Bond strength recovery of lap splices in pre-damaged RC beams retrofitted with CFRP

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ABSTRACT

This study investigated the bond strength recovery of lap spliced bars in pre-damaged concrete beams after retrofitting with carbon fiber-reinforced polymer (CFRP). Four point-loading test was performed on eight reinforced concrete beams with two bar splices at the mid-span. The test variables were rebar diameter (20 and 28 mm), and use of stirrups along the bar splice length. The beams were pre-damaged by initial four-point loading, and then retrofitted with CFRP only or CFRP and crack injection epoxy. The retrofitted beams were reloaded to evaluate the recovered bond strength. The test results showed that the bond strength can be restored completely after retrofitting with CFRP in the specimens with rebar diameter of 20 mm.

1. INTRODUCTION

The sufficient bond strength between reinforcing bars and concrete should be developed for structural integrity of reinforced concrete (RC) members. Many existing RC structures have been built prior to the modern codes for earthquake resistant design. For this reason, poor reinforcement details were used in splice region, which would be inherently vulnerable to earthquake load.

According to Sezen et al. (2003), inadequate lap-splice details at RC members is one of the most critical reasons causing the damage of RC structures. After retrofitting with fiber reinforced polymer (FRP), the seismic performance of pre-damaged RC members can be recovered or enhanced (Yalcin et al. 2008, ElSouri and Harajli 2011). However, the seismic performance of the repaired structures was closely related to the bond strength between the reinforcing bars and the pre-damaged concrete. Thus, the

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bar bond strength of the pre-damaged concrete needs to be investigated.

Various studies have been performed to investigate the bond strength of bar splices strengthened with FRP. Hamad et al. (2004) evaluated the bond strength of bar splice in RC beams strengthened with glass FRP composites, and the reported that the bond strength and ductility were effectively improved. Garcia et al. (2004) investigated the bond strength of bar splice strengthened with carbon FRP, and found that the maximum enhancement of the normalized bond strength was limited to 0.40. The bond strength between the rebars and the surrounding concrete can be significantly enhanced by wrapping FRP at the bar splice length.

In the present study, to investigate the bond recovery condition between the reinforcing bars and the pre-damaged concrete, the pre-damaged lap splice beam specimen was retrofitted with CFRP at the bar splice length.

2. EXPERIMENTAL PROGRAM

2.1 TEST SPECIMENS

Four-point bending test was performed on eight splice beam specimens. The beam length was 3100 mm, depth was 300 mm, width was 250 mm, and clear span was 2600 mm. The test parameters were the rebar diameter (20 or 28 mm), and use of stirrups along the bar splice length (see **Table 1**). All of the beams were simply supported, and tested under vertical loading. The applied load was in increments of 5 or 10 kN until beam failure. The failed specimens were retrofitted with CFRP or a combination of CFRP and crack injection epoxy, and then reloading was applied.

Table 1 Test parameters

Specimens	Rebar diameter (f_y= 400 MPa)	Mid-span stirrups (f_y= 400 MPa)	Retrofitting methods
M20-S0-C	20 mm	None	CFRP sheet
M20-S0-CE			CFRP sheet+Epoxy
M20-S125-C		D8@125	CFRP sheet
M20-S125-CE			CFRP sheet+Epoxy
M28-S0-C	28 mm	None	CFRP sheet
M28-S0-CE			CFRP sheet+Epoxy
M28-S125-C		D8@125	CFRP sheet
M28-S125-CE			CFRP sheet+Epoxy

A three-part notation is used to indicate the variables in each beam. The first part of the notation indicates the rebar diameter: M20 for 20 mm rebar diameter. The second part indicates the configuration of stirrups: S125 for stirrups at a spacing of 125 mm, S0 for absent stirrups. The third part indicates the retrofitting method: C for CFRP sheet, CE for combination of CFRP sheet and crack injection epoxy. For example, specimen M20-S125-CE represents the beam with a bars of 20 mm diameter, with stirrups at a spacing of 125 mm, and using a combination of CFRP sheet and crack injection epoxy for retrofitting at the bar splice length.

2.2 MATERIAL PROPERTIES

All the beam specimens were cast one day by commercial ready-mixed concrete. After 7 days of curing in a humid environment under room temperature, the concrete form was removed. The average concrete compressive strength was 54.4 MPa. The compressive strength of early high-strength mortar was 65 MPa. The yield strengths of rebars with the diameter of 20 and 28 mm were 491 and 438 MPa, respectively. The material properties of unidirectional CFRP sheets were given by the manufacturer: the ultimate tensile strength of 3400 MPa; tensile modulus of 230 GPa; ultimate rupture strain of 1.6%; and nominal thickness of 0.165 mm at a single layer.

2.3 RETROFITTING PROCEDURES

For the beam retrofitted with CFRP sheet, the retrofitted procedures were as follows: (1) the corners of the beams were rounded with a 25 mm radius; (2) the surface of the beams were cleaned; and (3) one layer of CFRP sheets with a width of 500 mm were wrapped around the lap splice length, and additional length of 200 mm was overlapped for anchorage. For the beams retrofitted with a combination of CFRP and low viscosity concrete crack injection epoxy, the cracks in the splice length should be sealed up with crack epoxy sealer and cured for 24 hours before injecting the low viscosity concrete crack injection epoxy. After the crack injection epoxy was cured, the retrofitted procedures same as those of CFRP retrofitting were applied. For the specimens without stirrups along the splice length, the early high-strength mortar was used to replace the spalling concrete before wrapping CFRP.

3. RESULTS AND DISCUSSION

In the pre-damage test, splitting failure occurred in all beam specimens, except the beams M20-S125-C and M20-S125-CE showing beam yielding. After retrofitting with CFRP or a combination of CFRP and crack injection epoxy, the flexural failure occurred in all beam specimens, except the beam specimens M28-S125-C and M28-S125-CE (see **Fig. 1**). The bond stress of reinforcing bars was restored in the specimens with a diameter of 20 mm, and the bond strength increased up to 32% (see **Table 2**). The CFRP confinement prevented the spalling of cover concrete in the beams without stirrups at the bar splice length. The effect of crack injection epoxy on the bond strength improvement was insignificant.

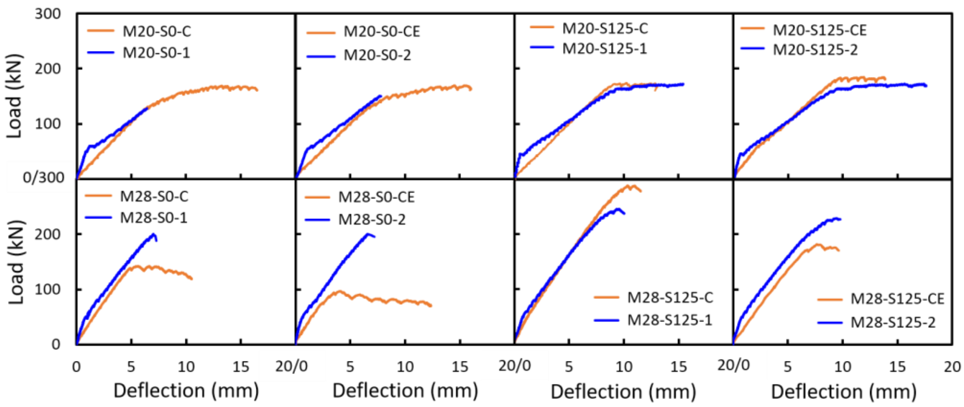

Fig. 1. Load-deflection relationship

Table 2 Test results

Specimens	Pre-damaged state				Retrofitting state				
	Ultimate load P_{pu} (kN)	Mid-span deflection δ_{pu} (mm)	Rebar stress f_{sp} (MPa)	Bond stress τ_p* (MPa)	Ultimate load P_{ru} (kN)	Mid-span deflection at δ_{ru} (mm)	Rebar stress f_{sr} (με)	Bond stress τ_r (MPa)	Bond ratio τ_r/τ_p
M20-S0-C	128.0	6.4	342.4	4.28	168.7	13.3	452.2	5.65	1.32
M20-S0-CE	150.4	7.7	402.9	5.04	169.3	14.5	453.8	5.67	1.13
M20-S125-C	172.0	11.1	461.1	5.76	174.2	10.3	467.0	5.84	1.01
M20-S125-CE	172.6	15.6	462.7	5.78	184.8	11.9	607.1	7.59	1.31
M28-S0-C	200.4	7.0	287.7	5.03	142.3	5.6	203.7	3.56	0.71
M28-S0-CE	200.2	6.6	287.4	5.03	96.8	4.0	138.3	2.42	0.48
M28-S125-C	245.6	9.4	353.5	6.19	287.8	10.3	415.3	7.27	1.17
M28-S125-CE	228.8	9.4	329.0	5.76	181.7	7.7	260.6	4.56	0.79

*$\tau_p = f_{sp}d_b/(4l_s)$, f_{sp} is the rebar stress, d_b is the rebar diameter, and l_s is the splice length.

4. CONCLUSIONS

In the present study, eight pre-damaged splice beams were retrofitted with CFRP along the bar splice length to investigate the bond strength recovery. The test results showed that the bond strength can be restored completely after retrofitting with CFRP in the specimens with a rebar diameter of 20 mm. After retrofitting, most of the specimens failed in flexure. On the other hand, as the specimens with a rebar diameter of 28 mm were governed by serious damage in the pre-damaged test, the retrofitting method was not applicable to improve the bond strength. Further studies are needed to evaluate the effective retrofitting method at each damage state.

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