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Effective bond length of CFRP sheets externally bonded to concrete beams under marine environment

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HIGHLIGHTS

- A new model for effective bond length under the marine condition is developed.
- Both CFRP stiffness and concrete strength had influence on effective bond length.
- Exposure condition had low effect on the epoxy performance between CFRP-concrete.

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ABSTRACT

Externally strengthened marine concrete structures by using carbon fiber-reinforced polymer (CFRP) are being used more extensively because of their exceptional properties, including high corrosion/environmental degradation resistance. Debonding of CFRP sheet from the concrete substrate is one of the typical failure modes observed by using this technique. Therefore, the strengthening technique efficiency strongly depends on the effectiveness of the CFRP-concrete bond. Numerous experimental studies have been conducted to investigate the bond behavior and most of the proposed bond strength models considering the influence of the effective bond length. This study was conducted to experimentally investigate the effective bond length of CFRP sheets subjected to marine environment exposure, which is identified as one the major gaps in this discipline. The concrete beam specimens exposed to marine environment were tested to determine the effective bond length. The three-point bending-type shear bond test was used to obtain the stress versus load relationship. The test variables were the type and exposure duration. The test results showed that the marine environmental exposure significantly influenced bond stress and effective bond length. Two factors, CFRP stiffness and concrete compressive strength, contributed to fix the effective bond length of the CFRP-concrete interface. The maximum bond stress, after 12 months of wet/dry cyclic exposure, was found higher than that subjected to full immersion exposure. The average maximum bond stress decreased with an increase in full-immersion exposure time to 12 months. Results indicated that the exposure condition influences the capacity of CFRP-concrete bond and resulted in a reduction in effective bond length by 16–29%. Moreover, debonding was observed as the dominating mode of failure for all tested specimens. The prediction models of effective bond length, considering the influence of marine environment, are also established. Therefore, the outcome of this study will help to resolve one of the debonding issues in strengthening marine structures.

1. Introduction

In recent decades, it has become a common practice to externally strengthen the concrete structures by using carbon fiber reinforced polymer (CFRP) laminates that enhance the designed capacity and elicited a growing interest [1–3]. CFRP composites offered many advantages, including high strength-to-weight ratio, high corrosion/environmental degradation resistance, and ease of handling during construction. Externally strengthened concrete structures by using CFRP sheets may offer an extension to the service life of the existing structures. CFRP application enhances the bending strength capacity of the beams via bonding perpendicularly to the axial direction. The most common premature failure of a strengthened specimen is the debonding of CFRP sheet from the concrete substrate due to stress concentrations [4]. The failure mechanism shows brittle behavior and occurs without preceding

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yielding. Therefore, CFRP-concrete bond line plays a significant role in the performance of strengthening; as it is defined as the extent of the bonded length of CFRP with the concrete substrate where concrete stress can be fully transferred to CFRP. The bond design capacity is mostly affected by five factors: effective bond length, concrete properties, thickness of the adhesive, and thickness and stiffness of FRP [5–8]. Furthermore, different environmental conditions, such as seawater, humidity, wet and dry cycles, freezing and thawing, presence of alkaline solution, etc., cause various degree of deterioration in the bond line.

When the specimen is subjected to a pure tensile load, an increase of bond line leads to a decrease of the bond strength at average stress [9]. This occurs because the bond stresses are not fully distributed throughout the whole bond line. As reported by previous studies, the bond stress is developed in the area from the loaded end of the FRP sheet to not more than 100 mm length. Furthermore, it is reported that bond stress distribution differs from one experiment to another: 75 mm [10], 101 mm, 60 mm [11], 20–90 mm [12], and 40 mm [13].

The applied load on a strengthened specimen generates a tension in concrete. The tension in concrete is transferred to CFRP sheet through the adhesive bond (in the form of shear stresses) in a short length near the applied load. Debonding shifts the active bond zone further away from the loading point, as the load increases. The shifting of the active bond zone continues until the complete FRP debonding from the concrete. It indicates that only a part of the bond line is effective, where most of the bond stress is maintained. In other words, FRP bond length is a required distance for the strain to become zero [4,14]. Furthermore, the length at which the FRP-concrete bond line resists the entire load is the effective bond length. Hence, the increase of failure load cannot be achieved if the FRP bond length exceeds the effective bond length [14].

The effective bond length is a factor to evaluate the concrete-FRP bond strength as well as to estimate the failure load of the bonded specimen. Hence, the concept of effective bond length was used in most of the proposed models with regard to bond strength [8,12,15–17]. Numerous analytical models have been established to estimate the effective bond length [6,8,18–25]. Table 1 shows a summary of the existing models. For the same specimen, various effective bond lengths might be obtained from different models, which could be attributed to the use of different and limited experimental data during the derivations.

In Table 1, L_e is the effective bond length, and n is the number of FRP layers. E_f is the elastic modulus of FRP, and t_f is the thickness of FRP. f_t, f_{ctm}, f'_c and f_{ck} are the axial tensile strength, mean tensile strength, cylinder axial compressive strength, and characteristic strength of the concrete, respectively. Several studies have been conducted to enhance the understanding of the bond behavior between the concrete and CFRP sheets. Most proposed equations disregard the effect of marine environmental condition on effective bond length. Therefore, the influence of marine environment on the performance of the effective bond length must be investigated to have a better understanding of the CFRP-concrete bond performance. To study the behavior of FRP-concrete bond, an extensive set of experiments was conducted in this work. As discussed previously, there are no generally accepted equations to predict the effective bond length [14], specifically the equation with marine environment condition influences. Therefore, the bending-type shear bond tests were conducted in an attempt to propose analytical models that can estimate the effective bond length for strengthened beams under marine environmental conditions.

Table 1
Existing effective bond length models.

References	Equation	Consideration factors
ACI 440.2R [23]	$L_e = \frac{23300}{(nE_f t_f)^{0.58}}$	E_f, t_f
CSA [24]	$L_e = \frac{25350}{(E_f t_f)^{0.58}}$	E_f, t_f
FIB B14 [26]	$L_e = \sqrt{\frac{E_f t_f}{C_2 f_{ctm}}} C_2 = 2$	E_f, t_f, f_{ctm}
	$L_e = C_2\sqrt{\frac{E_f t_f}{f_{ck} f_{ctm}}} C_2 = 1.44$	$E_f, t_f, f_{ck}, f_{ctm}$
TR55 [27]	$L_e = 0.7\sqrt{\frac{E_f t_f}{f_{ctm}}}$	E_f, t_f, f_{ctm}
CNR-DT 200/04 [20]	$L_e = \sqrt{\frac{E_f t_f}{2f_{ctm}}}$	E_f, t_f, f_{ctm}
Eurocode 8 [28]	$L_e = \sqrt{\frac{E_f t_f}{4f_{ctm}}}$	E_f, t_f, f_{ctm}
CIDAR [29]	$L_e = \sqrt{\frac{E_f t_f}{\sqrt{f'_c}}}$	E_f, t_f, f'_c
Lu [21]	$L_e = 1.33\frac{\sqrt{E_f t_f}}{f_t}$	E_f, t_f, f_t
Neubauer et al. [8]	$L_e = \sqrt{\frac{E_f t_f}{2f_t}}$	E_f, t_f, f_t
Yang et al. [22]	$L_e = 100mm$	–

2. Experimental methods

2.1. Specimens

The modified 3-point bending-type shear bond test was performed in accordance with the test method recommended by NCHR [30]. Concrete beams with dimensions of 150 mm (W) × 750 mm (L) × 150 mm (thickness) were prepared. The concrete beam of 650 mm clear span was simply supported at both ends and the load applied at mid-span. To initiate debonding at a specific cross-section, the specimens were notched at mid-span, through half of the beam height by using a saw-cut. Two control specimens were kept at room temperature while the rest were subjected to an accelerated aging process. The complete details of specimens used in this study are presented in Fig. 1.

The specimens were cast with ready-mix concrete and 48 h after casting, beams were cured for 28 days in ambient condition. Three cylinders were cast from the same batch of concrete and the average compressive strength was obtained as $f'_c = 23.17MPa$. Two specimens were made for each series of tests to ensure the accuracy of the obtained results, totaling 18 concrete

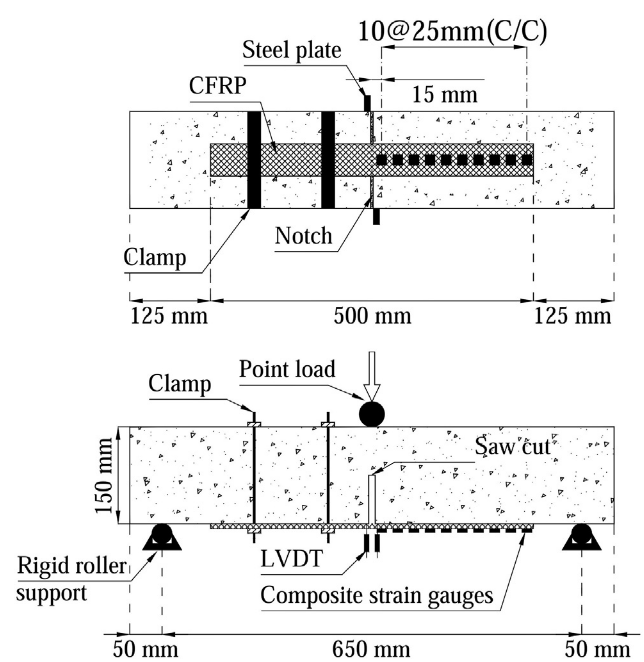

Fig. 1. Details of three-point bending-type shear bond test setup.