Comparison of Bond Stresses of Deformed Steel Bars Embedded in Two Different Concrete Mixes

Zuraida Zaini Rijal [1,a*], Ahmad Baharuddin Abd. Rahman [1,b], Roslli Noor Mohamed [1,c], Izni Syahrizal Ibrahim [1,d] and Sherliza Zaini Sooria [2,e]

[1]Faculty of Civil Engineering, Universiti Teknologi Malaysia, Malaysia

[2]Public Work Department, Malaysia

[a]zuraida27@live.utm.my, [b]baharfka@utm.my, [c]roslli@utm.my, [d]iznisyahrizal@utm.my

[e]sherliza@jkr.gov.my

Keywords: Bond; slip; deformed steel bar; bond performance; catenary tie.

Abstract. Catenary action in a precast concrete building structural system is one of the ways to avoid progressive collapse. The key for catenary action to work successfully depends on the strength performance of longitudinal ties, which closely depends on the bond performance between the ties and concrete. This paper investigates the effectiveness of deformed steel bar as catenary tie in precast concrete beam-column connection under column removal scenario. The main objective of the experimental work is to improve the bond performance between deformed steel bar and concrete topping. The parameter considered in the tests is the types of concrete for the topping. The different concrete mixes are normal concrete of Grade 40 and steel fiber reinforced concrete (SFRC). A series of pullout test specimens are conducted to investigate the bond behavior between the steel ties and the surrounding concrete. The results show the comparison of bond stresses of embedded deformed steel bars in two types of concrete mix. The deformed steel bar with concrete fiber provides higher bond strength as compared to bond in normal concrete. Therefore, it is more suitable for effective catenary tie in precast concrete beam-column connection for maximum efficiency and deformability in order to minimize progressive collapse.

Introduction

Progressive collapse of building structures typically occurs when an abnormal loading condition causes a sudden loss in the structural capacity of one or more critical members, which leads to a chain reaction of failure and ultimately catastrophic collapse [1]. Catenary action of the structural system is one of the ways to avoid collapse. The key for catenary action to work successfully is that longitudinal ties at the joint have sufficient strength and deformation capability, which closely depends on bond performance of ties in the concrete [2]. To ensure the effectiveness of catenary action force, it is crucial to have a good contact surface ("good bond") between the tie reinforcement and the surrounding concrete.

Basically, reinforced concrete (RC) elements are designed such that the concrete carries the compressive stresses and the steel resists the tensile stresses. Therefore, a good force transfer between the two materials can only be achieved by an interaction between both materials through bond between the reinforcement bars and the concrete. In structural systems, a good bond between reinforcing bars and concrete is crucial for structural strength and serviceability performance. Furthermore, bond has an important influence on the behavior of reinforced elements in the cracked stage. Crack widths and deflections are influenced by the distribution of bond stresses along the reinforcement bars and by the slip between the bar and the surrounding concrete [3, 4].

Typically, bond strength is contributed by three components; friction and adhesion, which are dependent on the bar surface condition; and bearing, which is dependent on the bar deformation pattern [5]. The relationship between bond stress, τ, and the relative slip, δ, between a steel reinforcing bar and concrete, is fundamental importance in predicting the complex interaction between the two materials. Many researchers have attempted to determine, experimentally, the bond stress versus slip response. Pullout test is normally used to determine the bond stress, where the actual bond stress varies significantly along the embedment length; results were typically reported as the average bond stress versus slip measured at one end of the specimen [6].

For a deformed bar, the bond stress is developed through initial chemical adhesion at small load levels, mechanical interlock between reinforcing steel ribs and the surrounding concrete as the load increases, and friction after the mechanical interlock fails. The mechanical interlock between concrete and reinforcing steel ribs leads to a concrete stress state in which the concrete directly in front of the ribs carries compression and the concrete above the ribs carries primarily shear [9].

Previous research regarding consequence of bond stress has indicated that three forces exist on the reinforcement bar-concrete interface: the chemical adhesion between the reinforcement bar and concrete; the frictional force between the rebar and concrete; and the interlock force resulting from the ribs of the reinforcement. It was also reported that bond resistance is mainly provided by the interlock effect. When bond stress is low, the rib will first induce inclined cracks because of the interface effect. After inclined cracks form, the tensile stress of the rebar is transmitted to the concrete through the contact force on the surface of the ribs. The radial component of this contact force is called the splitting pressure, and it may result in splitting failure provided it becomes large enough [8]. Due to the importance of the interaction between steel and concrete a lot of research has been done in the past. In all these projects the main focus was on the reinforcement bar, its geometrical characteristics and how these characteristics influence the bond strength. With the appearance of new concrete types, such as steel-fiber reinforced concrete (SFRC) and high strength concrete, the bond strength achieved with these concrete types is not properly documented, and the main focus of the research on bond shifted to the concrete and its composition [4]. The typical bond stress-slip curves of plain concrete and SFRC are illustrated in Figure 1. It can be observed from Figure 1 that the addition of fibers affects the mechanical behavior of reinforced concrete [7]. Large value of bond stress leads to concrete damage in the vicinity of the concrete-steel interface. This allows reinforcing steel to slip relative to the surrounding concrete and increases the flexibility of the structure. However, if the value of bond stress is low, bond-zone damage may result in loss of bond strength, loss of composite action, and failure of a structure [9]. Therefore, investigation on a good bond between deformed steel bar and concrete is important to ensure that the bond between concrete and reinforcement can provide catenary action to avoid catastrophic collapse.

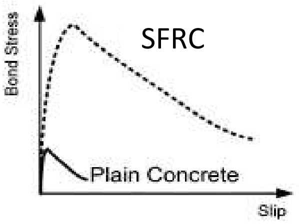

Figure 1: Typical bond stress-slip responses between SFRC and plain concrete [7].

The objectives of this study were to examine the improvement of the bond performance between deformed steel bar and concrete topping by changing the types of concrete for the topping. This paper discusses the bond between deformed steel bar and two concrete mixes; normal concrete C40 and SFRC, which is expected to give a good bond strength for catenary ties, in precast concrete beam-column connection, to function in maximum efficiency and deformability in order to minimize progressive collapse.

Methodology

In order to improve bond performance between deformed steel bar and concrete, an experimental program was conducted to investigate the bond performance of reinforcing steel bar 16mm diameter in two concrete mixes. The two mixes included a normal concrete strength grade C40 and Steel Fiber Reinforced Concrete (SFRC).

This study utilized pullout test. In pullout tests the bar to be tested is cast in the center of a concrete block. The bar is then pulled out of the block with the reactive force acting on the face of the block and cause compressive stresses in the concrete surrounding the bar. This test is useful because of the size of the concrete specimen [7]. The cylindrical pattern is the most representative to produce test data, and can be used as input verification of the thick walled cylinder model because of the uniform peripheral boundary conditions – stress and geometry (constant cover thickness in every direction). Furthermore, the cylindrical pattern of the specimen is compatible with the lower bound concept because the cover simulates the distance of the bar to the nearest free surface of an actual structural member [10].

Material

This study adopted deformed steel bar of 16 mm diameter and a nominal yield stress fy=500 MPa. The geometry of the deformed steel bar and its measured dimensions are shown in Table 1, Figure 1 and Figure 2. This investigation intended to evaluate and compare bond stresses in two types of concrete mix, namely normal concrete strength grade C40 and SFRC. As indicated in Figure 3, the fibers were 30 mm long and of 0.55 mm diameter. The fiber conforms to ASTM A820 Standards and the manufacturer specified minimum tensile strength values 1100 MPa for the 30 mm long fibers. Table 2 summarizes the fiber properties. The specimen for SFRC uses steel fibers equivalent to 1% of total weight of the concrete.

Table 1: Dimensions of steel bar profile

Nominal Diameter (mm)	**Dimension (mm)**					
	d1	**d2**	**t**	**s_r**	**t_r**	**r_h**
16	15.9	17.3	1.7	6.9	3.1	1.25

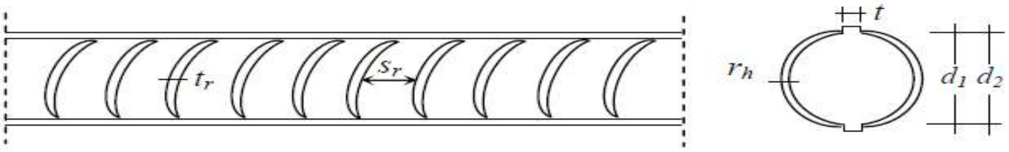

Figure 1: Geometry of the steel bars

Figure 2: Deformed steel bar

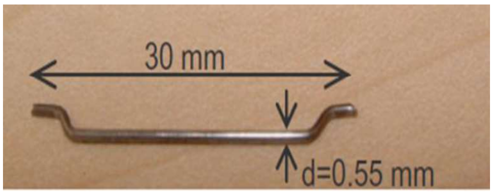

Figure 3: Steel Fiber geometries

Table 2: Properties of steel fiber

Diameter (mm)	**Length (mm)**	**Density (N/mm^3)**	**Tensile Strength (MPa)**	**Elastic modulus (GPa)**
0.55	30	78500	1100	200

Control specimens were also tested with plain concrete with no steel fibers. The concrete mix proportions used in the experimental studies are given in Table 3. The mix had a target 28-day compressive strength of 40 MPa. For SFRC, made from the same concrete mix grade C40, the volume of 1% fiber was initially mixed with cement and aggregates inside a drum-type mixer and the mixing operation was continued after adding water and super plasticizer until a uniform distribution was obtained. Workability of the SFRC concrete mix was observed to decrease with increasing fiber content. Compaction of concrete for cylinder samples was done using a vibration table. The SFRC mix had a target 28-day compressive strength of 52 MPa.

Table 3: Concrete mix proportions used in the study

Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	Super plasticizer (kg/m^3)
489	721	847	230	0.53

Test Setup

In order to examine the influence of concrete strength on the reinforcing steel bar bond performance, different concrete mixtures were used. A reinforcing steel bar was included in all test series for comparative judgment of bond capacity of reinforcing steel bar. The bond test program involved Direct Tension Pullout (DTP) test using the Dartec M9500 Universal Testing Machine. The proposed pullout specimen comprised of a concrete cylinders with dimensions of 100mm diameter and 150mm (height) with a concentric test bar of 75mm long embedded into concrete cylinders. The pullout test was performed 28 days after casting. The slip of the bar, at its free end, was recorded using linear variable differential transducers (LVDT) on one side of the specimen (measure slip between reinforcing steel bar and concrete). The test method specifies that the load was applied at a rate of 0.2 kN/sec. The data acquisition system collected the Dartec M9500 stroke and load data and the LVDT readings at every increment loading of 2.0 kN. The load rate was applied to the specimen until a slip of 0.1 in. (2.54 mm) was observed. The data gathered from the study is then used to produce the bond–slip curves relationship.

Figure 4: Experimental setup

Findings and discussion

The DTP test was loaded monotonically to failure and the average bond strength values, f_b were calculated assuming a uniform distribution along the embedded length L_b (mm) [10]:

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

where P is the applied load and D_b (mm) the diameter of the test bar. The slip measurements for the bar were obtained by using one LVDT that was placed near the bar at top of the cylinder (Fig. 4). Observation from the result shows the bearing forces induced by mechanical interlocking between a deformed reinforcing bar and surrounding concrete can lead to inclined cracks in the concrete matrix. Upon tension force, these internal inclined cracks grow wider and extend longer, leading to large residual slip. Furthermore, tensile stress caused by the radial component of the bearing forces lead to the formation of splitting cracks and ultimately to a bond failure (refer to Fig. 5a). Normally, degradation of bond strength and stiffness would be mainly caused by concrete crushing at the toe of the bar.

In SFRC, the fiber bridging effect helps control the crack opening and propagation, thus increasing bond strength. After initial cracking and increased bar pullout load, the radial compression exerted on the concrete by the bar ribs is redistributed to the whole matrix due to the presence of fibers (Fig. 5b). During further slippage, longitudinal cracks along the bar axis develop; this corresponds to the time at which the maximum bond strength is attained. For SFRC, further widening and propagation of the internal inclined bond cracks and of the longitudinal cracks are hindered by the fibers. Crack pattern shown appreciable damage tolerance and maintained integrity throughout the test due to the fiber bridging effect, which prevented cracks from opening widely (Fig. 5b).

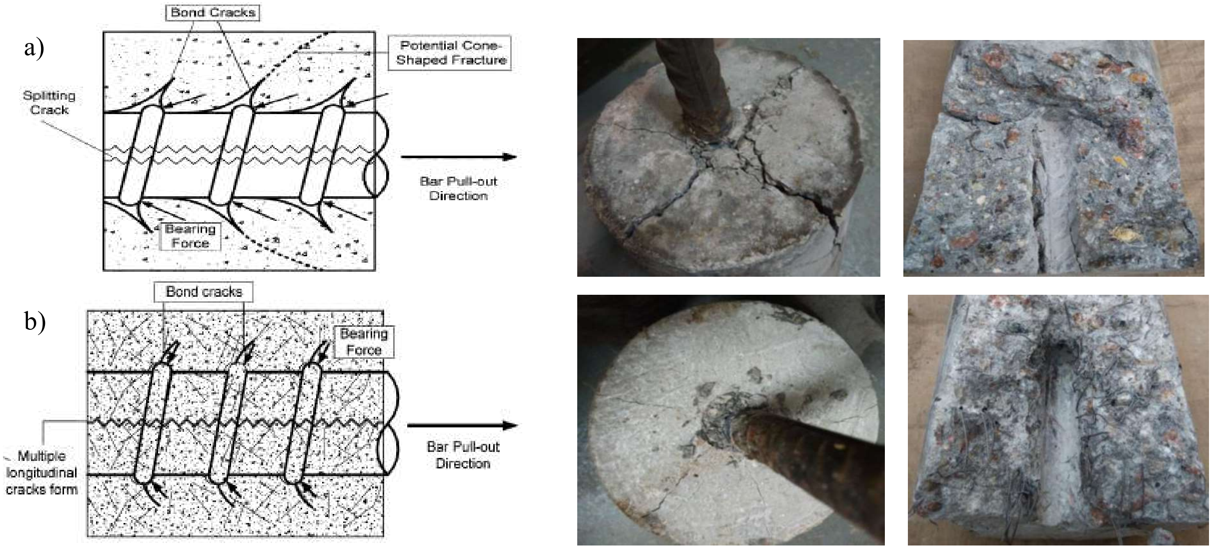

Figure 5: Bond mechanisms of reinforcing bar and crack pattern (illustration from [7]) in: (a) Normal Concrete, C40; and (b) Steel fiber reinforced concrete, SFRC

The main goal of the study is to compare bond strengths for normal concrete in Grade 40 and steel fiber reinforced concrete. When the bond stress-slip relations of the different concrete types are plotted for tests on specimen with a reinforcing bar of the same diameter, it can be seen that the bond strength of steel fiber reinforced concrete is larger than that of normal concrete in Grade 40 (as was expected due to the higher compressive strength) at all stress levels, resulting in a steeper curve. For bar diameters of 16 mm, the curves for normal concrete in Grade 40 is almost identical for small slip values, while the bond stress level for steel fiber reinforced concrete for the same slip is higher, although these two mixes have the same W/C ratio. It is clearly shown in Figure 6 that addition of fiber to the concrete mix has made the concrete significantly stronger.

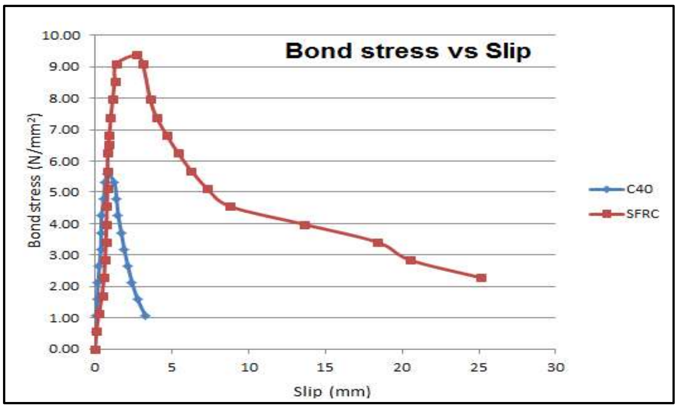

Figure 6: Comparison of bond stress-slip behavior of Deformed Steel bars 16mm dia. with different concrete mixes

The results show that the value of bond strength for SFRC is 9.38N/mm^2 and slip is 2.71mm, which is higher compare to that of normal concrete C40 where the bond strength value is 5.57N/mm^2 and slip is 0.83mm. Although these two concrete mixes have the same w/c ratio, but by adding fiber to the mix 68% higher bond strength can be observed.

Conclusions

The results show the comparison of bond stresses of embedded deformed steel bars in two types of concrete mix. Bond performance of specimens with normal concrete was inferior to that of SFRC specimens under direct loading (pullout test). The bond stress level reached was smaller (approximately 68% of that of the 1% fiber content specimens) and the residual slip was over four times greater at the same stress levels. Crack pattern for SFRC was much finer than that of normal concrete. This is because the widening and propagation of the internal inclined bond cracks and the longitudinal cracks in SFRC are hindered by the fibers. The deformed steel bar with concrete fiber provides higher bond strength as compared to the bond in normal concrete, therefore more suitable for effective catenary tie in precast concrete beam-column connection for maximum efficiency and deformability in order to minimize the progressive collapse.

References

[1] Tohidi, M., Yang, J. and Baniotopoulos, C., Numerical Evaluations of Codified Design Methods for Progressive Collapse Resistance of Precast Concrete Cross Wall Structures, Engineering Structures © 2014 Elsevier Ltd.

[2] Kaewkulchai, G and Williamson, E. B., Modeling the Impact of Failed Members for Progressive, Journal of Performance of Constructed Facilities © ASCE / November 2006 / 375

[3] Belarbi, A., Richardson, D. N., Swenty, M. K., and Taber, L. H., Effect of Contamination on Reinforcing Bar-Concrete Bond, Journal of Performance of Constructed Facilities © ASCE / May/June 2010, 206-214

[4] Desnerck, P., De Schutter, G. and Taerwe, L., A Local Bond Stress-slip Model for Reinforcing Bars in Self-compacting Concrete, Fracture Mechanics of Concrete and Concrete Structures - Assessment, Durability, Monitoring and Retrofitting of Concrete Structures, © 2010 Korea Concrete Institute, Seoul, ISBN 978-89-5708-181-5

[5] Ahlborn, T. M. & DenHartigh, T. C., A Comparative Bond Study of Stainless Steel Reinforcement in Concrete, Final Report CSD 2002-01, Michigan Technological University

[6] Abrishami, H. H. and Mitchell, D., D., Analysis of Bond Stress Distributions in Pullout Specimens, Journal of Structural Engineering / March 1996 / 255-261

[7] Chao, S. H., Naaman, A. E., and Parra-Montesinos, G. J., Bond Behavior of Reinforcing Bars in Tensile Strain-Hardening Fiber-Reinforced Cement Composites, ACI Structural Journal/November-December 2009, 897- 906.

[8] Yeih, W., Huang, R., Chang, J.J., and Yang, C.C., A Pullout Test for Determining Interface Properties between Rebar and Concrete, Advanced Cement Based Materials 1997,5,57-65.0 1997 Elsevier Science Ltd.

[9] Li, J., An Investigation of Behavior and Modeling of Bond for Reinforced Concrete, University of Washington, 2010.

[10] Tastani, S. P., and Pantazopoulou, S. J., Experimental Evaluation Of The Direct Tension - Pullout Bond Test, “Bond in Concrete – from research to standards” 2002, Budapest, Demokritus University of Thrace Bas. Sofias Street, Greece