NUMERICAL ANALYSIS OF THE MECHANICAL BEHAVIOR OF CARBON FIBER REINFORCED COMPOSITES BASED ON ELASTOPLASTIC MACROSCOPIC MODEL

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ABSTRACT

Carbon fiber reinforced plastics (CFRPs) are becoming increasingly important due to their high potentials to automotive, aircraft and ship applications. To the effective design of structural parts using CFRPs, reliable numerical modelling is indispensable. Therefore, many predicted models have been developed for the mechanical analysis of CFRPs. Micromechanical models have been used to predict the elastic behaviour of CFRPs, but their expensive computational cost remains a problem. Because the macroscopic behaviour of the complex composite structure should be described properly, various macroscopic models have been also developed based on continuum mechanics. However, it is still challenging to predict the failure behaviour of CFRPs at product level. In this study, continuum-based elastoplastic model (based on Chen and Sun's plastic model) was developed to analyse the mechanical behaviour of CFRP. Uniaxial tensile and compression tests of unidirectional CFRPs were carried out to determine the material parameters of the elastoplastic model. Initial and progressive failures of CFRPs were then determined by Puck's failure criterion and damage mechanics. The proposed model was implemented in ABAQUS using user material subroutine (UMAT). Finally, the nonlinear mechanical behaviour of CFRP was then predicted and compared with experiments, demonstrating the validity of the current model.

1 INTRODUCTION

Carbon fiber reinforced plastics (CFRPs) have been used in various engineering fields because of their high specific strength, rigidity and low density. In particular, the progressive failure analysis of composites was required to predict their mechanical behaviour under various loading condition for effective design. Therefore, the mechanical analysis of CFRPs has been well developed using numerical method in many studies and established in many work.

Micromechanical model[1] were based on the micro structure of the fiber and matrix. Theses model had an advantage in observing and evaluating the micro behaviour of the inside of composites. Micromechanical models have been used to predict the elastic behaviour of CFRPs, but their expensive computational cost remains a problem. Also, it was difficult to apply it to the mechanical analysis of the actual complex structure. Many macroscopic models [2,3] have been developed to analyse mechanical behaviour of composites included its non-linear behaviour, so many models were investigated and showed reasonable agreement between experimental. However, it was still challenging to predict the failure behaviour of CFRPs at product level.

In this study, macroscopic elastoplastic model was developed to analyse the mechanical behaviour of CFRP. Using the user material subroutine, developed model was implemented in finite element

analysis. Finally, the material parameters in model were defined and numerical simulation was compared with the experimental data for validation.

2 ELASTOPLASTIC MACROSCOPIC MODEL

2.1 Elasto-plastic constitutive model

In this study, plane stress condition was adopted to describe the mechanical behaviour of CFRP due to its simplicity and efficiency. First of all, the following decomposition of total strain increment into elastic and plastic component. The incremental form of the elastic behaviour was defined as generalized Hooke's law. The plastic strain increment was related by the associated flow rule. Nonlinear behavior was governed by the anisotropic elasto-plastic law modified by J.Cho et al.[4] based on the plasticity model proposed by Sun and Chen [5,6] . These were allowed by the plastic model which includes the yield criterion, plastic flow rule, hardening law. The plastic potential function (f) was introduced as:

$$f = \bar{\sigma} = \sqrt{a_1\left[\left(\sigma_{11} - \mu\sigma_{22}\right)^2 + \sigma_{11}{}^2\right] + a_2\sigma_{22}^2 + a_6\sigma_{12}^2} + b_1\sigma_{11} + b_2\sigma_{22} \quad (1)$$

where, a_1, a_2, a_6, b_1, b_2 were material parameter obtained from optimization of the effective stress-strain relationship of off axis test. The model was simplified by the basic assumption in J. Cho et al.[1]. Therefore, final plastic potential function in the case of unidirectional (equation (2)) and woven (equation (3)) was simplified as:

$$f = \bar{\sigma} = \sqrt{a_2\sigma_{22}^2 + \sigma_{12}^2} + b_2\sigma_{22} \quad (2)$$

$$f = \bar{\sigma} = \sqrt{2a_2[\sigma_{11}^2 - + \mu\sigma_{11}\sigma_{22} + \sigma_{22}^2] + \sigma_{12}^2} + b_2(\sigma_{11} + \sigma_{22}) \quad (3)$$

The effective stress and effective plastic strain were directly connected to the measured axial stress and plastic strain for given off-axis angle. To compared with that, master curve of hardening law of the effective stress ($\bar{\sigma}$) and effective plastic strain ($\bar{\varepsilon}$) was approximated by the following relationships.

$$\bar{\sigma} = \sigma_y^0 + A\left(\bar{\varepsilon}\right)^n \quad (4)$$

σ_y^0 and A were material parameter determined by the off axis tensile and compression test.

2.2 Damage model

In order to predict damage initiation and propagation, Puck's failure criterion [7] was adopted. It included two fiber failure (equation (5) and (6)) and three inter fiber failure mode (equation (7), (8), (9)). The evolution of damage was possible when the stresses reached the corresponding damage level.

$$\frac{1}{\varepsilon_{1t}}\left(\varepsilon_1 + \frac{\nu_{f12}}{E_{f1}} m_{\sigma f}\sigma_2\right) = 1 \quad \text{(fiber tension)} \quad (5)$$

$$\frac{1}{\varepsilon_{1c}}\left|\left(\varepsilon_1 + \frac{\nu_{f12}}{E_{f1}} m_{\sigma f}\sigma_2\right)\right| + (10\Upsilon_{21})^2 = 1 \quad \text{(fiber compression)} \quad (6)$$

$$\sqrt{\left(\frac{\tau_{21}}{S_{21}}\right)^2 + \left(1 - p_{vp}^{+}\frac{Y_t}{S_{21}}\right)^2\left(\frac{\sigma_2}{Y_t}\right)^2} + p_{vp}^{+}\frac{\sigma_2}{S_{21}} + \frac{\sigma_1}{\sigma_{11D}} = 1 \quad \text{(inter-fiber failure in transverse tension)} \quad (7)$$

$$\frac{1}{S_{21}}\left(\sqrt{\tau_{21}{}^2 + \left(p_{vp}^{-}\right)^2\left(\sigma_2\right)^2} + p_{vp}^{-}\sigma_2\right) + \frac{\sigma_1}{\sigma_{11D}} = 1 \quad \text{(inter-fiber failure in moderate transverse compression)} \quad (8)$$

$$\left(\left(\frac{\tau_{12}}{2(1 + p_{vv}^{-})S_{21}}\right)^2 + \left(\frac{\sigma_2}{Y_c}\right)^2\right)\frac{Y_c}{-\sigma_{22}} + \frac{\sigma_1}{\sigma_{11D}} = 1 \quad \text{(inter-fiber failure in large transverse compression)} \quad (9)$$

2.3 Numerical implementation

Abaqus/Standard finite element software (e ABAQUS/standard, Simulia Inc., USA) was used in this study. Following the actual experiments, numerical model for tensile and compression loading condition were built. The proposed elasto-plastic model and damage model were combined from the basic model based on the J.F. Chen et al.[8]. This model was implemented in user material subroutine (UMAT) and the computational algorithm is in figure 1. Material properties used in this analysis were obtained from experimental. Details on the implementations of this model will be presented at the conference later.

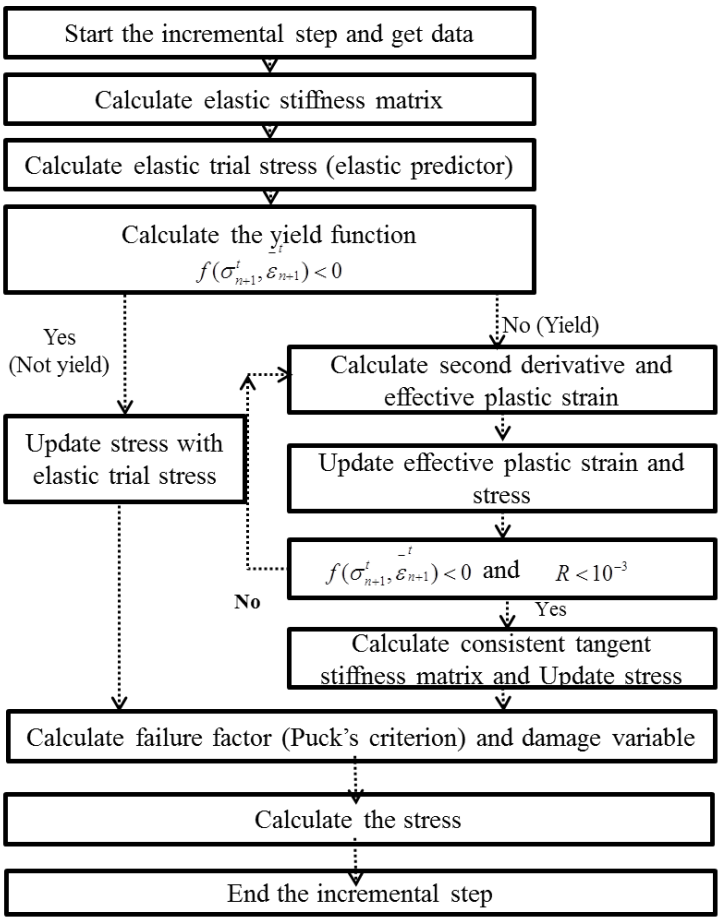

Figure 1: Flow chart of user material subroutine (UMAT)

3 EXPERIMENTAL

3.1 Materials and specimens

Commercial unidirectional and woven carbon fiber prepregs were used. The specimens were fabricated by hand lay-up of prerpregs and cured at 95℃ at 30min and 125℃ at 90min under 30kgf/cm^2 pressure. The specimens were cut having off-axis angles of 15, 30, 45, 60, 75, 90° with respect to the fiber direction (warp direction in the case of woven). Tab of glass fiber-reinforced plastic were attached on the side of the specimen using the adhesive.

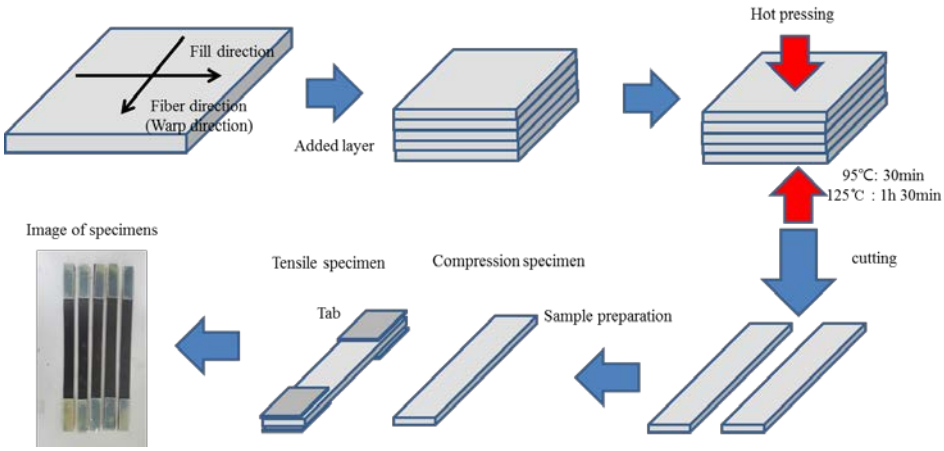

Figure 2: The method of sample preparation

3.2 Off-axis tensile test

Off-axis tensile test was carried out according to ASTM D3039. The specimens were prepared in 250 mm × 15 mm × 1 mm (length, width, thickness). The specimens were tested using a universal tensile machine (UTM, Instron 5582, Instron Corp., Norwood, MA, USA). The crosshead speed was 1.5mm/min (1% strain rate). At least, five specimens were tested. An extensometer with the 25mm gauge length was used for strain measurement.

3.3 Off-axis compressive test

Off-axis compressive test was carried out according to ASTM D6641. The specimens were prepared in 150 mm × 15 mm × 2.4 mm (length, width, thickness). The specimens were tested using a universal tensile machine (QUASAR 5, Galdabini, Milan, Italy) and test fixture fitted with UTM. The crosshead speed was 0.2mm/min (1% strain rate). At least, five specimens were tested. The strain gauge and extensometer with the 15mm gauge length was used for strain measurement.

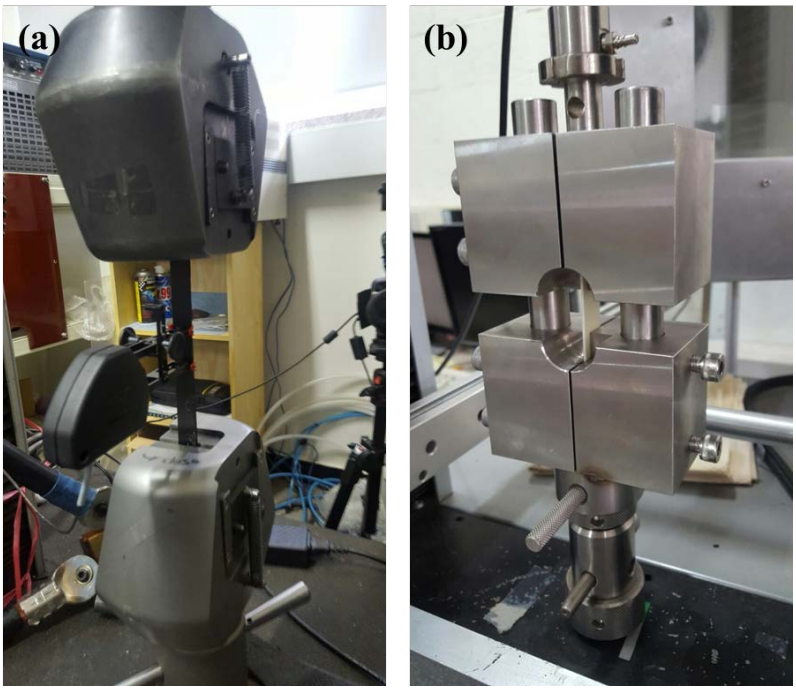

Figure 3: Test set up: (a) tensile test, (b) compression test

4 RESULTS AND DISCUSSION

In figure 4, stress-strain curve of simulation of off-axis tensile test was shown. It was confirmed that the stress-strain curve according to the off axis angle was consistent with the existing previous results [4].

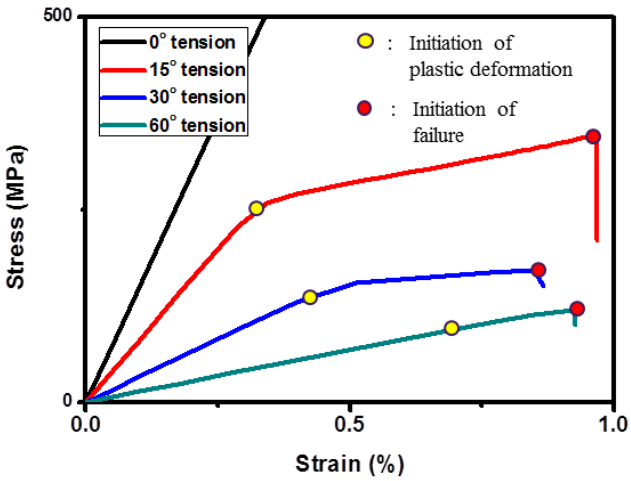

Figure 4: Simulation result: stress-strain curve of off-axis tensile test

More detailed behaviour can be seen in the figure 5 and 6. In the case of 0° tension (in figure 5), no plastic deformation was observed and only the elastic behaviour was followed by the initial failure. That phenomenon was consistent with the previous experimental results [9]. In figure 5 (b), also the failure occurred when the fiber failure criterion was satisfied in the whole area. Different from 0° test, especially, it was confirmed that nonlinear behaviour was observed at 15, 30, and 60 degrees. In figure 6 (a), that was caused by plastic deformation according to the fiber orientation angle. It was also seen that the intensity of effective plastic strain varied with the position of the specimen and increased with the progress of strain. After some plastic deformation (nonlinear behaviour), it was observed that failure was initiated if the stress state was satisfied with inter-fiber failure criterion. Using this model, the nonlinear mechanical behaviour of CFRP can be predicted, so the validity of this model will be verified by comparing with experimental results in the conference presentation.

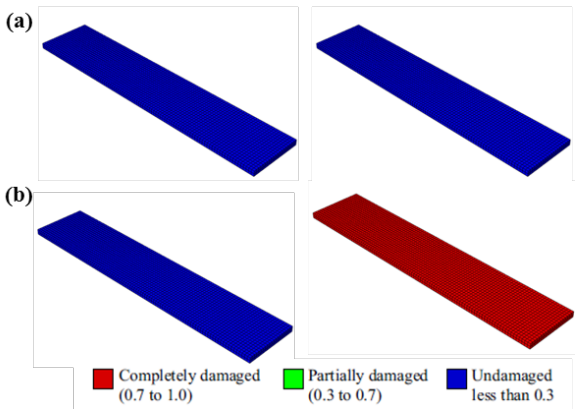

Figure 5: Simulation results of 0° off axis tensile test: (a) effective plastic strain, (b) fiber damage variable in fiber direction (d1)

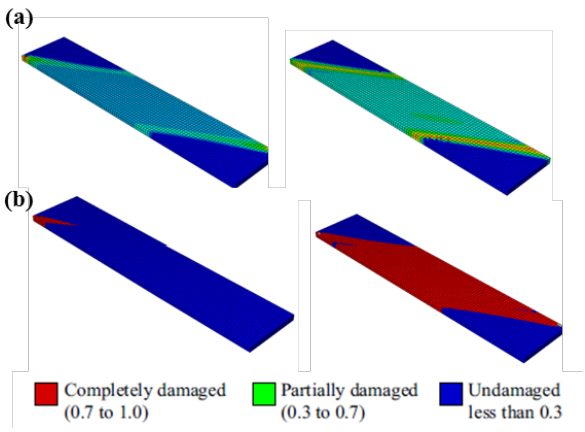

Figure 6: Simulation results of 30° off axis tensile test: (a) effective plastic strain, (b) matrix damage variable (d2)

5 CONCLUSION

In this study, the continuum-based elastoplastic model was developed to analyse the mechanical behaviour of CFRP. Off-axis tensile and compression tests of unidirectional CFRPs were carried out to determine the material parameters of the elastoplastic model. Initial and progressive failures of CFRPs were then determined by Puck's failure criterion and damage mechanics. The proposed model was implemented in ABAQUS using user material subroutine (UMAT). Finally, the nonlinear mechanical behaviour of CFRP was then predicted and compared with experiments, demonstrating the validity of the current model.

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