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# EFFECT OF ACTIVE CONFINEMENT ON THE LOCAL BOND STRESS-SLIP BEHAVIOR OF STEEL BARS EMBEDDED IN PLAIN CONCRETE WITH VARIABLE COVERS: EXPERIMENTAL INVESTIGATION AND ANALYTICAL MODELING

by
FARAH NAZIH ASSAAD

A thesis
submitted in partial fulfillment of the requirements
for the degree of Master of Engineering
to the Department of Civil Engineering
of the Faculty of Engineering and Architecture
at the American University of Beirut

Beirut, Lebanon
September 2015

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# ACKNOWLEDGMENTS

Special thanks are for Professor Mohamed Harajli and Professor Elie Hantouche for their great help and assistance in the laboratory and technical work of this research.

My recognition and gratitude are addressed to the Faculty of Engineering and Architecture at AUB for its support and for providing the laboratory facilities.

# AN ABSTRACT OF THE THESIS OF

Farah Nazih Assaad for Master of Engineering
Major: Civil Engineering

Title: Effect of active confinement on the local bond stress-slip behavior of steel bars embedded in plain concrete with variable covers: experimental investigation and analytical modeling

Reinforced concrete structures are mainly designed for the concrete to carry compressive stresses and the steel to resist tensile stresses. Therefore, a composite interaction between concrete and reinforcing steel bars is necessary to achieve a good performance. This interaction depends on the local bond and slip behavior between the two materials. In the past, various experiments investigated the composite action between the concrete and reinforcing bars to examine the performance of reinforced concrete structures. Under monotonic increasing load, the influence of numerous parameters on the bond behavior were studied and it mainly includes the concrete compressive strength $f_c'$, addition of fibers to concrete, bar diameter and geometry of the ribs, concrete cover, confining reinforcements, and transverse pressure.

This study summarizes the results of a series of experimental and analytical studies on the effect of active confinement on the local bond stress-slip characteristics of steel bars embedded in plain concrete. Twenty specimens representing the confined region of a beam-column connection were tested under monotonic increasing load in tension. Different types of confinement and their effect on the local bond stress-slip response of reinforcing bars were investigated and compared. These include concrete cover-steel bar diameter ratio, and transverse applied pressure or active confinement. Based on the parameters that influence the bond strength, splitting, pull-out, and mixed mode failures were identified. A comprehensive analytical model predicting the local bond stress-slip response for steel bars embedded in plain concrete subjected to active confinement (transverse pressure) was developed. The model accounts for most of the important parameters that influence the behavior as observed in the experiment. The proposed analytical model shows acceptable agreement when compared against experimental results conducted as a part of this research.

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# CHAPTER 1

# INTRODUCTION AND BACKGROUND LITERATURE

Reinforced concrete structures performance depends mainly on the composite interaction between concrete and reinforcing steel bars. This interaction depends on the local bond and slip behavior between the two materials. When structures are exposed to severe loading, such as earthquake loading, large local bond demand on the beam-column connection might exceed the capacity of the joint. This load will force the bar to slip from the surrounding concrete resulting in bond failure.

Bond failure between steel bars and concrete is generally categorized by two main modes, namely pullout and splitting (ACI 1990, ACI 1992). When the concrete is adequately confined, failure occurs in pullout mode by shearing off the concrete keys between the bar ribs. However, when the concrete is unconfined, failure occurs in splitting mode where the concrete between lugs will be fully intact (Eligehausen et al. 1983).

Previous experimental studies investigated the bond characteristics between the concrete and steel bars. This bond consists of three components: chemical adhesion, friction and mechanical interlock (Wang and Liu 2003). The first bond that occurs between the two materials is Chemical adhesion. It represents a chemical interaction between the cement paste and steel surface. Although it has a small effect but it does not allow any slip to occur. As the steel bar is loaded up to a certain level, chemical adhesion breaks down, and relative movement starts to occur between concrete and steel giving rise to friction that counteracts the slip effect. Friction is created by radial stresses between the rough steel surface and the concrete. Its effect continues until the bar has slipped enough to start mobilizing the mechanical interlock. Mechanical interlock is created by the ribs on the bar embedded in the concrete, and it becomes the primary mechanism that contributes to the bond resistance as illustrated in Figure 1 below. As the load continuous to increase, the steel bar is elongated more significantly. The radial forces are significantly reduced due to Poisson's ratio effect that causes the cross section to decrease, so friction becomes negligible at this stage and leaving the bearing of concrete becomes the primary force transfer mechanism. Cracks begin to form adjacent to steel rebar.

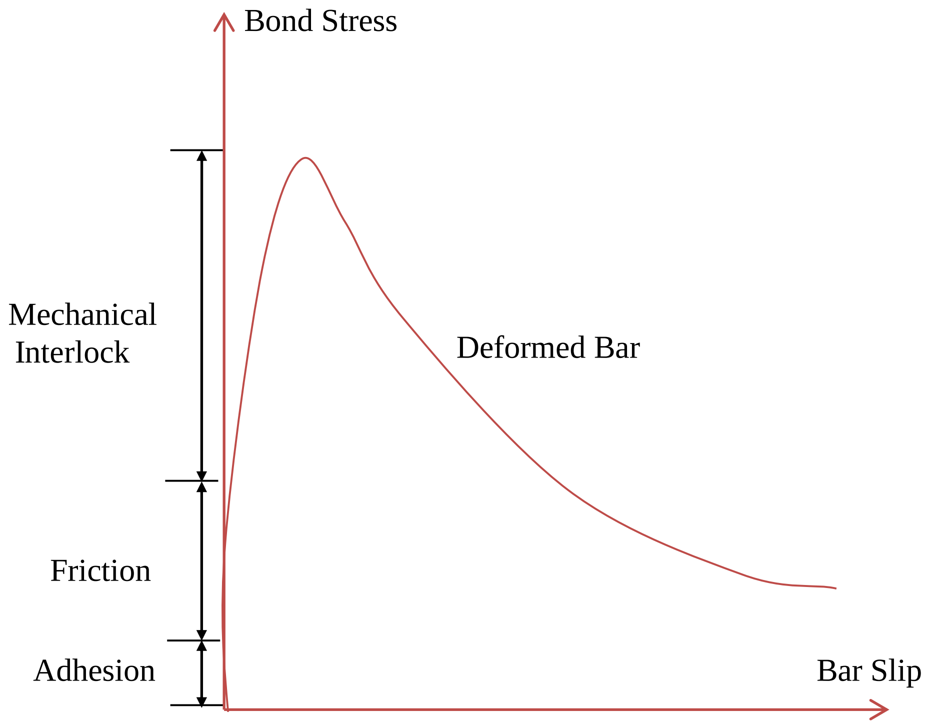


Figure 1. Bond between concrete and reinforcing steel

Several analytical models have been proposed and numerous experimentally based relationships have been derived to describe the bond mechanism under monotonic increasing load. The influence of major parameters on the bond behavior was identified and it mainly includes the concrete compressive strength $f'_c$, addition of fibers to concrete, bar diameter and geometry of the ribs, concrete cover to bar diameter $c/d_b$, confining reinforcements, and transverse steel bars, and passive confinement (FRP wraps) (Harajli 2009).

Eligehausen et al. (1983) tested 125 pullout specimens under variable system parameters and variable load histories. The results of the investigation provided that the bar size had a slight influence on the bond strength. However, the bond strength was increased approximately proportional to the square root of the concrete compressive strength. The study also provided that specimens with adequate confining reinforcement failed by pullout and attained a higher bond strength than specimens that failed by splitting without reinforcement. Harajli (1995) studied the bond and slip characteristics of reinforcing bars embedded in fiber reinforced concrete (FRC). He concluded that the presence of fibers in concrete did not have a significant effect on the local bond and slip response when pullout failure occurs. On the contrary, when splitting failure occurs, the presence of fibers reduced the splitting cracks and led to higher bond strength with comparing to bars embedded in plain concrete.

One of the earliest investigations into the bond behavior of steel bars with active confinement was reported in Eligehausen et al. (1983). He tested a series of specimens consisting of a reinforcing bar anchored with an embedded length of $5d_b$ and a 30 $N/mm^2$ concrete compressive strength. The results showed that the bond behavior was improved by applying transverse pressure to the specimen where an increase in the pressure from 0 to 13.5 MPa produced a 25% increase in the maximum bond resistance. However, there was an upper bound to the effectiveness of increasing the transverse pressure where the maximum bond strength reached an asymptote of around 17 $N/mm^2$ for a transverse pressure of 10 $N/mm^2$ and higher. Furthermore, additional studies provided that specimens without normal pressure failed by splitting of concrete where the concrete between lugs was fully intact, and specimens exposed to high pressure failed by pullout of the bar where the concrete between lugs was sheared off. Also, the bond strength was found to increase with the square root of the pressure when other factors are constant and with the square root of the concrete compressive strength (Untrauer and Henry 1965). X. Zhang et al. (2014) studied the bond behavior of deformed bars in concrete under biaxial lateral tensile compressive stresses and concluded that without applying lateral stresses, the failure mode will be primary affected by the variation of the ratio of concrete cover to bar diameter. However by applying biaxial lateral tensile-compressive stresses, the failure mode will be influenced by $f'_c$, $c/d_b$ and coupling effect of lateral stresses. Robins and Standish (1982) pulled 8 and 12 mm reinforcing bars from specimens laterally loaded on two sides and they found that this pressure did not affect the mode of failure of the specimen, but it had a noticeable influence on the bond strength of the bar which increased with increasing the pressure. They concluded that when the lateral stress was close to the cube compressive strength of the concrete, an increase in pullout load of up to 200% on the value for no lateral stress was achieved. And when the lateral stress was relatively modest (around 8 $N/mm^2$) the bond strength was increased by as much as 50%. Thus, the higher the applied pressure, the lower is the value of slip.

Although some research covered the effect of active confinement on the local bond strength, but the effect of active confinement on specimens with variable concrete cover was not considered. The Concrete cover to bar diameter ratio is one of the main parameters that affect the bond performance of plain concrete. Since the bond between steel and concrete fails either by splitting or by pullout, Eligehausen expected that when the concrete cover to bar diameter ratio is small, bond failure occurs in splitting mode. However, when this ratio is large, failure occurs in pullout mode by shearing off the concrete keys between the bar ribs. Wang and liu X (2003) clarified the splitting mode in their research about strain softening model for steel-concrete bond. They said that when loading a reinforced concrete structure, the bar tends to slip relative to the concrete due to difference of stiffness and cracks start to develop due to fail of the bond between steel and adjacent concrete. Since the bar is well confined by the cover, the concrete will crush in front of the ribs of the bar and the concrete key will slip experiencing a circumferential strain. When these circumferential tensile stresses exceed the tensile strength of the concrete, splitting cracks will be initiated. Therefore, providing a sufficient cover to bar diameter ratio will decrease these tensile bond stresses and the crack initiation load increases and consequently bond strength increases. Harajli (2009) studied the effect of several critical parameters on the local bond stress-slip response. His experimental observations reported a larger peak bond strength for specimens having $c/d_b$=1.5 by comparing to specimens having $c/d_b$=1.0 when other factors were kept constant and for both confined and unconfined concrete.

Besides the experimental observations, several analytical models have been also proposed. To describe the local bond stress slip relationship for pullout failure of steel bars embedded well confined concrete, Eligehausen et al. (1983) proposed one of the most commonly used bond laws in the literature as shown in equation 1 below:

$$\mathrm{u} = \mathrm{u}_1\left(\frac{\mathrm{s}}{\mathrm{s}_1}\right)^{\nu} \tag{1}$$

where $u_1$ is the peak bond stress, and proportional to $\sqrt{f_c'}$, $s_1$ is the slip at corresponding $u_1$, $\nu$ is an exponential coefficient equal to 0.4. For concrete with $f_c'$ equal to 30 MPa, $u_1 = 13$ MPa, and $s_1 = 1$ mm.

Harajli et al. (1995) updated this equation by assigning generalized parameters where $\nu = 0.3$, $u_1 = 2.57\sqrt{f_c'}$, and $s_1 = 0.15c_0$, where $c_0$= clear spacing between the steel bar ribs.

Harajli (2007) used a multiregression analysis for his experimental data and derived the characteristic parameters for the local bond stress slip relationship as shown in Figure 2: The residual bond stress $u_f = 0.35\, u_1$, $s_2 = 0.35c_0$, and $s_3 = c_0$.

For splitting mode, Eligehausen (1979) proposed the following equation to estimate the local bond strength:

$$\mathrm{u}_{\mathrm{max}} = 1.5\mathrm{f}_{\mathrm{ct}}\sqrt{\frac{\mathrm{c}}{\mathrm{d}_{\mathrm{b}}}} \tag{2}$$

where $f_{ct}$ is the axial tensile strength of concrete = $0.5\sqrt{f_c'}$.

Harajli (2007) also proposed to describe the local bond stress–slip response of unconfined steel bars in tension using four stages based on the results of his experiment as shown in Figure 2. The first stage includes an ascending relation from zero to $\alpha u_{max}$, where $\alpha = 0.7$, and following the bond law corresponding to pullout mode as stated in equation (1). The second stage corresponds to a linear increase in bond strength at a reduced rate from $\alpha u_{max}$ to $u_{max}$. The slip $s_{max}$ at which the peak bond $u_{max}$ is mobilized was calculated using equation 3 below:

$$s_{max} = s_1 \, e^{\left(\frac{1}{0.3}\right)\ln\left(\frac{u_{max}}{u_1}\right)} + s_0 \ln\left(\frac{u_1}{u_{max}}\right) \quad (3)$$

Where $s_0 = 0.15$ mm.

The third stage corresponds to an immediate drop in bond resistance to $\beta u_{max}$ after splitting where $\beta = 0.65$, and the last stage represents a progressively diminishing bond resistance. The relationship beyond splitting was assumed to be as follow:

$$u = \beta u_{max}\left(\frac{s}{s_{max}}\right)^{-0.5} \quad (4)$$

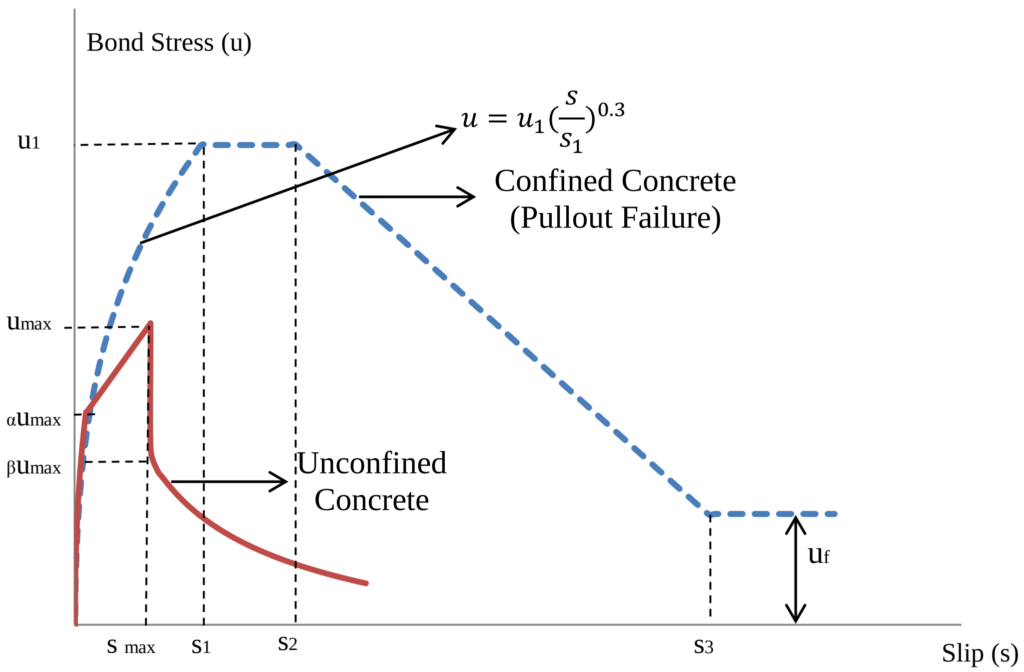


Figure 2. Proposed local bond stress-slip relationship in the literature

# CHAPTER 2

# RESEARCH OBJECTIVE

This research consists of an experimental testing of specimens representing as close as possible the conditions found in a beam-column joint and subjected to monotonic tensile loading. The main objective of the work was to study the effect of active confinement on the local bond and slip behavior of reinforcing bars embedded in plain concrete under monotonic increasing load in tension with variable concrete covers. To achieve this objective, prismatic specimens representing the confined region of the beam column connection were tested with an embedment length of the steel bar in the concrete equal to 5 times the bar diameter $d_b$. The influence of the parameters on the local bond was studied by varying the ratio of concrete cover to bar diameter $c/d_b$ (1.0, 1.5, 2.0, 2.5, 3.5) and the transverse applied pressure $P$ (0, 12.5, 25, 50, 75, 100 $kg/cm^2$). The main response of the specimens was determined by the local bond stress-slip response and mode of bond failure. Based on the parameters that influence the bond strength, possible failure modes (splitting, pull-out, and mixed mode) were identified. A simple analytical model describing the local bond stress-slip relationship for reinforcing bars embedded in plain concrete subjected to transverse pressure was developed. The model accounts for most of the important parameters that influence the local bond stress-slip response as observed in the experiment.

# CHAPTER 3

# EXPERIMENTAL PROGRAM

### 3.1. Test Specimens

The main objective when designing the specimens was to represent as close as possible the confined region of a beam column connection as shown in Figure 3, and subjected to simulated earthquake loading.

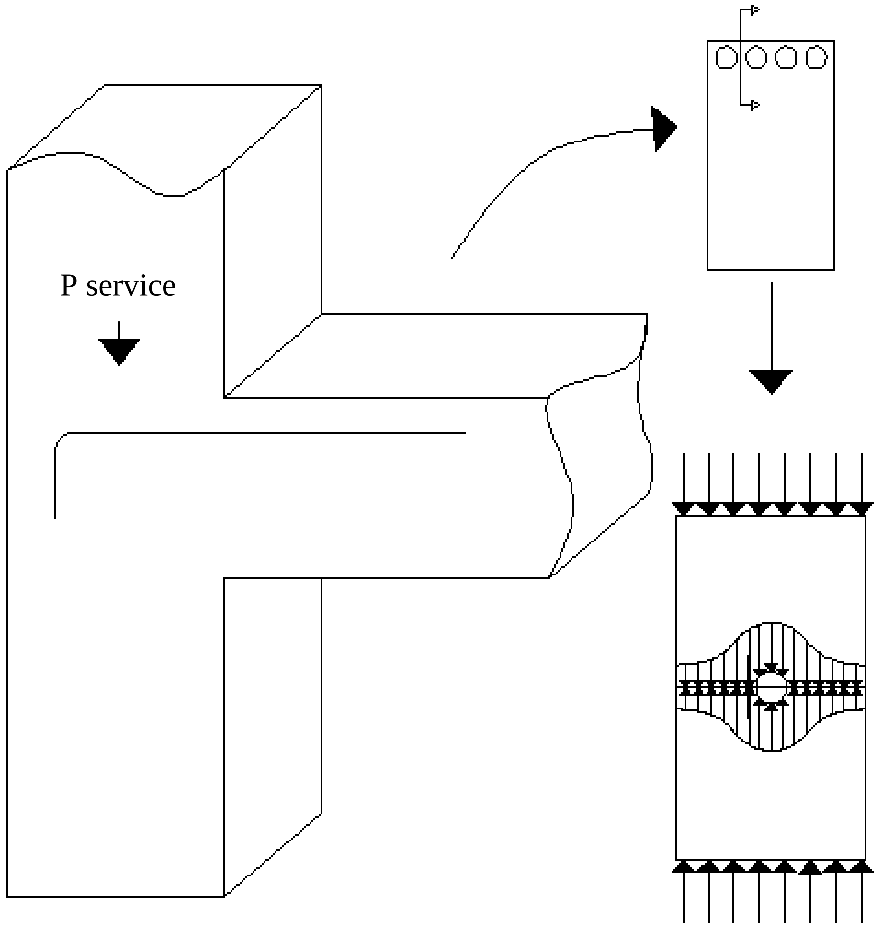


Figure 3. Beam-Column joint: stress distribution due to service loading

The test specimens consisted of prismatic specimen having dimensions and reinforcement details as shown in Figure 4. A reinforcing bar of 25 mm diameter was embedded at the center of the specimen in a horizontal position with an embedment length $L_b$ of $5d_b$. The bar was bonded only in the central part of the prism while PVC tubes were used on the sides to create unbounded regions and prevent any interruption to the bonded zone during loading as shown in Figures 4 and 5. Thin plastic sheets were placed above and below each PVC and perpendicular to the large side of the specimen in order to reduce the concrete splitting area.

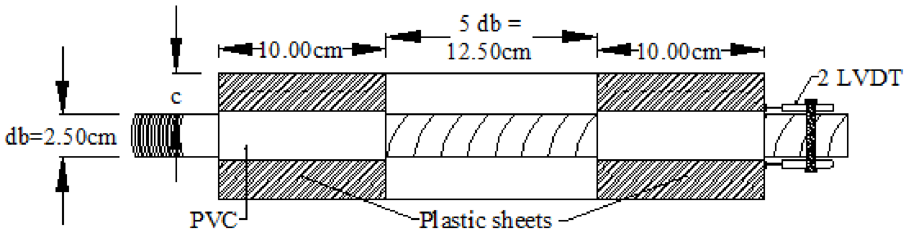


Figure 4. Specimen's geometry

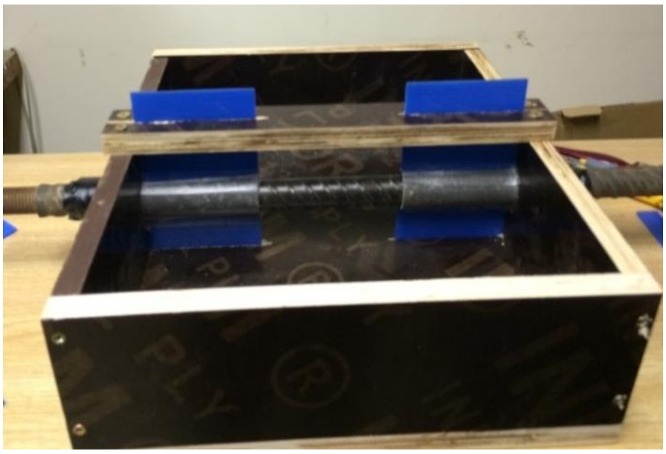

Figure 5. PVC tubes to create unbounded regions

Table 1. Details of test specimens

| **Test Series** | ***f'ᶜ* (MPa)** | **c/db** | **Applied Pressure (Kg/cm²)** |
|---|---|---|---|
| **I** | 26 | 1.0 | 0, 50, 75, 100 |
| **II** | 26 | 1.5 | 0, 50, 75, 100 |
| **III** | 28.5 | 2.0 | 0, 25, 50, 75 |
| **IV** | 26 | 2.5 | 0, 25, 50, 75 |
| **V** | 26 | 3.5 | 0, 12.5, 25, 50 |

Twenty specimens were tested under monotonic increasing load in tension. The test parameters included the ratio of concrete cover to bar diameter ratio ($c/d_b$) and transverse applied pressure ($P$) as shown in Table 1 above.

### 3.2. Casting and Materials

The specimens were cast using ready-mix concrete in a horizontal position, as shown in Figure 6, and compacted by needle vibrators. After a preserving period of at least 28 days in the laboratory at constant temperature and humidity, all specimens were tested. Since the concrete compressive strength was not a parameter in this investigation, the observed bond- slip relationships of all specimens were normalized to the average measured concrete compressive $f'_c$ using the following equation:

$$q(\text{average } f'_c) = q(\text{measured})\sqrt{\frac{\text{average } f'_c}{\text{actual } f'_c}} \quad (5)$$

The average $f'_c$ was 26 MPa for the specimens in test series I, II, IV and V, and 28.5 MPa for specimens in test series III as shown in Table 1

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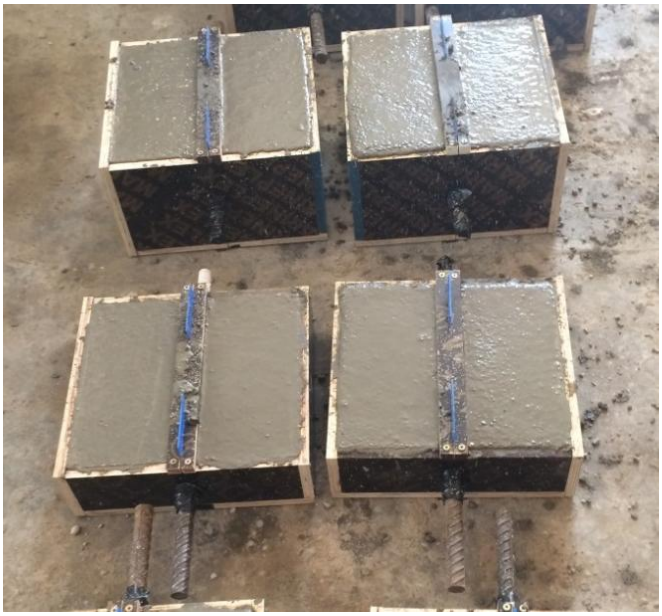


Figure 6. Test specimens after casting

### 3.3. Test setup and procedures

The specimens were tested in a servo hydraulic load frame machine (MTS). The system was designed to run a monotonic tension test. The specimen was placed on the lower bearing plate, where a threaded hole at the fixed base was available to anchor the bar as shown in Figure 7. A small distance between the specimen and the upper head of the system was left to reduce friction when running the monotonic tension test. Having the bar fixed at one end, it was pulled out from the concrete when the bearing plate pushed against the anchored end of the bar. So the bar was in tension and concrete in compression. TEFLON sheets were used between the specimen and the bearing plate to limit friction between them as much as possible. The transverse pressure was applied to the specimen before starting the test using a hydraulic jack from one side connected to a stiff plate from the other side by four threaded rods. A stiff plate was also placed between the specimen and the jack to ensure a uniform pressure. A load cell was available to measure the pullout force, while the slip of the bar was measured at the unloaded end of the specimen by two linear variable differential transformers (LVDTs) attached on two opposite sides of the bar. The test was monitored using a data acquisition system. The bar slip was controlled at a rate of 2 mm/min (0.03 mm/seconds) for all specimens. The local bond stress, $q$, versus the slip relation was found from the measured bar force, $F$, and the average of the slips measured by the two LVDTs. The test was stopped when splitting of surrounding concrete was observed or pullout failure occurred. Figure 8 shows the test specimen with transverse applied pressure.

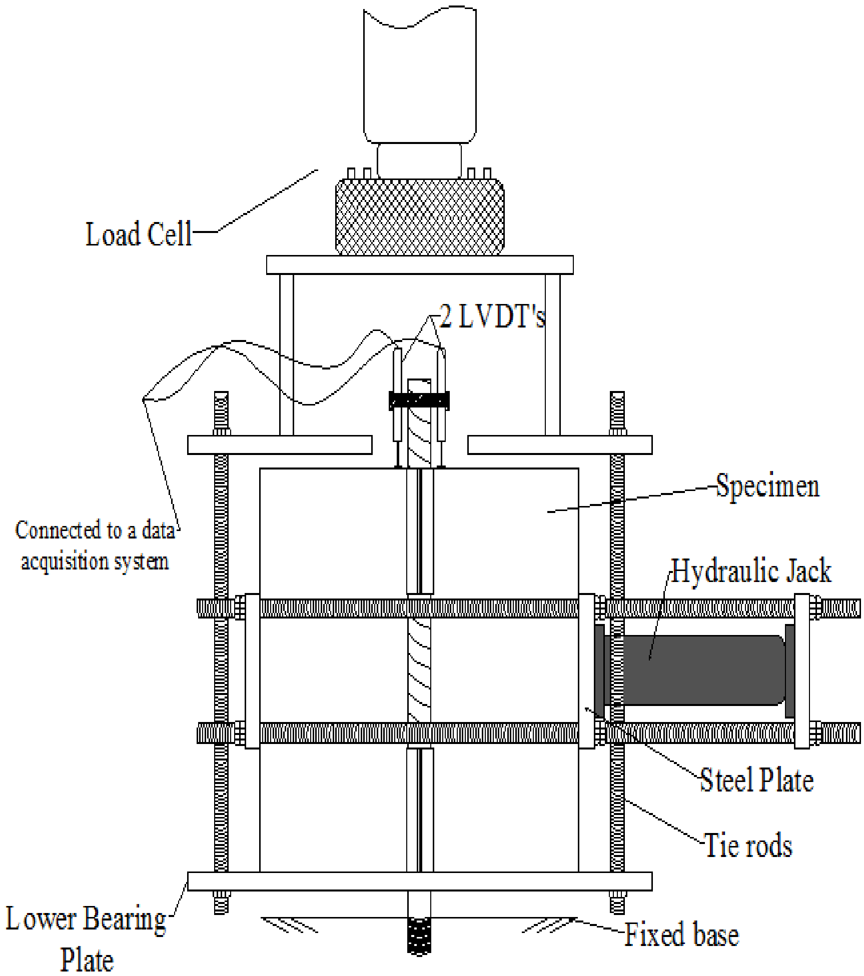



Figure 7. Schematic view of test setup with the device for applying pressure

Figure 8. MTS machine and Test setup

# CHAPTER 4

# EXPERIMENTAL RESULTS

## 4.1 Bond Stress-slip response

The experimentally measured local bond stress–slip responses for confined and unconfined concrete are presented in this section. The local bond stresses were calculated using the recorded applied forces at given slip values and by the following equation:

$$q = \frac{F}{\pi . L_b . d_b} \tag{6}$$

where $F$ is the recorded applied forces at given slip, $d_b$ is the reinforcing bar diameter and $L_b$ is the bond length of reinforcing bar (taken equal to $5d_b$).

The local bond stress-slip results for specimens in test series I, II, III, IV and V are shown in Figures 9, 10 and 11. The experimental results show that three modes of failure are identified and are presented in Table 2.

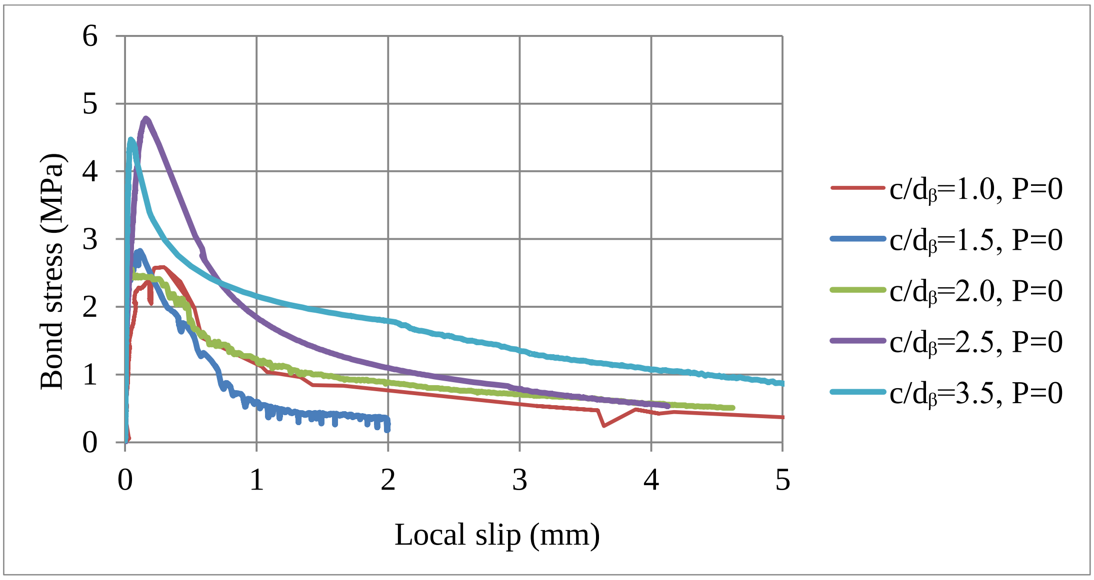



Figure 9. Observed local bond stress-slip response for splitting bond failure

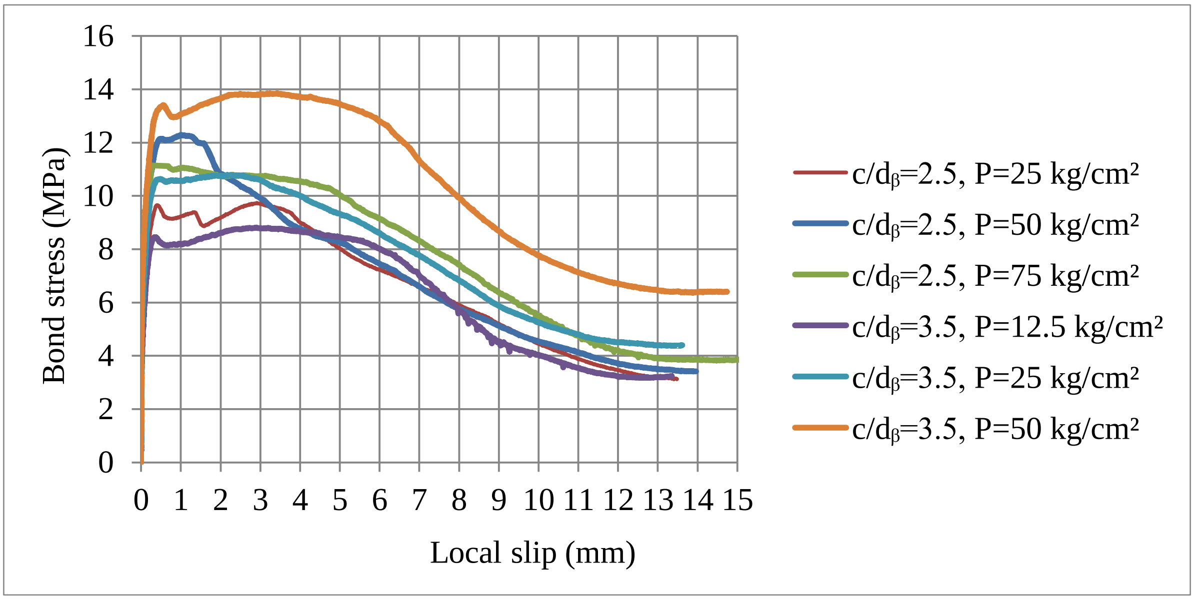



Figure 10. Observed local bond stress-slip response for Pullout bond failure

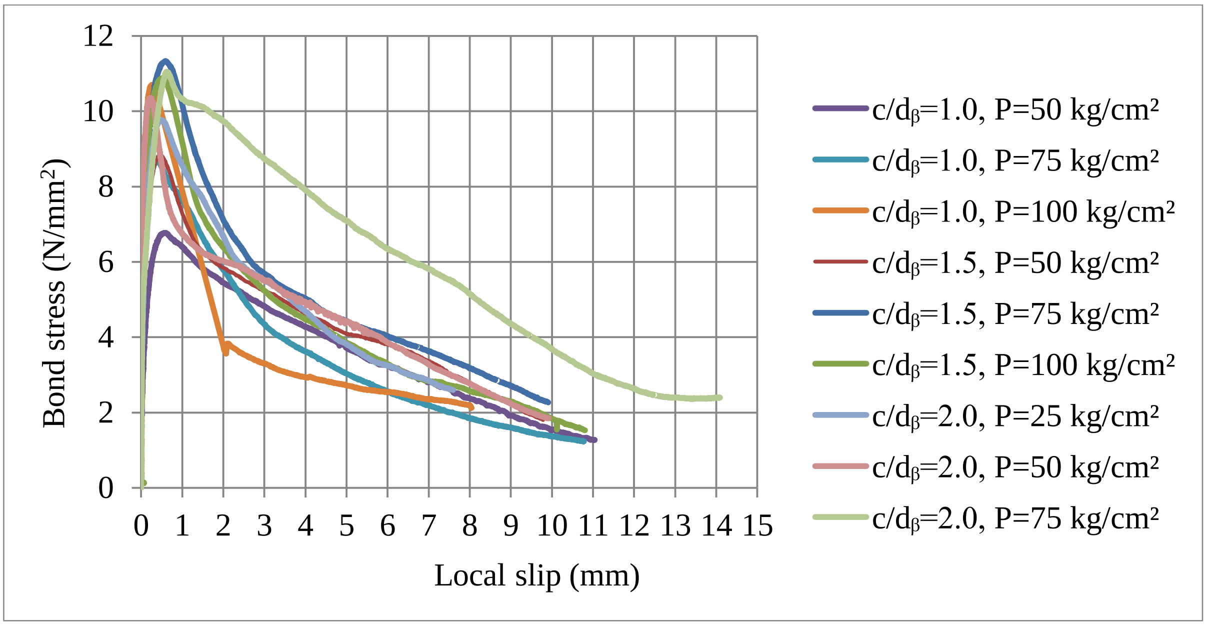



Figure 11. Observed local bond stress-slip response for Mixed bond failure

Table 2. Modes of failure of the specimens

| $c/d_b$ | Applied Pressure (kg/cm2) | Failure mode |
|---|---|---|
| **1.0** | 0 | Splitting |
| | 50 | Mixed |
| | 75 | Mixed |
| | 100 | Mixed |
| **1.5** | 0 | Splitting |
| | 50 | Mixed |
| | 75 | Mixed |
| | 100 | Mixed |
| **2.0** | 0 | Splitting |
| | 25 | Mixed |
| | 50 | Mixed |
| | 75 | Mixed |
| **2.5** | 0 | Splitting |
| | 25 | Pullout |
| | 50 | Pullout |
| | 75 | Pullout |
| **3.5** | 0 | Splitting |
| | 12.5 | Pullout |
| | 25 | Pullout |
| | 50 | Pullout |

#### *4.1.1. Splitting bond failure*

For the unconfined control specimens (for $c/d_b$ between 0 and 3.5 and in absence of transverse pressure), a splitting crack was developed and propagated in the plane of the longitudinal axis of the steel bar as shown in Figure 12. Additional increase in the slip of the bar beyond splitting resulted in widening of the crack, with a quick loss of load resistance of the specimens. Figure 13 shows the splitting failure of the unconfined control specimen where the concrete between the lugs was fully intact. Figure 9 shows the typical plots of unconfined control test specimens which encountered splitting failure. It can be seen that when splitting failure occurs, the bond stress-slip relation generally demonstrates three stages of response. Before the onset of splitting, the response is similar to that of the pullout failure. When splitting crack develops, specimens failed by splitting of the concrete at a small bond stress ($q$ < 5.0 MPa). A sudden drop in bond resistance was encountered immediately at post-splitting. The comparison of the responses of the unconfined specimens in Figure 9 shows that the concrete cover to bar diameter ratio have a marked effect on the bond resistance. The use of a relatively moderate amount of concrete cover ($c/d_b$ =2.0, 2.5, and 3.5) increased the peak bond strength by more than 200% than the peak bond when compared with smaller $c/d_b$ of 1.0 and 1.5.

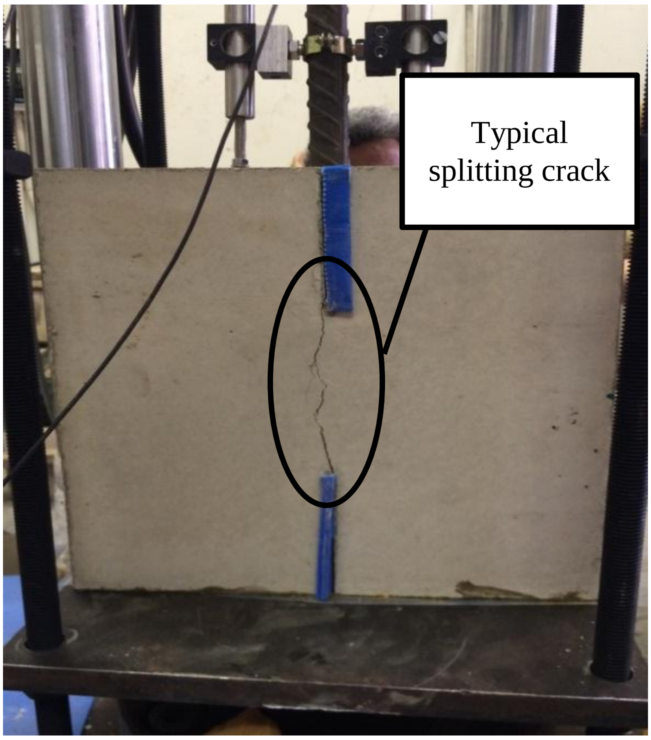



Figure 12. Typical splitting crack for unconfined specimens

Figure 13. Splitting failure of the unconfined control specimens

### *4.1.2. Pullout bond failure*

For fully confined specimens with applied transverse pressure (active confinement) on specimens with large concrete cover to bar diameter ratio ($c/d_b$= 2.5 and 3.5), the bar was pulled out from the concrete where the concrete between the bar ribs was sheared off as shown in Figure 14. Figure 10 shows the typical plots of fully confined test specimens which encountered pullout failure. It can be observed that, the confined specimens were able to sustain larger loads and therefore failed in a more ductile manner as compared to unconfined specimens shown in the bond stress-slip responses shown in Figure 9. Also, irrespective of $c/d_b$, increasing the amount of active confinement on specimens lead to noticeable increases in the peak bond strength, where it attained higher values as compared to confined specimens with moderate amount of active confinement. However, there was an upper bound to the effectiveness of increasing the transverse pressure where the maximum bond strength reached an asymptote for a pressure equal or larger than 50 $kg/cm^2$. A gradual drop in the bond resistance was recorded after failure.

Figure 14. Pullout failure of fully confined specimens

### *4.1.3. Mixed mode bond failure*

This failure mode represents a mixed mode between splitting of concrete and pullout of the bar, and it resulted from moderately confined specimens ($c/d_b \leq 2.0$ with applied pressure), as shown in Table 2. Figure 11 shows the observed bond stress-slip responses of moderately confined test specimens which encountered mixed mode failure. The results show a different response than the typical bond stress-slip responses of splitting and pullout failure modes. Three stages of responses were identified. The first one is an ascending relation from zero to the ultimate bond stress before failure, where the response was similar to pullout. The ultimate bond stress attained an intermediate value between unconfined (6 MPa $< q <$ 11 MPa) and fully confined specimens, as shown in the bond stress-slip graphs of Figure 9 ($q <$ 5 MPa) and Figure 10 (8 MPa$< q <$ 15 N/mm$^2$), respectively. A gradual drop in the load and then a progressive diminishing in the bond resistance were recorded after failure.

# CHAPTER 5

# ANALYTICAL MODELING

A simple analytical model describing the local bond stress-slip relationship for reinforcing steel bars embedded in concrete with variable covers and subjected to transverse pressure (active confinement) is developed. The general local bond stress-slip response can be described using the idealization shown in Figures 15 to 17. Figures 15, 16, and 17 show the bond stress versus slip for the failure modes of splitting, pullout, and mixed mode, respectively. This model is formulated using a multiple regression analysis for the available experimental results. Assumptions were taken and statistical tests were used to determine the best fit of the data and the accuracy of the model. The statistical software package – *R* – was used as a tool to develop the models. Note that the proposed models are consistent with previous work available in the literature performed by Ciampi et al. (1982), Eligahausen et al. (1983) and Harajli et al. (2004).

The proposed models consist of a monotonic envelope curve and are applicable for unconfined concrete where mostly splitting failure occurs (Figure 15) and fully confined concrete where pullout failure occurs (Figure 16), and moderately confined where mixed mode failure occurs (Figure 17).

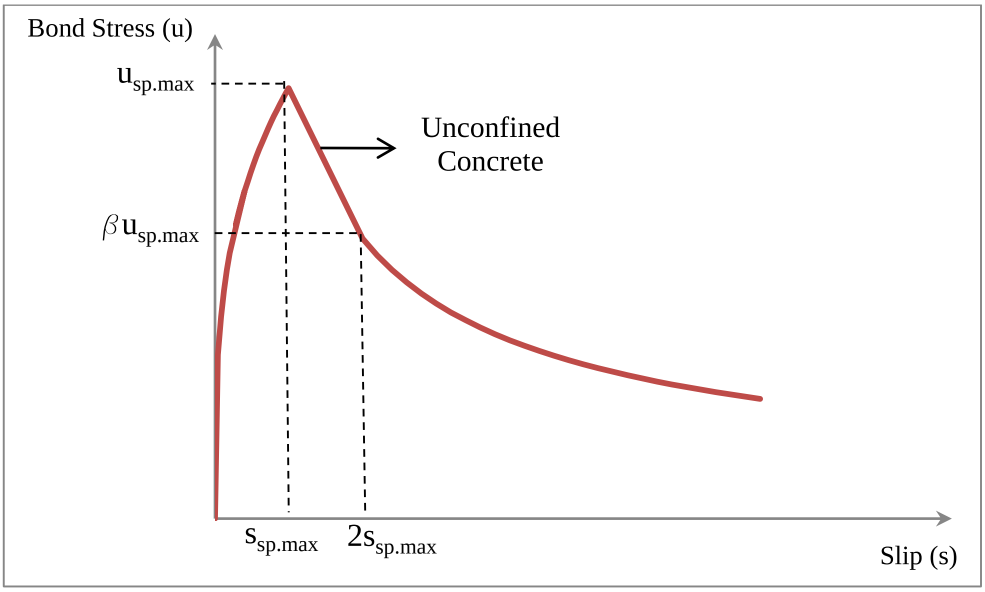



Figure 15. Proposed local bond stress-slip relationship for Splitting mode failure

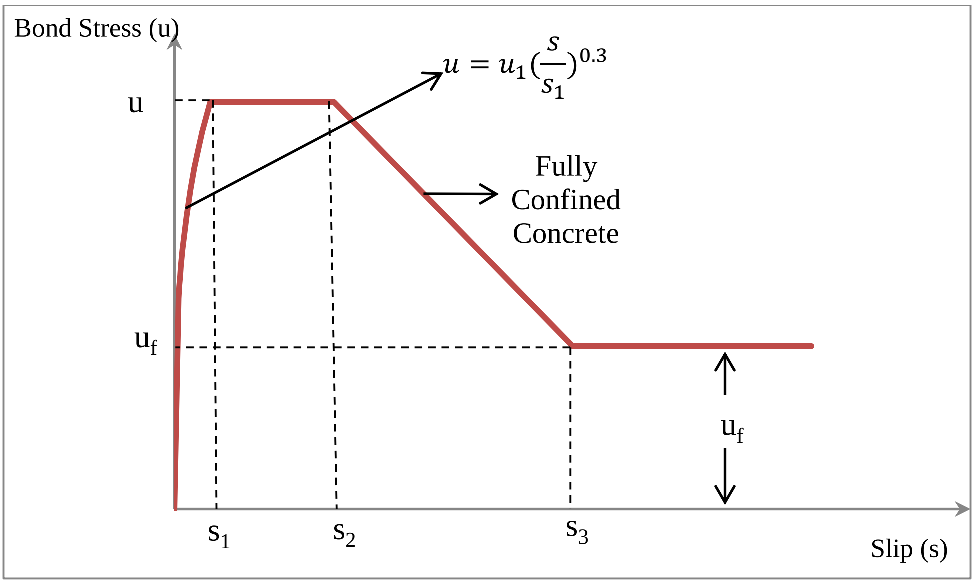



Figure 16. Proposed local bond stress-slip relationship for Pullout mode failure

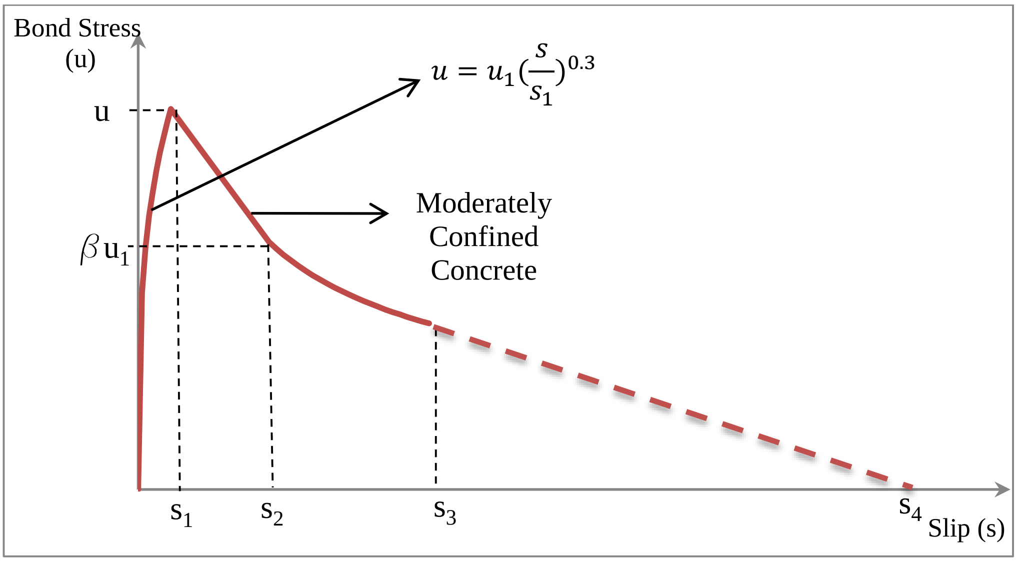



Figure 17. Proposed local bond stress-slip relationship for Mixed mode failure

### 5.1. Local bond stress-slip relationship for splitting failure (unconfined concrete)

Based on the results of the experimental work, the local bond stress–slip response of unconfined steel bars in tension (control specimens) can be described using three stages as shown in Figure 15.

The first stage (before splitting occurs) includes an ascending relation from zero to the local splitting bond stress $u_{sp.max}$, similar to the expression derived earlier (Harajli et al, 1995) and can be written as follows:

$$u = u_1(\frac{s}{s_1})^{0.3} \quad (7)$$

where $u_1$ is the peak bond stress resulted from confined concrete, and proportional to the square root of $f'_c$, and $s_1$ is the slip at the corresponding $u_1$.

After identifying the important parameters that impact the local splitting bond stress which is found to be $f'_c$ and $c/d_b$, $u_{sp.max}$ of unconfined concrete can be written as follows:

$$u_{sp.max} = 0.5\sqrt{f_c'}\sqrt{\frac{c}{d_b}} \tag{8}$$

It is noted that the slip, $s_{sp.max}$, corresponding to the peak bond, $u_{sp.max}$, is assumed to be equal to 0.25 mm based on the results obtained in the current investigation.

The second stage corresponds to a linear drop in bond resistance after splitting occurs. This bond stress is dropped from $u_{sp.max}$ to $\beta u_{sp.max}$, where $\beta = 0.65$ (Harajli et al., 1995, Eligahausen et al., 1983) having a corresponding slip equal to $2s_{sp.max}$.

The last stage represents a progressively diminishing bond resistance. The bond stress post-splitting at each slip can be computed using the following relationship calculated as follow:

$$u = \beta u_{sp.max}(\frac{s}{2\, s_{sp.max}})^{-0.65} \tag{9}$$

**5.2 Local bond stress-slip relationship for pullout failure (well confined concrete)**

Applying multiregression analysis on the experimental results, and referring to the proposed equations in the literature, the local bond stress slip relationship for pullout failure of steel bars embedded in fully confined concrete by transverse pressure can be described using the following stages:

An ascending relation from zero to $u_1$ following the expression derived earlier (Harajli et al, 1995) corresponding to pullout mode (Eq. 7).

For concrete exposed to transverse pressure, the peak bond stress $u_1$ can be calculated using the expression below:

$$u_1 = 0.5\sqrt{f_c'}\sqrt{\frac{c}{db}}\; e^{0.15\sqrt{Pressure}} \tag{10}$$

Referring to Figure 17, the characteristic parameters of the local bond stress–slip relationship for pullout failure were derived using multiregression analysis of the experimental data as follow:

$s_1$ =0.45 mm, $s_2$ =4.5 mm, and $s_3$ =11.0 mm, and $u_f$ =0.4$u_1$.

### 5.3. Local bond stress-slip relationship for Mixed mode failure (moderately confined concrete)

The local bond stress–slip response of moderately confined concrete can be described using three stages as shown in Figure 17:

The first stage includes an ascending relation following the bond law corresponding to pullout mode from zero to $u_1$, where $u_1$ can be calculated using Eq. 6. The slip $s_1$ at which the peak bond $u_1$ is mobilized is equal to 0.45mm based on the results obtained in the current investigation.

The second stage corresponds to a linear drop in bond resistance after failure from $u_1$ to $\beta u_1$, where $\beta = 0.65$, and at a corresponding slip equal to $s_2$=1.8 mm based on the results obtained in the current investigation, and from the regression analysis.

The last stage represents a progressively diminishing bond resistance. The relationship beyond failure at each slip can be computed using the following relationship calculated as follows:

$$u = \beta u_1 (\frac{s}{1.8})^{-0.5} \quad (11)$$

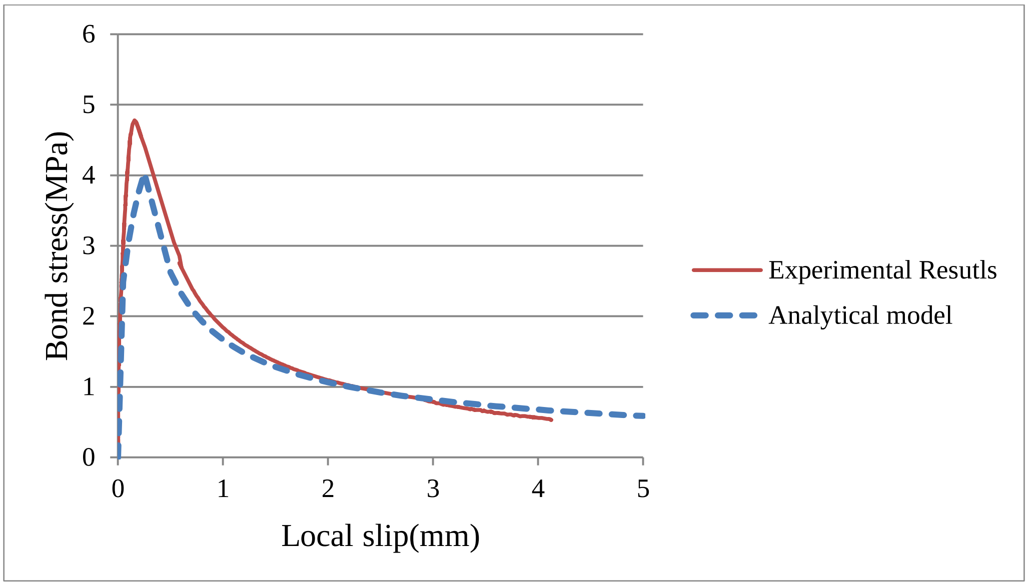
Referring to Figure 17, the characteristic parameters of the local bond stress–slip relationship for a mixed mode failure were derived using multiregression analysis of the experimental data as follows:

$s_1$ =0.45 mm, $s_2$ =1.8 mm, and $s_3$ =4.0 mm, $s_4$ =Zero.

### 5.4. Analytical model versus experimental results

The proposed models presented in the previous section for predicting the stress-slip response for the three failure modes (Splitting, Pullout, and Mixed failure) are valid against the experimental results conducted as a part of this research. It can be seen that the pre-failure ascending relation following the bond law corresponding to pullout mode shows a good agreement when compared with the experimental results obtained in the current investigation. Similarly, the peak bond stress predicted for both confined and unconfined specimens predicted the peak bond stress attained by the experimental results as shown in Figures 18(a)-(b), 19(a)-(b) and 20(a)-(b) for splitting, pullout and mixed mode failure, respectively. For the post-failure stage, the proposed models predict with acceptable agreement the experimental results. So the suggested analytical model is capable to predict and reproduce the bond stress and slip curve with good accuracy for fully confined, unconfined and moderately confined specimens. However, additional experimental test will be performed to validate the proposed model, improve the analytical predictions and to cover parameters other than those investigated in the current study.

(a)




(b)

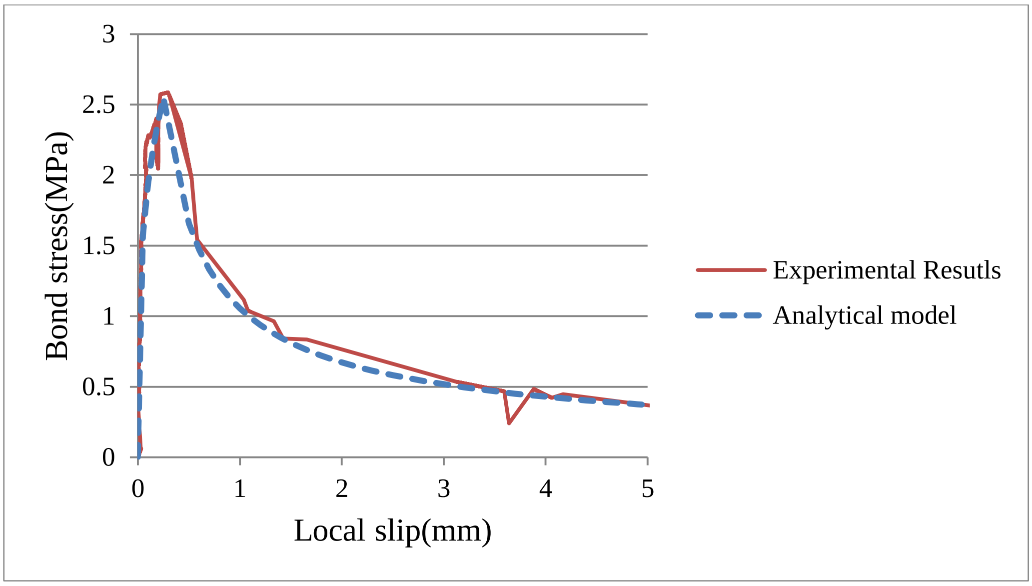
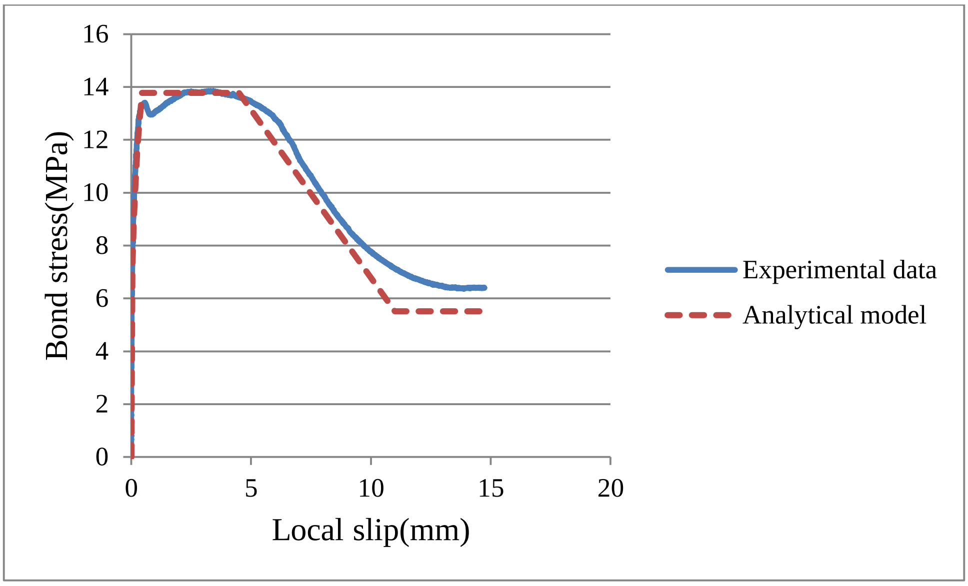



Figure 18. Comparison between experimental results and analytical model for unconfined specimen (a): with c/db=2.5, (b): with c/db=1.0

(a)




(b)

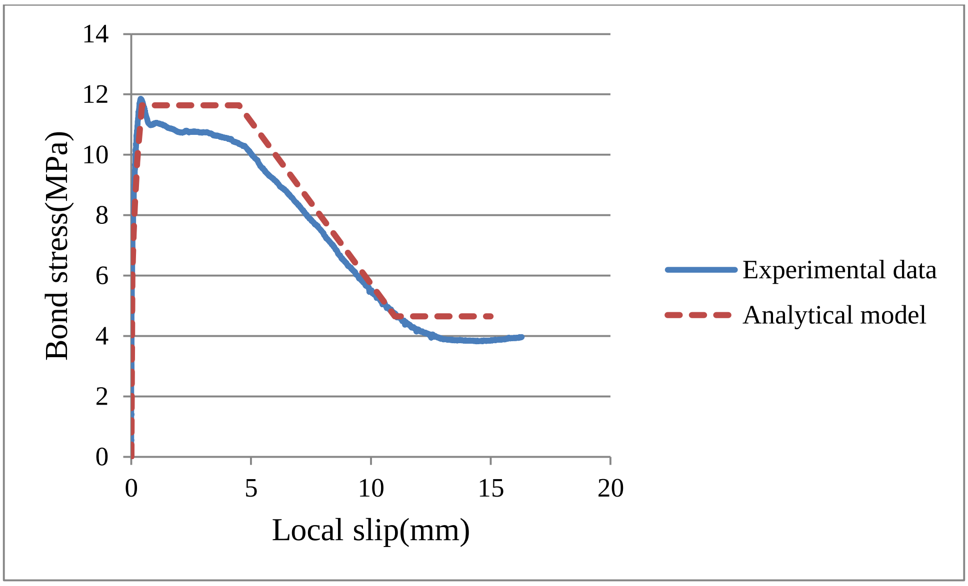
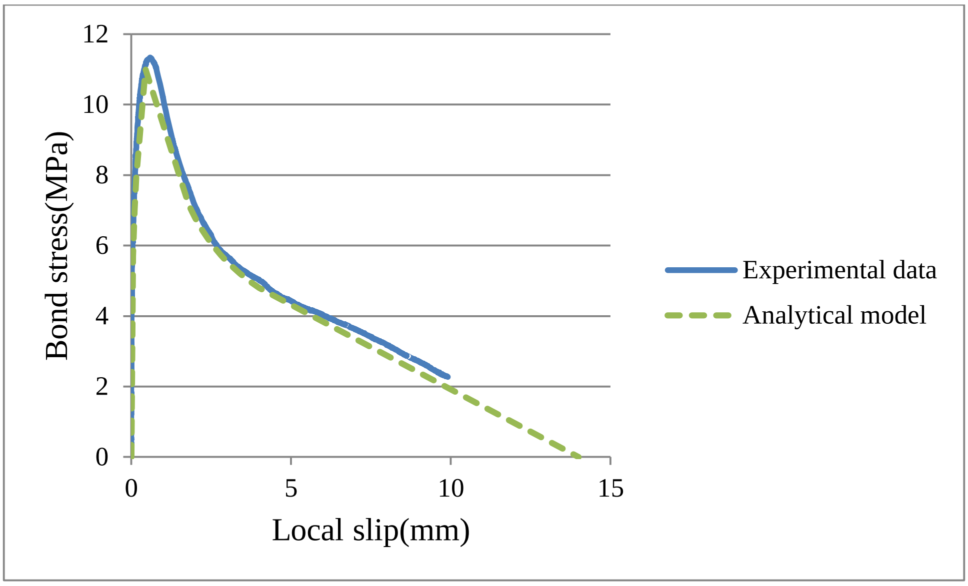



Figure 19. Comparison between experimental results and analytical model for fully confined specimen with (a): c/db=3.5, P=50 kg/cm$^2$, (b): c/db=2.5, P=75 kg/cm$^2$

(a)




(b)

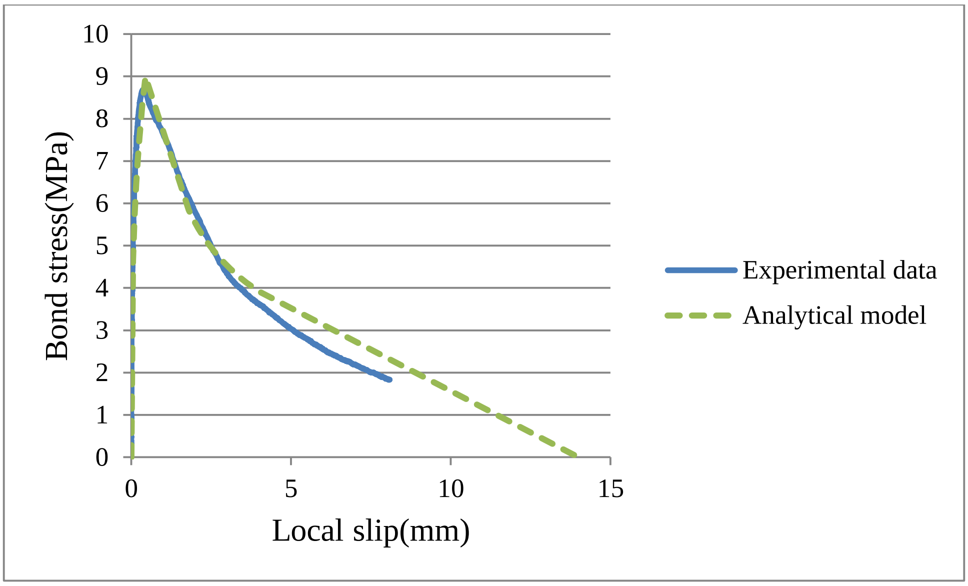



Figure 20. : Comparison between experimental results and analytical model for moderately confined specimen with (a): c/db=1.5, P=75 kg/cm$^2$, (b): c/db=1.0, P=75 kg/cm$^2$

# CHAPTER 6

# CONCLUSIONS

This paper presented a summary of a series of experimental and analytical studies to evaluate the bond performance of steel bars in tension under different conditions. The local bond stress–slip relationship derived in the experiment for confined concrete with transverse pressure and unconfined concrete were combined with numerical analysis to explain the mechanism by which the confinement influences the bond. Based on the results of this investigation, the following conclusions can be drawn:

1- Bond failure can be classified into three categories: Splitting failure, mixed mode failure, and pullout failure. When the concrete is unconfined, irrespective of the ratio of concrete cover to bar diameter, splitting failure will occur. However, when the concrete is fully confined by transverse pressure, pullout failure will occur. Furthermore, a relatively moderate amount of confinement will lead to a mixed mode failure between splitting and pullout.

2- A larger peak bond stress was recorded for specimens with high $c/d_b$ by comparing to specimens with low $c/d_b$ when other factors were kept constant and for both confined and unconfined concrete.

3- The bond behavior was improved by applying transverse pressure to the specimen. However, there was an upper bound to the effectiveness of increasing the transverse pressure where the maximum bond strength reached an asymptote at high pressure for different test series at different concrete cover.

4- The proposed analytical model is capable of predicting and reproducing the bond stress and slip curve with good accuracy for confined, unconfined and moderately confined specimens. However, additional experimental test will be performed to validate the proposed model, improve the analytical predictions and to cover parameters other than those investigated in the current study.

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