INTERACTION BETWEEN TRANSVERSE CRACKS AND EDGE DELAMINATION CONSIDERING FREE-EDGE EFFECTS IN COMPOSITE LAMINATES

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Abstract

The high-cycle fatigue characteristics, especially the initiation and propagation of edge delamination, were investigated with quasi-isotropic carbon fiber reinforced plastic (CFRP) laminates with a stacking sequence of $[45/0/-45/90]_S$. To investigate the influence that transverse cracks have on the initiation and propagation of edge delamination, two types of specimens are used. One was a specimen where transverse cracks were arbitrarily introduced by static tensile loading before conducting the fatigue tests. The other was an undamaged specimen as new. As a result, it was found that the single transverse crack introduced before the fatigue test did not seriously affect the initiation of edge delamination. Moreover, the difference of the fatigue damage growth behavior depending on the applied stress level was observed. Under the test conditions of low-applied stress level and high-cyclic loadings, it was observed that the edge delamination grew before, or simultaneously with, the transverse crack propagation.

1 Introduction

CFRPs are expected to be a primary structural material in the fields of transportations and so on replacing metal materials, because a great fuel saving becomes possible by lightening the structures. To establish the damage tolerance design of CFRP laminates, it is essential to understand the behavior of the microscopic damage. In this point of view, many studies on microscopic damage progress under static and fatigue loadings have been conducted [1-5].

Liu and Nairn [6] conducted the fatigue tests with various types of CFRP cross-ply laminates. They showed that the transverse crack density growth rate could be expressed as a function of the energy release rate range derived by the variational principle. Yokozeki et al. [7] studied transverse cracks propagating in the width direction of specimens with several CFRP cross-ply laminates and quasi-isotropic laminates under fatigue loading. They showed that the derived energy release rate was independent of the crack length, and the transverse crack growth in the width direction could be evaluated as a function of the energy release rate range. Takeda et al. [8] conducted fatigue tests to determine the effects of toughened interlaminar layers with quasi-isotropic CFRP laminates by evaluating the transverse crack density growth rate and the delamination ratio growth rate as a function of the energy release rate range. Moreover, it is known that microscopic damage of CFRP laminates grows as interacting between matrix cracks and delamination. Some studies were conducted with respect to the interaction between matrix cracks and delamination [9-12].

Many studies on microscopic damage growth of CFRP laminates have been conducted for 2 or 3 decades as mentioned above. However, the studies about the high-cycle fatigue characteristics of CFRP laminates over 10^8 cycles have hardly been conducted and the long-term reliability of CFRP laminates has not been established yet, though it is noted that high-cycle fatigue fractures are the main cause of the destruction of the structures in metal materials. In recent years, Hosoi et al. [13] researched the growth of transverse cracks and delamination of the quasi-isotropic CFRP laminates in the high-cycle region. As a result, it was observed that the transverse crack growth delayed under the test condition at the low-applied stress level, and it is suggested that a threshold limit exists for transverse crack growth. However, from the viewpoints of establishment of the long-term reliability and the damage tolerance design, it is important to make a design where delamination is not initiated even if there are matrix cracks in the structure.

Therefore, in this study, the effects that the transverse cracks have on the initiation and propagation of the edge delamination were investigated under high-cycle fatigue.

2 Experiments

2.1 Materials

The material system used in this study was T800H/3631. The stacking sequence of laminates was $[45/0/-45/90]_S$. The specimen geometry is shown in Fig. 1. All specimens were 210 mm long, 30 mm wide, and 1.1 mm thick with 55 mm GFRP end-tabs leaving a 100 mm gauge section. The fiber volume fraction and the cure temperature of the specimen were 57 % and 453 K, respectively. Then, Young's modulus, tensile strength and failure strain of the laminates were 59.4 GPa, 775 MPa and 1.46 %, respectively.

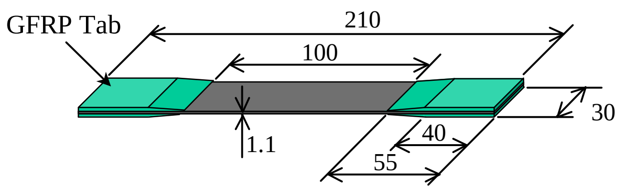


Fig. 1. Specimen geometry used in fatigue tests.

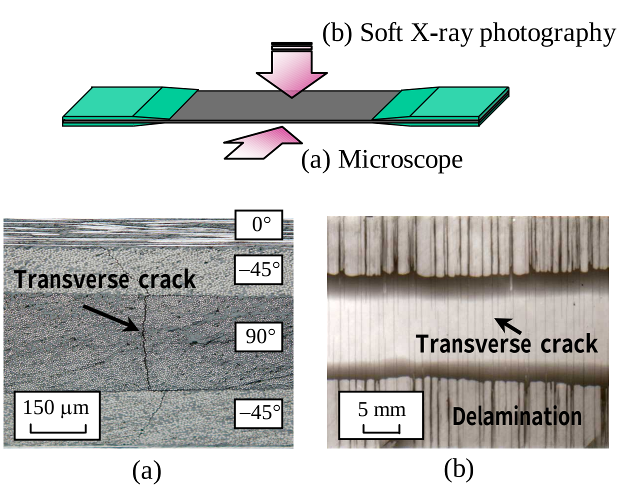


Fig. 2. Damage behavior observed with (a) microscope and (b) soft X-ray photography.

In this study, to investigate the effects that the transverse crack has on the initiation and propagation of edge delamination, two types of specimens were prepared. One was the specimen where transverse cracks were arbitrarily introduced by static tensile loading before conducting the fatigue tests. The other was an undamaged specimen as new. In this study, these specimens are named "pre-damaged specimen" and "undamaged specimen", respectively.

2.2 Test conditions

Tensile fatigue tests were conducted at room temperature with a sine waveform under load control conditions using a hydraulic-driven testing machine. All tests were run at a stress ratio of R=0.1. For examination of the fatigue life of the specimen, the applied stress level was set within σ_{max}/σ_b=0.70-0.90 and for investigation of the fatigue damage growth, the applied stress level was set at σ_{max}/σ_b=0.20-0.60. In this study, σ_{max} and σ_b show the maximum applied stress in the fatigue tests and the tensile strength, respectively. In the case of the fatigue tests at a frequency of 5 Hz, the applied stress level was set within σ_{max}/σ_b=0.20-0.90. At a frequency of 100 Hz, the applied stress level was set within σ_{max}/σ_b=0.20-0.35 to control the specimen temperature rising under fatigue tests.

2.3 Damage observation

The damage behavior was observed in detail with a microscope and soft X-ray photography. The transverse crack and the delamination which initiated at specimen edges were observed with a microscope. Then, the transverse crack and the delamination which propagated inside the specimen were observed by soft X-ray photography. The representative photos are shown in Fig. 2.

To evaluate the growth of transverse crack and delamination quantitatively, they are defined as follows. Transverse crack density was defined as the number of transverse cracks per gauge length (40 mm) in the center of the specimen. Transverse crack length was defined as the average length of all transverse cracks in the gauge length and the delamination ratio was defined as the area of delamination in the gauge area.

3 Experiment Results

In this study, the influence that transverse cracks have on initiation and propagation of edge delamination was investigated under high-cycle fatigue loading up to 3.0×10^8 cycles. First, the results showing the temperature change of the specimen under fatigue test are presented in section 3.1. Next, the results of the fatigue life of the specimen and its fatigue damage growth behavior are shown in section 3.2. Then, the effects that pre-introduced transverse cracks have on the initiation and propagation of edge delamination are described in section 3.3. The difference of the fatigue damage growth behavior, depending on the applied stress level is shown in section 3.4.

3.1 Measurement of specimen temperature change under fatigue tests

The prepreg of CFRP has mechanical and thermal anisotropy, so it is known that the anisotropy influences the fracture mechanism of the laminates. This is because residual thermal stress is caused by the variation in test temperatures from the curing temperature in the specimen. And then, it is predicted that the temperature of the specimen rises due to visco-elastic characteristics during the fatigue test at a frequency of 100 Hz. Moreover, in this study, the specimens which had pre-introduced transverse cracks as initial damage before the fatigue test were also used. It is forecasted that the friction on the transverse crack surfaces causes the temperature rising of the specimen. Hence, the temperature change in each test condition was measured with an infrared temperature sensor.

Figure 3 shows the results of the temperature change of the specimen. From these results, a remarkable temperature rise was not observed and the temperature of the specimen was sufficiently low in comparison with the glass transition temperature of the specimen under each test conditions. It was then observed that the temperature of the specimen remained constant after about 150 seconds. According to the study conducted by Hosoi et al. [13], it was noted that the variation of the frequency between 5 Hz and 100 Hz did not influence the fatigue damage behavior by much within the small temperature change under the fatigue test. Hence, in this study, the applied stress level was set within σ_{max}/σ_b=0.20-0.35 when the fatigue test was conducted with a frequency of 100 Hz.

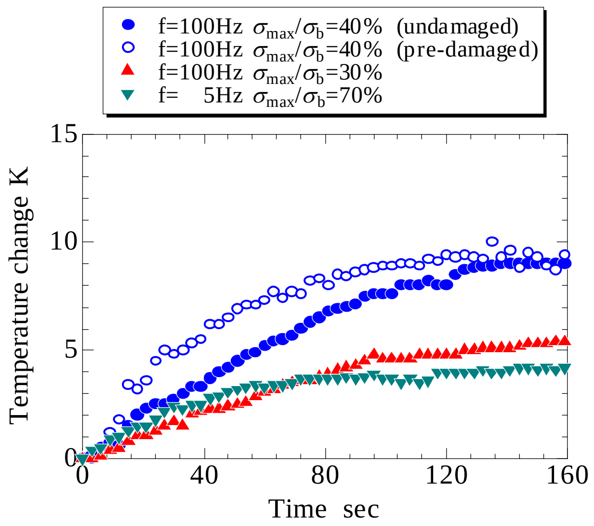


Fig. 3. Temperature change of specimen surface subjected to cyclic loading under frequencies of 5 Hz and 100 Hz.

3.2 S-N diagram and damage growth behavior

Figure 4 shows the S-N diagram obtained form the fatigue tests. The average fatigue life in each test condition was calculated with the method of least squares as follow equation.

$$\sigma = -19.03\ln(n) + 796.2 \qquad (1)$$

Using equation (1), fatigue damage growth, such as transverse crack growth and delamination growth, was evaluated as a function of normalized fatigue life. These results are described in section 3.3.

Generally, the quasi-isotropic CFRP laminates with a stacking sequence of $[45/0/-45/90]_S$ show a highly complex fracture mode [13, 14]. Fatigue damage growth behaved as follows under the test conditions of the applied stress level leading to fracture up to 10^6 cycles. In the primary stage of the fatigue test, transverse cracks were initiated in the 90° ply. Afterwards, delamination occurred in the interlaminar area of the –45°/90° plies or the 90°/90° plies. Almost simultaneously with the initiation of delamination, matrix cracks were initiated in the –45° ply from the tip of the transverse crack of the 90° ply. Then, the transverse crack of 90° ply and

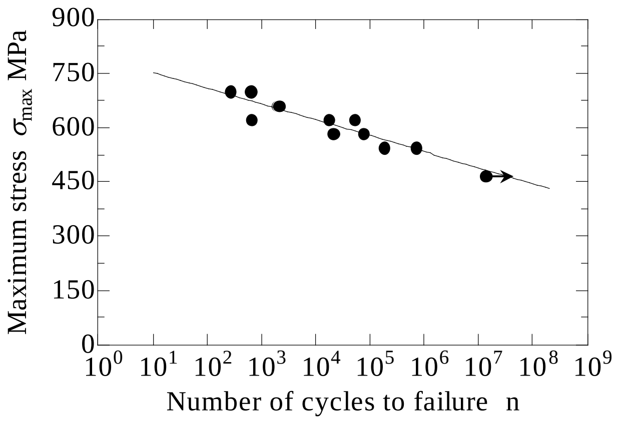


Fig. 4. S-N diagram

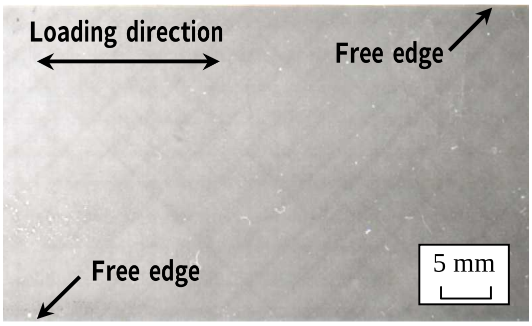
the delamination propagated to the width direction of the specimen. Moreover, matrix cracks of the 45° ply were observed at the edge. Finally, the specimen was radically fractured by the fibers breaking in the 0° ply.

3.3 Effects of transverse cracks on initiation of delamination

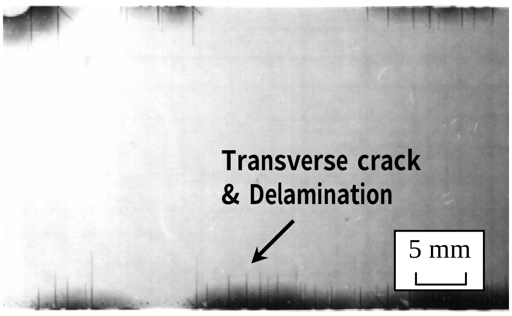
In this study, the fatigue damage growth behavior of the "undamaged specimen" was compared to that of the "pre-damaged specimen" to investigate the influence that transverse cracks have on the initiation and propagation of edge delamination. Figures 5 show the pictures of internal damage of the CFRP laminates with soft X-ray photography. The pictures of Figs. 5 show (a) "undamaged specimen" before the fatigue test, (b) the internal damage behavior under the test conditions of the applied stress level of σ_{max}/σ_b=0.50, the cycles of n=1.0×10^4 and the frequency of f=5 Hz with "undamaged specimen", (c) "pre-damaged specimen" before the fatigue tests and (d) the internal damage behavior under the test conditions of the applied stress level of σ_{max}/σ_b=0.40, the cycles of n=2.0×10^4 and the frequency of f=5 Hz with "pre-damaged specimen", respectively.

As shown in the Figs. 5 (b) and (d), it was observed that the edge delamination was initiated where the space of the adjacent transverse cracks was narrow. And then, delamination was not caused where there was no transverse crack under the test conditions. Hence, it was thought that the initiation of the edge delamination was concerned with the stress concentration at the transverse crack tip. On the other hand, comparing to the fatigue damage behavior in the "pre-damaged specimen" as shown in Figs. 5 (c) and (d), it was found that edge delamination was initiated emerging from the transverse cracks that were caused by cyclic loadings without emerging from the pre-transverse cracks that were introduced before the fatigue test. Therefore, it was thought that the effect caused by a single transverse crack introduced before the fatigue test was small with regard to the initiation of the edge delamination and it was related to the adjacent transverse crack space under the test conditions.

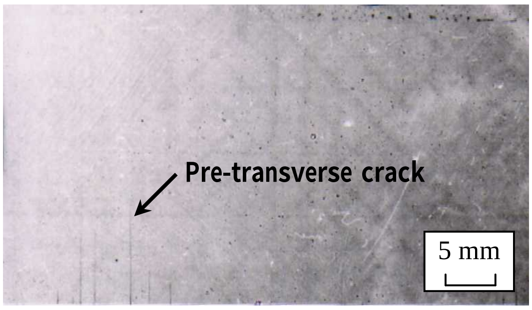
Moreover, the results investigating the internal damage growth behavior with the two types of



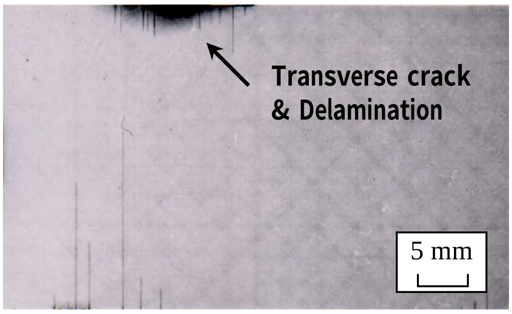
(a) Undamaged specimen before the fatigue test. (n=0)



(b) σ_{max}/σ_b=0.50, n=1.0×10^4 cycles, f=5 Hz (Undamaged specimen)



(c) Pre-damaged specimen before the fatigue test. (n=0)



(d) σ_{max}/σ_b=0.40, n=2.0×10^4 cycles, f=5 Hz (Pre-damaged specimen)

Fig. 5. The comparison of the internal damage growth behavior between "undamaged specimen" and "pre-damaged specimen"

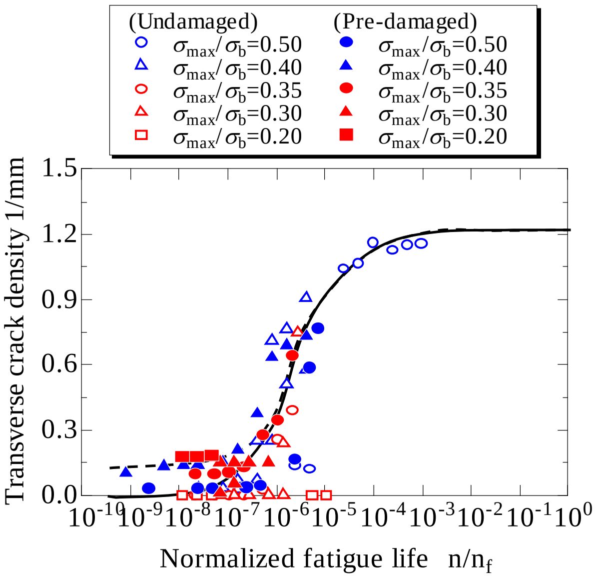


Fig.6. The transverse crack density as a function of the normalized fatigue life in “undamaged specimen” and “pre-damaged specimen”.

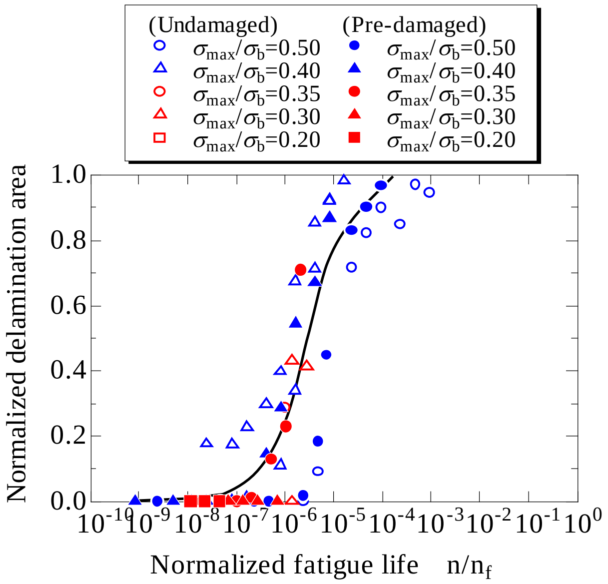


Fig.8. The delamination growth as a function of the normalized fatigue life in “undamaged specimen” and “pre-damaged specimen”.

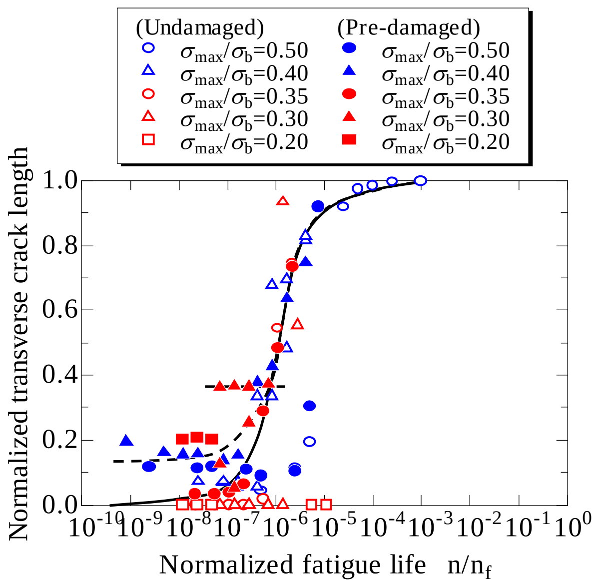


Fig.7. The transverse crack length as a function of the normalized fatigue life in “undamaged specimen” and “pre-damaged specimen”.

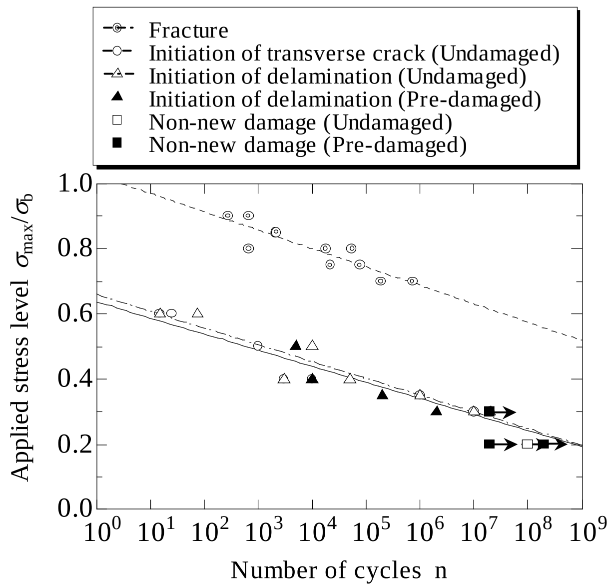


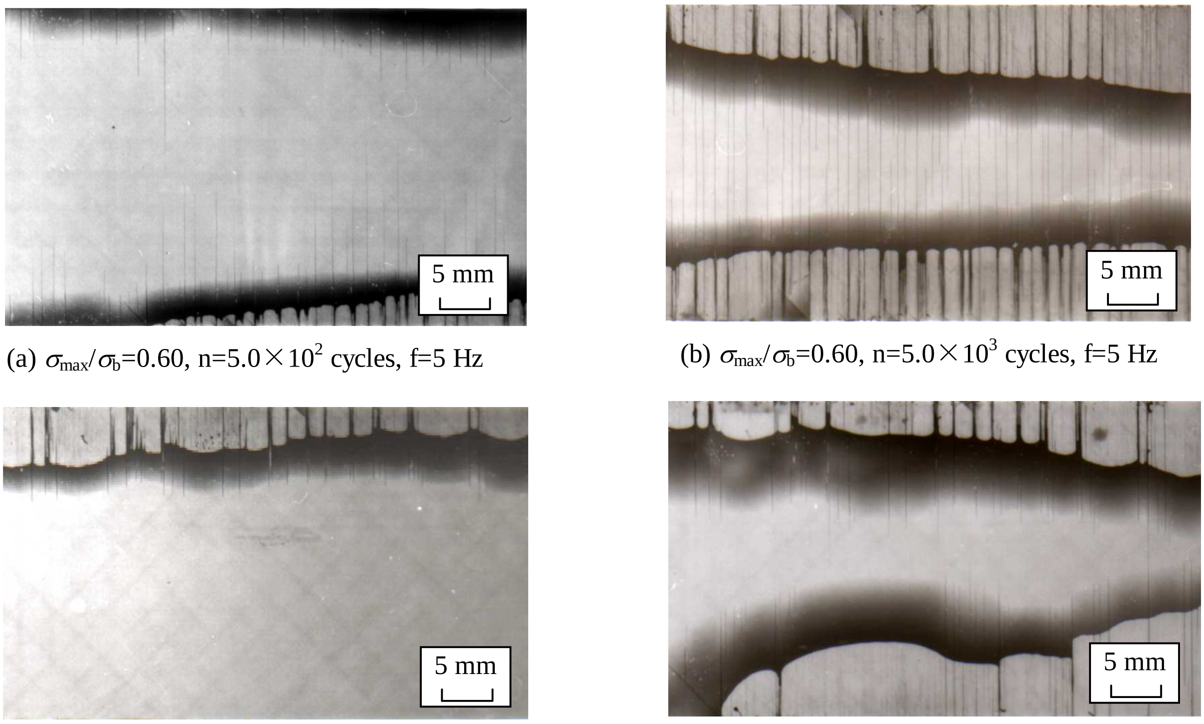
Fig.9. The number of cycles to the initiation of transverse crack and delamination

specimens are shown in Fig. 6-8. Figure 6 shows the transverse crack density initiated at the specimen edge as a function of the normalized fatigue life predicted with the S-N curve. Figure 7 shows the normalized transverse crack length propagated in the width direction of the specimen as a function of normalized fatigue life. Figure 8 shows the delamination growth as a function of the normalized fatigue life. In these graphs, hollow plots show the results of “undamaged specimen” and solid plots show the results of “pre-damaged specimen”. From these results, it was found that the fatigue damage behavior of each specimen was similar. Then, Fig. 9 shows the results evaluating the number of cyclic loadings in the damage initiation under each applied stress level. From the graph, it was found that the number of cyclic loadings in the initiation of transverse crack and delamination was almost the same, and the results are approximately collinear by evaluating with a logarithmic function. In this study, under the test condition of the applied stress level of σ_{max}/σ_b=0.20, the initiation and propagation of damage, such as transverse crack and delamination, were not observed up to 3.0×10^8 cycles. These results mean there may be a threshold limit in the initiation and propagation of damage, or that damage may initiate when cyclic loadings of about 1.0×10^9 are applied, estimating from the approximate line shown in Fig. 9. In this respect, more investigations are needed in the future.

3.4 The difference of damage behavior depending on the applied stress level

In this study, the different fatigue damage growth behavior was observed depending on the applied stress level. Figures 10 show the difference of the internal damage in the case of the applied stress level of σ_{max}/σ_b=0.60 and σ_{max}/σ_b=0.35. Figures 10 (a) and (b) show the results under the test condition of the applied stress level of σ_{max}/σ_b=0.60 and Figs. 10 (c) and (d) show the results of the applied stress level of σ_{max}/σ_b=0.35. As described in section 3.2, it is known that transverse cracks generally propagate to the specimen width direction before delamination growth though that depends on the laminate configuration. However, as shown in Figs. 10 (c) and (d), when the fatigue tests were conducted under the test conditions of applied stress level of σ_{max}/σ_b=0.35 or 0.30, it was observed that delamination grew before, or simultaneously with, the transverse crack propagation.

Figures 11 show the fatigue damage behavior of the specimen when the fatigue tests similar to this study were conducted by Hosoi et al. [13]. The specimen used in the study was $[-45/0/45/90]_S$ quasi-isotropic CFRP laminates made from the prepreg of T700S/2500. Figure 11 (a) shows the results in the case of the applied stress level of σ_{max}/σ_b=0.50 and Figs. 11 (b) and (c) show the results in the case of the applied stress level of σ_{max}/σ_b=0.30. In that study, it was also observed that the transverse cracks did not propagate before delamination when the fatigue test was conducted with the low-applied stress level, while the transverse cracks propagated before delamination in the case of the fatigue test with the high-applied cyclic loadings. Hence, it is thought that the results obtained in this study have reproducibility.



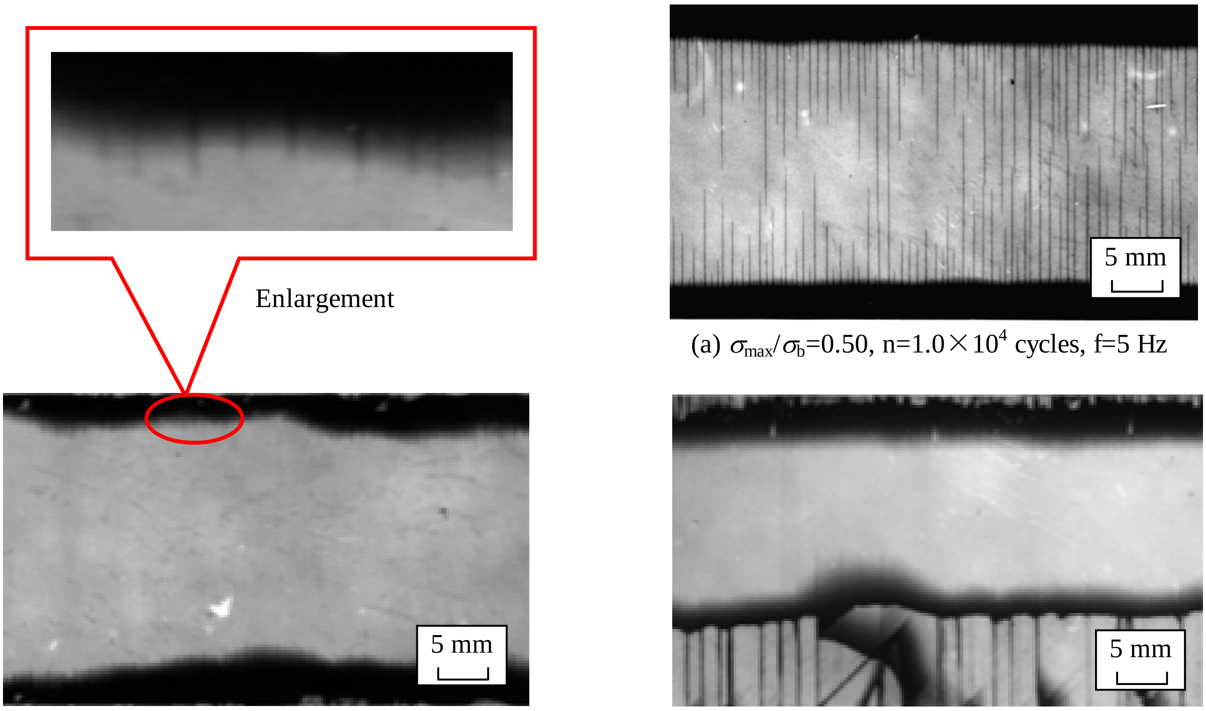
(a) σ_{max}/σ_b=0.60, n=5.0×10^2 cycles, f=5 Hz

(b) σ_{max}/σ_b=0.60, n=5.0×10^3 cycles, f=5 Hz

(c) σ_{max}/σ_b=0.35, n=1.0×10^6 cycles, f=100 Hz

(d) σ_{max}/σ_b=0.35, n=2.0×10^6 cycles, f=100 Hz

Fig. 10. The difference of the internal damage growth behavior depending on the applied stress level (T800H/3631).



(a) σ_{max}/σ_b=0.50, n=1.0×10^4 cycles, f=5 Hz

(b) σ_{max}/σ_b=0.30, n=1.0×10^6 cycles, f=100 Hz

(c) σ_{max}/σ_b=0.30, n=9.0×10^6 cycles, f=100 Hz

Fig. 11. The difference of the internal damage growth behavior depending on the applied stress level (T700S/2500).

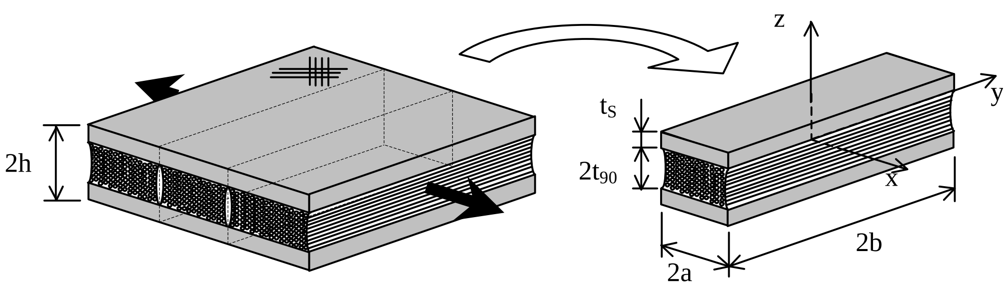
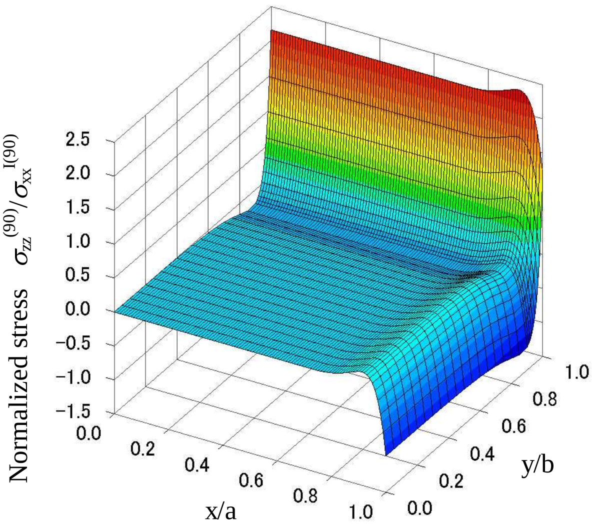


Fig. 12. The analytical model of $[(S)/90_n]_s$ laminate and its representative unit.

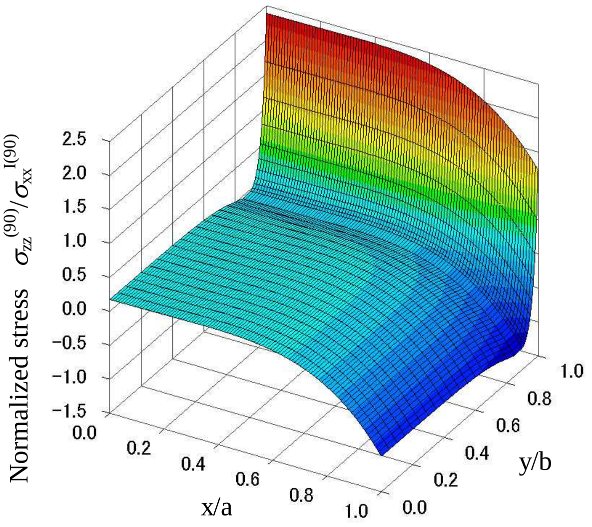
4 Stress analysis of cracked laminate

Hosoi et al. [15] proposed the analytical model of the laminates containing the transverse cracks considering the free-edge effects and the residual thermal stress, by modifying the model proposed by Hasin [16]. Using the stress analysis, the change of the stress states in the laminates by the difference of the crack density was calculated. Though the results by the stress analysis show good agreement with the results by the finite element analysis, it is note that in the analysis, the variation of the in-plane normal stress in the through-thickness direction is neglected, and that the stress concentration at the transverse crack tip cannot be considered.

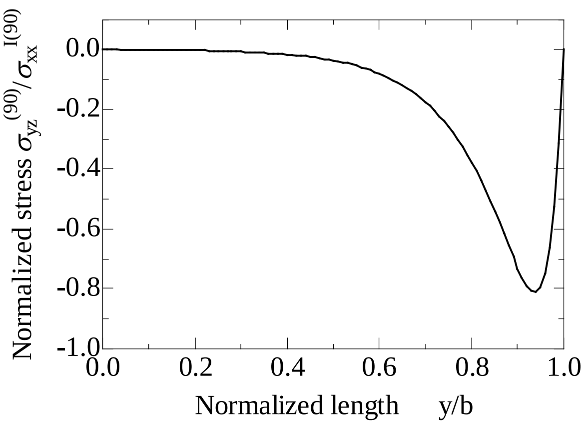
The analytical model was shown in Fig. 12. The model applied in this analysis was the cross-ply laminates of the form $[(S)/90_n]_S$ which contain distributions of transverse cracks within the 90° plies, where (S) is an orthotropic sub-laminate. Two types of the model of $[45/0/–45/90]_S$ laminates were considered in this study. Model 1 was a=5.0 mm, b=5.0 mm t_{90}=0.144 mm and t_S=0.432 mm. In model 2, the transverse cracks space was changed to a=0.75 mm. Sub-laminate (S) is $[45/0/-45]_T$ and its mechanical properties were calculated with the classical laminate theory. The test temperature is 298 K and the residual stress free temperature is 453 K. In the analysis, the material properties of T800H/3631 were used [15].



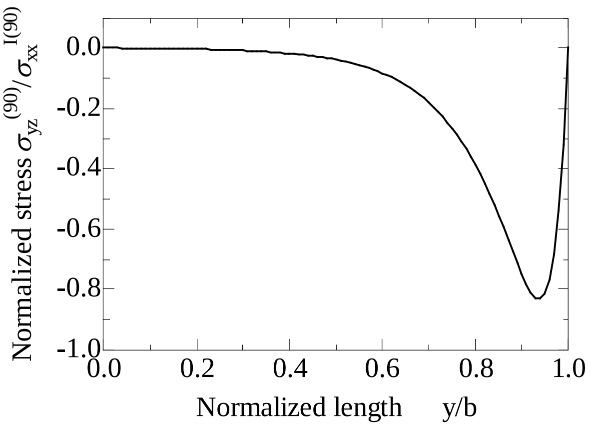
(a) Stress distribution of σ_{zz} at z=0 in xy-plane with model 1 (a=5 mm, b=5 mm)



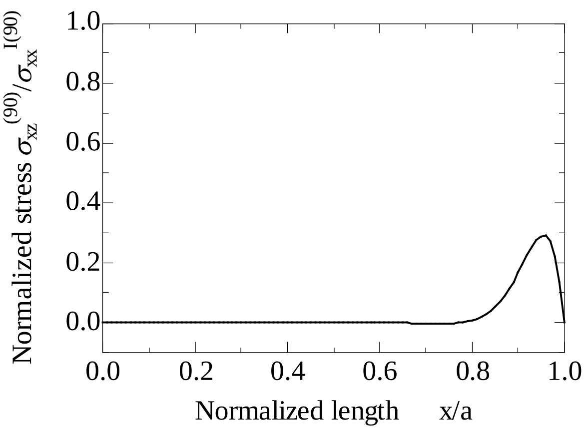
(b) Stress distribution of σ_{zz} at z=0 in xy-plane with model 2 (a=0.75 mm, b=5 mm)



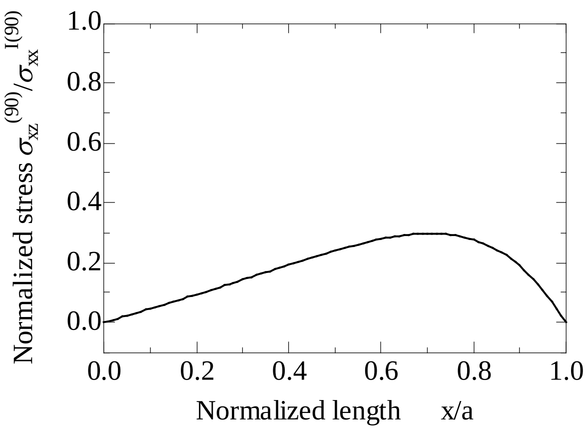
(c) Stress distribution of σ_{yz} at x=0 and z=t_{90} in y-axis with model 1 (a=5 mm, b=5 mm)



(d) Stress distribution of σ_{yz} at x=0 and z=t_{90} in y-axis with model 2 (a=0.75 mm, b=5 mm)



(e) Stress distribution of σ_{xz} at y=0 and z=t_{90} in x-axis with model 1 (a=5 mm, b=5 mm)



(f) Stress distribution of σ_{xz} at y=0 and z=t_{90} in x-axis with model 2 (a=0.75 mm, b=5 mm)

Fig. 13. Stress distribution calculated by the proposed model. (a), (b): Stress distribution of σ_{zz}, (c), (d): Stress distribution of σ_{yz}, (e), (f): Stress distribution of σ_{xz}.

Figures 13 (a)-(f) show the stress states calculated with the analytical model. Figures 13 (a), (c) and (e) show the results in model 1 and Figs. 13 (b), (d) and (f) show the results in model 2. Each stress distribution was normalized with the initial stress of 90° plies containing the residual thermal stress in the undamaged laminates, $\sigma_{xx}^{I(90)}$. Figures 13 (a) and (b) show the stress states of σ_{zz} calculated at z=0 in the xy-plane, Figs.13 (c) and (d) show the stress state of σ_{yz} calculated in the y-axis at x=0 and z=t_{90} and Figs. 13 (e) and (f) show the stress state of σ_{xz} calculated in the x-axis at y=0 and z=t_{90}. From Figs. 13 (a) and (b), it is found that the large peeling stress are applied at the specimen edges, and does not change by much when the transverse crack space is changed. As shown in Figs. 13 (c) and (d), the shear stress applied to the specimen-width direction is also not influenced by the transverse crack space. Figs. 13 (e) and (f) show the shear stress caused by the transverse cracks. It is found that the shear stress of σ_{xz} is not so large comparing to that of σ_{yz} in the y-axis, though the stresses cannot be compared precisely because the stress concentration at the transverse crack tip is ignored in the analysis.

5 Discussions

5.1 Effects of initial damage for initiation of delamination

The delamination growth of CFRP laminates is roughly classified into the two modes. One is the edge delamination initiating from the specimen edges as observed in this study. Another is the local delamination emerging from the transverse crack propagated to the inside of the specimen. It is thought that the initiation and propagation of the edge delamination are mainly related to three factors. The first is the fracture by the mode I called free-edge effects that the peeling stress was applied at the specimen edges as shown in Figs. 13 (a) and (b). The second is the fracture by the mode II that is caused by the difference of the mechanical properties between 90° ply and its adjacent plies. The third is the stress concentration at the transverse crack tip. As shown in Fig. 5 (b), the delamination was initiated at the area where the transverse cracks were dense, and it was thought that edge delamination growth was promoted by the stress concentration at the transverse crack tip.

However, the edge delamination was initiated at the area where the transverse cracks caused by cyclic loadings were dense without emerging from pre-transverse cracks introduced before the fatigue test as shown in Figs. 5 (c) and (d). Moreover, the damage growth behavior of the "pre-damaged specimen" and the "undamaged specimen" was similar, as shown in Figs. 6 to 9. Considering these results, it is thought that the effect that the pre-introduced transverse cracks have on the initiation of the edge delamination is small. Furthermore, considering that delamination propagated before, or simultaneously with, the transverse crack propagation under cyclic loadings of the low-applied stress level as shown in Figs. 10, it is thought that the edge delamination is mainly caused by cyclic loadings applied at specimen edges, which are the large peeling stress and the interlaminar shear stress between 90° ply and its adjacent plies. However, the effect of the stress concentration at the transverse crack tip should be large in the laminate configuration that the local delamination causes.

5.2 Difference of damage behavior depending of applied stress level

As shown in Figs. 10 and 11, the difference of the fatigue damage growth behavior was observed depending on the applied stress level. It is thought that the main reason is the interaction between the existence of threshold limit on the initiation and propagation of transverse cracks and the free-edge effects. That is, the transverse crack growth delayed in the case of the low-applied stress level because a threshold limit for the transverse cracks may exist [6, 13], and the large peeling stress was applied at specimen edges as shown in Figs. 13 (a) and (b). Therefore, under the fatigue tests of the low-applied stress level, it is thought that the edge delamination growth is mainly caused by the mixed mode of mode I and mode II without the transverse crack growing inside the specimen.

6 Conclusions

In this study, the initiation and propagation of the edge delamination considering the effects of the pre-introduced transverse cracks were investigated under the high-cycle fatigue. The following results were obtained.

1. In the results of the influence that the transverse cracks has on the initiation and propagation of the edge delamination with the two types of specimens, "pre-damaged specimen" and "undamaged specimen", it was found that the effect of the pre-introduced transverse cracks on the initiation of edge delamination was small. That is the

reason why the edge delamination was initiated at the area where the transverse cracks caused by cyclic loadings were dense without emerging from the pre-transverse cracks. Moreover, the results indicate that the effect of the stress concentration at the transverse crack tip is not sensitive to the initiation of the edge delamination. It is thought that the main factors of the initiation of the edge delamination are from mode I by the free-edge effects and mode II by the difference of the mechanical properties between the 90° ply and adjacent plies.

2. The fatigue damage growth behavior was investigated under each applied stress level. As a result, it was observed that the delamination grew before, or simultaneously with, the transverse crack propagation under the test conditions of applied stress level of σ_{max}/σ_b=0.35 or 0.30 while the transverse cracks propagated to the specimen width direction before the delamination growth under the test conditions of applied stress level of $\sigma_{max}/\sigma_b \geq 0.40$. That is the reason why we believe the threshold limit of the transverse crack initiation may exist and the large peeling stress caused by the free-edge effects is applied at the specimen edges. Hence, it is thought that the edge delamination is initiated and propagates without the transverse cracks under the low-applied stress level.

3. When the fatigue test was conducted under the test conditions of the applied stress level of σ_{max}/σ_b=0.20, the initiation and propagation of damage, such as transverse cracks and delamination, was not observed up to 3.0×10^8 cycles. The results may indicate the existence of a threshold limit of the initiation and propagation of damage. However, the transverse cracks or delamination may be initiated at around 10^9 cycles according to the prediction shown in Fig. 9. As for the damage initiation under the giga-cycle fatigue, more detailed experiments are needed in the future.

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