Iranian Journal of Science & Technology, Transaction B: Engineering, Vol. 34, No. B4, pp 397-406
Printed in The Islamic Republic of Iran, 2010

LOSS OF CONCRETE-STEEL BOND STRENGTH UNDER MONOTONIC AND CYCLIC LOADING OF LIGHTWEIGHT AND ORDINARY CONCRETES*

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Abstract– In this study, loss of concrete-steel bond strength of lightweight and ordinary concrete under monotonic and cyclic loading is examined for plain and deformed steel bars. Here, lightweight and ordinary concrete-steel bond strength is determined by pull-out test for a variety of specimens in various configurations. For each specimen, a bond strength-slip curve is obtained through monotonic loading. Following this process, an identical specimen is subjected to cyclic loading under similar conditions using the same test setup. These examinations reveal several insights. Lightweight concrete-steel bond strength is greater than the ordinary concrete-steel bond strength for plain steel bars under monotonic loading. Ordinary concrete-steel bond strength is greater than lightweight concrete-steel bond strength under both monotonic and cyclic loading for deformed steel bars. The loss of concrete-steel bond strength is greater in plain bars than in deformed bars.

Keywords– Concrete-steel bond, bond strength, lightweight concrete, ordinary concrete, monotonic and cyclic loading, plain and deformed bars, slip

1. INTRODUCTION

Although the properties of structural concrete produced with ordinary aggregates are admirable, their high unit mass may be a source of problems in the construction of tall buildings. For example, foundations produced with ordinary concrete may entail higher costs. Further, long span bending members made with this concrete may not be capable of carrying their own weight. Finally, buildings constructed with higher density materials are naturally heavy and will generate greater inertia forces during earthquakes. On the other side of the equation, the use of the lightweight concrete in reinforced concrete structures has many advantages, which include low unit mass, high fire resistance, high heat insulation capacity, and high sound insulation capacity. In addition, lightweight concrete has the residual benefit of requiring less steel reinforcement for members subject to bending, reductions in the dimensions of foundations, and simpler less expensive formwork during casting. However, there are shortcomings to the use of the lightweight concrete. These shortcomings include a reduction in mechanical strength and immediate and delayed form-changeability [1-5].

In order to use lightweight concrete as structural elements in reinforced concrete constructions, the bond strength between concrete and steel should be at a level consistent with reinforced concrete calculations. Early researchers, who examined the mechanical behavior of reinforced concrete, quickly realized that the bond between concrete and steel was critical to the overall performance of the material. In fact, some research was undertaken long before the establishment of the first code on bond strength in reinforced concrete. Pioneering experimental work was conducted by Considere [6] in 1899 and Abrams

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*Received by the editors October 14, 2008; Accepted March 18, 2010.

[7] in 1913. By the second half of the 20th century, many researchers were actively involved in the subject [8-13].

Although the number of studies on lightweight concrete-steel bond strength is far less than the number of studies on ordinary concrete, there are some studies that have been done in recent years. Mitchell and Marzouk [14], Campione et. al. [15], and Chen et. al. [16] all studied the bond characteristics of lightweight concrete. The results of those studies show that the lightweight concrete-steel bond strength is 30% weaker than the concrete-steel bond strength in ordinary concrete. However, the difference between the bond strength of lightweight concrete and ordinary concrete decreases when deformed steel members and steel rods with large diameters are brought into the comparison. Specifically, bond strength between concrete and steel is stronger with highly deformed members in comparison to steels having plain surfaces. Similarly, the bond strength between concrete and steel is higher for rods with large diameters than rods with smaller diameters. For this reason, some researchers prefer decreasing bond strength allowable stress for steels having a large diameter to these limitations [9]. Also, in recent years, some research has been carried out on concrete-steel bond characteristics of high strength concrete [17-19].

Here, it is appropriate to mention that in spite of these research efforts, there is no exact solution for bond strength. It was thought that the bond strength problem was solved by the introduction of deformed steel; instead, the problem became more complex. Specifically, it appeared that the bond strengths in deformed steel varied by the square of the steel's diameter rather than by the diameter itself. Consequently, the subject of concrete-steel bond strength is still not well defined even today [20].

In general, reinforced concrete structures are exposed to the effects of horizontal loads, such as those generated by earthquake and wind. For this reason, the bond behavior under cyclic loading for reinforced concrete members is much more important. The main factors influencing bond behavior under cyclic loads are concrete compressive strength, cover, bar size, anchorage length, rib geometry, steel yield strength, loading type [10, 22-25].

The experiments used in determining concrete-steel bond strength can be grouped as tensile and bending experiments. Although it is often misleading to measure the end-point without load in pull-out experiments, it is employed in the current study with the understanding that this approach, although used as a comparison, will not affect the results.

2. EXPERIMENTAL STUDY

a) Concrete-steel bond stress

The Concrete steel bond strength is formulated in technical literature as,

$$\tau_{bd} = \frac{\phi \sigma_s}{4 l_b} \qquad \text{(MPa)} \tag{1}$$

Here, l_b (mm) is bond length of steel, where bond length corresponds to the portion of the steel bar that is embedded within the concrete; ϕ is the diameter of the steel; and σ_s (MPa) is the tensile stress in steel. If equation (1) is written as $\sigma_s = F/(\pi\phi^2/4)$ and $l_b = 30\phi$, it then comes out as,

$$\tau_{bd} = \frac{F}{30\,\pi\,\phi^2} \qquad \text{(MPa)} \tag{2}$$

Where, F (kN) is applied tensile load to steel bars.

In this study, the degradation of concrete-steel bond strength is examined as a function of concrete density, where lightweight and ordinary concrete are examined; bar surface roughness, where plain and deformed steel bars are evaluated, and bar diameter. Specimens are made with lightweight and ordinary concrete, using plain and deformed bars, having diameters of 8, 10, 12 and 14 mm. Finished specimens are subjected to monotonic and two levels of cyclic loading. In this manner, a total of 48 specimens are prepared, where each specimen has a unique concrete density, bar surface roughness, bar diameter and loading state. Under monotonic loading, specimens are subjected to loads until a slip of 0.25 mm occurs or the bar yields. When a monotonic test load is established, for a given configuration, two new specimens are evaluated using 0 to 80% of the monotonic test load over 50 and 150 cycles.

b) Material properties

***Aggregate properties*:** *Dacitic tuff*, a natural lightweight aggregate, was used in the production of lightweight concrete (LWC), while *Limestone* aggregate was used in the production of ordinary concrete (OC), the maximum aggregate size used was 16 mm. The mechanical properties of these aggregates were determined from their rock blocks by testing core specimens with 75 mm diameters and heights of 150 mm. Micro-strains were measured by 20 mm length strain-gauges, bonded to the surface of the core specimens. The physical and mechanical properties of these aggregates are given in Table 1.

Table 1. Physical and mechanical properties of aggregates

Properties	Lightweight Aggregate		Ordinary Aggregate	
	Fine (<4 mm)	Coarse (>4mm)	Fine (<4 mm)	Coarse (>4mm)
Loose density (kg/m^3)	1100	900	1450	1400
Dry density (kg/m^3)	1840	1860	2626	2658
Saturated density (kg/m^3)	2110	2120	2660	2670
Water absorption (%)	17.0	14.0	0.52	0.42
Average compressive strength* (MPa)	39.4		73.4	
Initial modulus of elasticity (MPa)	4762		60000	
Poisson's ratio	0.08		0.17	

**Determined from 75 mm diameter and 150 mm height cores of the rock blocks.*

***Steel properties*:** As mentioned previously, plain surface and deformed surface steel bars having diameters 8, 10, 12 and 14 mm were used in determining the lightweight and ordinary concrete-steel bond strength. Some properties of these steel bars, obtained through tensile test, are given in Table 2.

Table 2. Some mechanical properties of steel bars

Ø (mm)	Type of steel bar	Characteristic tensile strength (MPa)	Characteristic yield strength (MPa)	Characteristic ultimate strain (%)
8	plain	480	330	18.4
	deformed	706	571	18.0
10	plain	530	360	21.3
	deformed	697	500	17.0
12	plain	440	320	15.5
	deformed	673	575	16.0
14	plain	420	280	20.4
	deformed	675	562	14.0

c) Mixture, production and curing of concretes

Concrete mixture: The gradations of lightweight and ordinary aggregates used in the production of lightweight and ordinary concretes were the same. A water-cement ratio of 0.50 was used in the production of concrete, and mix designs are given in Table 3. In the production of concretes, CEM-II 32.5N type Portland cement was used.

Table 3. Mix design of concretes

Concretes	W/C	Cement (kg/m^3)	Water (kg/m^3)	Aggregate (kg/m^3)		Total Aggr. (kg/m^3)	Absorbed water (kg/m^3)
				Fine (45%)	Coarse (55%)		
LWC	0.50	350	175	560	690	1250	212.0
OC	0.50	350	175	823	1006	1829	3.80
LWC: Lightweight concrete OC: Ordinary concrete							

Production and curing of concretes: A 120 liter capacity drum mixer was used in the mixing of concrete. After weighing, each class of aggregate was poured into the mixer and agitated for 3 minutes while continuously adding water. Standard test cylinders were used to make compression specimens. Bond test specimens were made in custom molds that included lateral holes to support plain and deformed steel bars. All specimens were cast in three steps. Each step was separated by a vibration on a shaking table with a fixed duration and fixed frequency. At each step, compression specimens were vibrated for 5 seconds and bond test specimens were vibrated for 15 seconds. All vibrations had a frequency of 2800 cycles per minute. After 24 hours, the specimens were taken out of their molds and carefully placed into a curing bath that maintained a 23°C ± 2°C water temperature for 21 days. All specimens were tested at 28 days.

Concrete properties: The mean and characteristic compressive strengths, initial elastic moduli, Poisson ratios and dry unit weights of lightweight and ordinary concrete are given in Table 4. In the standard cylinder compression tests, the strains were measured by TML-PL90 type (90 mm length) strain gauges.

Table 4. Some physical and mechanical properties of concretes

Concretes	Dry density (kg/m^3)	Mean compressive strength (MPa)	Characteristic compressive strength (MPa)	Initial elasticity modulus (MPa)	Tangent modulus (for 0.5 fc) (MPa)	Poisson's ratio
LWC	1807	19	18.4	6600	4100	0.16
OC	2400	37	35.6	37000	26000	0.23
LWC: Lightweight concrete OC: Ordinary concrete						

3. CONCRETE-STEEL BOND TESTS AND RESULTS

As mentioned before, the purpose of this study is to investigate the lightweight concrete-steel bond strength and ordinary concrete-steel bond strength under monotonic loading and loss of bond strength under the cyclic loading. For this purpose, prismatic specimens were prepared with a 150 x 250 mm cross section and a depth that was equivalent to 30 times the diameter (30ϕ) of the embedded steel bar. In this manner, the depth of the specimen was identical to the bond length. Specimen details and an image are presented in Fig. 1. Steel bars were placed in a horizontal position within the moulds before casting and each bar normally extended on both sides of the mould. Two specimens were prepared and tested for each diameter of steel bar. Before the experiment, specimens were painted in white to make any micro crack, slip behavior or crack propagation visible to the naked eye. The test setup and specimen details are given in Fig. 2. Bar slips were measured by an LVDT, which was positioned against one end of the steel bar that extended from the bottom face of the concrete block. A load-cell with a capacity of 500 kN was used to record applied load. Load and displacements were collected by a data-logger that could record 8 data points per second.

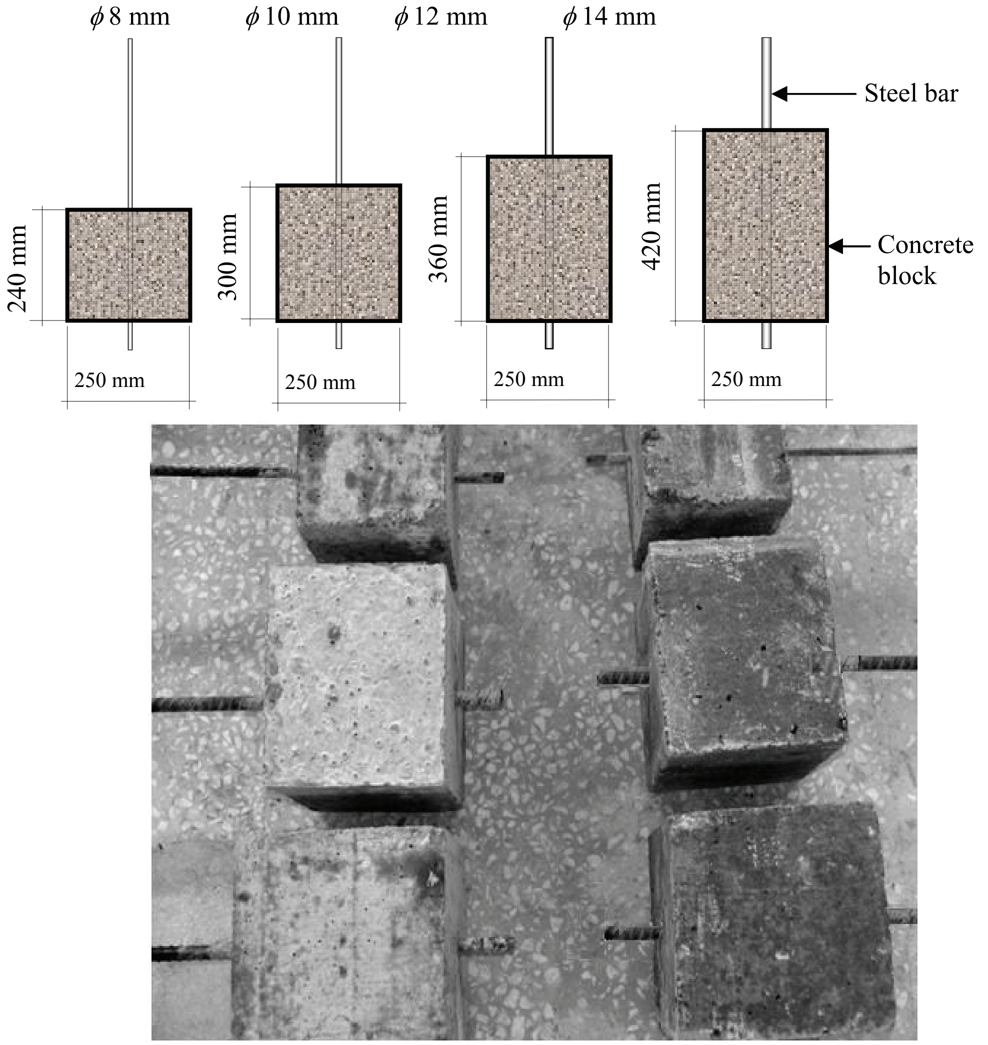

Fig. 1. Specimen details and an image from some specimens

a) Monotonic tests results

In the monotonic tests, the bond strength (τ_{bd}) is defined as the load at which the reinforcement steel slips by a distance of 0.25 mm. Based on this definition, Table 5 provides, for both lightweight and ordinary concrete, values for σ_s and τ_{bd} when a 0.25 mm slip occurs, as well as maximum values for σ_s and τ_{bd} recorded during testing. The bond stress-slip curves under monotonic loading for plain and deformed bars, with diameters of 8, 10, 12 and 14 mm, are given in Fig. 3. From these tables and figures, it can be noted that “lightweight concrete-steel bond strengths” are 30%, 32%, 39% and 42% stronger than “ordinary concrete-steel bond strengths” for plain steel bars with diameters of 8, 10, 12 and 14 mm, respectively. These results may be explained by the fact that lightweight concrete has more micro grains of aggregate than ordinary concrete and that those increased number of grains provide greater adherence between the concrete and steel.

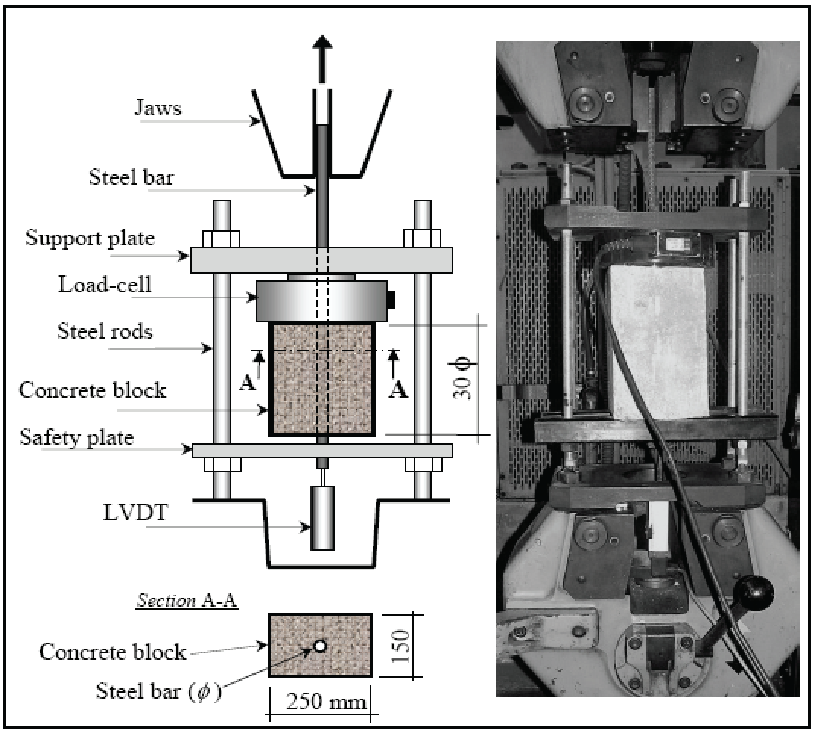

Fig. 2. Concrete-steel bond test set-up

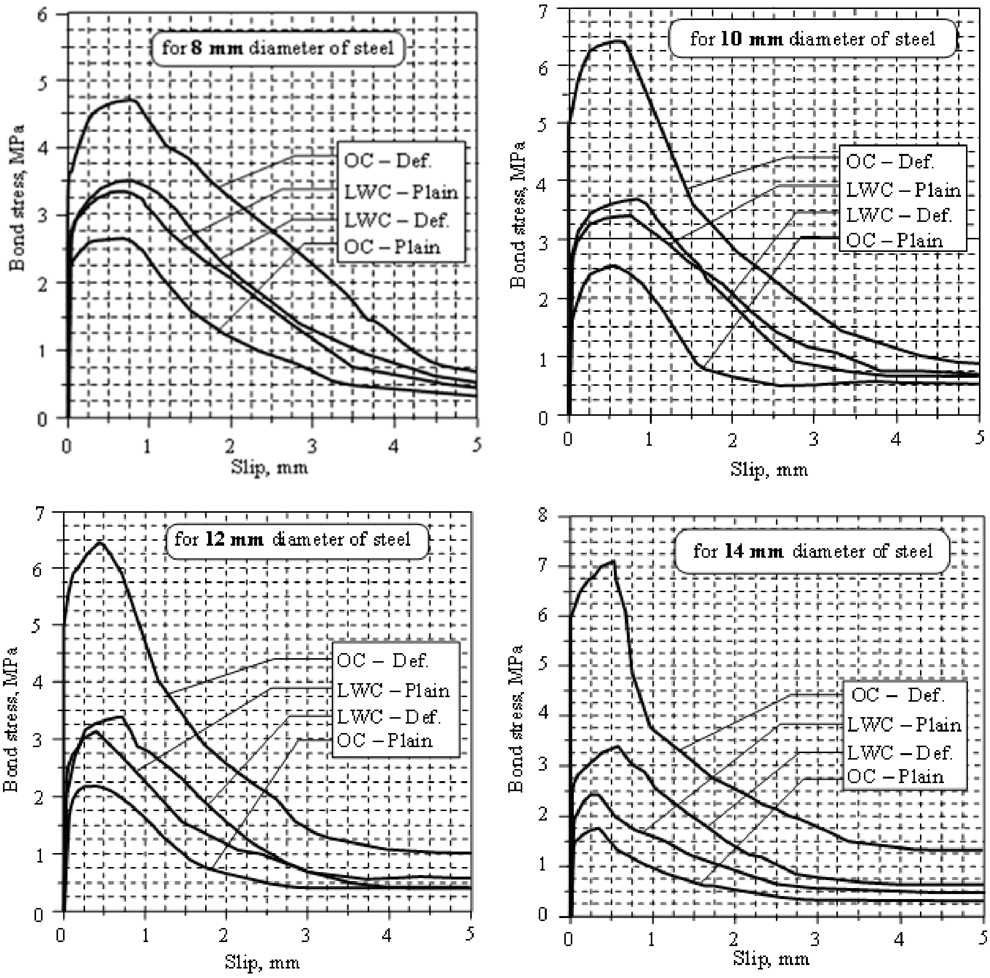

Fig. 3. Bond stress – slip curves for 8, 10, 12, and 14 mm diameter bars

Table 5. Concrete-steel bond strengths under monotonic loading

Concrete	Steel bar		σ_s (for 0.25mm slip) (MPa)	Max. σ_s (MPa)	τ_{bd} (for 0.25 mm slip) (MPa)	Max. τ_{bd} (MPa)
	ϕ(mm)	Surface				
LWC	8	plain	380	403	3.17	3.36
		deformed	258	281	3.23	3.51
	10	plain	390	395	3.25	3.29
		deformed	278	298	3.47	3.72
	12	plain	360	370	3.06	3.10
		deformed	252	267	3.15	3.34
	14	plain	285	290	2.45	2.45
		deformed	246	262	3.07	3.28
OC	8	plain	310	318	2.58	2.65
		deformed	345	375	4.31	4,69
	10	plain	296	306	2.47	2.55
		deformed	500	515	6.25	6.44
	12	plain	270	270	2.20	2.20
		deformed	494	519	6.17	6.49
	14	plain	208	210	1.73	1.75
		deformed	537	570	6.71	7.13

LWC: Lightweight concrete OC: Ordinary concrete

In an inverted process, the ordinary concrete-steel bond strengths are 34%, 52%, 96% and 119% stronger than lightweight concrete-steel bond strength for deformed steel bars with diameters of 8, 10, 12 and 14 mm, respectively. However, lightweight concrete-steel bond strengths in plain steel bars are 2%, 7%, 3% and 25% less than lightweight concrete-bond strengths in deformed steel bars with diameters of 8, 10, 12 and 14 mm, as in the same sequence above. In addition, ordinary concrete-steel bond strength for deformed steel bars is, on average, three times higher than ordinary concrete-steel bond strength for plain steel bars.

The slip of the plain steel bars in the lightweight concrete occurred after the yield stress of the steel. Contrarily, the slip of the deformed steel bars in lightweight concrete occurred when the bar reached approximately half of the yield stress. This behavior suggests that a bond length of 30ϕ is insufficient for deformed steel bars in lightweight concrete. Here, it should be noted that the current ACI 318 [24] and ACI 408 [27] recommend that calculated bond strength should be reduced by 30% when using lightweight aggregates.

b) Cyclic tests results

The cyclic loading was applied 50 times and 150 times with loads ranging from zero to 80% of steel stress (0.80 σ_s) at 0.25 mm slips. The loading protocol is given in Fig. 4. The bond strengths for the 0.25 mm slip obtained in these tests is given in Table 6. After 50 cycles, lightweight concrete-steel bond strength for deformed steel bars was 8% less than under monotonic loading for deformed steel bars with diameters of 8, 10, 12 and 14 mm. Similarly, after 150 cycles, lightweight concrete-steel bond strength was 20% less than under monotonic loading. In the case of plain steel bars and lightweight concrete, lightweight concrete-steel bond strengths, after 50 cycles, were 15%, 20%, 32% and 58% less than under monotonic loading for plain steel bars with diameters 8, 10, 12 and 14 mm, respectively. With regard to 150 cycles, the lightweight concrete-steel bond strengths were 42% and 51% less than under monotonic loading for plain steel bars having diameters 8 mm and 10 mm, respectively. In the lightweight concrete study, the steel bars having 12 mm and 14 mm diameters slipped before finishing 150 cyclic loads. In all experimental results, the concrete surrounding the steel bars experienced significant damage.

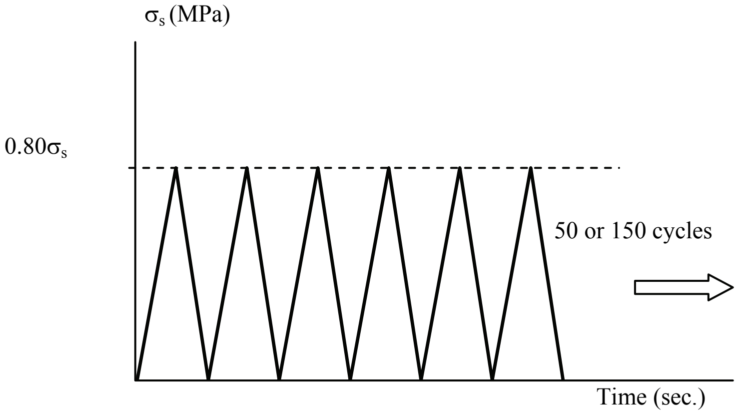

Fig. 4. Cyclic loading protocol

Table 6. Concrete-steel bond strength ratios between monotonic and cyclic loading

Concrete	Steel bar		Monotonic loading	Cyclic loading (50 and 150 times)		$\frac{\tau_{bd}}{\tau_{bd(50)}}$	$\frac{\tau_{bd}}{\tau_{bd(150)}}$
	ϕ (mm)	Surface	τ_{bd} (MPa)	$\tau_{bd(50)}$ (MPa)	$\tau_{bd(150)}$ (MPa)		
Lightweight	8	Plain	3.17	2.76	2.23	1.149	1.422
		Deformed	3.23	3.04	2.74	1.063	1.179
	10	Plain	3.25	2.72	2.15	1.195	1.512
		Deformed	3.47	3.22	2.91	1.078	1.192
	12	Plain	3.06	2.32	slip	1.319	-
		Deformed	3.15	3.01	2.65	1.047	1.189
	14	Plain	2.45	1.55	slip	1.581	-
		Deformed	3.07	2.89	2.53	1.062	1.213
Ordinary	8	Plain	2.58	2.35	2.21	1.098	1.167
		Deformed	4.31	4.18	4.08	1.031	1.056
	10	Plain	2.47	2.22	2.02	1.113	1.223
		Deformed	6.25	6.08	5.87	1.028	1.065
	12	Plain	2.20	1.92	1.55	1.146	1.419
		Deformed	6.17	6.02	5.86	1.025	1.053
	14	Plain	1.73	1.42	1.17	1.218	1.479
		Deformed	6.71	6.62	6.31	1.014	1.063

Similar results were obtained for ordinary concrete. After 50 cycles, the ordinary concrete-steel bond strength for deformed steel bars was about 3% less than under monotonic loading. After 150 cycles, the ordinary concrete-steel bond strength for deformed steel bars was 6% less than under monotonic loading. With regard to ordinary concrete with plain steel bars, the ordinary concrete-steel bond strength after 50 cycles was 10%, 11%, 15% and 22% less than under monotonic loading for plain steel bars with diameters of 8, 10, 12 and 14 mm, respectively. In the same manner, after 150 cycles, the ordinary concrete-steel bond strength was 17%, 22%, 42% and 48% less than under monotonic loading for plain steel bars with diameters 8, 10, 12 and 14 mm, respectively.

These results suggest that after 50 cycles, the loss of concrete-steel bond strength in ordinary concrete is not as significant as the loss of concrete-steel bond strength in lightweight concretes for both plain and deformed bars. Interestingly, the loss of concrete-steel bond strength, after 150 cycles, was significantly greater for plain steel bars than deformed steel bars. This change was more significant for ordinary concrete. Further, for lightweight and ordinary concretes, loss of concrete-steel bond strength related to cyclic loading grew with increases in bar diameter. Hence, from the above study, current code related concrete-steel bond lengths, based on cyclic loading similar to that generated by earthquakes or wind, are not sufficient for the design reinforced concrete structures.

4. CONCLUSION

The main results and conclusions which can be obtained from this study are critical to the design of reinforced concrete structures. Firstly, lightweight concrete-steel bond strength is 35% greater than ordinary concrete-steel bond strength (τ_{bd}) for plain bars. Here, the difference in strength increases as the diameter of the steel bar increases.

Secondly, for deformed steel bars, the ordinary concrete-steel bond strength is, as expected, greater than lightweight concrete-steel bond strength. It is also shown that a bond length (l_b) of 30ϕ is insufficient for deformed bars in lightweight concrete. Here, the loss of bond strength for deformed steel bars in ordinary concrete is not as significant as the loss of bond strength for deformed steel bars in lightweight concretes.

Finally, in the design of bond length, reinforced concrete structural members exposed to earthquakes and wind loads must take into account the loss of bond strength. Further, identical studies must be undertaken to examine the bond strength for repaired and retrofitted structures because unforeseen cyclic loading may occur at any time and test the limits of the expected bond strength.

REFERENCES

1. Neville, A. M. (1975). *Properties of concrete.* Pitman Publishing, London.
2. ACI Committee 213, (2003). Guide for structural lightweight aggregate concrete-ACI 213R-03. American Concrete Institute, Detroit, USA.
3. Husem, M. (2995). Comparative study of lightweight concrete produced using one of the natural lightweight aggregates present in the Eastern Black Sea Region with ordinary concrete. Ph.D. Thesis (in Turkish), Karadeniz Technical University, Trabzon, Turkey, 1995, 170p.
4. Kheyroddin, A. & Naderpour, H. (2008). Nonlinear finite element analysis of composite RC shear walls. *Iranian Journal of Science and Technology, Transaction B, Engineering*, Vol. 32, No. B2, pp. 79-89.
5. Eshghi, S. & Zanjanizadeh, V. (2008). Retrofit of slender square reinforced concrete columns with glass fiber-reinforced polymer for seismic resistance. *Iranian Journal of Science and Technology, Transaction B: Engineering*, Vol. 32, No. B5, pp. 437-450.
6. Considere, E. (1899). Influence des Armatures métalliques sur les propertiétés des morties et bétons. Génie, XXXIV, No 14-16.
7. Abrams, D. A. (1913). Test of bond between concrete and steel. *University of Illinois, Bull*. Vol. 71.
8. Bichara, A. (1951). Etude du probléme de l'Adhérence dans le béton armé. Cahier du *C.S.T.B.*, pp. 117-127.
9. Brachet, M., Adam, M., Perchat, J. & Virlogeux, M. (1976). Bilen et perspective d'Emploi des bétons légers de structure, *Annales de I'ITBTP*, Vol. 345, pp. 47-127.
10. Rehm, G. & Eligehausen, R. (1979). Bond of ribbed bars under cycle repeated loads. *ACI Journal,* Symposium paper, pp. 297-309.
11. Ligehausen, R., Popov, E. P. & Betero, V. (1983). Local bond stress-slip relationships of deformed bar under generalized excitations. Report No. UCB/EERC-83/23, Earthquake Engineering Research Center, Berkeley, Calif., p. 185.
12. Shah, S. P. & Chung, L. (1986). Effect of cyclic loading rate on response of model beam-column joints and anchorage bond. *Proceeding of the 3rd U.S. National Conference on Earhquake Eng.,* EERI, San Francisco.

13. Azizinamini, A., Ghosh, S. K., Roller, J. J. & Stark, M. (1993). Bond performance of reinforcing bars embedded in high strength concrete. *ACI Structural Journal*, Vol. 90, No. 5, pp. 554-561.
14. Mitchell, D. W. & Marzouk, H. Bond characteristics of high-strength lightweight concrete, *ACI Structural Journal*, Vol. 104, No. 1, pp. 22-29.
15. Campione, G., Cucchiara, L., La Mendola, L. & Papia, M. (2005). Steel–concrete bond in lightweight fiber reinforced concrete under monotonic and cyclic actions. *Engineering Structures*, Vol. 27, No. 6, pp. 881-890.
16. Chen, H. J., Huang, C. H. & Kao, Z. Y. (2004). Experimental investigation on steel–concrete bond in lightweight and normal weight concrete. *Structural Engineering and Mechanics,* Vol. 17, No. 2, pp. 141–52.
17. Esfahani, M. R. & Rangan, B. V. (1998). Reinforcing Steel-Concrete Bond in Normal and High Strength Concrete. *International Conference on High Performance High Strength Concrete*, Proceedings book, pp. 367-378, Perth, Australia.
18. Harajli, M. H. (2004). Comparison of bond strength of steel bars in normal and high-strength concrete. *Journal Materials in Civil Engineering-ASCE,* Vol. 16, No. 4, pp. 365-374.
19. Alavi-Fard, M. & Marzouk, H. (2002). Bond strength of high strength concrete pull out cyclic loading. *Canadian Journal of Civil Engineering*, Vol. 29, pp. 191-200.
20. Alavi-Fard, M. & Marzouk, H. (2004). Bond behaviour of high strength concrete. *Magazine of Concrete Research*, Vol. 56, No. 9, pp. 545-557.
21. Pul, S., Husem, M., Gorkem, S. E. & Yozgat, E. (2007). Lightweight and ordinary concrete-steel bond strength. *2nd. International Symposium on Connection between Steel and Concrete*, Proceedings book, Vol. 2, pp. 1141-1150, Stuttgart, Germany.
22. Balaazs, G. L. (1986). Bond behavior under repeated loads. *Studi e Ricerche-Corso Flli. Pesenti, Politecnico di Milano*, Vol. 8, pp. 395-430.
23. Soretz, S. & Holzenbei, H. (1979). Influence of rib dimensions of reinforcing bars on bond and bend ability. *ACI Journal*, Vol. 76, No. 1, pp. 111-127.
24. Luccioni, B. M., Lopez, D. E. & Danesi, R. F. (2005). Bond-slip in reinforced concrete elements. *Journal Structural Eng.,* Vol. 131, No. 11, pp. 690-1698.
25. Harajli, M. H. (2009). Bond stress–slip model for steel bars in unconfined or steel, FRC, or FRP confined concrete under cyclic loading. *Journal of Structural Engineering-ASCE*, Vol. 135, No. 5, pp. 509-518.
26. ACI Committee 318, (2008). Building code requirements for structural concrete (ACI 318-08) and commentary (ACI 318R-08). American Concrete Institute, Farmington Hills, Michigan USA.
27. ACI Committee 408, (2003). Bond and development of Straight Reinforcing Bars in Tension -ACI 408 R-03. American Concrete Institute, Farmington Hills, Michigan USA.