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STUDY ON DAMAGE DEVELOPMENT OF WOVEN FABRIC COMPOSITES UNDER LOW TEMPERATURE

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SUMMARY: To investigate the damage development of woven fabric composites under low temperature, the experimental results of low cycle fatigue tests and the numerical results based on damage mechanics have been described. Low cycle fatigue tests for woven glass fiber / vinylester composites have been performed at the room temperature and at temperatures below the freezing point. The damages are investigated by In-situ observation of the microscopic damage propagation during the fatigue test. The results show that the velocity of the crack propagation at room temperature is quite different from the one at low temperature. The occurrence and the propagation of the transverse crack in the fiber bundle depend on the temperature. It is expected that the reason for the above-mentioned differences lies in the temperature dependency of the mechanical property of the vinylester resin. The damage propagation has been analyzed by finite element method based on damage mechanics. The numerical results have shown that the location of transverse cracks in bundles at room temperature differs from those at low temperature. As the numerical results have a good agreement with the experimental results, it can be concluded that the fatigue strength at arbitrary temperature can be simulated by the temperature dependency of the strength of resin.

KEYWORDS : Woven Fabric Composites, Low Temperature, Low Cycle Fatigue, In-situ Observation, FEM, Damage Mechanics

INTRODUCTION

Polymer composites have been used widely in many structural applications working under extreme environmental condition, such artificial satellites, reusable launch vehicles vessels and so on[1]. Investigation of the mechanical behavior under low temperature below the freezing point is one of the very important points to be investigated. Some papers have described that the mechanical properties of FRP are quite different at the room temperature and below the freezing point[2][3]. The temperature dependency of mechanical properties may influence the development of damages in woven fabric composites. Especially, the estimation of damage propagation is very difficult, because matrix cracks and delamination at the crossover points of fiber bundle may occur leading to complicated fracture modes in comparison with uni-directional fiber reinforced composites.

To predict the mechanical properties for woven fabric composites, several papers on the micro-mechanical analysis have been published[5-9]. Ishikawa and Chou have developed one-dimensional mosaic model[5]. The one-dimensional models were extended to two-dimensional model[6]. Naik has described an analytical method, where the shape of a weave is approximated to a collection of cross-ply laminates[7]. Whitcomb has presented a three-dimensional finite element model of the plain weave fabric unit-cell geometry[8]. While 3D analyses give much more insight into stress distribution inside the weave, it has several problems such as mesh generation and so on[9]. Zako has developed a simple algorithm of mesh generation for woven structure by giving the dimension of bundles and pitch length[10], and proposed to adopt the concept of damage mechanics for 3D analysis[11]. It is expected that the approach is useful to grasp the damage condition inside fiber bundles and mechanism of damage occurrence.

Furthermore, if we consider the application of woven fabric composites to the structures working below the freezing point, it is very important to estimate the characteristics of low-cycle fatigue below the freezing point. However, there are few papers about low cycle fatigue characteristic of woven fabric composites at low-temperature. And, we have a few papers about the mechanism of damage development considering the effect of temperature[4].

The aim of this study is to the estimate damage development of woven fabric composites under low temperature. The experimental results about low cycle fatigue test for woven fabric composites at the room temperature and below the freezing point, and the numerical results of the mechanical behavior for woven fabric composites by finite element analysis based on damage mechanics are described.

LOW CYCLE FATIGUE TEST

Test specimens and experimental setup

Test specimens are cut out of a lamina plate. The lamina is fabricated by the hand-lay up method, using vinylester resin(supplied by Showa polymer Co. LTD.: R-806) reinforced by E-glass woven cloth fabric(supplied by Asahi fiberglass Co. LTD.: MS250). The geometry and structure of the test specimen for In-situ SEM observation are shown in Fig.1. The shape of specimen is rectangular. Aluminum tabs are attached at the ends of the specimen.

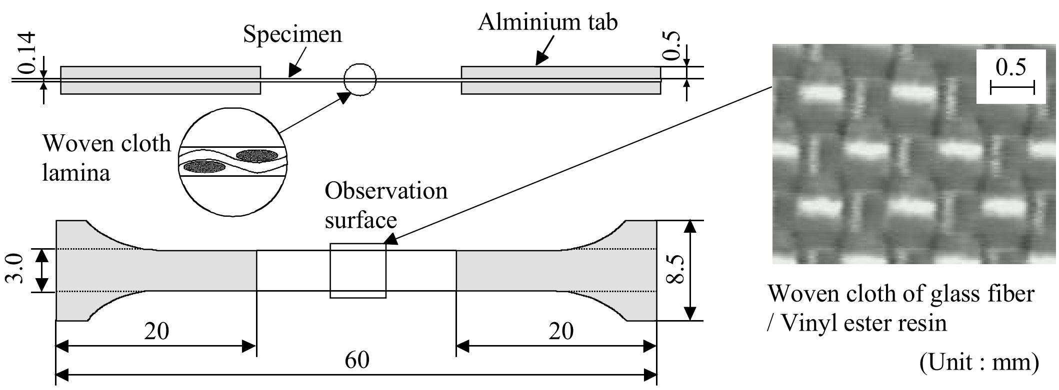
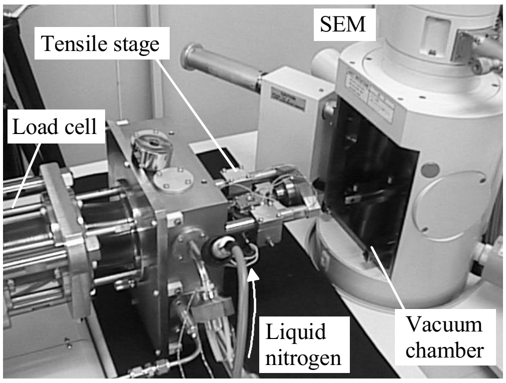


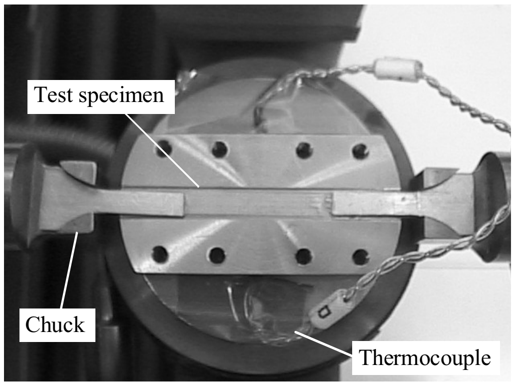
Fig.1 Geometry of specimen and structure of woven FRP

The density of woven cloth is 4 bundles / 3.0 mm.

The experimental equipment for In-situ SEM observation is shown in Fig.2. Testing device is composed of an electro hydraulic servo-type fatigue tester, SEM and liquid nitrogen vessel. In-situ observation can be performed by inserting the tensile stage into the vacuum chamber of SEM. For the experiments below the freezing point, the tensile stage is cooled by liquid nitrogen vessel. Tension-tension fatigue test is carried out by stress control with a frequency of 0.2Hz.



(a) Fatigue testing machine with SEM



(b) Tensile stage

Fig.2 Overview of the experimental equipments

Results of fatigue test

Figure 3 shows the relation between the stress amplitude and the number of cycles to failure. The results show the tendency that the fatigue life increase with the decreasing of the temperature and the difference in the fatigue life is very significant at high stress amplitudes. Matrix cracks have occurred at the crossover point of the fiber bundles on the upper surface of the specimen as shown in Fig.4. The SEM images of the crack propagation are recorded by a video camera, and the maximum length of the crack is measured. The results, for the cases of fatigue stress amplitude of 155 and 142 MPa at each temperature, are shown in Fig.5. The rate of crack development for number of cycles can be almost approximated to two straight-line parts for each experiment. In order to clarify this phenomenon, the damage development during the fatigue test has been observed on the upper surface and at the cross section of the

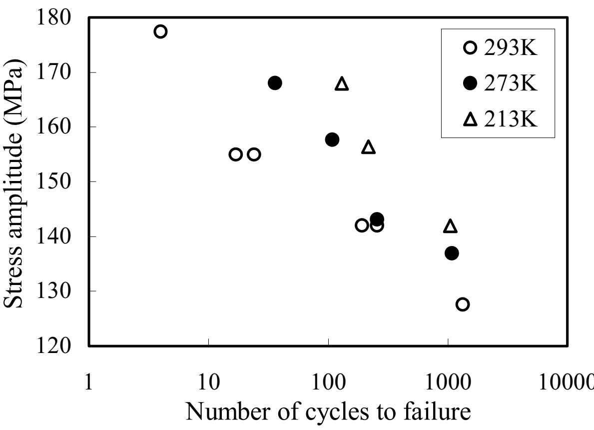


Fig.3 S-N diagram at each temperature

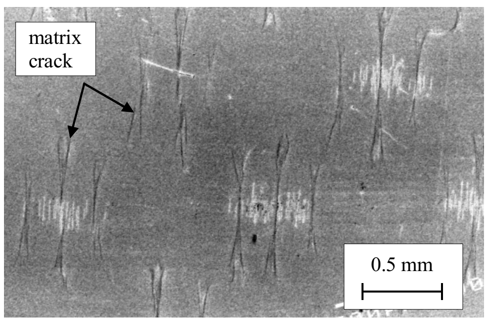
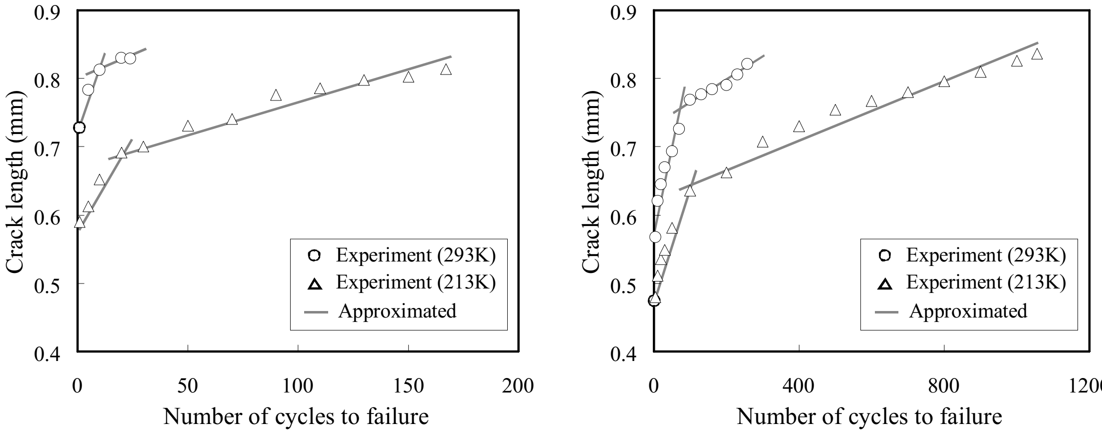


Fig.4 SEM image at the surface of damaged specimen (At 293K, stress amplitude 155MPa, $N/N_f = 1$)

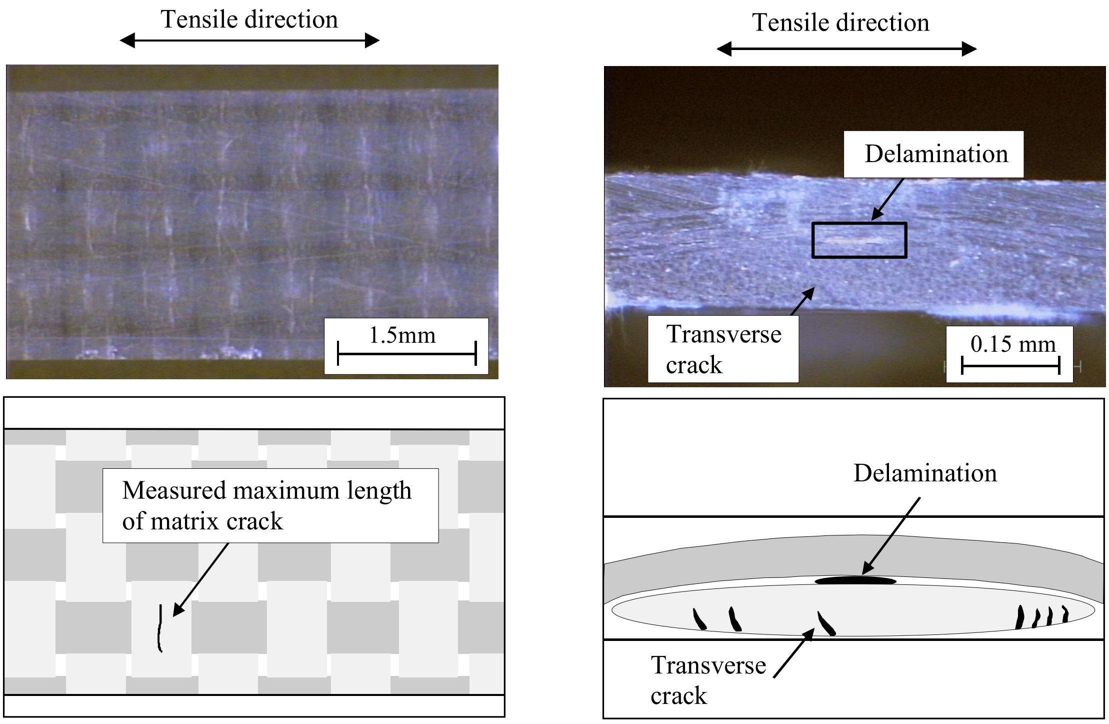
specimen by means of CCD. Figure 6 shows the observational results of damage development at the room temperature. Parameters N and N_f mean the number of cycles and fatigue life, respectively.

In Fig.6(a), the small matrix cracks appeared on the upper surface, and transverse cracks appeared in the fiber bundles perpendicular to loading direction. And, the very small delamination also occurred at each crossover part. In Fig.6(b), the matrix cracks propagate widely at each crossover part of fiber bundle. However, the delamination does not propagate. In Fig.6(c), it looks like the propagation of matrix cracks had stopped. However, inside of the specimen, the delamination has being propagated gradually along the fiber bundle. From these



(a) Case of stress amplitude 155MPa (b) Case of stress amplitude 142MPa

Fig.5 Crack propagation on fatigue life at each stress amplitude



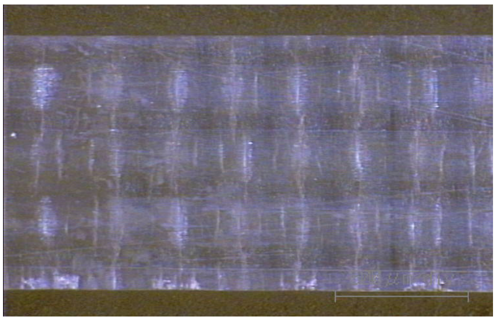
(a-1) Surface of specimen (a-2) Cross section of specimen

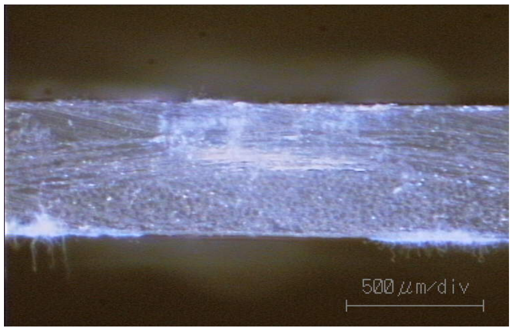
(a) In the case of $N/N_f = 0.016$

Fig 6 Damage development at 293K

observation, there is two propagation modes of matrix crack. Initial slope of the approximated line in Fig.5 indicates the occurrence of transverse crack and the propagation of matrix crack. And the sequential slope means that the matrix cracks do not propagate.

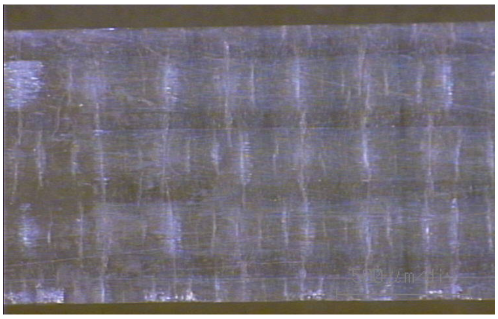
After the failure, the specimen is cut in the center of its width. The damage states at the cross sections of specimens are investigated by SEM. Figure 7 shows the cross section of fiber bundle in a damaged specimen. It is recognized that a few transverse cracks took place in a bundle at 293K and only one transverse crack occurs at 213K. It is very important to perceive the occurrence location and the number of transverse cracks.

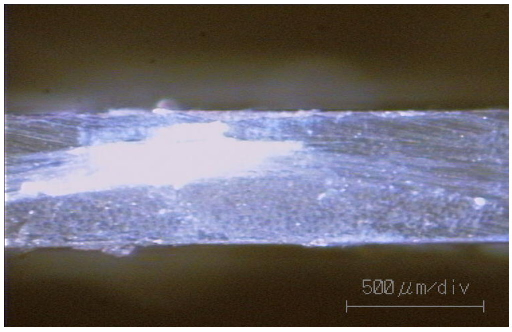




(b-1) Surface of specimen (b-2) Cross section of specimen

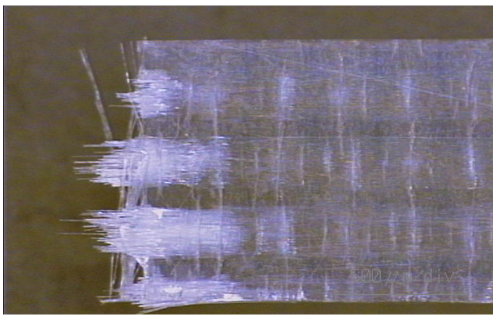
(b) In the case of $N/N_f = 0.16$

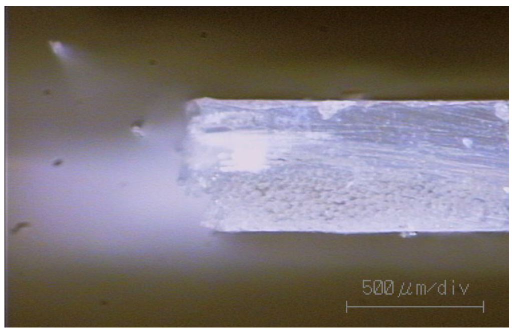




(c-1) Surface of specimen (c-2) Cross section of specimen

(c) In the case of $N/N_f = 0.48$

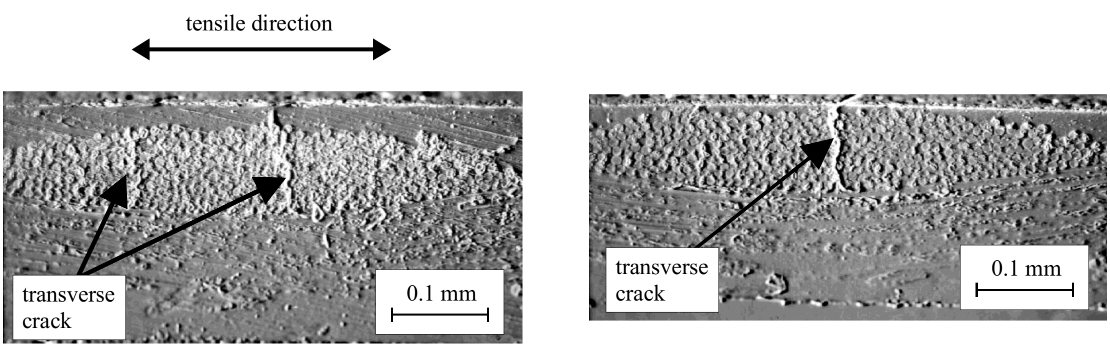




(d-1) Surface of specimen (d-2) Cross section of specimen

(d) In the case of $N/N_f = 1$

Fig 6 Continued



(a) At 293K (b) At 213K

Fig.7 Cross sectional images of fiber bundle in damaged specimen

FEM ANALYSIS BASED ON DAMAGE MECHANICS

It is expected that the reason for the above-mentioned differences of damage lies in the temperature dependency of the mechanical properties of the vinylester resin. To investigate the mechanical properties, a tensile test has been carried out. The specimens for tensile test have been made of vinylester resin. Temperature dependency of Young's modulus and tensile strength are shown in Fig.8. In this figure, Young's modulus E and tensile strength F are normalized by the values at T=293K, respectively. It is revealed that Young's modulus and tensile strength tend to increase with the decrease of temperature.

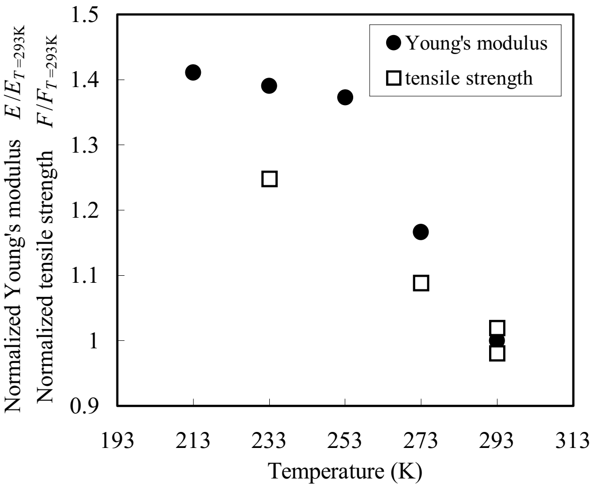


Fig.8 Temperature dependency of Young's modulus and tensile strength for vinylester

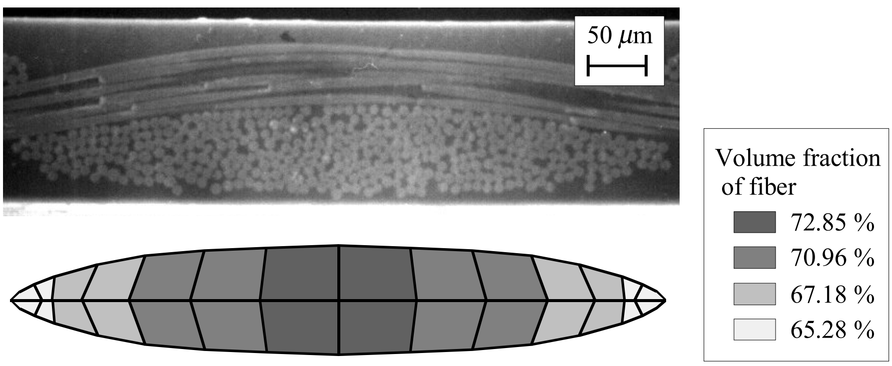
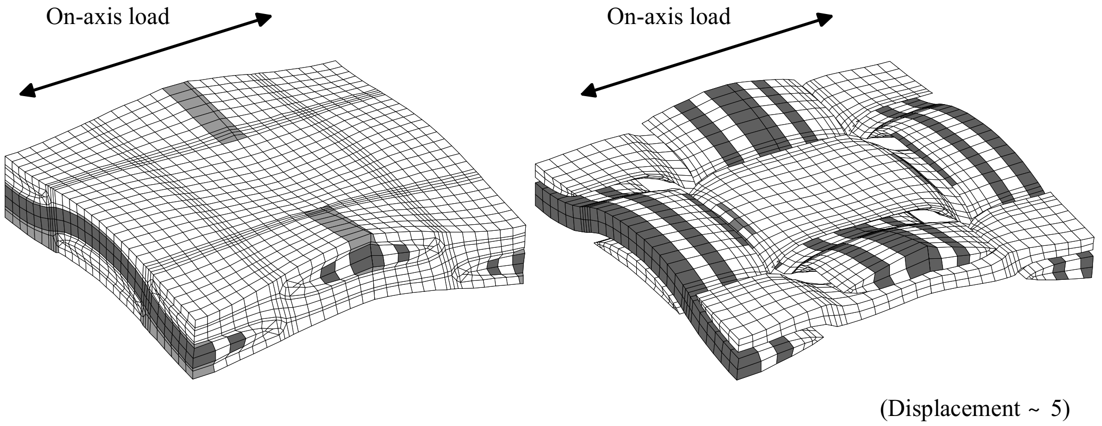


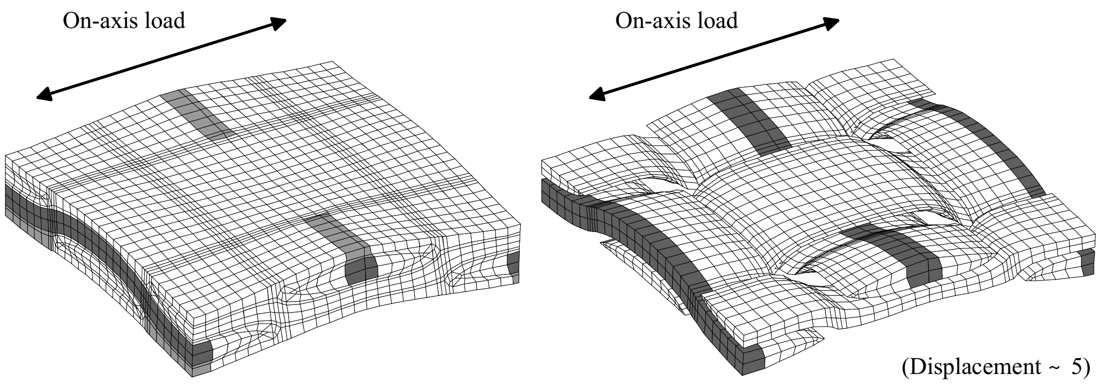
Fig.9 Distribution of volume fraction of fiber in a fiber bundle

The mechanical behavior of woven fabric composites under on-axis tensile load can be analyzed by finite element method based on damage mechanics [10][11]. In order to perceive the microscopic damage, a woven fabric composite is treated as a heterogeneous body composed of fiber bundle and matrix, where the fiber bundle is considered anisotropic while the matrix is considered to be isotropic. Figure 9 shows a SEM image indicating the distribution of the volume fraction of fiber. The temperature dependency of the mechanical properties of the vinylester is also considered. The occurrence of damage can be predicted by using Hoffman's criterion. The constitutive equation can be obtained by the characterization of the damage mode by Murakami's damage tensor [12]. The details of its derivation are reported in ref.[10]. Figure 10 shows the deformation and the damage states of woven fabric composite at 293K. In this figure, the black parts indicate the damaged elements judged by Hoffman's criterion. A transverse crack occurs at the center of bundle because of the decreasing of the interfacial bonding force between fiber and resin due to the high volume fraction of fiber. The cracks also appear at the edge parts of the fiber bundle at 293K. However, at 213K, the non-occurrence of cracks at the edge parts of bundle is due to the increase of the mechanical properties in Fig.11. These results derive the differences in the fatigue lives at each temperature.



(a) Illustration of fiber bundle and matrix (b) Illustration of only fiber bundle

Fig.10 Deformation and damaged state of woven fabric composite at 293K (σ = 105MPa, ε =1.63%)



(a) Illustration of fiber bundle and matrix (b) Illustration of only fiber bundle

Fig.11 Deformation and damaged state of woven fabric composite at 213K (σ = 103MPa, ε =1.15%)

CONCLUSION

Low cycle fatigue test for woven fabric composites has been carried out at the room temperature and below the freezing point. The results showed that the fatigue life tends to increase with the decrease of the temperature, and the difference in the fatigue lives is very significant at high stress amplitudes. The occurrence and propagation of the transverse crack in the fiber bundle depend on the temperature.

Furthermore, the mechanical behavior of composites under uni-axial static tensile load has been also analyzed by finite element method based on damaged mechanics. The numerical results show that the fiber bundle perpendicular to the loading direction suffered from transverse cracks at the central and edge parts at room temperature. Below the freezing point, however, only one transverse crack appeared at the central part of the bundle. From both experimental and numerical studies, it has been proved that the temperature must be taken into consideration as one of the main factors controlling the low cycle fatigue behavior.

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