Third International Conference on Sustainable Construction Materials and Technologies http://www.claisse.info/Proceedings.htm

Experimental Study on Residual Bond Strength between Post-installed Rebar and Concrete after Elevated Temperatures

Chi-Ping Wang[1*], Shengmin Wu[2], Chun Hao Chen[1], Bo Hsuan Chen[1]

[1] *Department of Civil Engineering, Feng Chia University, Taiwan*
[2] *Department of Construction Engineering, Chaoyang University of Technology, Taiwan*
[*]*100 Wen-hwa Rd. Seatwen, Taichung 407, Taiwan, R.O.C..*
cpwang@fcu.edu.tw, swu@cyut.edu.tw, j9789782000@hotmail.com,
blue790915@hotmail.com

ABSTRACT

This paper describes a preliminary experimental study on the bond effect between post-installed rebar and concrete after exposure to elevated temperature. Three levels of high temperature, 400°C, 500°C and 800°C, in addition to 25°C (room temperature) are considered. The bond effect is investigated by comparing the ultimate shear stresses between rebar and concrete as rebars are pulling-off in the pull-out tests. Adhesive material tests are also carried out to determine the variations of compressive strength and flexural strength due to different temperatures. The experimental results show that temperature higher than 300 °C could cause the adhesive material change its appearance significantly, so that the material loses its strength. The post-installed rebar systems totally lose their bond strength when the temperature reaches 800°C. However, rebar systems may retain 80% bond strength if the specimens are exposed to 500°C or less.

Keywords. Retrofit, Post-installed Rebar, Pull-out Test, Bond Strength, Elevated Temperature.

INTRODUCTION

Post-installed rebar technique has been commonly used in concrete construction for years whenever there is a need of alteration or reinforcement. Nowadays, many aged or damaged reinforced concrete structures are strengthened and repaired by retrofit technique utilized post-installed rebars to avoid demolition and reconstruction.

Poor bonding between steel and concrete is one of the main reasons causing the damage and deterioration of reinforced concrete structures. Since most of the epoxy resin-based adhesives have high strength, material stability, durability, and good bonding effect, the performance of bonded rebar is usually considered even better than the cast-in reinforcement. Study has pointed out that the bond strength of rebar adhesive is significantly higher than that the embedded reinforced, especially in lower embedment depth (Hamad, 2006).

However, concrete may expose to elevated temperatures during a fire. Study has showed that the adhesive can only withstand 120^{o}C within a short period of time, otherwise softening and bond failure would occur (Technical Handbook, 2006). Besides, when the reinforced concrete exposed to the temperatures over 200 °C, the bond strength of rebar gradually decreases as the exposure time increases (Chiang, 2000, and Chiang, 2003). Therefore, once the reinforced concrete structures containing post-installed rebar suffer the invasion from fire damage, whether the appropriate bond strength between steel rebar and concrete could retain is a significant concern.
There are studies conducted on the bond strength of cast-in rebars at high temperature (e.g., Ferhat Bingol, 2009, Bouazaoui, 2008, Chiang, 2000, and Chiang, 2003). However, information on the bond between post-installed rebar and concrete is limited. In order to ensure the security of anchorage in engineering applications, and to correspond the needs of fire safety for structures, there must be more efforts put in this area. Therefore, the main purpose of this study is to investigate the influence of high temperature on the bond strength of concrete specimens consisting of post-installed rebar.

EXPERIMENTAL PROGRAMS

There are two categories of experimental tests conducted in this study. One is to understand the material strength of adhesive under different temperatures (via compressive test and four-point bending test), and the other is to determine the influence of high temperature on bond strength (via pull-out test). Ten cylindrical adhesive specimens, and ten flat adhesive specimens were prepared for compressive tests, and bending test, respectively. Five temperatures ranging between 25^{o}C and 300^{o}C are chosen. Sixteen sets of pull-out tests in three series were conducted. Most pull-out test sets contain five identical specimens. Three elevated temperatures, 400^{o}C, 500^{o}C, and 800^{o}C in addition to room temperature (25^{o}C) are chosen. All the holes in concrete were prepared by utilizing a heavy-duty electric drill with a 12 mm drill bit. The inclination angle between the longitudinal axis of each post-installed rebar and the perpendicular direction to the concrete surface was measured and controlled within a tolerance of 6 ^{o} (ICBO 2001). The general experimental conditions and the tests parameters of pull-out tests are summarized in Table 1.

Materials. Based on the limitation of the testing equipment, only #3 steel deformed reinforcing bars (nominal diameter d = 10 mm) were used. Ready-mix concrete with design compressive strength of 27.6 MPa were cast in-situ as the base material. Any drilling or heating process was carried out after the concrete reaches its 28-day strength. Two brands of adhesives (so called Adhesive I and Adhesive II herein) were selected as the bonding material. These adhesives are both two-component injection type with epoxy resin and hardening agent. The extruded adhesive was cured in air for at least 24 hours before any further treatment. One spray-applied fire resistive material, whose major components including cement, vermiculite and inorganic fire resistive material, was also used to protect the rebar outside from the concrete against the damage when the specimens were heated in the furnace. All the above-mentioned materials used to prepare the test specimens were obtained from the same batch to minimize variations between samples.

Specimens. The sizes of adhesive specimens for material tests are as listed in Table 1. One specimen of each adhesive was heated to the target temperature, 100^{o}C, 200^{o}C, 300^{o}C, or 400^{o}C for 30 minutes, and was air-cooled to room temperature. The rest unheated specimens were to be tested as the reference.

Table 1. Experimental conditions and test parameters

	Main Descriptions		Supplementary Descriptions
Apparatus	MTS material test system		Servohydraulic load frames, Max. capacity: 250 kN
	high-temperature furnace		Max. temp: 1000 ^{o}C
Test control	Load control, Static loading		Procedure following ASTM or ICBO
Material	concrete	Ready-mixed concrete	$f'c$ = 27.6 MPa (Design) $f'c$ = 32.6 MPa (Measured in Lab)
	rebar	deformed steel bars	F_y = 273 MPa, F_u = 383 MPa (Nominal) P_u = 41.4 kN (Measured in Lab)
	adhesive	I (Commercial brand)	two-component injection type
		II (Commercial brand)	two-component injection type
Adhesive material test	Compressive specimen (cylinder)		2.5cm dia. x 5cm height
	Bending specimen (flat bar)		2cm x1cm x 11cm
	Temperature (T, ^{o}C)		25, 100, 200, 300, 400
Pull-out test	Concrete specimen (cylinder)		15cm dia. x 15cm height
	Embedment length h_{ef} of #3 rebar		5cm
	Temperature (T, ^{o}C)		25, 400, 500, 800

The specimens for pull-out tests were divided into three series. The first series, Series N, is the reference test set with specimens not heated. These specimens were prepared by the standard process as follows.

a. Drill a 5cm deep hole in the center of the prepared concrete specimen, and completely clean the hole.
b. Install a rebar into the cleaned hole with proper amount of adhesive, and make no movement of the entire system for 24 hours.

The second series, Series A, contains the install-then-heat specimens. These specimens were first made by the above mentioned standard process. 24 hours after rebar installation, the chosen fire resistive material was spray-applied on the surface of the part of rebar outside of the concrete. Then the specimens were heated to the target temperature, 400^{o}C, 500^{o}C or 800^{o}C. After a heating duration of 30 minutes at the target temperature, the specimens were air-cooled in lab and the fire resistive material was removed.

The third series, Series B, contains the heat-then-install specimens. The concrete cylinders were first put in the furnace and heated to the target temperature, 400^{o}C, 500^{o}C or 800^{o}C for 30 minutes. After air-cooled in lab, rebar was installed in the concrete cylinder by the standard process.

There two sets of pull-out tests not included in the above series. One set contains specimens similar to Series A except that the fire resistive material was sprayed all over the surface of the entire specimen. The other set contains specimens similar to Series B except that the concrete cylinders were protected by fire resistive material before they were sent into furnace.

The purpose of making these two sets of pull-out tests is to check the effect of fire resistive material.

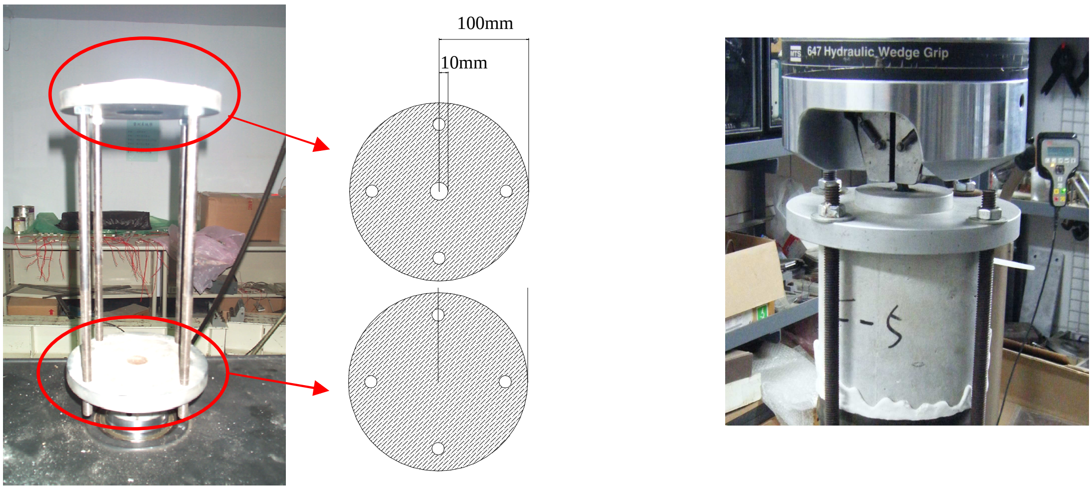
Testing Procedure. Adhesive material tests and pull-out tests were performed 24 hours after the specimens were made. Strain gages were attached in the center on both top and bottom surfaces of adhesive bending specimens to record the compressive and tensile strains during the tests. The setup of adhesive material tests are shown in Figure 1. Figure 2 depicts the specimen grip and setup of pull-out tests. Maximum load and failure mode were recorded for each pull-out test and the bond strength of each specimen was calculated as follows:

$$\tau_{bond} = \frac{P_u}{\pi d h_{ef}} \quad (1)$$

where τ_{bond} represents the average shear stress (bond strength), P_u:is the ultimate pull-out load, d is the nominal diameter of rebar, and h_{ef}: denotes the embedment length of rebar.

(a) Compressive test (b) Bending test

Figure 1. Setup of material test of adhesive



(a) Specimen grip (b) Assembly of specimen

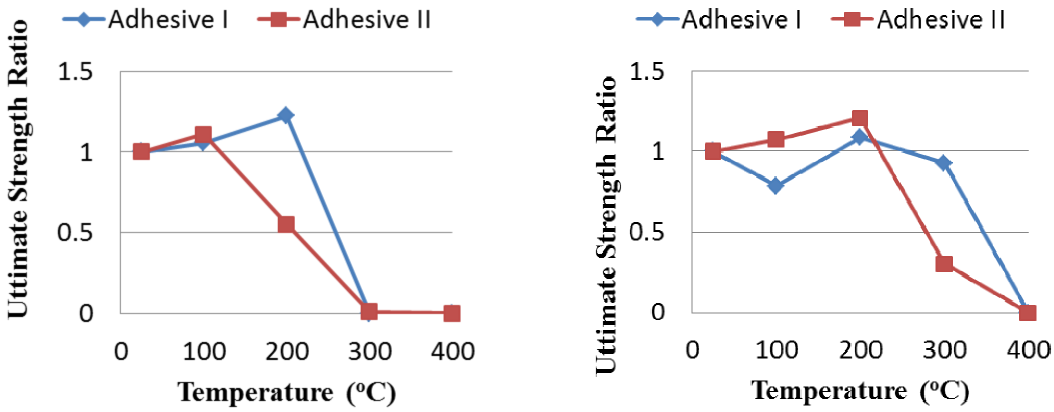
Figure 2. Setup of pull-out test

TEST RESULTS AND DISCUSSIONS

Although it is indicated in previous study that adhesive may not perform well under temperature above 120 ^{o}C, adhesive specimens in this study were exposed to temperatures up to 400 ^{o}C to examine the material strength change due to different temperature. Since the adhesive is not a ductile material, bending test is chosen to replace the tensile test. The appearance of adhesive specimens after heated to the selected temperatures is shown in Table 2, and the variations of capacity ratio (ultimate strength of heated specimen divided by the ultimate strength of unheated specimen) are illustrated in Figure 3. Table 3 depicts the comparison between the specimen under room temperature and the specimens protected by the fire resistive material. All other results of pull-out test results are listed in Table 4.

Table 2. Appearance of adhesive material sample after heating

Temp (^{o}C)	Specimen for Compression Test		Specimen for Bending Test	
	Adhesive I	Adhesive II	Adhesive I	Adhesive II
25				
100				
200		 		
300				
400	 	 		



(a) Compression test (b) Bending test

Figure 3. Variations of capacity ratios

Material Tests of Adhesives. It can be observed from the specimen appearance in Table 2 that the color of compressive specimen slightly varied at 100°C. When the temperature reached 300°C not only the color but also the texture of the compressive specimens showed severely change. Similar phenomenon also occurred for the bending specimens. The ultimate compressive capacity of unheated specimens made by adhesive I and Adhesive II are 1.06 kN and 1.11 kN, respectively, that yields a difference less than 5%. The ultimate total load of bending test for the unheated specimen of adhesive I is 51.5 kN, and that is 49.2kN for adhesive II. The difference between these two adhesive materials is again no more than 5%. From the variations of ultimate strength ratios shown in Figure 3, it is found that the adhesive materials could retain their strength if the temperature was below 200°C, but the materials totally lose their strength if the temperature reaches 400°C.

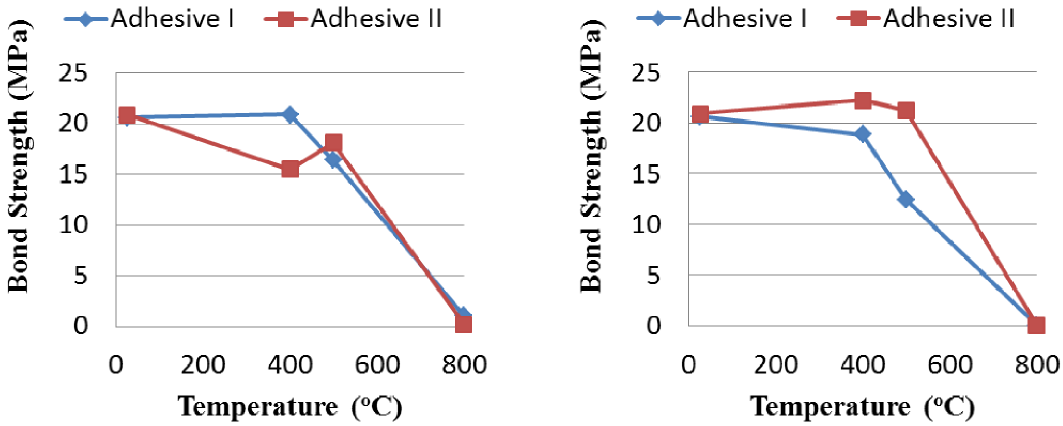
Effect of Fire Resistive Material. The effect of fire resistive material is examined by comparing the bond capacity obtained by pull-out test of the specimens protected by firproof material with that of the unheated specimens. From the test results indicted in Table 3, it can be found that the average bond strength of the install-then-heat specimens (set O-1) reduced about 12%, but the average bond strength of the heat-then-install specimens (set O-2) increased 18%. This result showed that the fire resistive material used in this study developed a good protection function so that the entire system under 500 °C can still retains almost 90% bond strength (set O-1). Moreover, if the concrete itself was covered by the fire resistive material, the material strength probably increased a certain degree that make the post-installed rebar display a higher bond strength (set O-2) than the unheated specimens.

Influence of Elevated Temperatures on Bond Strength of Post-Installed Rebar System. The comparisons among pull-out test results of heated and unheated speimens are shown in Figure 4. The curves displayed in Figure 4 (a) indicate that the install-then-heat specimens (series A) of both adhesives totally lost their bond strength when the specimens were heated to 800°C. If the specimens were exposed to temperatures not higher than 500°C, more than 80% of the bond strength was remained. Similar situation was found for the heat-and install specimens (series B) as shown in Figure 4 (b). Bond strength higher than that of unheated specimens can be found for the heat-and-install specimens with Adhesive II. This phenomenon was also discussed in Series O test. Some specimens displayed bond failure at 500 °C and 800°C are shown in Figure 5.

Table 3. Pull-out test results

Adhesive I							
set (Temp)	description	Sample number	Failure Type#	Ultimate capacity (kN)		Average Bond strength τ_{bond}(MPa)	Difference $\frac{\tau_{bond} - \tau_{bond,25^\circ C}}{\tau_{bond,25^\circ C}}$
				Test result	average		
I-1 (25 °C)	unheated	1	B	29.6	32.3	20.6	0
		2	B	33.2			
		3	B	31.2			
		4	B	36.6			
		5	B	30.7			
O-1 (500 °C)	Install-then-heat‡	1	B	28.0	28.5	18.1	-12.1%
		2	F	39.4*			
		3	F	39.5*			
		4	B	28.9			
		5	F	39.8*			
O-2 (500 °C)	Heat-then-install†	1	B	33.7	38.2	24.3	+18.0%
		2	B	40.8			
		3	B	40.1			
		4	F	40.5*			
		5	F	41.1*			

Failure Type: F-steel rebar fracture, B-bond failure.
‡The whole specimens were covered by fire resistive material before heating.
†The concrete cylinders were covered by fire resistive material before heating.
*The value is not included in the calculation of average strength due to rebar fracture.



(a) Heat-then-install specimens (Series A tests)

(b) install-then-heat specimens (Series B tests)

Figure 4. Comparisons of pull-out test results

Table 4. Pull-out test results

series	Adhesive I set (Temp)	Adhesive I Sample No.	Adhesive I Ultimate capacity (kN) Test result	Adhesive I Ultimate capacity (kN) average	Adhesive I Bond strength Average (MPa)	Adhesive II set (Temp)	Adhesive II Sample No.	Adhesive II Ultimate capacity (kN) Test result	Adhesive II Ultimate capacity (kN) average	Adhesive II Bond strength Average (MPa)
N	I-1 (25 ^oC)	1	29.6	32.3	20.6	II-1 (25 ^oC)	1	30.1	32.9	20.9
		2	33.2				2	38.5		
		3	31.2				3	43.0*		
		4	36.6				4	30.7		
		5	30.7				5	32.3		
A	I-2 (400 ^oC)	1	41.7*	32.9	20.9	II-2 (400 ^oC)	1	22.2	24.3	15.5
		2	37.4				2	25.9		
		3	30.3				3	31.6		
		4	24.3				4	23.8		
		5	39.4				5	18.0		
	I-3 (500 ^oC)	1	25.2	25.7	16.4	II-3 (500 ^oC)	1	21.2	28.4	18.1
		2	26.2				2	39.1		
		3	39.7*				3	38.9		
		4	41.8*				4	19.6		
		5	39.0*				5	23.2		
	I-4 (800 ^oC)	1	0.293#	1.64	110	II-4 (800 ^oC)	1	5.41	0.297	19.9
		2	12.9				2	2.80		
		3	16.4				3	0.49		
		4	37.6*				4	--		
		5	19.2				5	--		
B	I-5	1	24.6	29.5	18.8	II-5	1	31.2	34.9	22.2
		2	26.8				2	34.7		
		3	37.1				3	38.7		
	I-6	1	34.1*	19.5	12.4	II-6	1	33.95	33.3	21.2
		2	23.1				2	21.3		
		3	34.0*				3	36.1		
		4	18.3				4	38.2		
		5	17.1				5	36.8		
	I-7	1	--	--	--	II-7	1	--	--	--
		2	--				2	--		
		3	--				3	--		
		4	--				4	--		
		5	--				5	--		

The test results of specimens failed either due to rebar fracture (values followed by *) or due to poor rebar installation (values followed by #) are not included in calculation of average bond strength.

-- represents the specimens are severely damaged after heating to the target temperature.

Only results of specimen fail in bond failure type were included in calculating the average.

(a) 500℃ (b) 800℃

Figure 5 Bond failure of pull-out test

CONCLUSIONS

Several conclusions are drawn from this study.

1. The compressive and bending strength of the two adhesives used in this study are very close. The material strength of both adhesives severely changed if the material is exposed to temperature higher than 300 °C.
2. The effect of fire resistive material used in this study is quite good. With the protection provided by the fire resistive material, the bond strength of specimens can be remained to an accepted degree after exposure up to 500 °C
3. If the specimens are exposed to temperatures not higher than 500 °C, more than 80% of the bond strength could be retained. However, all specimens heated to 800 °C totally lose their bond strength.

ACKNOWLEDGEMENTS

The authors wish to sincerely thank the National Science Council of Taiwan, R.O.C. for the financial support (Project No. NSC 101-E-2221-035-049).

REFERENCES

Bouazaoui, L., and Li, A. (2008), "Analysis of Steel/Concrete Interfacial Shear Stress by means of Pull out Test," International Journal of Adhesion and Adhesives, Vol. 28, Issue 3, pp. 101-108.

Chiang, C.-H., Tsai, C.-L., and Kan, Y.-C. (2000), "Acoustic inspection of bond strength of steel reinforced mortar after exposure to elevated temperatures," Ultrasonics 38 (1) , pp. 534–536.

Chiang, C. H., and Tsai, C. L. (2003), "Time-Temperature Analysis of Bond Strength of a Rebar after Fire Exposure," Cement and Concrete Research, No. 33, pp.1651-1654.

Ferhat Bingol, A., and Rustem Gul (2009), "Residual Bond Strength between Steel Bars and Concrete after Elevated Temperatures," Fire Safety Journal No. 44, pp. 854-859.

Hamad, B. S., Hammoud, R. Al, and Kunz, J. (2006), "Evaluation of Bond Strength of Bonded-in or Post-Installed Reinforcement," ACI Structural Journal, vol. 103., no. 2, pp.207-218.

"Technical Handbook," 3rd Edition (2006), Fischer Fixing Systems.