PREDICTION OF DELAMINATION OF STEEL-POLYMER COMPOSITES USING COHESIVE ZONE MODEL

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Abstract
Steel-polymer composites, which have good properties in vibration and noise, are widely used in automobile, flight, and architectural fields. Weak interfacial failure is one of the main factors of failure in steel-polymer composites that consist of multiple thin layers. One method to investigate a failure mechanism is the usage of finite element method. A widely used numerical simulation tool for delamination is cohesive zone modeling. Cohesive zone models relate tractions to displacement jumps at an interface where delamination may occur. To characterize traction-separation laws in mode I, II of cohesive element, we carried out the analytical derivation using peel mechanics and simplified equilibrium equations. Three different angle (60^o, 90^o, 120^o) peel tests were performed to obtain the cohesive model parameter in mode I, II. Finite element simulations using cohesive zone model were performed to replicate the experimental peel test with the purpose of determining the precise interfacial properties. Using this model, we predicted the delamination behavior of steel-polymer composites in various stress conditions. Finally, it was shown that a cohesive zone model provides well-fitted prediction of failure due to the delamination between steel-polymer composites.

1. Introduction

Steel-polymer composites are widely used in automobile, flight, and architectural fields because of their good properties for vibration, noise and lightness [1, 2]. However, their weak interface between steel and polymer layers is main problem of using steel-polymer composites for industrial fields. To solve this problem, many researches that ehhanced the interfacial properties were performed properties [3, 4].

As the effort to increase interfacial properties, many studies have been conducted on the prediction of delamination failure in steel-polymer composites. One widely used method is cohesive zone modeling based on damage mechnaics. Cohesive zone model, the concept of which firstly suggested by Dugdale [5], many researchers have developed this model for solving delamination problems [6-15]. This method is simple [16] and easily implemented in finite element simulation [8, 17-19]. Due to these reasons, cohesive zone modeling is widely used for describing delamination failure in composites.

In order to predict the delamination at interface, evaluating precise interface properties is also important. Lab shear test [20], which measures interface strength in shear direction, is a widely used method. When the strength in normal direction is needed, tensile adhesive test can be used [21]. However, to measure the adhesive properties in various directions, each test method has to be proceeded individually.

In this study, to measure adhesive properties at interface in mode I and II, peeling test was used. To characterize traction-separation laws in mode I, II of cohesive element, we carried out the analytical

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derivation using peel mechanics, simplified equilibrium equations and simplified model for predition of delamination between steel and polymer. Finally, numerical simulation using cohesive zone model was performed to validate these models.

2. Experimental

2.1. Materials

In this research, steel offered from POSCO (Korea) were used, and polymer used in this study was nylon-6 obtained from Goodfellow (USA).

2.2. Peeling test

To prepare specimen for peeling test, after stacking the nylon-6 film on the steel, the pressure of 0.5 MPa was applied at the temperature of 260℃ using hot-press. The nylon-6 polymer attached on side of the steel was eliminated and certain length (40 mm) of film was peeled manually for the grab site which connected it to UTM machine (Galdavini, Germany). The rate of peeling was 5 mm/min.

3. Theoritical background

The schematic of peeling thin film from substrate is shown in Fig. 1. The length (dL) is peeled from the substrate by the force (F). An energy conservation of the peeled film through the length (dL) shows that the work done by the force is equal to the change of the energy of the system.

$$dW_p = dU_E + dU_S + dU_P + dU_K \tag{1}$$

In this study, dW_p, dU_E and dU_S were used by expression derived by Kendall [22]. Additionally, dU_P and dU_K were derived by simlifed relationship in peel mechanics. Finally, Combining and solving all values in equation (1), we obtain governing equation of peeling.

$$G = \frac{1}{2bd}\left(\frac{F}{b}\right)^2 + \left(\frac{F}{b}\right)(1-\cos\theta) + \frac{\sigma_y d^2\theta}{2l} \tag{2}$$

In this study, fracture energy (G) was divided as normal and tangential components in order to consider a contribution of energy release rate of normal and tangential directions (G_n and G_t), respectively. Therefore, combining equation (2) and failure criterion, we obtained equation (3) for measuring fracture energy of normal and tangential directions ($G_{n,c}$ and $G_{t,c}$).

$$\frac{\frac{1}{2bd}\left(\frac{F\sin\theta}{b}\right)^2 + \left(\frac{F\sin\theta}{b}\right)(1-\cos\theta) + \frac{\sigma_y d^2\theta}{2l}}{G_{n,c}} + \frac{\frac{1}{2bd}\left(\frac{F\cos\theta}{b}\right)^2 + \left(\frac{F\cos\theta}{b}\right)(1-\cos\theta)}{G_{t,c}} = 1. \tag{3}$$

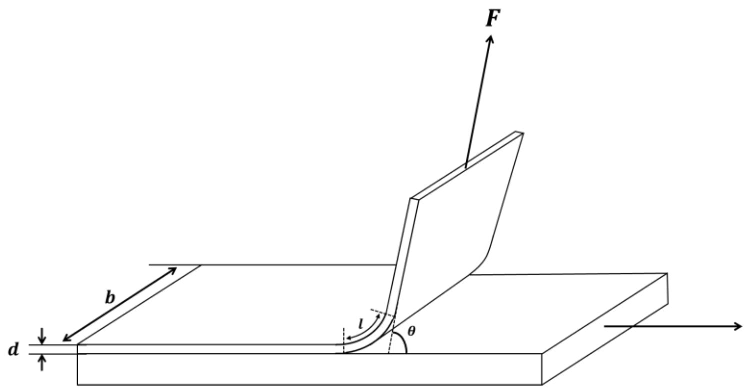

Figure 1. Schematic illustrations of peeling thin film from substrate

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4. Numerical simulation

To simulate the peel test, commercial finite element analysis software ABAQUS/standard® was used. In this study, two dimensional model was used. To describe the delamination behavior of the interface, cohesive zone modeling was used. A bilinear traction-separation law was adopted in representation of the steel/polymer interface. The bilinear traction-separation laws of normal and tangential separation are shown in Fig. 2.

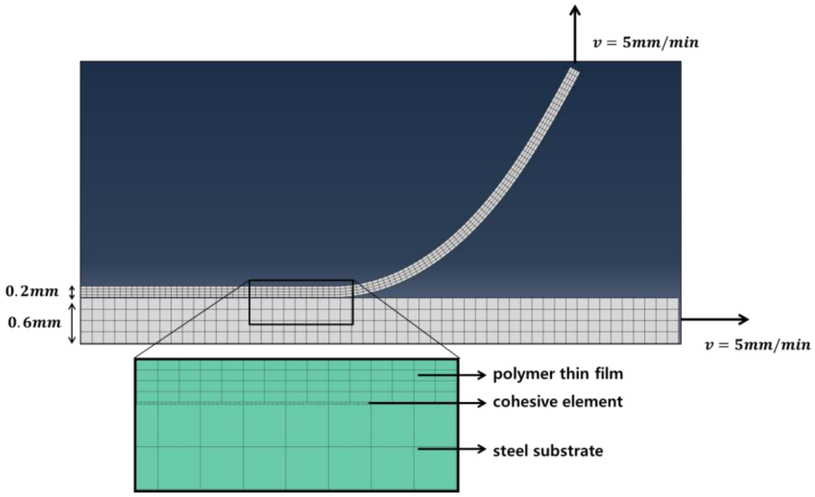

Figure 2. Finite element model setting for peeling test

critical separation length ($\delta_{n,c}$ and $\delta_{t,c}$) were set as 0.5mm in order to retain a sufficient number of element (N_e = 10) in cohesive zone. Stiffness (K_{nn} and K_{tt}) was set as 100N/mm^2 and the maximum traction ($\sigma_{n,c}$ or $\sigma_{t,c}$) was calculated

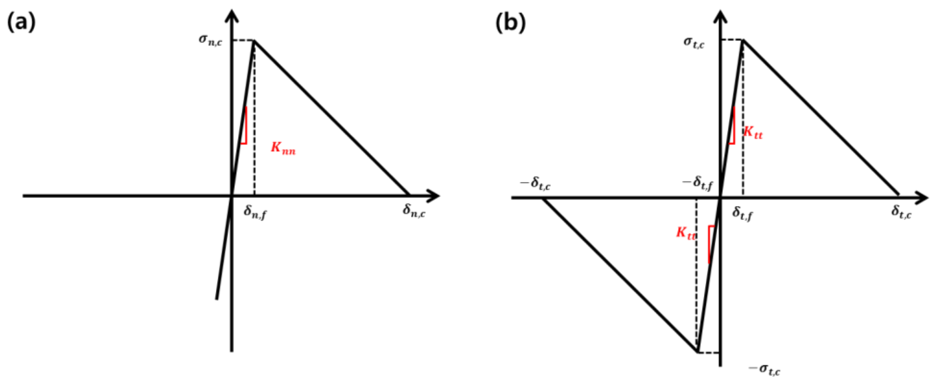

Figure 3. Bilinear traction-separation law : (a) Normal direction. (b) Tangential direction

5. Results and discussion

The peel strength of different angle (60°, 90° and 120°) was measured using peeling test. To define adhesive properties between steel and nylon, the fracture energy on normal and tangential directions ($G_{n,c}$ and $G_{t,c}$) was calculated using the value of 60 ° and 90 ° peel strength from equation (3), and peel forces for all angles were predicted. As it is shown in figure 4., there is good agreement between theoretical prediction from equation (3) and experimental peel force.

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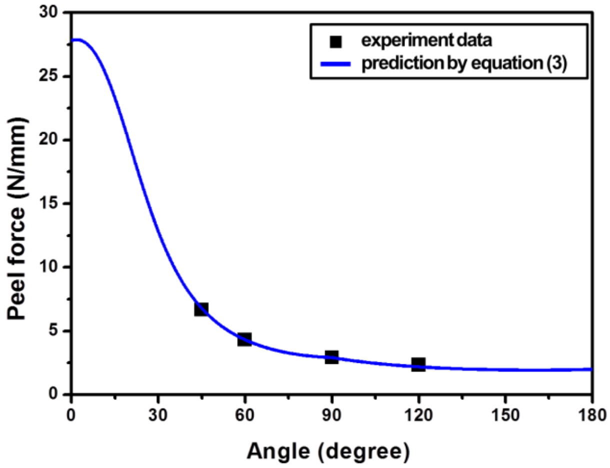

Figure 4. Comparison peel strength according to the peel angle of experiment and prediction in case of steel – nylon 6

In order to validate our model by cohesive zone model, numerical simulations were run to analyze 60°, 90° and 120° peel test using cohesive zone model. Steady-state peel forces were obtained regardless of angles and the simulated peel forces using finite element model with cohesive element agree well with the experimental results (see Fig.5)

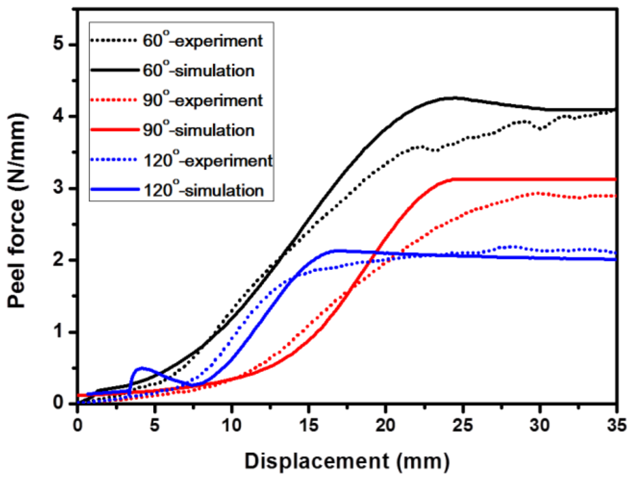

Figure 5. Comparison displacement versus peel force of experiment and simulation results in case of steel – nylon 6

6. Conclusion

In this study, peeling tests were performed in order to measure adhesive properties between steel and nylon. A theoritical approach for identification of adhesive properties between steel and nylon was developed. A simple model to measure the adhesive properties in normal and tangential directions based on the peel mechanics was derived and compared with the experiemental values. From comparison results, it is concluded that the peel force of all angles could be predicted using peel strength of only two angles. To validate these model, numerical simulation using cohesive zone model was perforemed. As a result, it was shown that a cohesive zone model provides well-fitted prediction of failure due to the delamination between steel-polymer sandwich composites

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