Influence of Curing at Different Temperatures on the porosity and Strength of CFRP

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1. Introduction Recent years, CFRP has been widely used for the steel structure reinforcement. One of the main disadvantages of using CFRP composites to reinforce and repair steel structures is the lack of knowledge about the effect of CFRP curing temperature on CFRP performance. In this study, the influence of curing conditions at different temperatures on the porosity of CFRP was studied, and a pull-off test was carried out to explore the influence of curing conditions at different temperatures on the bonding strength of CFRP resin and carbon fiber[1].

2. Specimens and test method In this study there are two parts off porosity calculation and pull-off test. In the porosity calculation, all the CFRP specimens were made by carbon fiber sheet (Mitsubishi TR50D12L) wetting layered using epoxy matrix (Mitsubishi XL-800). Basic curing information of XL-800 that used for this study is shown in Table 1. Following the supplier's recommendations, the operating environment of XL-800 resin should between 15°C to 35°C, and the RH less than 85% in site. There are two kinds of CFRP specimens, one kind was cured in 15°C (±5°C) for 2 weeks and the other kind was cured in 35°C (±1°C) for 5 days. The dimension of CFRP laminates were 150 mm×60 mm of seven layers. In order to avoid the edge effect, the edge part was cut off and the CFRP was cut into120×50 mm. The digital micrometer (accuracy0.001mm) was used to measure the thickness of CFRP laminates by repeated five times at each spot, and the selected spots are shown in Fig. 1. All specimens were weighed using a scale with an accuracy of 0.01 mg to obtain their weight (m_c) as the reference value. The porosity (V_p) for each specimen was calculated using Eq. (1):

$$v_P = 1 - \frac{m_c}{V_c \cdot \rho_{ER}} + \frac{n \cdot \rho_f^s}{t_c} \cdot \left(\frac{1}{\rho_{ER}} - \frac{1}{\rho_f}\right) \quad (1)$$

where V_p is the porosity of CFRP, m_c is the weight of CFRP, V_c is the volume of CFRP, t_c is the thickness of CFRP, ρ_{ER} is the density of epoxy, ρ_f is the density of carbon fiber, $\rho^s{}_f$ is the surface density of carbon fiber, n is the layer number of carbon fiber.

To observe the permeation degree of CFRP and epoxy resin, micrographs of CFRP panels were carried out with SEM under high vacuum condition. Pull-off test was used to study the curing temperature on bond strength of CFRP, there are two kinds of specimens which cured in 15°C (±5°C) for 2 weeks and 35°C (±1°C) for 5 days. The steel surface was treated by four method: 1) blast, 2) steel wire brush, 3) disc grinder and 4) belt sander. Before bonding, the surface of CFRP was polished with #120 sandpaper to increase the adhesion. After the residual grinding particles on the resin surface are removed with adhesive tape, wiping the dolly (Aluminum alloy, diameter: 20mm) surfaces with acetone solution to remove impurities and grease. After preparing the specimens, a uniform vertical compressive stress of 0.9 MPa was applied to the dolly and maintained for 30 min to adhere it to the core area. A two-liquid epoxy resin (Three Bond 2082C) with a mixture of 1:1 was used as adhesive for dolly bonding. Then, curing all dolly specimens for 48 hours under 35°C. All pull-off tests were repeated three times to obtain the average value of the adhesion strength. Pull-off testing was performed using a tension-compression testing machine, tensile speed was performed at quasi-static 0.5 mm/min. The flow chart of specimen making is shown in Fig. 2.

Table 1. Basic curing information of A/B mixed XL-800

Ambient temperature (°C)	15	25	30	35
Viscosity (cps)	16000	11300	9630	7360
Gel time (min)	287	92	47	31
Tactile hardening time (hrs)	13	8.5	7	5
Curing period (day)	14	7	5	5

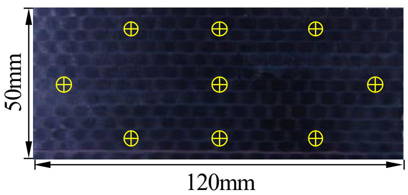

Fig.1 CFRP laminate specimen for porosity calculation

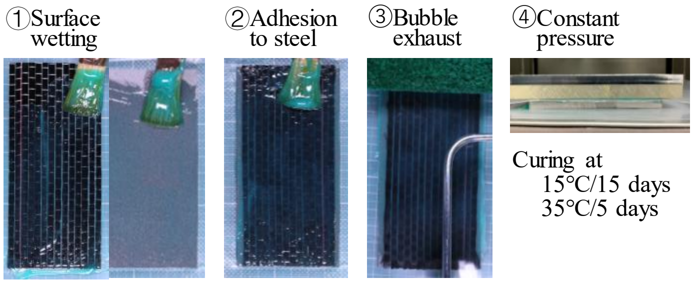

Fig.2 Flow chart of pull-off specimen fabricating

3. Test results The measured parameters, weight ratio of carbon fiber, and porosity of cured CFRP as shown in Table 2. There is a significant difference in the thickness and volume of CFRP cured at 15°C and 35°C. For CFRP cured at 15°C, its weight proportion of carbon fiber is higher than that cured at 35°C, while the porosity is less. The SEM microphotos of CFRP cross-

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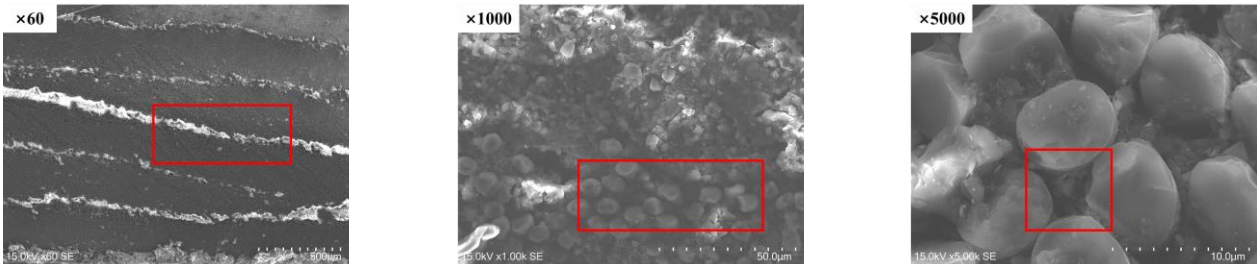
sections is shown in Fig.3. Through the SEM photos with 60 times magnification, it shows the CFRP cured at 35℃ has more cavities compared with the CFRP cured at 15°C. Under the condition of 35℃ curing, the cavity mostly appears in the interior of each layer of carbon fiber, which indicates that under the condition of high temperature curing, the gel time of resin is relatively short, and the air inside of fibers cannot get out as the interlaminar resin harden quickly. In the contrast, CFRP under 15℃ curing shows there are no obvious large bubbles whereas large numbers of the small pin-holing dispersed both at the boundary line among sheet layers and interior of carbon fiber layers. Microscopic view in Fig.3 shows there are gaps uniformly exist between each carbon fiber of CFRP-15, while fibers of CFRP-35 tend to be more tightly arranged excepted the pore zone.

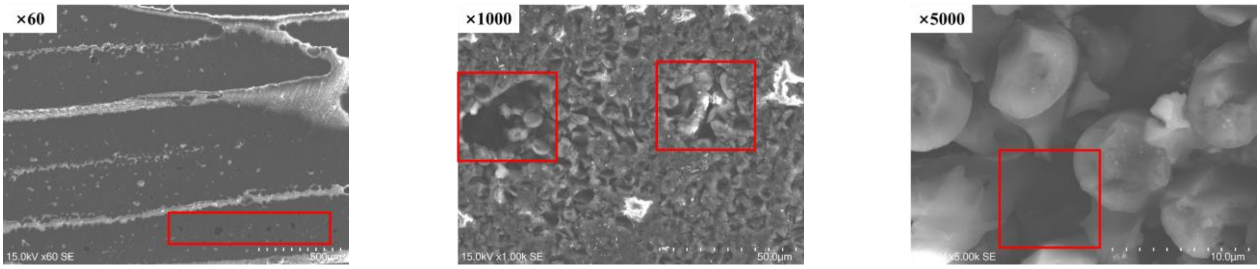
From the pull-off test result, the bond strength of 35°C curing is slightly greater than that of 15°C curing, as shown in Fig. 4. The failure modes of both cases were delamination unrelated to steel surface treatment. The fractured surface shows most of the fibers were flake peeling in 35°C case, while the scattered fibers could be found in 15°C case. Above all, during the initial curing stage, epoxy resin remains liquid for a longer time at the ambient environment of low temperature, which is more conducive to resin penetration and porosity reduction under pressure. However, the epoxy resin owns statue of lower viscosity under the warm temperature, which enhance the wettability to fiber and increase the adhesive bond strength significantly.

Table 2. Porosity calculation of CFRP laminate

Curing condition	Number of layers n	m_f (g)	m_c (g)	Area (mm^2)	t_c (mm)	m_f / m_c	V_p
15℃ (±5℃)	7	8.37	17.3	5978	2.06	0.483	0.065
35℃ (±1℃)	7	8.26	18.6	5900	2.33	0.443	0.088



(a) 15℃ curing (×60) (b) 15℃ curing (×1000) (c) 15℃ curing (×5000)



(d) 35℃ curing (×60) (e) 35℃ curing (×1000) (f) 35℃ curing (×5000)

Fig. 3 SEM microphoto of CFRP cross-section

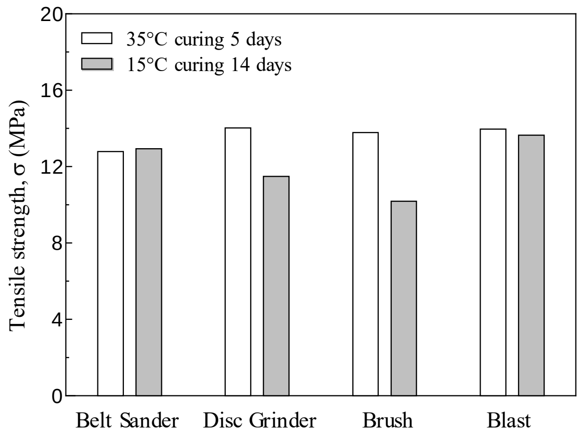


Fig. 4 Results of pull-off test

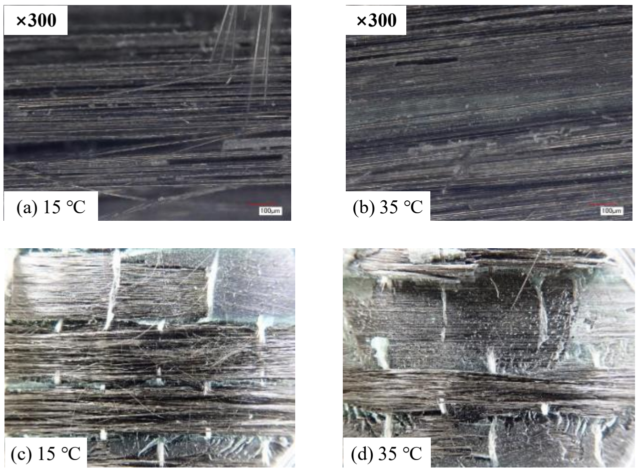


Fig. 5 Stripping state of CFRP

4. Summay & Findings 1) Low-temperature curing is more conducive to resin infiltration and reduce the porosity of CFRP, because the low temperature increases the curing time of the resin, the resin has more time to penetrate between the carbon fibers. 2) It can be judged from the experimental results that CFRP cured at 35℃ has stronger adhesion than CFRP cured at 15℃.

References [1] EH Saidane, D. Scida, M. Assarar, R. Ayad. Assessment of 3D moisture diffusion parameters on flax/epoxy composites. Composites Part A. Applied Science and Manufacturing, Vol80-pp.53-60. 2016.