Bond of high strength concrete under monotonic pull out loading.

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• Written August 18, 2003.
• Word Count: 5097
• Six Tables.
• Fourteen Figures.
Abstract:

An experimental investigation was conducted on high strength concrete specimens to examine the bond strength characteristics under monotonic loading. The range of compressive strengths tested was between 70 to 95 MPa. The influences of load history, confining reinforcement, bar diameter, concrete strength, reinforcement spacing and rate of pull out were investigated experimentally. The internal concrete strains close to the contact surface and also the steel strain were measured. The test set up, load application, instrumentation and measurement, and test procedure were designed to measure strains and deformations. Several specimens with reinforcement bar diameters of 20, 25 and 35 mm were tested. The test results revealed that the bond strength of high strength concrete is higher than the corresponding normal strength concrete. However, the bond behavior of high strength concrete is more brittle compared to normal strength concrete. The concrete strains were measurement around the steel reinforcement. Concrete strains measurements are useful to identify the internal crack pattern and to predict possible failure modes. The area under the curve of the bond stress-slip curve can define the bond energy. The bond energy is related to ductility and can be used along with the bond strength in evaluating the bond behavior of high strength concrete.

Keywords: Bond; high strength concrete; confining; reinforcement diameter and spacing; load history and rate of loading.
Introduction

High strength concrete is used mostly in the construction of bridges, high rise buildings, marine and offshore structures. Bond strength between high strength concrete and reinforcement is an important factor in designing any reinforced concrete structure under various kinds of loading. Therefore, this study is conducted to investigate bond behavior between high strength concrete and steel reinforcement, and to determine the internal stress and strain along the reinforcement interface with high strength concrete. The experimental data are valuable to understand the bond behavior of high strength concrete.

Several experimental and theoretical investigations were conducted by Somayaji and Shah\(^1\) and Jiang \(et\ al.\)\(^2\), on the behavior of bond for normal strength concrete. Improved tools for measurement of local bond and local slip were introduced and applied. The observations of secondary cracks are reported, as well as the distribution of strain in concrete in the vicinity of the reinforcing bar. Darwin \(et\ al.\)\(^3\) studied development length criteria for conventional and high relative rib area of reinforcement. On the basis of a statistically based expression, the development reinforcement length and splice strength of reinforcement for concrete with strengths between 17 and 110 MPa, with and without confining reinforcement, was investigated. The effects of cover, spacing, development/splice length, geometric properties of the development and spliced reinforcement were incorporated into their design equation.

Azizinamini \(et\ al.\)\(^4\) and Azizinamini \(et\ al.\)\(^5\) examined bond performance of reinforcing bars and tension development length of reinforcing bars embedded in high strength concrete. The effects of concrete compressive strength, splice length, and casting position on the bond strength of reinforcing bars have been studied. It was concluded that in the case of high strength concrete,
increasing the tension development length (or equivalent tension splices) was not an efficient way of increasing the bond capacity of deformed reinforcing bars, especially when the concrete cover is small. Azizinamini et al.\textsuperscript{6} indicated that when calculating the tension development length of high strength concrete and tension splice a minimum number of stirrups should be provided over the splice region. Based on the 70 beam specimens an expression is recommended to calculate the extra number of stirrups required. De Larrard et al.\textsuperscript{7} has investigated the effect of bar diameter on bond strength in high performance concrete. It was concluded that bond capacity increases with the tensile strength of the concrete and it is at a higher rate with smaller reinforcement. It was also found that the bond is greater for smaller bar diameters than for larger bar diameters.

Eligehausen et al.\textsuperscript{8} conducted one of the main comprehensive investigations on the effect of the bar diameter embedded in normal strength concrete. It was concluded that the maximum bond capacity decreased slightly with the increasing bar diameter. The frictional bond resistance was not influenced significantly by the different bar diameter, lug spacing, or the relative rib area.

Experimental investigation

This investigation was designed to test the confined region of a joint in a high strength concrete structure in order to study the behavior of the bond between reinforcement and high strength concrete. The load history, confining reinforcement, bar diameter, concrete strength, bar spacing, and rate of pull out were considered as the main study parameters. The study parameters were evaluated under monotonic loading in tension and compression. The internal strain in concrete close to the contact surface area was measured using strain gauges. A summary of the test program is presented in Tables 1 to 3. The test results are subdivided into six
series (M1-M6) as shown in Tables 4 to 6. Only one parameter was changed at a time, while all other parameters were kept constant. The influence of each study parameter on the bond behavior under monotonic loading was examined.

Test specimens

The test specimen represented the confined region of a joint in high strength concrete structures. The test set up, specimens size, number of specimens and testing parameters were similar to that conducted on normal strength concrete by Eligehausen et al.\textsuperscript{8} The reinforced high strength concrete specimen was confined by extra reinforcement representing the joint reinforcement. The confinement index is calculated as defined by the Canadian Building Code CSA.\textsuperscript{9}

The confinement index for the tested specimen was greater than 2.5 without the contribution of the extra steel confining reinforcement. Extra top and bottom 10mm stirrups were added to the specimens to ensure good confinement of reinforcement. The dimensions of tested specimen were 250 mm in length, $15d_b$ (tested bar diameter) in width and $5d_b$ to $7d_b$ in thickness as shown in Fig. 1. The bond length is located at the middle of the specimen and the rest of the specimen is de-bonded by the use of two small PVC pipes at the end of each specimen. The embedment length of rebar diameters of 25 and 35 mm in the high strength concrete block were taken as 75 and 100 mm, respectively as well as extra reinforcement was provided with top and bottom stirrups. These embedment lengths were short enough to result in a fairly uniform bond stress when the rebar is pull-out, but not long enough to reduce the scatter usually observed in test results when a very short bonded length was used. Three concrete strain gauges were used to measure the concrete strain at the middle and edge of the specimen. In each testing series a minimum of three specimens were fully
instrumented to measure steel and concrete strain gauges. The position of the concrete strain gauges is shown schematically in Fig.2 for a typical test specimen that was considered in this investigation.

**Concrete mix design**

The high strength concrete mixture contained a normal Portland cement, type 10 in accordance with Canadian Standards Association CSA⁹, and 10% of silica fume used on the basis of weight as detailed in Alavi-Fard.¹⁰ The cement content ranged between 450 – 470 Kg/m³ and a water cement ratio of 0.29 was used. A non-chloride water-reducing agent, retarder and superplasticizer were used in the mix. The target compressive strengths for the high strength concrete specimens ranged between 70 to 95 MPa.

Local aggregates were used for the concrete mix design. The coarse aggregate was mostly crushed quartzite sandstone with a maximum nominal size of 20 mm. The fine aggregate was identical in composition to the coarse aggregate with a minor percentage of sandstone and shale. The tested specimens were cured for 28 days at the concrete laboratory, and then were transferred for the structural laboratory for testing.

**Steel reinforcement**

The reinforcing bars were steel conforming to Canadian Standard Association CSA-G40.20-M94. Two samples of each bar size with diameter of 10, 25, and 35 mm were tested for tensile strength. A hydraulic machine was used to apply load and electrical resistance strain gauges were used to measure the strain up to yield. The recorded yield stress of the steel bars was found between 450 - 475 MPa.

**Test set-up**
A test frame was designed to carry out the experimental program. Some additional accessory parts were designed and fitted to facilitate the examination of bond strength investigation. Figure 3 shows the test set-up with a specimen mounted. The vertical loading frame consisted of two main vertical W-shape columns connected by two horizontal cross channels as detailed by Alavi-Fard and Marzouk. An electro-hydraulically controlled testing actuator with capacity 700 kN was used to apply monotonic tensile and compression load. A load cell was attached to the actuator to measure the load. The load cell was connected to an internal amplifier via the controller. The output voltage from the controller was feed into the input channel of the data acquisition system. All tests were run under displacement control. The displacement was measured at the end of the loaded steel bar by the use of the built in Linear Variable Differential Transducer (LVDT) in the actuator and confirmed by the external Linear Potential Differential Transducer (LPDT) at the unloaded end of the bar. The typical displacement rate was at 1.51 mm/minute for the steel bar. The slip is the relative displacement between the steel bar and the high strength concrete block. The slip is calculated as the difference between the LVDT reading minus the elongation of the steel bar outside of the concrete block. Therefore, the maximum measured slip represents the maximum local slip at the middle of the embedded length with a relatively acceptable accuracy. Since the bond location is situated at the middle of the specimen, the bond length is short compared to the specimen size, therefore, it can be assumed that the stress distribution is uniform along the tested bond length. The main objective was to record the bond stress versus the slip displacement during the duration of the test. The area under the bond stress-slip displacement curve is defined as the bond energy. The specimens were tested over a three-month testing period at the structural laboratory of Memorial University of Newfoundland. Figure 4 shows a tested specimen after failure.
Test results

Loading history

The details of the test specimen under monotonic loading can be found in Tables 1 to 3. The maximum magnitudes of slip, load, and bond strength for each specimen are shown in Tables 4 to 6. A typical bond stress-slip curve for high strength concrete specimen is shown in Fig. 5. The comparison of results for four specimens under pull out test with an embedded bar diameter of 35 and 25 mm each are plotted in Figs. 6 and 7, respectively. The bond stress and slip curve for push-in tests has been plotted on the graphs, Fig. 8. The comparison between pull out test of Fig. 7 and push-in test of Fig. 8 indicates that there was no major difference between the two types of loading. In all of the tested specimens, the main cracks developed in the longitudinal direction, while some minor cracks also developed in the transverse direction. The test results indicated a nonlinearity of the bond stress-slip behavior in the ascending portion of the curve, especially close to maximum stress. All results confirmed the sudden drop of the stress level at the beginning of the descending section of the curve and followed by the gradual decrease of stress. The slope of the curves in the ascending section in case of the push-in was higher than that of the pull out test. Hence, the total bond energy in compression is slightly higher than expected for the pull out test. However, this difference is not large enough to provide a distinct difference between the two behaviors.

The average equivalent bond stress for experimental phase of this investigation is calculated as the result of tension or compression force divided by contact surface area (bond area). Also, the curves are normalized based on the result of the value of tested bond stress divided by cube root of compression strength of concrete.
Concrete and steel strains

The steel strain and internal concrete strain for a typical specimen with embedded bar diameter 35 mm is plotted in Figs 9 and 10. The specimen is tested under push-in load. The two strain gauges STC1 and STC2 are installed in the bond area and the strain gauge STC3 is far from the bond area, as shown schematically in Fig. 2. There are differences between the magnitudes of concrete strain reading of STC1 and STC2 due to the location of the strain gauges and the distance from the bond surface. The concrete strain reading of STC3 is not very significant, since it is very far from the location of the bond failure. The result indicated that when secondary cracks started to open, the concrete strain gauges were damaged. Figure 10 shows the measured steel strain for a typical bond specimen. The steel strain gauge was glued to the steel bar at the middle of the specimen. The steel stress–strain curve demonstrates the increase of steel strain proportional to the load and the decrease of the strain at the beginning of the descending portion of the bond stress-slip curve.

Confining reinforcement

The influence of different confinement bar diameters on local bond behavior of deformed bars was investigated in series M2 of Tables 2 and 5. The vertical and horizontal steel reinforcement shown in Fig.1 represent the extra confining reinforcement for tested specimen. The selected different vertical bar diameters were ranged from (0.3 to 0.6) of the tested bar diameter. Table 5 presents the measured values of slip, load, and bond strength at maximum load. All of the tested concrete specimens have adequate concrete cover, edge distance and bar spacing requirement. The normalized bond-stress-displacement curves for different size of confining reinforcement for a 35
mm bar diameter with respect to the maximum load and maximum deflection are presented in Fig. 11.

When no extra reinforcement was provided as confinement, the bond stresses vanished as soon as the longitudinal crack developed through the cover. The failure mode was of a sudden splitting type. In addition, a large energy was released due to sudden splitting of the specimen. However, when extra confinement was provided the total area of the bond energy curve for specimens with different confinement bars of 10 mm and 20 mm diameters were higher than that for a confinement bar diameter of 25 mm. A 10 mm diameter stirrup was used for confinement of 25 mm and 35 mm bar diameters efficiently. Also, the failure mode for specimens with extra confinement was characterized by pulling out bar from concrete rather than the sudden splitting behavior for specimens with no confinement. Therefore, high strength concrete needs extra steel to reach an adequate level of bond energy and ductility. The confinement reinforcement of high strength concrete is considered adequate, when the diameter of the confinement bar is from 0.3 to 0.6 of the tested bar.

**Bar diameter**

The bond test results of the 20, 25 and 35 mm bar diameters are shown in series M3 of Tables 2 and 5. The effect of varying bar diameter on the bond strength is illustrated in Fig. 12. All curves of this Figure are normalized with respect to maximum bond stress and maximum displacement of a 25 mm bar diameter. The bond strength of the 20 mm bar diameter is greater than the tensile capacity of the bar cross section area. Therefore, the bar is broken during testing and this curve does not demonstrate the entire bond behavior. The ascending slope of the curve for a 20 mm bar
diameter is much steeper than for the 25 and 35 mm bar diameters. Further comparison between the area under the curve shows that the area under the curve for the bar with a diameter of 35 mm is less than for the bar diameter of 25 mm. Hence, the experiment results show that the bond resistance is higher for the smaller diameter than that for larger diameter bar. In general, the results of this series agree with the findings of Eligehausen et al.\textsuperscript{8}, using a similar test set-up for normal strength concrete. However, the bond strength values are different for each concrete strength level. The sudden drop of the stress level at the beginning of the descending section of the bond stress-displacement curve is attributed to the characteristics of the high strength concrete.

**Bar spacing**

The influence of different lateral bar spacing on local bond behavior was investigated in series M5 of Tables 3 and 6. The lateral bar spacing was taken as $3.5 \, d_0$ for all the tested specimens as shown in the plan view of Fig. 1. However, this spacing was changed in four specimens during this investigation to examine the effect of the lateral spacing on the bond behavior. Two specimens were tested with bar diameter of 25 mm and lateral spacing of 25 and 50 mm and the other two specimens were tested with bar diameter of 35 mm and bar spacing of 35 and 70 mm.

In the case of bar diameter of 25 mm there was no significant difference between the two in the ascending portion, while in the descending portion there was a small difference. The bond strength for specimen with bar spacing of 25 mm was about 20 percent less than for a specimen with 50 mm bar spacing.

The test results for the specimen with bar diameter of 35 mm shows that the increase in bar spacing had more influence on the bond resistance of the initial part of the bond stress-slip relationship than on the bond strength. The bond strength is improved with the increase of lateral bar
spacing. The result of observation and comparison between bond strength for this series of tests showed a possible difference of 20% in the bond strength due to the lateral bar spacing.

**Rate of loading**

This section presents the experimental results from the testing of three specimens tested under different displacement rates of 75, 1.51, and 0.0151 mm/minute as shown in series M6 of Tables 3 and 6. Figure 13 shows a comparison of the normalized bond stress-displacement response for the three specimens tested under different rates of loading for a tested bar diameter of 35 mm. Although at the initial stage of loading there was a noticeable difference for the specimen with rate of loading of 1.51 mm/minute the bond-displacement curves were similar. The result indicated that the bond strength is approximately the same under different rates of loading for a tested bar of 35 mm as presented in series M6 of Table 6.

**Concrete strength**

The influence of the concrete compressive strength on the bond behavior was investigated in series M4 of Tables 3 and 6. In principal, the results of this series of tests agree with the previous study for normal concrete strengths of 30 MPa and 55 MPa, Eligehausen *et al.*[^1] The main difference between high strength concrete and normal strength concrete is the instantaneous drop of the curve at the beginning of the descending branch of the curves, as a result of losing adhesion. This brittle behavior is well illustrated in series M4 of tests especially for concrete with higher strength. The results of all tests in this series confirmed the nonlinear-brittle behavior of the bond for high strength concrete. In the case of high strength concrete the capacity of bond strength is higher than the...
normal, however, the impact of the instantaneous drop in the bond stress for high strength concrete must be recognized. The bond strength is strongly dependent on concrete strength and this parameter has a direct effect on bond behavior. A comparison of normalized bond stress with regard to the maximum load of specimen with compressive strength of 94.96 MPa to other specimens, with different concrete strengths for 25 mm bar diameter is shown in Fig. 14.

**Test results and code of practice**

The load required to pull a reinforcing bar out of a concrete block will obviously increase as the length of a bar cast into the block increases. When the embedded length becomes long enough, the bar will yield in tension before it pulls out of the block. The minimum embedded length required to develop the yield force of the bar is called the minimum required development length. The development length requirements are used by all North American codes to indicate the bond strength of concrete. Both of the Canadian Standard CSA⁹ and the American ACI-318¹², express the bond strength of concrete as a function of the square root of concrete compressive strength. The test results of the current investigation indicated that the bond strength of high strength concrete, from 70 to 95 MPa is more appropriately proportional to the cube root rather than the square root based on the statistical sensitivity analysis conducted by Alavi-Fard.¹⁰ Therefore, the test results were normalized with regard to the cube root of the compressive strength as given in Tables 4 to 6. The ratio between the normalized test results versus the CSA⁹ Standard prediction is given in Tables 4 to 6. This ratio indicates that the square root of the compressive strength approach adopted by the Canadian Standard does not provide a good prediction of the bond strength for the tested high strength concrete specimens. The bond strength of concrete is proportional to the compressive strength, to the power of
1/3 in the British Code BS 8110\textsuperscript{13}, to the power of 2/3 in both of the CEB-FIP\textsuperscript{14} and Norwegian NS-3474\textsuperscript{15} Codes.

More recently, Azizinamini \textit{et al.}\textsuperscript{6} recommended a new expression for confinement of the tension development length and lap splice for high strength concrete to ensure adequate ductility. A modification to the ACI-318\textsuperscript{12} expression has been recommended based on the assumption that the bond strength of high strength concrete of 69 MPa and over is proportional to the fourth root of the compressive strength.

**Failure mechanism**

There are two types of failure mechanisms that are known for the pull out test. The first type is splitting of the concrete cover and the second type is pull out of the bar. There are several parameters, which govern the mode of failure such as: type of loading, rate of loading, thickness of the cover, bar diameter, confinement reinforcement and bar deformation patterns. The test results of the current investigation revealed that the behavior of the bond stress-slip response was brittle and nonlinear for high strength concrete. The magnitude of the maximum slip at failure was estimated by five times the slip at the maximum bond stress. Therefore, the primary cracks will be developed and observed before failure of the specimen. The longitudinal crack at the surface of the specimen appeared approximately at the maximum load and the bar failed due to pull out from the concrete block. The rib of the deformed bar can be a major cause of longitudinal splitting along the bar for a confined specimen. The face angle, height and spacing of the ribs of the deformed bar have an important effect on the bond energy on high strength concrete.

Splitting type failure occurred when the cracks flowing from the contact area of the bar
reached the surface of the high strength concrete prism. The splitting failure was initiated by the wedging action of the ribs as the reinforcement bar moved with respect to the concrete. Splitting was characterized by planar-like cracks in those planes radial to the axis of the rebar. In a recent study by Alavi-Fard and Marzouk\textsuperscript{16} on five deformation patterns of steel reinforcement for high strength concrete, it has been found that, the Canadian Standard deformation is one of the most efficient patterns to be used for high strength concrete reinforcement. Furthermore, the wedging action of the rib had a higher percentage of failure to the bond specimens. In the case of the unconfined specimens, failure occurred only due to longitudinal splitting along the bar and at the same time it was accompanied with a large amount of energy.

Summary and conclusion

The bond strength of high strength concrete is subjected to the effects of several factors. In this investigation, the effect of the load history, confinement, bar diameter, concrete strength, bar spacing and pulls out rate were examined. The range of the tested concrete compressive strengths was between 70-95 MPa.

The bond stress-slip curve of high strength concrete is characterized by a sharp drop of the stress at the beginning of the descending portion of the bond stress-slip curve. The area under the curve of the bond stress-slip curve can be defined as bond energy. The bond energy is recommended to be used to evaluate the bond behavior rather than the maximum bond stress.

The influence of extra confinement on bond is significant on improving the ductility and the bond energy, especially after reaching the maximum bond strength. The test results revealed that a confinement bar diameter from 0.3 to 0.6 of the confined bar is adequate for high strength concrete
under monotonic loading.

The result of tests examining the effect of varying bar diameter embedded in high strength concrete indicates that the bond is higher for the smaller bar diameter than for the larger one. The bond strength for 25 mm bar diameter is approximately 15 percent higher than that of 35 mm bar diameter. A sharp drop of the bond stress-slip curve at the beginning of the descending portion was confirmed for all bar diameters. The level of bond stress drops by about 30 percent of maximum bond stress at the beginning of the descending branch of the bond stress-slip curve.

Results of the investigation regarding the influence of the later bar spacing revealed that the bond strength could be improved by selecting a proper lateral bar spacing and adequate concrete cover. An investigation into the bond strength subjected to the effect of the concrete strength concluded that the bond strength for high strength concrete is higher than the corresponding one for normal strength concrete. However, the behavior of high strength concrete is more brittle and it must be reflected in the bond model.

The current Canadian Standard CSA\textsuperscript{9} must be modified to reflect the reality of bond strength results of high strength concrete of compressive strength 70 MPa and over. The use of the square root of the compressive strength to predict the bond strength will lead to unsafe bond design. The use of the square root expression for the bond strength of high strength concrete of compressive strength, 70 MPa and over was abandoned by the latest proposed revision of the ACI-318.\textsuperscript{12} It is important at this point to publish all the available test results to guide the Canadian Code committee to adopt the appropriate expression, whether its cube root like the European codes or fourth root like the American Code. Based on the limited test result, the bond strength is more appropriately proportional to the cube root rather than the current square root.
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