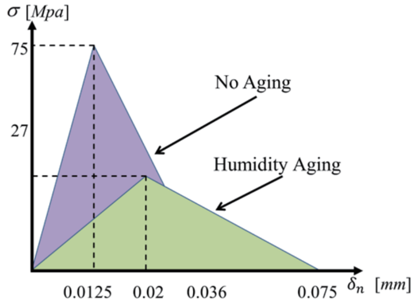
Failure Modes	Reference specimen (no exposure)			Humidity aged specimen		
	K [N/mm^3]	σ_{max} [MPa]	G_C [J/m^2]	K [N/mm^3]	σ_{max} [MPa]	G_C [J/m^2]
I	3,000	35	0.5	2,000	40	1.5
II-1	6,000	75	1.35	1,300	27	1

Table 3. Adhesive strengths of single-lap joint specimens according to humidity exposure

Items	Reference specimen (no exposure)		Humidity aged specimen	
	Failure load [kN]	Failure displacement [mm]	Failure load [kN]	Failure displacement [mm]
Test	10.79	0.74	13.41	0.73
FEA	10.62	0.78	13.20	0.77
Error (%)	1.6	5.1	1.6	5.6



(a) Mode I



(b) Mode II

Fig. 11. Cohesive zone models for each failure mode according to humidity exposure

the reference and exposed composite SLJ specimens are shown in Table 3. Generally, it is known that the strength of materials exposed to abnormal temperatures or humidity will undergo a reduction, but the adhesive strength of the exposed specimen has increased by about 25% rather than decreased. In addition, the strengths predicted using the finite element analysis are in good agreement with the experimental values, and the fracture behavior is similar to the results of the test specimen, as depicted in Fig. 8.

The CZMs for each failure mode are determined according to humidity exposure. Fig. 11 shows the humidity aging effect on the CZM. In mode I, both the critical stress (σ_{max}) and fracture toughness (G_C) increase according to humidity aging, and the penalty stiffness (K) almost remains constant. On the contrary, the critical stress and stiffness in mode II decrease significantly as a result of exposure to the high relative humidity, but the fracture toughness decreases slightly as the failure displacement of the humidity-aged specimen increases significantly. From these aging effects on the CZM shown in Fig. 11, it can be concluded that the increase in the adhesive strength of the exposed specimen is due to the increase of fracture toughness in mode I. In addition, it can be seen that the crack propagates rapidly and reaches total de-bonding immediately as the critical stress decreases and the failure displacement increases in the CZM of mode II (Fig. 12(b)).

5. Conclusion

In this paper, a parametric study on the bilinear CZM is carried out using a finite element analysis for composite SLJ specimens, and the mechanical behavior and adhesive strength characteristics are analyzed according to the CZM parameters for each failure mode. When the superposition of failure modes is not considered, the most dominant parameter for adhesive strength is the fracture toughness (G_C), followed by critical stress (σ_{max}). On the contrary, the penalty stiffness (K) does not affect adhesive strength. When modes I and II overlap, the crack propagates slowly when the fracture toughness of mode II is greater than mode I. In addition, the second peak point exists if the fracture toughness of mode II is about two times larger than mode I. Based on these parametric study results, the CZMs are determined using the finite element analysis for reference (no exposure) and exposed specimens (exposed for four months of 100% R.H. at 25°C.). The adhesive strength and crack propagation behaviors are also predicted, and they are in good agreement with the experimental results. The predicted adhesive strength of the exposed specimen, rather than decreasing, increases by about 25%. Subsequently, the CZMs for each failure mode are determined according to humidity exposure. In addition, the humidity aging effect is analyzed using the predicted CZMs. Ultimately, it is concluded that the increase in adhesive strength of the exposed specimens is due to the increase in fracture toughness in the CZM of mode I. The crack also propagates rapidly, and it reaches total de-bonding immediately as the critical stress decreases and the failure displacement increases in the CZM of mode II. Based on the results of this paper, the fracture behavior of SLJs exposed to high relative humidity can be predicted efficiently.

Acknowledgement

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