FATIGUE LIFE PREDICTION OF THICK CFRP LAMINATES WITH TOUGHENED INTERLAMINAR LAYERS IN THE OUT-OF-PLANE DIRECTION AT DIFFERENT STRESS RATIO

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Keywords: fatigue, thick CFRP laminates, out-of-plane, stress ratio, constant fatigue life model

Abstract
The fatigue life of thick carbon fiber reinforced plastic (CFRP) laminates with toughened interlaminar layers in the out-of-plane direction was evaluated at different stress ratios. The spool shaped specimens were cut out the unidirectional thick CFRP laminates which pile up 88 plies of the prepreg with toughened interlaminar layer, T800S/3900-2B. The fatigue tests were conducted under the stress ratios of R = 0.1, -1, -3 and -6 to evaluate the effect of the stress ratio. As the results of the fatigue tests, the fatigue life of the specimens became shorter as the stress ratio became smaller, i.e. as the absolute values of the compressive stress became higher. It was found that the fatigue properties of the CFRP laminates in the out-of-plane direction are affected by the stress amplitude from the experimental results. In addition, the fatigue life under the different stress ratio was evaluated equivalently using the proposed model, modified H-κ model, which considers the strain energy. The analytical results showed good agreement with experimental results. In addition, the fatigue properties of the thick CFRP laminates in the out-of-plane direction were evaluated with the constant fatigue life diagram derived from the proposed model.

1. Introduction

Carbon fiber reinforced plastic (CFRP) laminates with toughened interlamilnar layers, in which polyamide particles are added, have been developed to improve the compression after impact (CAI) strength [1]. The CFRP laminates with toughened interlaminar layers have approximately double CAI strength of the conventional ones without toughened interlaminar layers and they are used as the main structural members of the latest airplane. On the other hand, it has been pointed out that it is important to evaluate precisely the mechanical properties of the thick CFRP laminates with toughened interlaminar layers in the out-of-plane direction. The mechanical properties of the CFRP laminates are different between in plane transverse direction and out-of-plane direction due to the effect of the toughened interlaminar layers. In addition, understanding for the mechanical properties in the out-of-plane direction of the thick CFRP laminates with toughened interlaminar layers is never enough.

Excerpt from ISBN 978-3-00-053387-7

Sato et al. [2] have investigated the effect of toughened interlayers on the mode I fatigue crack propagation of unidirectional CFRP laminates. They showed that the fatigue crack growth resistance was greater for the toughened interlaminar crack growth for the intralaminar crack growth. Authors [3,4] have conducted the static tensile tests and tensile fatigue tests using thick CFRP laminates with toughened interlaminar layers in the out-of-plane direction. We showed that the fracture occurred mainly by not the toughened interlaminar delamination but intralaminar delamination under both static and fatigue tests, and the fatigue strength in the out-of-plane direction was lower than that in the in-plane transverse direction. In addition, authors [5] conducted the fatigue tests at stress ratio of R = 0.1 and -1 to evaluate the effect of the compressive stress on the fatigue properties of thick CFRP laminates in the out-of-plane direction. As the results, it was found that the fatigue life decreased due to the effect of the compressive stress. Thick CFRP laminates, however, were subjected to fatigue loading with higher compressive stress under practical environment. Therefore, to evaluate quantitatively fatigue properties in the out-of-plane direction of thick CFRP laminates with toughened interlaminar layers, the model to predict its fatigue life was proposed considering the effect of the stress ratio.

2. Experiments

2.1. Specimens

The unidirectional thick CFRP laminates, which pile up 88 layers of the prepreg with toughened interlayer, T800S/3900-2B, were formed with an autoclave. The fiber volume fraction of the laminates is V_f = 56%, and the cure temperature is 453 K. The dimensions of the specimen are shown in Fig. 1. The specimens were machined from the approximately 17 mm thick laminates. The shape of specimens is a cylinder solid with a narrow part like a spool shape. The diameters of the minimum and maximum cross-section surfaces are 18.75 mm and 25.0 mm, respectively. The roughness on the specimen surface was less than Ra=0.4 μm. Metal tabs were bonded to the upper and lower surfaces of the specimen.

2.2. Test conditions

Static tensile tests and fatigue tests were conducted with a hydraulic testing machine. The shaft centering device was used to attach the specimen to the testing machine. The static tensile tests were performed under displacement control at a crosshead speed of 0.1 mm/min. Four strain gages were stuck on the surface of the minimum cross section of the specimen. Fatigue tests were run at a frequency of f = 5 Hz and a stress ratio of R = 0.1, -1, -3 and -6 under load control. The stress level was set at σ_{max}/σ_b = 0.3 -0.75. The fatigue test was interrupted when the specimen did not fracture up to 10^6 cycles. The fracture surface of the specimens was observed with optical microscopy.

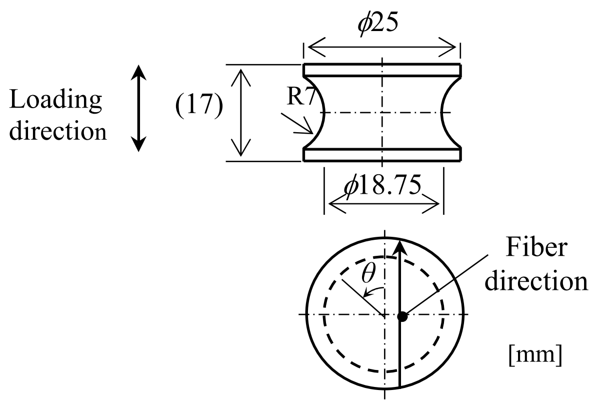

Figure 1. Specimen geometry.

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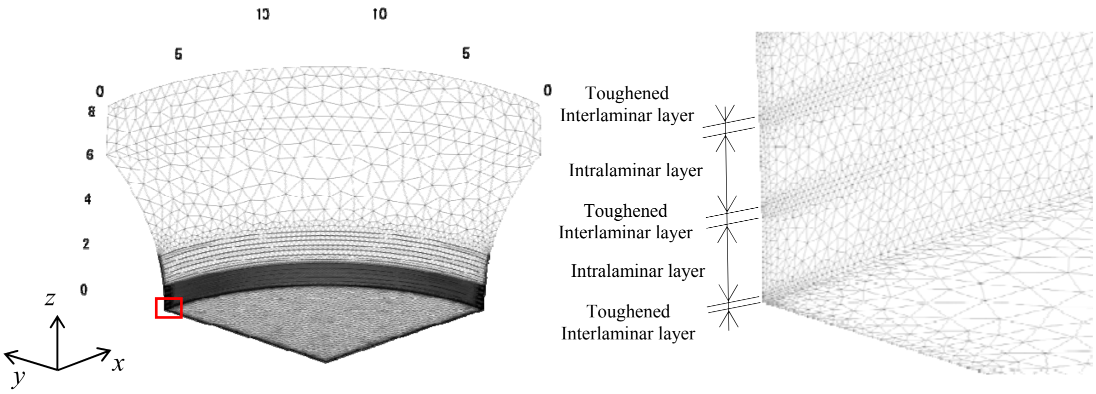
3. Stress analysis

Three-dimensional finite element (FE) analysis was carried out using the COMSOL program code. A one-eighth model was constructed for the analysis. The quadratic tetrahedron elements were used in the model. The minimum element size and the number of elements were 2 μm and 827168, respectively. The FE model is shown in Fig. 2. Each intralaminar and toughened interlaminar layer was modelled near the minimum cross section of the specimen and the other part was modelled as an orthotropic material. The thickness of the intralaminar and the toughened interlaminar layers was 165.4 μm and 22.6 μm from the observation of the specimen surface, respectively. The displacement in a direction perpendicular to loading direction was fixed on the top surface of the model to express the restriction by the tab. The force was applied on the top surface of the model. The model was calculated as the room temperature of 293 K. The values of material properties in Ref. [5] were used for the stress analysis.

Figure 3 shows the stress distribution of σ_z of thickness direction along the surface of $\theta = 0°$ direction when the force which corresponds to the nominal stress of 30 MPa at the minimum cross section area, was applied on the top surface of the model. It is found that the stress singularity field occurred near the interface between the intralaminar and toughened interlaminar layers. The maximum stress of σ_z is applied on the surface of $\theta = 0°$ direction in the first intralaminar layer from the central plane. The compressive stress is applied in the toughened interlaminar layers on the surface in the $\theta = 0°$ direction because of the free-edge effect.



(a) General view (b) Enlarged view

Figure 2. One-eigth FE model of the specimen.

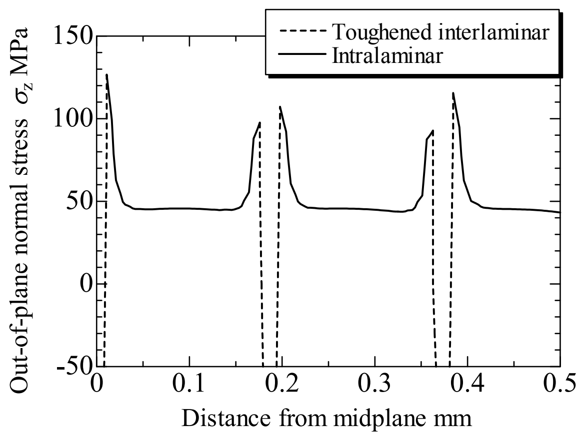


Figure 3. Stress distribution of σ_z of thickness direction along the surface of $\theta = 0°$ direction.

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4. Experimental results

4.1. Evaluation of fatigue life

Figure 4 shows the S-N curve at the stress ratio of R = 0.1, -1, -3 and -6. The vertical axis shows the average maximum stress on the surface at the minimum intralaminar cross-section calculated by FEM. The fatigue life became shorter as the stress ratio became smaller, i.e. as the absolute values of the compressive stress became higher. It was cleared that the fatigue properties in the out-of-plane direction of the CFRP laminates is affected due to the stress amplitude from the experimental results. It is thought that the difference of the fatigue life is caused by the plastic deformation of the matrix resin. The stress concentration occurs at matrix resin around carbon fibers under loadings and the local plastic deformation is caused around the carbon fibers even when the compressive stress is applied in the specimen [5].

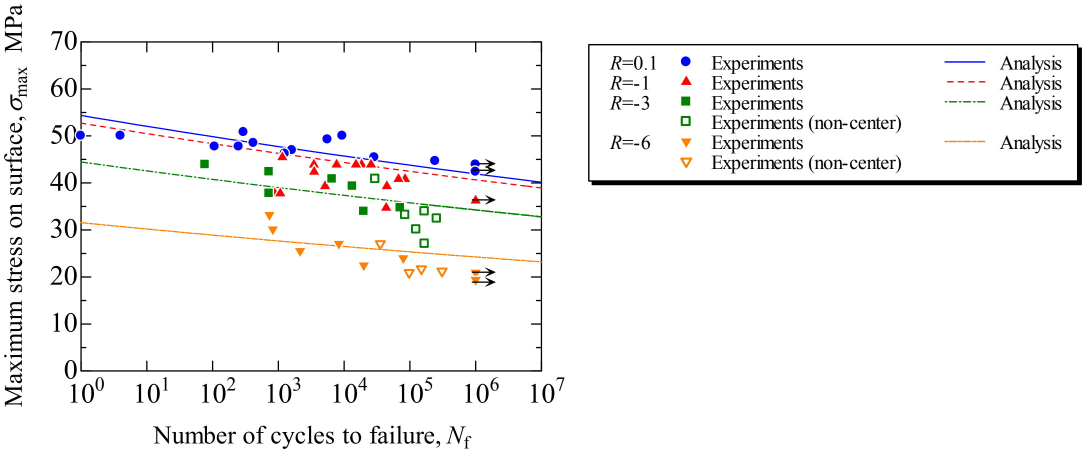
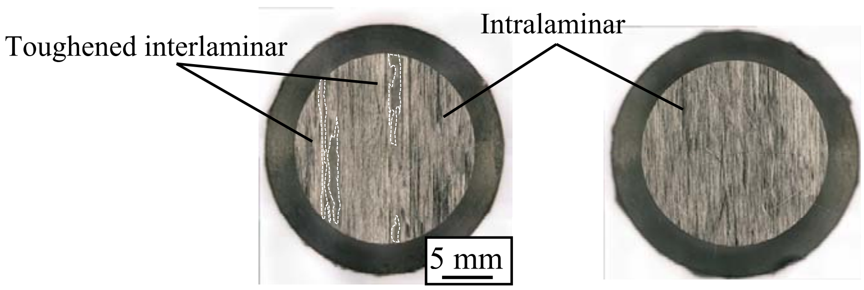


Figure 4. S-N curve of thick CFRP laminates in the out-of-plane direction at different stress ratios.

4.2 Damage observation

Figure 5 shows the fracture surface after the fatigue test at stress ratio of R = 0.1 and -6. The main fracture surface was intralaminar delamination. It is thought that the intralaminar delamination propagated because the intralaminar fracture toughness is lower than the toughened interlaminar fracture toughness. The similar fracture surface was observed for the specimens after static tensile tests and all fatigue tests. It was difficult to observe the initiation and propagation of a crack in this study. The stiffness reduction of the specimen was only a few percent until just before the fracture, and the stiffness reduced just before the fracture, and the fatigue crack was not observed by a digital microscope at $N/N_f = 0.9$ under the test condition of $\sigma_{max}/\sigma_b = 0.72$ and R = 0.1. Therefore, it is thought that the total fatigue life was dominated by the crack initiation.



(a) R = 0.1 (b) R = -6

Figure 5. Fracture surfaces of the specimen after fatigue test.

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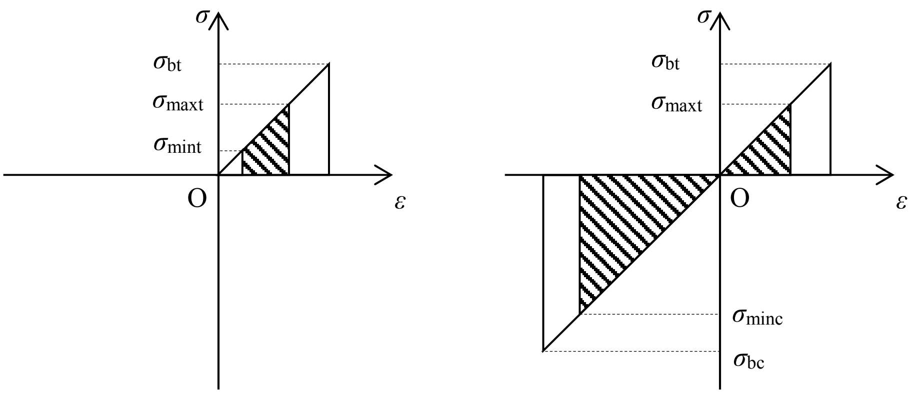
5. Prediction of fatigue life

Authors have proposed the H-κ model which can predict the fatigue life to transverse crack initiation in the cross-ply CFRP laminates subjected to tensile fatigue loading [6]. In this study, the fatigue tests were conducted under the loading conditions not only tension-tension but also tension-compression. Thus, the H-κ model was modified to consider the compressive loading. This model is based on the elastic strain energy as shown in Fig. 6. The equation to predict the fatigue life is shown as,

$$N_\mathrm{f} = H\left(\left|\frac{\sigma_{\max\mathrm{t}}{}^2 - \sigma_{\min\mathrm{t}}{}^2}{\sigma_\mathrm{bt}{}^2}\right| + \left|\frac{\sigma_{\max\mathrm{c}}{}^2 - \sigma_{\min\mathrm{c}}{}^2}{\sigma_\mathrm{bc}{}^2}\right|\right)^{-\kappa}, \tag{1}$$

where, $\sigma_{\max}$, $\sigma_{\min}$ and σ_b are maximum stress, minimum stress and strength of the specimen, respectively and t and c of subscripts show tension and compression, respectively. H and κ are constants decided by the experiments. In the case of tension-tension fatigue tests, $\sigma_\mathrm{maxc} = \sigma_\mathrm{minc} = 0$, and in the case of tension-compression fatigue test, $\sigma_\mathrm{mint} = \sigma_\mathrm{maxc} = 0$. In this study, H and κ were decided by fitting S-N curve in the tension-tension fatigue tests of R = 0.1, and σ_bc was decided by fitting S-N curve in the tension-compression fatigue tests of R = -6 as the apparent compression strength. The prediction results are shown in Fig. 4. The analytical results showed good agreement with experimental results. In addition, the constant fatigue life (CFL) diagram can be obtained using equation (1). The calculated CFL diagram is shown in Fig. 7.



(a) Tension-tension fatigue tests (b) Tension-compression fatigue tests

Figure 6. Concept of modified H-κ model.

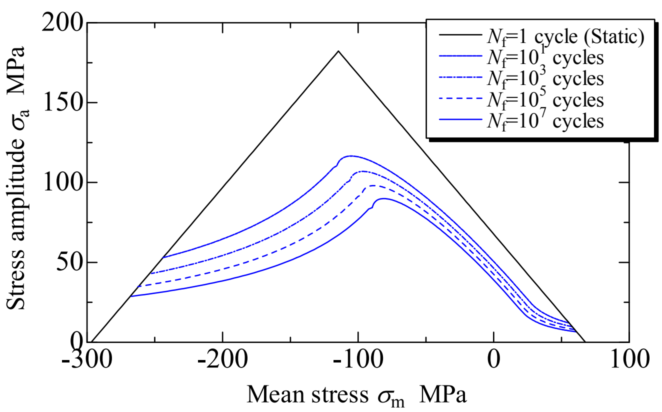


Figure 7. Constant fatigue life diagram calculated from the proposed model.

6. Conclusions

The effect of the stress ratio on fatigue properties in the out-of-plane direction of thick CFRP laminates with toughened interlaminar layers was evaluated. The fatigue tests were conducted at the stress ratio of R = 0.1, -1, -3 and -6 in this study. From the results of the fatigue tests, it was cleared that the fatigue life of the laminates was affected by the compressive loading and it became shorter as the stress ratio became smaller. In addition, to evaluate quantitatively the effect of stress ratio on the fatigue life of the laminates, the modified H-κ model was proposed. The fatigue life predicted using the modified H-κ model showed good agreement with experimental results. Furthermore, it was shown that the fatigue properties of the thick CFRP laminates in the out-of-plane direction can be evaluated with the CFL diagram derived from the proposed model.

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Excerpt from ISBN 978-3-00-053387-7