EVALUATION OF STATIC AND FATIGUE STRENGTH OF ADHESIVELY BONDED JOINTS

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1. INTRODUCTION

Recently, externally bonded patch plates, CFRP laminates (JSCE ed. (2013)) for instance, have proven to be effective for the application of repairing or strengthening the steel structures. However, one of the major points of concern in the use of this method is the adhesive debonding from the end of patch plates which usually occurs ahead of the yielding of steel member or patch plates. In this paper, the debonding strength under tensile test and fatigue loading test of adhesively bonded joints are experimentally evaluated.

2. EXPERIMENTAL SPECIMEN AND METHOD

2.1 Specimen geometry and materials

Fig. 1 shows the shape and dimensions of the steel to steel adhesively bonded joint specimen. The patch plates (300×50×t_p mm) were adhesively bonded to the both interfaces of the plain steel plate (600×50×9 mm) at the middle. Two types of epoxy resin were used as adhesive, Konishi E250 and Konishi E258R. Material properties of steel plate, epoxy resin and CFRP laminates are given in Table 1. Before bonding, the surfaces of the steel and patch plates were blasted by alumina and cleaned by acetone, and after bonding the specimens were cured at 40 °C for 24 hours. The thickness of adhesive was controlled to be approx. 0.4 mm using glass beads.

2.2 Test setup and experimental condition

Table 2 shows the experimental series and conditions, and Fig. 2 shows the setup of the tensile test and fatigue test. In tensile test, the specimens were subjected to the static load under displacement control with the speed of 2 mm/min. The below end of the patch plates were fixed by fixture in order to control and observe the debonding at the upper end of the patch plates. The adhesive debonding was observed at one side of the specimen utilizing the digital microscope with the speed of 1 frame per second. In fatigue test, the specimens were subjected to cyclic load with the frequency of f=15 Hz (5 Hz for some cases of E250). The applied stress ratio R is set to 0.1 in all cases. The same as tensile test, fixture and microscope were utilized. Microscope was used to observe the debonding propagation from 0 to 35 mm from the patch plate end. Due to occurrence of high shear stress and normal stress at the end of patch plates, debonding strength is considered to be evaluated in the function of principal stress given by Eq. (1).

$$\sigma_{ep} = \frac{\sigma_e}{2} + \sqrt{\left(\frac{\sigma_e}{2}\right)^2 + \tau_e{}^2} \qquad (1)$$

Here, σ_e and τ_e are normal stress and shear stress of adhesive which are calculated using the convergence equations (JSCE ed. (2013)).

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Static strength evaluation

Fig. 3 shows an example of debonding image of E250 captured from the microscope. From image analysis, the average debonding failure load of E250 and E250R is 72.5 and 162.1 kN, respectively.

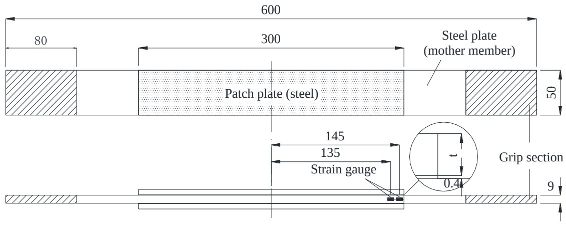


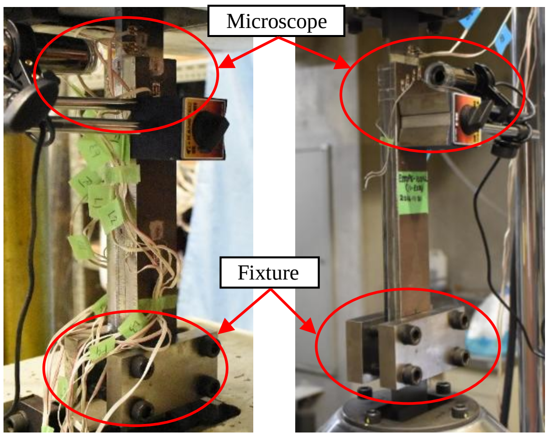
Fig. 1 Experimental setup

Table 1 Experimental condition

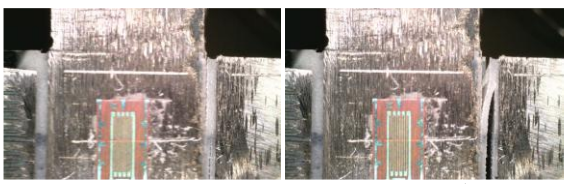
Materials	Elastic modulus E (GPa)	Poisson's ratio ν	Yield Strength σ_y (MPa)	Tensile Strength σ_{tu} (MPa)
Steel plate (SM490YA)	210	0.28	410	554
Adhesive (Konishi E250)	2.6	0.34	–	–
Adhesive (Konishi E258R)	3.6	0.34	–	–
CFRP laminates (High-strength type)	E_{11}=150	ν_{12}=0.34	–	2,680
	E_{22}=8	ν_{23}=0.05		
	E_{33}=8	ν_{31}=0.05		

Table 2 Experimental series and conditions

Specimen series	Adhesive type	Patch plate thickness t_p (mm)	Loading speed (mm/min)	Frequency f (Hz)	Principal stress range $\Delta\sigma_{ep}$ (MPa)	Number of specimens
Tensile test	E250	16	2	–	–	3
	E258R	16	2	–	–	3
Fatigue test	E250	9	–	15, 5	22.1–36.3	8
		6	–	15, 5		4
		4.5	–	15, 5		1
		CFRP: 1.2	–	15, 5	32.3	1
	E258R	9	–	15	34.3–55.8	6
		6	–	15		4
		4.5	–	15		1
		CFRP: 1.2	–	15	44.5	1



(a) Tensile test **(b)** Fatigue test
Fig. 2 Test setup



(a) Initial debonding **(b)** Complete failure
Fig. 3 Debonding image at patch plate end (E250)

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Fig. 4 shows the relationship between tensile stress and shear stress. The experimental shear stress values at X=140 mm from the center of patch plate were obtained from strain gauges attached on patch plate near adhesive end. From the figures, the variation of the debonding shear stress of adhesive is very small to each other in either case of E250 or E258R. Also, good agreement is verified to the debonding strength obtained from the image analysis (dotted lines in Fig. 4). Comparing to theoretical values, the experimental values are relatively smaller. This might be due to the assumed elastic modulus of adhesive is large. Table 3 lists the debonding failure load, maximum tensile stress, and maximum principal stress occurs at adhesive tip which is calculated from Eq. (1). The average maximum principal stress of E250 and E258R is 40.8 and 109.1 MPa, respectively. The maximum principal stress of E258R is relatively larger than that of E250, accounting about 2.67 times.
Fig. 5 plotted the experimental data and the failure envelopes based on principal stress criterion of E250 and E258R. The failure envelopes are obtained from Eq. (1). From the figure, the experimental data has been fitted to the failure criteria for either E250 or E258R.

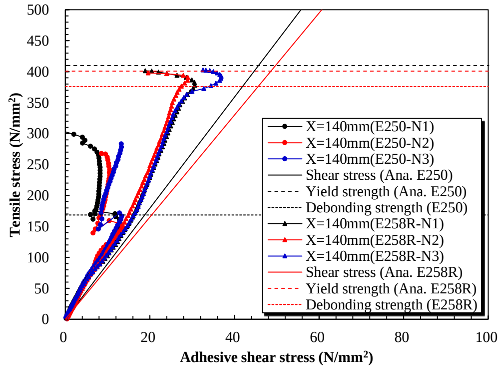

Fig. 4 Tensile stress – shear stress relations

Table 3 Maximum principal stress

Adhesive	Debonding load $P_{\max}$ (kN)	Tensile stress σ_{tu} (MPa)	Max. principal stress $\sigma_{ep\_\max}$ (MPa)
E250	72.5	168.6	40.8
E258R	162.1	375.9	109.1

3.2 Fatigue strength evaluation

Fig. 6 and Fig. 7 plotted the estimated debonding propagation life in the range of 5–30 mm of adhesive in the function of principal stress range ($\Delta\sigma_{ep}$) and the ratio of principal stress range against maximum principal stress by tensile test ($\Delta\sigma_{ep}/\sigma_{ep\_\max}$), respectively. From Fig. 6, although the fatigue life of E258R can be evaluated, the variation can be identified in case of E250 and its fatigue life is not possible to be evaluated in the function of principal stress range. However, the fatigue life evaluation can be explained under $\Delta\sigma_{ep}/\sigma_{ep\_\max}$ as indicated in Fig. 7. The fatigue life can be evaluation independently to the type of patch plate and adhesive. The regression line equation and it correlation coefficient is given in the figure, and all data are in range of $\pm 1.3\sigma$ (σ: standard deviation). Variation seen in E250, which might be caused by creep phenomena of adhesive due to the relative high stress range to static strength in E250, can be explained from the figure. Regarding to the failure modes, the test specimens were completely debonded by tensile test after the fatigue loading test. Three kinds of failure modes (adhesive failure, cohesive failure and mixture of adhesive and cohesive failure) were identified in E250. However, only cohesive failure is seen in E258R. Failure modes might also take part in the variation in E250.
Moreover, from the regression line of initial debonding life, the fatigue limit of E250 and E258R is confirmed to be approx. at $\Delta\sigma_{ep}/\sigma_{ep\_\max}$=0.35 ($10^7$ number of cycles). Two run-out tests were verified for the fatigue limit, $\Delta\sigma_{ep}/\sigma_{ep\_\max}$=0.28 for E258R in this study and $\Delta\sigma_{ep}/\sigma_{ep\_\max}$=0.31 for E250 in previous study (Nakamura *et al*. (2016)).

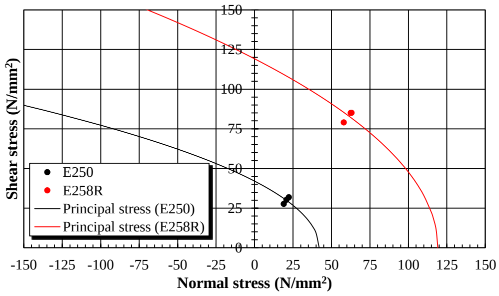

Fig. 5 Failure envelopes based on principal stress criterion

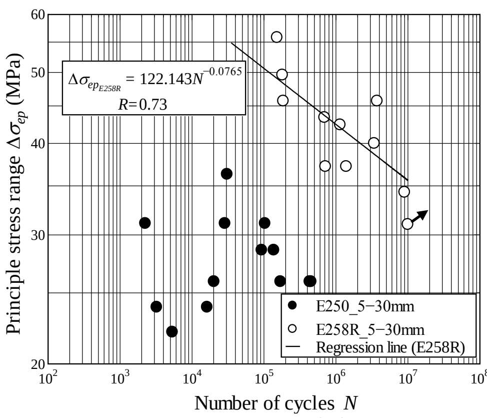

Fig. 6 Debonding propagation life from 0–30 mm

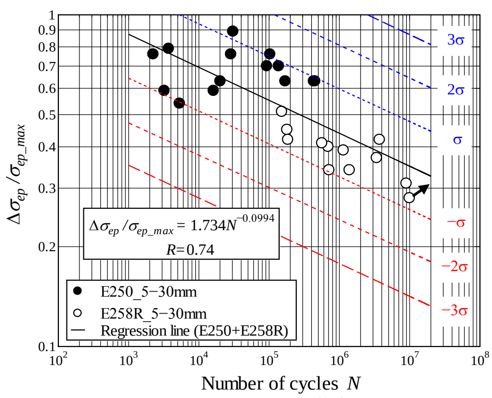

Fig. 7 Debonding propagation life from 0–30 mm

4. CONCLUSIONS

To sum up, the following conclusions can be drawn from the evaluation.

(1) Under principal stress evaluation, the static strength of E258R is relatively greater than that of E250, approx. 2.67 times.

(2) The fatigue life of adhesively bonded joints can be evaluated in the function of principal stress ratio $\Delta\sigma_{ep}/\sigma_{ep\_\max}$ independently to either the thickness/type of patch plate or type of adhesive. Variation seen in E250 can be caused by creep phenomena or failure modes.

(3) The fatigue limit of E250 and E258R is approx. at $\Delta\sigma_{ep}/\sigma_{ep\_\max}$=0.3.

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