Effect of brittle and ductile adhesive on the bond behavior of CFRP-steel composite using CZM method

Kyushu University Student Member ○Weijie LIU
Kyushu University Regular Member Muye YANG
Kyushu University Fellow Member Shigenobu KAINUMA

1. Introduction Carbon fiber-reinforced polymer (CFRP) has proven to be a material capable of being used in many engineering applications, highlighting its good properties for reinforcement of steel structures. The bond behavior between CFRP and steel is one of the key issues. Several failure modes of CFRP-steel composite have been investigated by scholars, such as CFRP-adhesive interface debonding, adhesive-steel interface debonding, cohesive failure and CFRP delamination. Referring to the existed researches, the debonding of CFRP-adhesive and adhesive-steel can be avoided by appropriate surface treatments. Moreover, cohesive failure within an adhesive layer can be considered as the most common and ideal failure mode. In this study, to simulate the effect of brittle and ductile adhesive on the bond behavior of CFRP-steel composite, the FE model of a single-lap joint under the tensile load was established using cohesive zone model (CZM) method.

2. Cohesive zone model By introducing a potentially useful simulation method CZM, the onset of damage initiation and propagation can be predicted. Moreover, CZM based on a relationship between stresses and relative displacements connecting initially superimposed nodes of the cohesive elements [1]. There are three modes of crack type, where tensile stresses occur in mode I crack, and shear stresses occur in mode II and mode III crack. A constitutive model for cohesive elements follows the traction-separation law (TSL), which is capable of simulating gradual degradation of the materials based on the simple correlation between the traction (T) and relative displacement (separation). TSL can take different shapes, e.g., trapezoidal, exponential, etc. Herein, the bilinear CZM was selected, the representation of the fracture process zone and the constitutive bilinear CZM as shown in Fig. 1, where δ_c, δ_m are the critical opening displacement and maximum opening displacement for each mode, respectively. The areas under the TSL in each mode of loading (tension and shear) are equated to the critical energy release rate G_c for each mode, calculated by Eq. (1). Furthermore, a complex stress state is present in the adhesive joint. Thus, damage initiation was predicted by using quadratic stress criterion as shown in Eq. (2), which is a formulation for interface elements including a mixed-mode damage model. Besides, the power-law in Eq. (3) was used as an energetic criterion after the curve goes into a softening region, i.e., irreversibly plastic phase. Within this part, damage value D defined by Eq. (4) becomes non-zero and increases till the value of one, indicating damage propagation and thus failure in the element.

3. Numerical modeling In this study, the single lap joint model was established as a two-dimensional (2D) element model by using the finite analysis software MSC. Marc 2017, in which the CZM can be used to simulate the cohesive fracture behavior of adhesively bonded joints. The dimension of specimen, loading case and boundary conditions are shown in Fig. 2, and the tensile displacement load of 0.1mm/sec was applied to all models. The overlap length of CFRP (0.2 × 130 mm) and steel plate (9 × 150 mm) was set as 90 mm using a 0.2 mm thick adhesive. The material properties are summarized in Table 1. Three structural adhesives were simulated in models for comparison, material parameters referred to as follows: the brittle epoxy Araldite® AV138, the ductile epoxy Araldite® 2015 and the high strength and ductile polyurethane Sikaforce® 7888.

In the Marc program, a normal to shear traction ratio β_1 and Mode I to Mode II energy release rate ratio β_2 were introduced to govern a mixed-mode fracture for any arbitrary simulation. The adhesive layer was built as a single layer using a four-node interface/cohesive elements. Besides, the CFRP and steel plate were discredited by the four-node solid plane elements, and the CFRP and steel elements near the interface are coupled with the cohesive elements through sharing nodes. The width of specimens is in-plane and is utilized as a fixed value of 50 mm when defining the geometry properties.

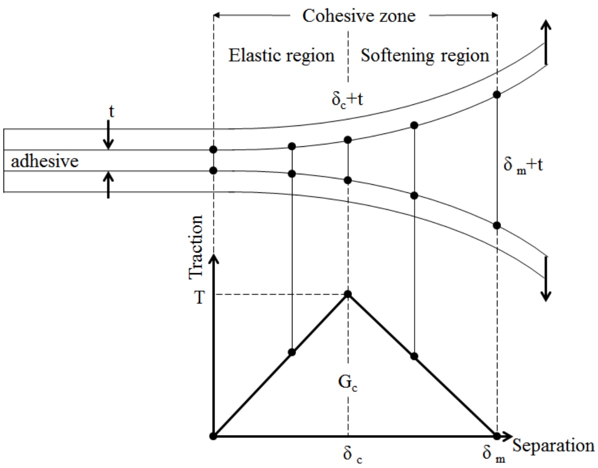

Fig.1 Fracture process at the cohesive zone and corresponding traction-separation law

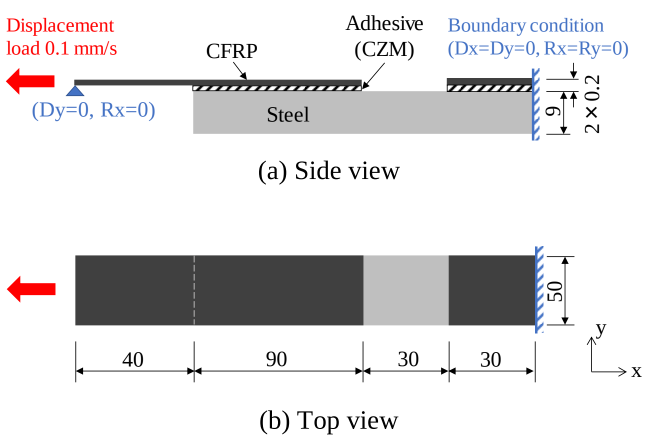

Fig.2 Image of single-lap joint and model dimensions in FE analysis (unit: mm)

$$G_i=\begin{cases}\dfrac{1}{2}\dfrac{T_{m,i}}{\delta_{c,i}}\delta_i^2 & 0\le\delta_i\le\delta_{c,i}\\[2ex] \dfrac{1}{2}T_{m,i}\left(\delta_{m,i}+\dfrac{\left(\delta_i-\delta_{m,i}\right)^2}{\delta_{c,i}-\delta_{m,i}}\right) & \delta_{c,i}<\delta_i\le\delta_{m,i}\\[2ex] \dfrac{1}{2}T_{m,i}\delta_{m,i} & \delta_i>\delta_{m,i}\end{cases} \quad (1)$$

$$\left(\frac{T_I}{T_{m,I}}\right)^2+\left(\frac{T_{II}}{T_{m,II}}\right)^2+\left(\frac{T_{III}}{T_{m,III}}\right)^2=1 \quad (2)$$

$$\left(\frac{G_I}{G_{c,I}}\right)^m+\left(\frac{G_{II}}{G_{c,II}}\right)^n+\left(\frac{G_{III}}{G_{c,III}}\right)^p=1 \quad (3)$$

$$D(\delta)=\frac{G(\delta)-G_{\delta=\delta_c}}{G_c-G_{\delta=\delta_c}} \quad (4)$$

Table 1 Material properties used in FE model [2]

	Young's modulus (GPa)	Poisson's ratio v	Tensile failure strain ε_f (%)	Tensile failure strength (MPa)	Shear failure strength (MPa)	G_{IC} (N/mm)	G_{IIC}, G_{IIIC} (N/mm)
T700SC	230	0.25	-	4900	-	-	-
SS400	206	0.30	-	450	-	-	-
Araldite-AV138	4.89	0.35	1.21	39.45	30.20	0.20	0.38
Araldite-2015	1.85	0.33	4.77	21.63	17.90	0.43	4.70
Sikaforce7888	1.89	0.33	43	28.60	20.00	1.18	8.72

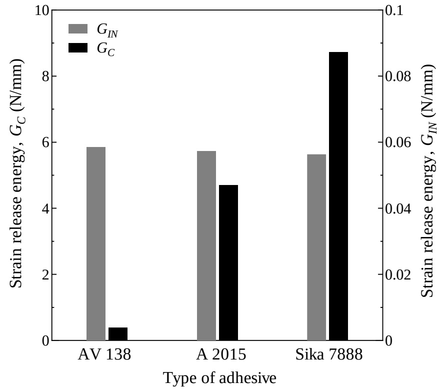

Fig.3 Energy release rate of damage initiation (D＞0) and debonding occurs

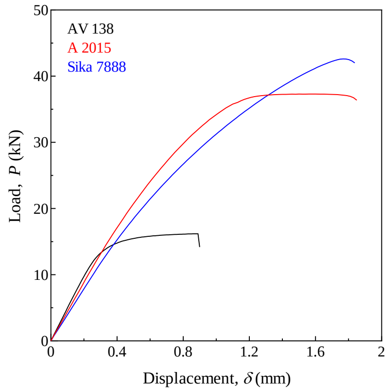

Fig.4 P-δ curves of three models

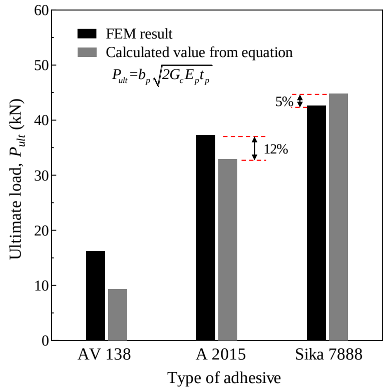

Fig.5 Equational and FEM values of P_{ult}

4. FEM results The effect of adhesives on the damage initiation and debonding initiation of CFRP-steel single-lap joint was compared in Fig.3, according to two critical values G_{in} and G_c in mode II. We assumed that the energy release rate of the damage initiation equals to the value of G in Eq.(1) when the displacement tends to be δ_c. For all these brittle and ductile adhesives, AV 138, A 2015, and Sika 7888, their energy release rates of damage initiation are approximate. However, for the critical energy release rate G_c (damage D reach to one, i.e., debonding occurs), Sika 7888 owns the largest G_c in mode II reflected as a better performance against the shear deformation after the cohesive zone of adhesive get access to the soften region, which should attribute to its high strength and ductility. For the strong and brittle adhesive AV 138, its G_c is only about 8% of that of the moderate ductile adhesive A 2015.

Fig.4 shows the relationship between load and displacement, P-δ curves of three models. The magnitude of the ultimate loads of single-lap joint shows a positive correlation with the critical energy release rate. Furthermore, the first stage of P-δ curves all shown a linear growth, and the second stage caused by the damage initiation would lead to a reduction of curve slope. The third stage defined as progress from the debonding occurrence until the whole peeling, which was indicated as the slope approaching zero (i.e. load capacity cannot keep rising with the increase in displacement). Obviously, the brittle AV138 owns the minimum value of both the ultimate load and displacement, while the Sika 7888 would probably fail most rapidly for its short peeling process at the third stage, due to uniform deformation at the overlap area.

In addition, the ultimate load P_{ult} of three joints calculated according to FEA and empirical Eq. (5)[1] were compared in Fig.5, where E_p = Young's modulus of CFRP; b_p = width of CFRP; t_p = thickness of CFRP.

$$P_{ult}=b_p\sqrt{2G_cE_pt_p} \quad (5)$$

The ultimate loads of three joints showed a similar distribution according to two methods. The estimation discrepancy between FEA and empirical equation is largest for AV 138, whereas for the ductile adhesives A 2015 and Sika7888, the difference of ultimate bearing capacities calculated from two methods was less than 12% and 5%, respectively.

5. Summary The FE model of a single-lap joint using the CZM method shows that the effect of brittle and ductile adhesive would lead to different bond behaviors. Generally, the ductile adhesive owns a larger critical energy release rate, which contributed to the ultimate load of joint significantly.

References 1) C. Li, L. Ke, J. He, et al., Effects of mechanical properties of adhesive and CFRP on the bond behavior in CFRP-strengthened steel structures. Composite Structures, vol.211, 163-174, 2019. 2) R. Campilho, TAB. Fernandes, Comparative evaluation of single-lap joints bonded with different adhesives by cohesive zone modelling. Procedia Engineering, vol.114, pp.102-109, 2015.