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Experimental and analytical verification of the characteristics of shear fatigue failure in the adhesive interface of porous foam materials †

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Abstract

In the past, many studies have been conducted to examine the effect of static load and fatigue load on the adhesive interface between two different materials or the same materials, but little research has been done on porous materials. Thus, this study was carried out to examine the effect of fatigue load on the adhesive interface formed by aluminum foam, which exhibits porous characteristics. For the experiment, five specimens were fabricated with the thicknesses varied in increments of 10 mm from 25 mm to 65 mm. The aluminum foam was bonded using the single-lap method, and MTS landmark was used to conduct the fatigue experiment. Based on the initial static experiment, the maximum reaction force at which total failure occurred in the adhesive interface was obtained, and fatigue load was applied on the lower load cell in the 10 Hz sine graph form. The results of the experiment showed that for all five of the specimens, the adhesive strength of the adhesive agent was maintained in the adhesive interface during the 5000 cycle of the fatigue load. Also, based on the correlation between displacement and repeated load cycles, it was discovered that the adhesive interface underwent total failure after a sharp displacement in the interface in all five cases when the load was repeated for more than 5000 cycles In addition, a numerical analysis was performed based on the experimental results, and the stress distribution was visualized. The numerical analysis results showed similar tendencies as the experimental results, which confirmed the reliability of the analysis results. Thus, it was deemed that it would be possible to analyze the fatigue failure behavior of actual, bonded structures made of a porous material based on the experimental and numerical analysis results obtained through this study.

Keywords: Adhesive interface; Aluminum foam; Fatigue load; Porosity; Single-lap method

1. Introduction

Automobile manufacturers, which used to use a single material in the past, are opting for composite materials that are more lightweight and stronger as a means to enhance the car efficiency and meet the countless new restrictions. An example of this is the use of aluminum foam, which is lightweight and has excellent shock absorption, in the manufacture of bumpers and crash boxes. A preferred method of applying porous aluminum foam to bumpers and crash boxes is the adhesion method because welding or drilling and fastening by bolts and nuts is characterized by long processing time and increased weight, especially for the latter example [1-3]. However, aluminum foam has an uneven surface, making it highly probable that the characteristics of its adhesive interface are different from other materials that are commonly used. This means that application based on the characteristics of the adhesive interfaces of other materials will likely result in damage or defect, and the accurate fatigue failure behavior cannot be identified. Thus, it is very important to conduct research to understand the fatigue damage and duration of the adhesive interface of a porous material in order to apply aluminum foam appropriately, and this type of research is especially important if the material is applied to the bumper or the engine room, where vibration load is exerted continually [4-7].

In the past, there has been a considerable amount of research on materials with even surfaces. In 1996, Ikegami et al. [8]. studied the effects of the joint configuration, loading mode, adhered yield strength, curing process, and adhesive thickness on the adhesive interface based on the static strength of epoxy adhesively bonded butt, single-lap and double-lap joint. On the other hand, Goncalves et al. [9]. used the three-dimensional FE method to analyze the stress behavior of single-lap adhesively bonded joints, and as a result, it was discovered that stress concentration occurs in the adhesive interface. Moreover, in 2006, Kim et al. [10]. discovered that the biggest failure strength occurs in co-cured joint specimens through the

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strength and failure modes and of single-lap adhesively bonded composite joints formed using different bonding method.

As such, many studies have been performed to examine the stress occurring in the adhesive interface according to the thickness of the adhesive agent. In addition, in 1999, Crocombe and Richardson [11] examined the effects of frequency and mean load on the fatigue behavior of four adhesively bonded joints with different structural configuration, and showed a correlation between the fatigue load frequency and the adhesive strength of the adhesive interface. Then, in 2000, Briskham and Smith [12] applied aluminum to aluminum and composite to aluminum adhesive joints with various aluminum pretreatments to study the potential of unstressed and cyclic stress durability. The specimen proven to have durability in the fatigue load experiment was used as the standard for the aerospace pretreatment. Meanwhile, Casas-Rodriguez et al. [13] studied the behavior and impact-fatigue life of adhesive joints exposed to low-velocity impact loading. The results showed that fatigue load had a greater impact on the adhesive interface than the static load.

A great number of preceding studies examined the effect of static load and fatigue load on the adhesive interface where two different materials or the same materials were bonded. However, there has not been much research on such effect on the adhesively bonded porous material. Thus, this study was conducted with an aim to examine the effect of fatigue load on the adhesive interface of aluminum foam with porosity [14-17].

2. Experimental study

2.1 Specimen and material properties

The specimens used in the experiment were fabricated as shown in Fig. 1. The adhesive agent layer of the interface was about 1 mm for all of the specimens, while the overlap zone was set at 130 mm. The thickness of the specimen was designated as a variable, and there were five cases in which the thickness varied in increments of 10 mm from 25 mm to 65 mm. In the initial state, necking occurred in the DCB aluminum foam and thus, the thickness of the neck area was increased to mitigate this issue [18].

2.2 Relevant fatigue experiment theory

It is known that the fatigue failure of material is dominated by maximum and minimum values of repetitive stress, it's gap, and the number of repetition. The fatigue limit is that failure of the material does not occur under some constant stress range. Maximum stress range which the fatigue failure does not occur is called by the fatigue limit. There are several theories on whether the stress range that does not cause the failure is exist or not even if the limitless fatigue load is applied. At using material in reality, it is needed to decide the endurance limit like the limitless repetition. If the failure is not occurred

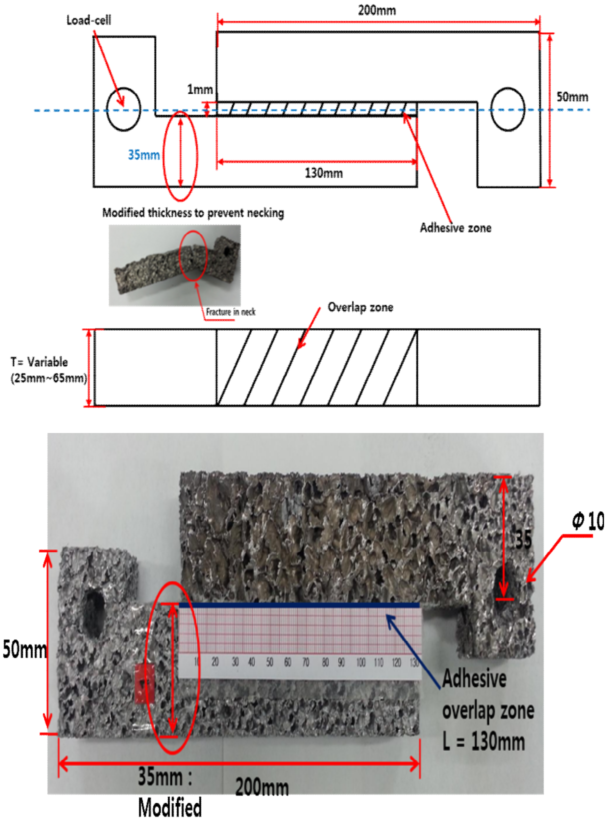


Fig. 1. Experiment specimen.

under the standard number of repetition, the failure can not to be occurred. The fatigue limit has been generally decided with the standard of the count number of 10^6 to 10^7. However, the standard of fatigue limit is set up as 1 to 10^3 downward in order to take account of the strength of aluminum foam in this study. In addition, the symmetry stress, the asymmetry stress and the random stress are applied as shown by Fig. 2 to evaluate fatigue life of normal materials. Therefore, this study has been conducted through symmetry stress.

The symmetry stress is mainly composed of two components as the mean stress, σ_m and the stress amplitude, σ_a. As σ_r becomes the stress width, it can be defined as the difference of maximum stress, $\sigma_{\max}$ and minimum stress, $\sigma_{\min}$.

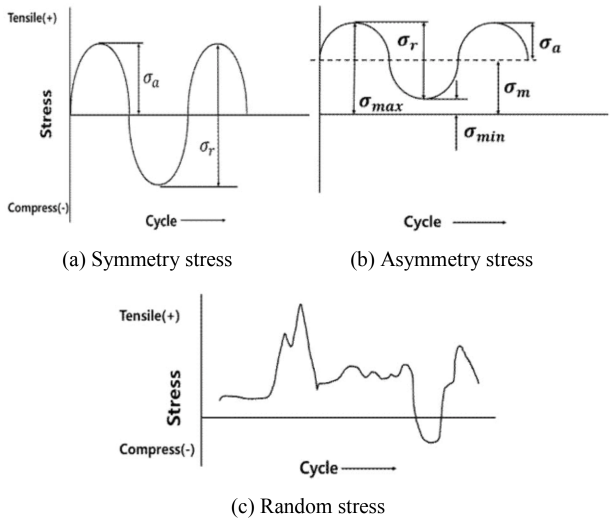
$$\sigma_r = \sigma_{\max} - \sigma_{\min} \tag{1}$$

$$\sigma_a = \frac{\sigma_r}{2} \tag{2}$$

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2}. \tag{3}$$

Then, the stress ratio, R is

$$R = \frac{\sigma_{\min}}{\sigma_{\max}}. \tag{4}$$



(a) Symmetry stress (b) Asymmetry stress

(c) Random stress

Fig. 2. Fatigue stress cycle.

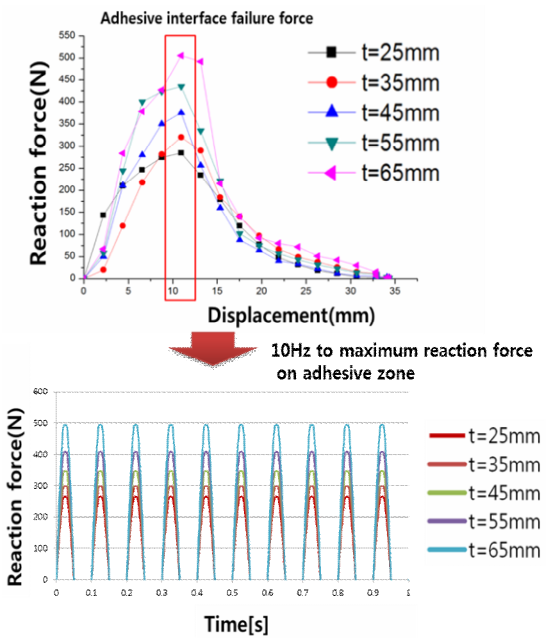


Fig. 3. Fatigue load data from static experiment.

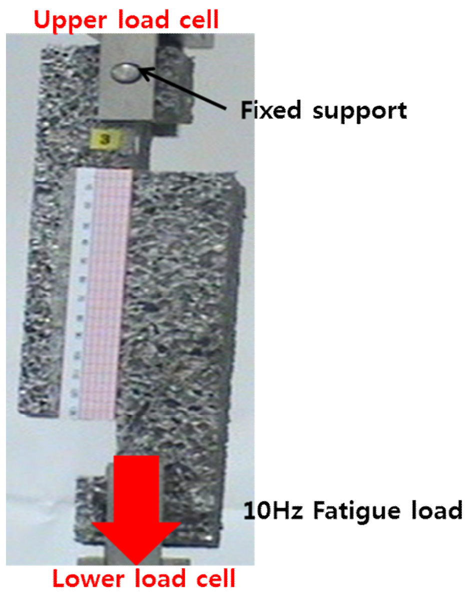


Fig. 4. Experiment setting with fatigue load.

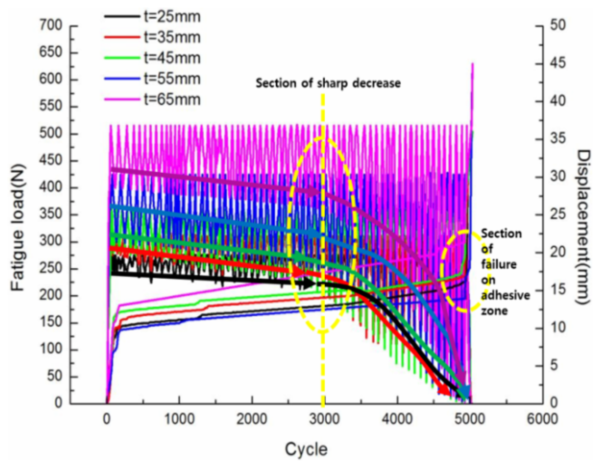


Fig. 5. Experiment data for five specimens.

2.3 Experiment method and conditions

MTS landmark was used in the experiment. The maximum tensile stress was 50 kN, and it was possible to carry out static and fatigue experiments. Based on the initial static experiment, the maximum reaction force at which total failure occurred in the adhesive interface was obtained, and fatigue load was applied on the lower load cell in the 10 Hz sine graph form. The negative Y direction fatigue load was excluded because it was in the opposite direction. Fig. 3 shows the data obtained from the static experiment corrected to the sine values so that they are consistent with the experimental conditions.

After setting the fatigue load values in MTS landmark, the specimen was mounted on the equipment as shown in Fig. 4. The upper load cell was locked in using the fixed support, and the fatigue load value was set only for the lower load cell.

3. Result of experiment

A fatigue experiment was conducted based on the maximum reaction force values for the adhesive interface obtained through the static experiment, and the results were obtained for each model as shown Fig. 5.

The results of the experiment showed that for all five of the specimens, the adhesive strength of the adhesive agent was maintained in the adhesive interface during the 5000 cycle of the fatigue load. The amplitude of the fatigue load increased steadily before surging after 3000 cycles. Based on this, it can be inferred that the adhesive interface of porous materials can withstand constant force for 3000 cycles, but the adhesive strength deteriorates considerably after repeated loads of more than 3000 cycles.

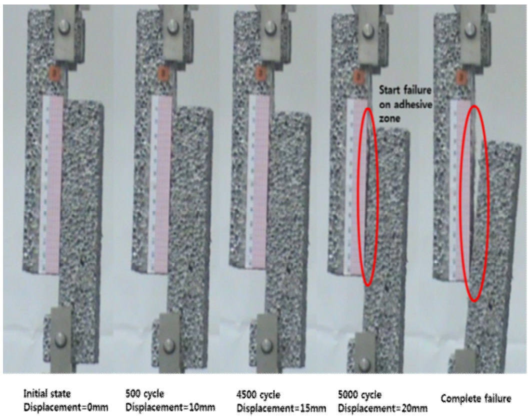


Fig. 6. Progression of displacement following fatigue load cycle.

Moreover, based on the correlation between displacement and repeated load cycles, the following results were confirmed: repeated loading in the early stages caused a sharp displacement of 10 mm in the adhesive surface, but the adhesive strength was maintained in the interface for about 3500 cycles after the displacement; then, after 4500 cycles of repeated loading, another sharp displacement occurred in all five cases and total failure occurred in the interface.

Fig. 6 shows the displacement of specimen data related to upper Fig. 4 data, which is for t = 45 mm. A displacement of about 10 mm occurred between the initial state and the 500 cycles of fatigue load. Afterwards, the displacement progressed to about 15 mm until the 4500th cycle. After 5000 cycles of fatigue load, the displacement progressed to about 20 mm before failure began to occur in the adhesive interface. Beyond the 20 mm point, total failure occurred in the adhesive interface and the specimen became separated.

4. Stress visualization with fatigue load and experiment verification through numerical analysis

4.1 Numerical analysis setup

The failure characteristics of the adhesive interface under fatigue loading that were identified through the experiment were compared to the results of a numerical analysis. Also, although there is a limitation in the experimental verification where the stress propagation process related to fatigue load cannot be observed, the stress propagation process can be represented using the numerical analysis method. Fig. 7 shows that CATIA V5 was used for the modeling process, as was the case in the experiment, while the analysis model was divided by finite elements for the numerical analysis.

The nodes of the team beams must be matched in the adhesive zone in order to derive accurate result values because the node points on both sides, as shown in Fig. 8, are analyzed based on Eq. (5). However, F_x and δ_x are 0 because they are in the shear direction

$$G_c = (F_x\delta_x + F_y\delta_y) / 2\beta. \tag{5}$$

Table 1. Properties of aluminum foam.

Young's modulus (MPa)	2374
Poisson's ratio	0.29
Density (kg/m^3)	186.05
Yield strength (MPa)	1.8
Shear strength (MPa)	1.5

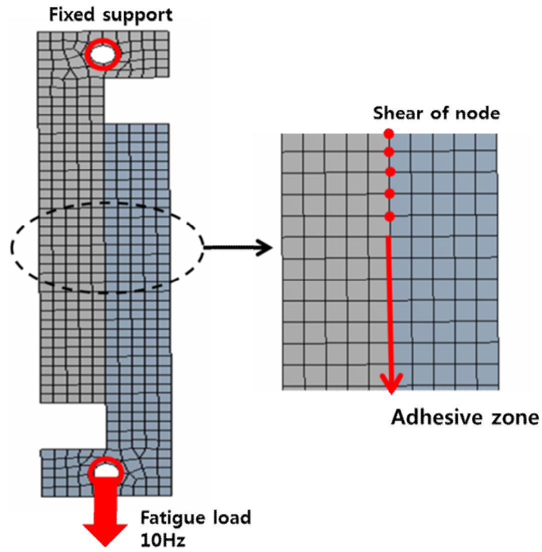


Fig. 7. FE model and boundary condition.

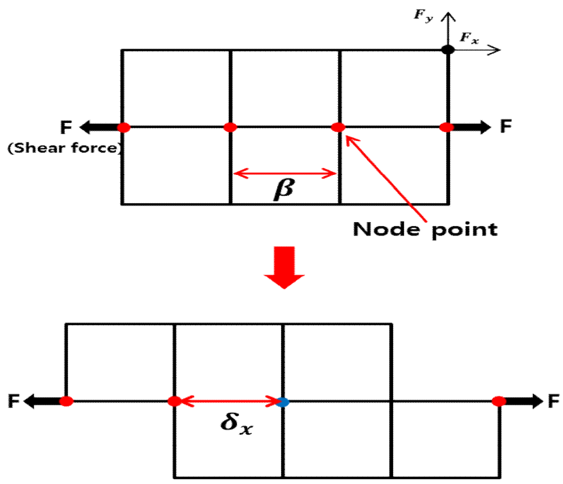


Fig. 8. Basic concept of numerical analysis theory.

As for the analysis conditions, the upper load cell was confined, while only the lower load cell was subject to fatigue loading, as was the case in the experiment. At this time, the value shown in Fig. 3, which was the value used for the experiment, was entered as the fatigue load. The adhesive strength of the adhesive zone was set at 1 MPa in the normal and binomial directions. Table 1 shows the properties of the aluminum foam.

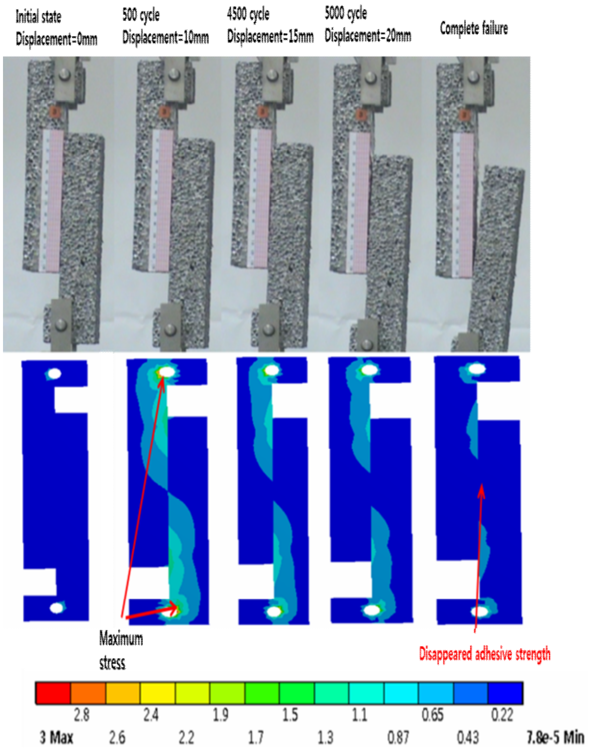


Fig. 9. Stress visualization and comparison between experiment specimen and analysis model for t = 25 mm.

4.2 Stress visualization and verification through numerical analysis results

The numerical analysis was conducted according to the analysis conditions described in Sec. 4.1, and as a result, the stress propagation process could be visualized. Because all five cases exhibited similar stress propagation processes, the stress propagation process of the specimen with thickness of 25 mm was compared to the experimental process in Fig. 9. The stress propagation process was observed based on the number of cycles of fatigue loading when displacements occurred. After about 500 cycles of fatigue loading, a sharp displacement occurred as shown in Fig. 5. At this time, the maximum stress occurred as shown in Fig. 9. Stress occurred around the adhesive zone afterwards, but it gradually disappeared. This was deemed to be due to the deterioration of the adhesive strength against the fatigue load. In other words, after about 5000 cycles of fatigue loading, the stress on the adhesive interface in the analysis model almost disappeared, as was the case in the experimental model.

4.3 Comparison between experiment data and numerical analysis result

Fig. 10 shows a comparison between the experimental data and the analysis graph for t = 25 mm. Both graphs show a sharp displacement in the adhesive interface between the initial state and after 200 to 500 cycles of fatigue loading. Also,

Table 2. Mean loads and fatigue lives at experiment and simulation data.

Model (t:mm)	Experiment mean load before 3000 cycles (N)	Experiment mean load after 3000 cycles (N)	Fatigue life N_f (Cycles)
t = 25	275	170	4856
t = 35	300	183	4798
t = 45	329	215	4913
t = 55	364	261	4751
t = 65	452	317	5017
Model (t:mm)	Simulation mean load before 3000 cycles (N)	Simulation mean load after 3000 cycles (N)	Fatigue life N_f (Cycles)
t = 25	250	250	4972
t = 35	297	297	4892
t = 45	381	381	4964
t = 55	475	475	4896
t = 65	523	523	4894

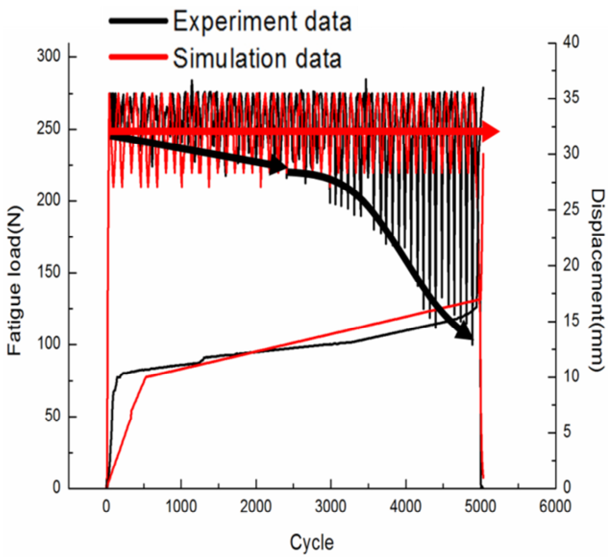


Fig. 10. Mean loads and fatigue lives comparing between experiment data and analysis data.

after 5000 cycles of fatigue loading, a dramatic increase in the displacement and the disappearance of the fatigue load were observed. However, the experimental data showed a positive correlation between the amplitude of the fatigue load and the number of cycles, whereas in the numerical analysis data, the amplitude repeated at a constant level until it suddenly dropped near the 5000th cycle. The difference between the two sets of data is thought to be due to the fact that in the analysis, the stickiness of the adhesive agent cannot be rendered. Nevertheless, the data on major behaviors in the adhesive interface were very similar between the experimental and numerical analysis results.

Table 2 shows the detailed results of mean loads and fatigue lives at experiment data and simulation data. Because there is the dramatic turning point at 3000 cycles at experiment data, the mean loads are categorized as the ranges before 3000 cycles and after 3000 cycles. According to the Table 2, the mean load data between experiment and simulation data at the range before 3000 cycles show that the simulation mean load data can be verified quantitatively by approaching approximately 80% to the experimental data. However, the simulation mean load data become much higher than the experiment data at the range after 3000 cycles. On the whole, all of fatigue lives of N_f at experiment and simulation data show nearly same tendency about 5000 cycles.

5. Conclusions

The following conclusions were reached based on the results of the experiment and numerical analysis regarding the fatigue characteristics of adhesive interface of DCB aluminum foam with a porous surface.

(1) The maximum reaction force according to the thickness was identified through a static test, and a fatigue load of 10 Hz was applied on each of the 5 specimens. In all five specimens, a 10 mm displacement occurred in the adhesive surface after about 200 cycles of fatigue loading. Then, gradual failure began to occur in the adhesive interface until about the 4800th cycle. After 5000 cycles of fatigue loading and a displacement of more than 20 mm, total failure occurred in the interface.

(2) A numerical analysis was conducted based on the experimental results, enabling the visualization of the stress distribution, which could not be observed during the experiment. Also, the numerical analysis results showed similar tendencies as the experimental results, which confirmed the reliability of the analysis results.

(3) The fatigue failure behavior of actual, bonded structures made of a porous material can be analyzed based on the experimental and numerical analysis results obtained through this study. Also, performing a computer simulation and an experiment in combination using the methods described in this paper will allow fast and convenient identification of the fatigue failure characteristics of adhesively bonded structures consisting of porous materials.

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Nomenclature

σ_m : Mean stress
σ_a : Stress amplitude
σ_r : Stress width
$\sigma_{\max}$: Maximum stress
$\sigma_{\min}$: Minimum stress
G_c : Critical fracture energy
F_x : Fatigue force to X direction
δ_x : Displacement of node point with X direction
F_y : Fatigue force to Y direction
δ_y : Displacement of node point with Y direction
β : Distance of node point FE model

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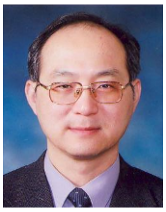

Jae-Ung Cho received his M.S. and Doctor Degree in Mechanical Engineering from Inha University, Incheon, Korea, in 1982 and 1986, respectively. Now he is a professor in Mechanical & Automotive Engineering of Kongju National University, Korea. He is interested in the areas of fracture mechanics (Dynamic impact), composite material, fatigue and strength evaluation, and so on.