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A Comparative Bond Study of Deformed Steel Bar in Different Concrete Grades and Concrete Fiber

Zuraida Zaini-Rijal and Ahmad Baharuddin Abd. Rahman
Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia

Abstract: In this study, the bond behaviour of deformed steel bar diameter embedded in different concrete grades and concrete fiber was investigated. Deformed steel bars of 16 and 20 mm diameter were constantly embedded at a depth of 65 mm in cylinder specimens. The pullout loads, bond strength, compressive strength, splitting tensile strength and flexural strength of the specimens were determined. It was found that the bond strength between deformed steel bar and concrete was increased parallel to the increase of mechanical properties of the concrete. It was demonstrated that the deformed steel bar with concrete fiber provides higher bond strength compared to bond with other concrete grades. Therefore the use of concrete fiber is suitable for structural deformability resistance.

Key words: Bond, deformed steel bar, concrete, concrete fiber, specimens

INTRODUCTION

In structural system, force transfer through bond between reinforcing bars and concrete. It is a fundamental issue in structural strength and serviceability performance to have a good bond between reinforcing bars and concrete. Insufficient bond can lead to a significant decrease in stiffness and the load carrying capacity of the structure (Chao *et al*., 2009). The bond has a crucial effect on the behaviour of cracked phase of reinforced concrete structures. The distribution of bond stresses influenced crack widths and deflections along the reinforcement bars and the slip between the concrete and reinforcing bar (Belarbi *et al*., 2009).

Basically, bond strength is contributed by three components which are adhesion, friction and bearing. Adhesion and friction are reliant on the bar surface condition and bearing is dependent on the bar deformation pattern (Barbosa and Filho, 2013; Hosseini *et al*., 2013, 2014; Rahman *et al*., 2015). The major contribution of bond strength is provided by bearing strength of concrete in front of the bar rib. Figure 1 shows the detailed interaction between concrete and steel bar.

Many factors influence the bond strength such as the compressive and tensile strengths of concrete, the bar size and deformation pattern, state of stress in both bar and concrete, position of reinforcing bars, the aggregate size, the concrete cover, confinement and casting direction (ACI, 2003).

According to Barbosa and Filho (2013), the concrete compression strength and concrete tensile strength are the main parameters that influence the anchorage length and the spreading of the tensions concentrated on the bar ribs. Other factors that affect the bond stress are the diameter of the bar as increase in bar diameter reduces the maximum bond stress; surface of the bars roughness and irregularities (increase the bond); type and disposition of the ribs.

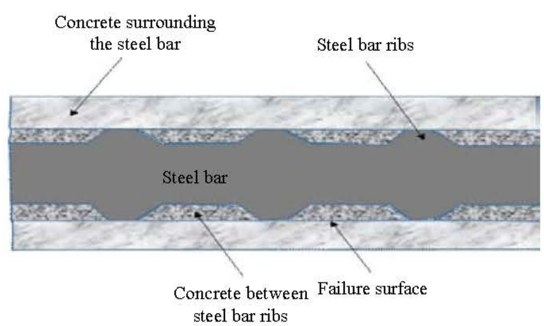

Fig. 1: Interaction between concrete and steel bar ribs

Recently, pullout test data from some previous studies have not satisfied current bond requirements for various concrete strengths. Therefore, this study shows the experimental results gained from twelve specimens for pullout test using two types of diameter of deformed steel bar embedded in different concrete strength inclusive of concrete fiber. The main parameters influencing the bond response of different concrete strength are investigated. Furthermore, concrete fiber is also taken into consideration in this experiment to prove that concrete

Corresponding Author: Zuraida Zaini-Rijal, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia

fiber can improve bond performance between concrete and reinforcing bar. The acquired results could contribute to the development of procedures of the correct design of bond on structural concrete members.

Many researchers as mentioned in the reference, studied the various aspects of bond stress and slippage of reinforcement but only a few worked on different concrete strength. The aim of this study is to produce a basic bond data in order to improve structural design.

MATERIALS AND METHODS

Experimental study: In this study, pullout test was used to identify bond strength and its behaviour. Deformed steel bar sizes of 16 and 20 mm diameters were used in this study. The nominal yield strength, tensile strength and elongation ratio of the deformed steel bars were 570, 680 MPa and 10%, respectively. The geometry of the deformed steel bar and its measured dimensions are shown in Table 1 and Fig. 2. This investigation intended to evaluate and compare bond stresses in four types of concrete mix, namely C30, C40, C50 and CF (concrete with fiber).

Preparation and production of concrete mixtures: Concrete mix produced in this study was concrete in grades of 30, 40, 50 and concrete fiber. Table 2 shows the material quantities required for 1 m^3 concrete. In this study, all concrete mixes are using the same type of aggregate which is granite size 10 mm.

Concrete mix for CF is made from the same concrete mix of grade 40. The volume of steel fiber was 0.5% of total volume of concrete added to the mixture in order to produce CF. The fiber mix included hooked-end steel fibers 0.55 mm in diameter and 35 mm long with aspect ratio of 64. The fiber manufacturer had specified minimum tensile strength values of 1100 MPa for the 35 mm long fibers that conforms to ASTM A820 Standards. Actually, fraction of 0.5% of steel fiber was chosen for this study due to higher compressive strength results after doing the compressive test to specimens containing volume fraction of steel fiber of 0.25, 0.5, 0.75 and 1%.

Test specimen and setup: A modified version of the pullout test was selected to fulfil the objectives of this research. The details of pullout specimen used in this research are shown in Fig. 3. Basically, this experiment followed the specification of ASTM C-234-86 but in this study, no bond breakers were used in order to match the geometry of the samples (Yeih *et al*., 1997). The proposed pullout specimen was comprised of a concrete cylinder

Table 1: Dimension of deformed steel bar

	Dimension (mm)					
Nominal diameter (mm)	d_1	d_2	t	s_r	t_r	r_h
16	15.6	17.3	3.7	9.6	4.6	1.7
20	19.6	21.3	5.2	11.7	4.6	1.7

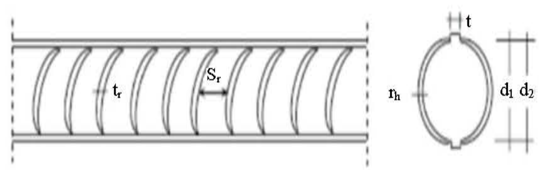

Fig. 2: Geometry of the deformed steel bar

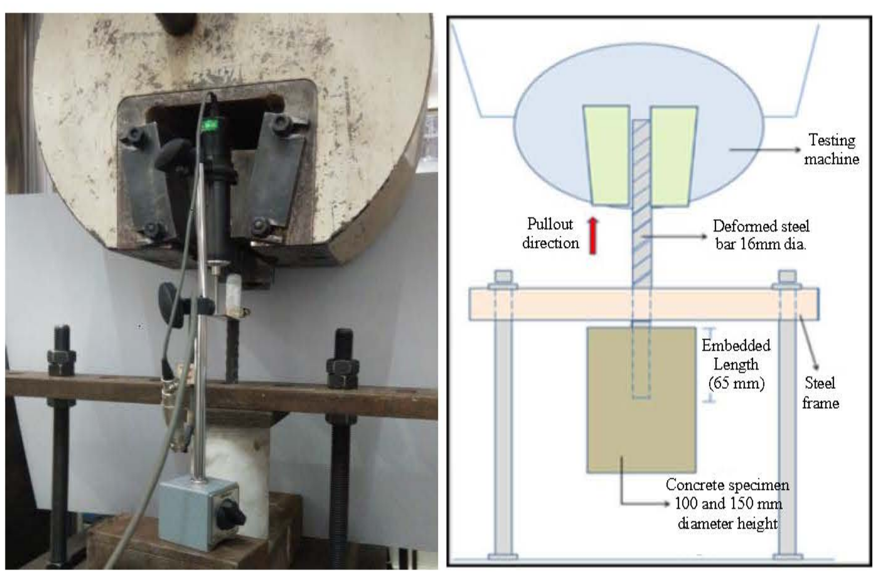

Fig. 3: Pullout test setup

Table 2: Material quantities required for 1 m^3 concrete mixtures

Concrete mix	w/c	Cement (kg)	Water (kg)	Aggregate (kg) Fine	Aggregate (kg) Coarse	Superplaticizer (kg)
C30	0.55	425	235	875	810	1.06
C40	0.48	485	235	810	810	1.21
C50	0.42	490	205	810	875	4.90
CF	0.48	485	235	810	810	1.21

Material quantities required for 1 m^3 concrete mixture

with dimensions of 100 mm diameter and 150 mm height with a concentric test bar of 65 mm long embedded into concrete cylinders.

In this study, 16 and 20 mm diameter bars with an embedded length of 4.1 times diameter (4.1 D_b) and 3.3 D_b were used in order to ensure that pullout occurred before the bar yielding. The pullout test was performed 28 days after casting. The slip of the bar was recorded at its loaded end by using Linear Variable Differential Transducers (LVDT). The test method specifies that the load was applied at a rate of 0.2 kN/sec. The data gathered from the study are then used to produce the bond-slip curve relationship.

RESULTS AND DISCUSSION

Table 3 lists the results of the compressive and splitting tensile strength tests conducted on the cubic and cylinder specimens at the end of 28 days curing periods. Normally, concrete strength is influenced by water to cementitious materials (w/c) ratio as well as properties of coarse aggregate. Since, the coarse aggregate used in all the concrete mix are the same type, the factor that influences the concrete strength for all the specimens is (w/c) ratio. The results show that lower water cement ratios will produce relatively stronger concretes and higher water cement ratios will produce weaker concretes. Since, concrete C50 is produced by using the lowest (w/c) ratio (Table 2), it gained higher compressive strength than other concrete mixes. For splitting tensile test, the results show CF gained higher tensile strength than other concrete mix. This indicates the presence of steel fiber in concrete produced effective action in resisting the tensile cracks.

Table 4 shows the flexural test result for all concrete mix specimens. The result shows the stiffness of the materials in bending test and the response of the maximum tensile stress value that can be sustained before the specimen fails. It shows CF obtained higher flexural strength than other concrete mix. This indicates steel fiber in CF delays the bending failure of the concrete due to the strength of the intact fibers in concrete.

Table 5 presents the results of the direct pullout test at 28 days for all concrete specimens. The pullout test was

Table 3: Compressive and splitting tensile test results

Concrete mix	28 days (MPa) f_c	28 days (MPa) f_{ct}
C30	31.70	4.06
C40	44.74	5.57
C50	58.20	5.60
CF	48.97	5.98

f_c = compressive strength; f_{ct} = splitting tensile strength

Table 4: Flexural test results

Concrete mix	Load (kN)	Flexural strength (MPa)
C30	9.10	2.73
C40	13.20	3.95
C50	10.87	3.26
CF	13.89	4.17

Each value is the average of 3 specimens

loaded monotonically and the average bond strength values (f_b) were calculated by assuming a uniform distribution along the embedded length (L_b) (ACI, 2013):

$$f_b = \frac{P}{(\pi \cdot D_b \cdot L_b)}$$

Where:

P = The applied load to the specimens

D_b (mm) = The diameter of the test bar

The slip measurements of the bar were obtained by using one LVDT that was placed near the bar at the top of the cylinder (Fig. 3).

Table 5 shows the values of bond stress and slip for all specimens which was the maximum load and ultimate bond stress to pull the embedded deformed steel bars out from the concrete. Comparing the bond stress values, CF gained higher value than other concrete mix. It shows that the existence of fibers in concrete fiber positively developed the bond stress of 16 mm bars slightly by up to 8% compared to high concrete grade, C50. For 20 mm bars, the maximum bond stress values showed about 26% increment compared to C50. This is due to the influence of steel fibers which controls the development and spreading of cracks. All the results were based on fixed embedded length of 65 mm for both diameters, 4.1 D_b and 3.2 D_b, respectively.

Observation of the pullout test shows the mechanical interlocking between a deformed reinforcing bar and surrounding concrete induced bearing forces that can lead to inclined cracks in a concrete matrix. In addition, the radial component of the bearing forces initiated tensile stress that caused the formation of splitting cracks and eventually to a bond failure (Fig. 4a). Generally, concrete crushing at the toe of the bar mainly caused the degradation of bond strength and stiffness.

In contrast to the CF specimens, the propagation and crack opening can be minimized by the fiber bridging

Table 5: Pullout test results

Concrete mix	Diameter of bar = 16 mm				Diameter of bar = 20 mm			
	Pullout load (kN)	Bond stress (MPa)	Bond increment* (%)	Slip (mm)	Pullout load (kN)	Bond stress (MPa)	Bond increment* (%)	Slip (mm)
C30	17	5.20	0	1.68	20	4.90	0	1.04
C40	23	7.04	35	0.59	24	5.88	20	0.65
C50	25	7.65	47	2.06	27	6.61	35	3.03
CF	27	8.26	59	2.03	34	8.32	70	1.98

All the increments are compared to bond stress value of C30

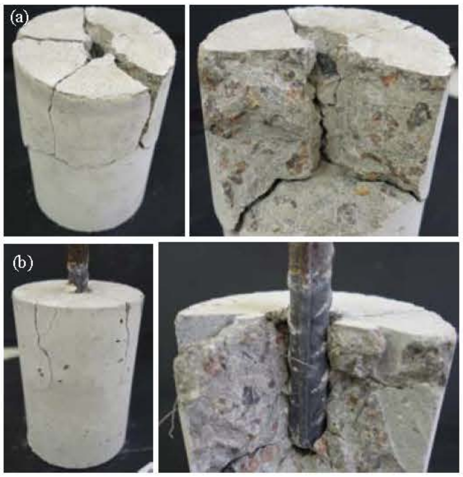

Fig. 4: Pullout failure mode: a) Concrete C30, C40 and C50-splitting and b) CF-pullout

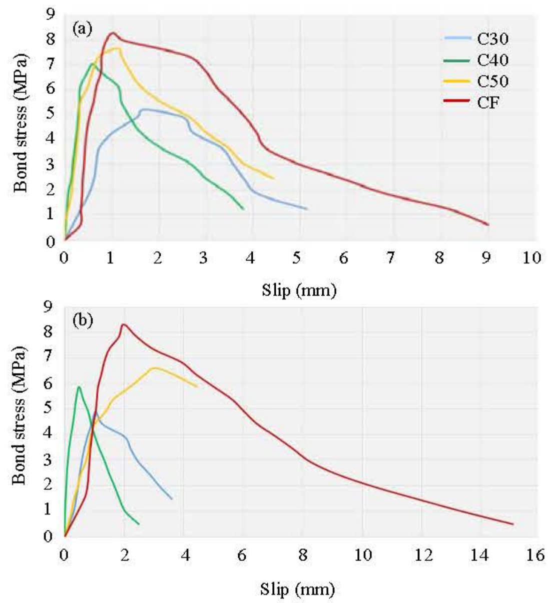

Fig. 5: Bond stress-slip behavior of specimens: a) 16 mm diameter and b) 20 mm diameter

effect thus increasing bond strength. Furthermore, the existence of fibers in concrete help to rearrange the radial compression applied to the concrete after initial cracking and increased bar pullout load (Fig. 4b). During additional slippage, longitudinal cracks developed along the bar axis meaning that this when the maximum bond strength is achieved. However, for CF, fibers obstructed further propagation and widening of the longitudinal cracks and the internal inclined bond cracks. Figure 4 illustrates the failure mode of the specimens in pullout test.

Figure 5a and b shows the monotonic average bond stress against slip for specimens with 16 and 20 mm diameter bars, respectively. Initially, all samples demonstrated the linear load slip behaviour up to the development of micro cracks. As soon as the micro cracks were formed, the rebar began to slip-up and the stiffness of the bond stress-slip curve was decreased and the peak of the curve became non uniform. The existence of fibers demonstrated ductile bond behavior and showed the increment in the bond strength compared to other concrete grades. The ductile behavior may be attributed to the effect of fiber in bridging the crack (Dancygier *et al*., 2010). The density of fibers which affected a large of fibers confinement action in addtion to minimize the radial cracking (near the reinforcement bar). The influence of fiber contents on the ductility of bond failure is also dependent on flexural toughness strength. In some cases, areas under the bond stress-slip curve have been found to follow an almost linear tendency with respect to fiber content (Dancygier *et al*., 2010).

Figure 6 presented the relation between compressive strength and bond stress for all concrete mixes. It is shown that increase in compressive strength is significantly related to the increases of bond stress. In the case of CF however, the compressive strength is less than high concrete strength C50 but presence of fiber in concrete produced highest bond stress. This is due to the influence of steel fibers that controls the development and spreading of cracks. Overall, it is noticed that in term of bond stress between deformed steel bar and concrete, highest compressive strength of the surrounding concrete produced significantly higher values for smaller diameter rather than larger diameter. Thus, the higher compressive strength concrete is beneficial for smaller diameter bars to increase the bond stress. It was also worth noting that CF produced almost the same bond stress values with either smaller or larger diameter of deformed steel bar.

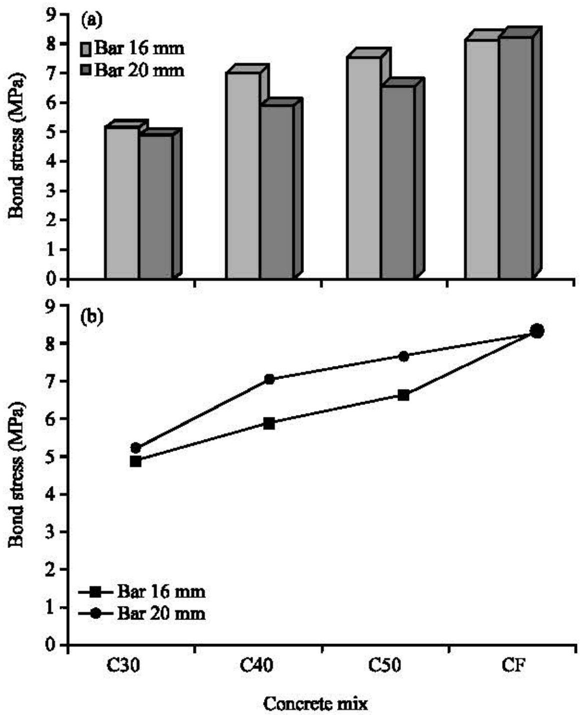

Fig. 6: Relation between compressive strength and bond stress

CONCLUSION

Experimental results of this study, indicate that the increment in the pullout load is more reliant on the compressive strength and splitting tensile strength of the concrete. The increase in diameter of deformed steel bar results in a significant increment in the pullout load. Bond strength is increased when mechanical strength of concrete such as compressive strength, splitting tensile strength and flexural strength of concrete increases. Contribution of mechanical properties of concrete to the bond strength was significant for smaller diameter bars where the bond stress for 16 and 20 mm diameter bars increased marginally by up to 59 and 70%, respectively. Overall, higher pullout load and bond stress is demonstrated by concrete fiber compared to other concrete grades due to the confinement and bridging effect of steel fibers. Existence of steel fiber in concrete increased the bond strength of deformed steel bar embedded in concrete fiber. Therefore, the use of steel fibers in concrete can be suitable for mega structure, especially for maximize the efficiency of structure performance.

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