TENSILE FORCE AND BOND STRESS OF LONGITUDINAL REINFORCEMENET IN HEAVILY REINFORCED CONCRETE BEAM

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ABSTRACT

This dissertation presents an experimental study related to the tensile force and bond stress of longitudinal reinforcement in heavily reinforced concrete beam. The test variables in this study include the ratio of longitudinal and shear reinforcement. The beam specimens are simply supported with two point load with 130mm wide, 230mm deep and 1800mm long. The tensile force behavior and bond stress of longitudinal reinforcement is observed at support region. From experimental and analytical analysis, all beam specimens are not encounter failure in bond at support region. The beam with higher longitudinal and shear reinforcement ratio experienced lower bond stress compared to the lower longitudinal and shear reinforcement ratio. Besides that, the tensile force at the support is increased significantly after the occurrence of the diagonal cracks. As the reinforcement in the middle beam yield, the tensile force at the support stops increasing. Additionally, a computer program developed to determine the bond stress-slip curve at the support zone by applying Second Order Runge-Kutta method. Bond stress along longitudinal reinforcement beyond the outer part of the support also examined theoretically using local bond stress-slip model that modified from CEB-FIP Model Code 1990.

ABSTRAK

Disertasi ini mempersembahkan kajian eksperimental yang berkaitan dengan daya terikan dan tekanan ikatan pada tetulang utama bagi rasuk konkrit yang berat. Pembolehubah dalam kajian ini meliputi nisbah tetulang utama dan tetulang ricih. Spesimen rasuk adalah disokong mudah dengan dua beban titik dengan lebar 130 mm, 230 mm dalam dan1800 mm panjang. Kelakuan daya terikan dan tekanan ikatan pada tetulang utama dilihat di kawasan sokongan. Dari analisis eksperimental dan analitik, semua specimen rasuk tidak mengalami kegagalan dalam ikatan pada kawasan sokongan. Rasuk dengan nisbah tetulang utama dan tetulang ricih yang lebih tinggi mengalami tekanan ikatan lebih rendah berbanding dengan nisbah tetulang utama dan tetulang ricih yang lebih rendah. Selain itu, daya terikan pada penyokong meningkat secara signifikan setelah terjadinya retak menyerong. Sejurus tetulang di tengah rasuk gagal, daya terikan pada penyokong berhenti meningkat. Selain itu, program komputer dihasilkan untuk menentukan lengkung tekanan ikatan-slip di zon sokongan dengan menggunakan kaedah Kedua Runge-Kutta. Tekanan ikatan sepanjang tetulang utama di bahagian luar dari sokongan juga diperiksa secara teori menggunakan model tekanan ikatan-slip yang diubahsuai dari CEB-FIP Kod Model 1990.

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LIST OF ABBREVIATIONS

ASTM - American Society of Testing and Materials
ACI - American Concrete Institution
BS - British Standard
CEB-FIP - Comité Euro-international du Beton-Federation internationale

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CHAPTER I

INTRODUCTION

1.1 Background of Study

Concrete is a construction material composed of cement (commonly Portland cement) as a binder and aggregate as filler together with water and chemical admixtures. Reinforced concrete generally known as the concrete contains reinforcement bar and it is used throughout the world to build infrastructures and buildings, not only in the industrialized parts of the world, but also, increasingly, throughout the developing countries. Its advantages greatly outweigh any disadvantages. These include the fact that the tensile strength of concrete is low compared with its compressive strength; consequently its resistance to cracking is low. The history of the structural use of concrete is distinguished by the efforts made to remedy this weakness, in the first place by the addition of reinforcement made of steel or other materials (like glass fibers), and later by prestressing.

Beam is one of the important structural parts in any building. It is used to transfer load from roof and column to the foundation. There are many types of beam that widely used in construction such as concrete beam and steel beam. The feature that distinguishes each type of beams is the types of material used and its reinforcement. Each type of beam has its own advantages and disadvantages. For example, a concrete beam is good in compressive strength but low in tensile strength. To overcome this problem, steel reinforcement added in concrete beam which steel is good in tensile strength but low in compressive strength.

Nowadays, the concrete beams with steel reinforcement still have the market in construction industry although there are many alternative materials used as the reinforcement such as Glass Fiber Reinforced Polymer (GFRP). It is because the good ability and its criteria are well known among industrial people. The study of concrete beams heavily reinforced need to carry out to improve the ability and effectiveness of building structure.

Concrete beams have its own properties such as compressive strength and tensile strength. This study is just concentrates on tensile force. The tests were carried out to the four concrete beam samples which have different in ratio of shear link and longitudinal reinforcement. Finally a comparison had been made to examine the effect of longitudinal reinforcement ratio on bond stress- slip behavior.

1.2 Objectives of Study

The objectives of this study are:-

i. to determine the tensile force behavior of longitudinal reinforcement of concrete beams with heavy reinforcement.
ii. to observe bond stresses behavior occurred between the bar and concrete along the longitudinal reinforcement at the support region due to the effect of longitudinal reinforcement and shear reinforcement ratio.

1.3 Problem Statement

The applications of concrete beams with heavy reinforcement are sometimes necessary in construction industry. The use of heavy reinforcement can avoids the occurrence of yielding and cracking in concrete beams, besides that, it may reduce the excessive of deflection. So the behavior of tensile force of longitudinal reinforcement of concrete beams with heavy reinforcement and the bond stress between bar and concrete along the longitudinal reinforcement at the support region are need to identify. Therefore, the experimental and analytical studies are needed to carry out.

1.4 Scope of Study

The study concentrates in laboratory testing and analytical study. For the laboratory testing, there are four concrete beams prepared and these samples were cast for 28 days. The beam specimens were simply supported with two point load with the dimension 130 mm wide, 230 mm deep and 1800 mm long. The diameter of longitudinal reinforcement used are 10 mm and have a yield strength, f_y = 540 MPa. While the shear reinforcement provided by 8 mm stirrups and the yield strength, f_{yv} = 700 MPa. Strain gauges mounted at three positions i.e. midpoint of the beam, midpoint of the shear span and at support.

The analytical study was carrying out to determine the bond stress-slip curve at the support zone with a computer program. This program developed using one of the numerical methods which is Second Order Runge-Kutta method.

1.5 Importance of Study

The importance of this study is to identify the tensile force behavior of longitudinal reinforcement in heavily reinforced concrete beams. This type of beam is a regular use in any construction nowadays. The outcome from this study is it can minimize or avoid the use of other expensive and lightweight material such as fiber reinforced polymer (FRP) to replace steel reinforcement. Due to this outcome, it may give a few advantages such as lower the cost of construction project.

1.6 Review of Report

The literature review of this study is included in Chapter 2. The material used and the method applied is briefly explain in this chapter to give better understanding. Chapter 3 is about the methodology, the procedure of testing been carried out and analytical method involved in this study. In this chapter, all the materials and equipment are listed and been recognized all its function to ensure the fluencies of this study. After all testing of beam samples finished, the result obtained recorded and discuss in chapter 4. The result present in graph view. All results then discussed. Chapter 5 is the conclusion and recommendation. From all experimental and analytical study accomplished, the conclusion been made whether the objective of this study is achieved or not. Then, the recommendation proposed to improve the study for the future.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Concrete is one of the most widely used construction materials in the world nowadays. Roughly, concrete is made by mixing small pieces of natural stone (called aggregate) together with a mortar of sand, water, *portland cement* and possibly other cementitious materials such as fly ash. One of the concrete's advantages is that it is readily moulded into virtually any required shape. Due to this criteria, concrete become the preferred construction material for a wide range of buildings, bridges and other civil engineering structures.

Generally, in civil engineering there are many important elements such as column, beam, floor and more. Each of these elements has their respective functions in a building or any structure. In this project, the beam elements were chosen because these elements are very important and can have a big impact on a building or structure.

All the matters involved in this project will be described in detail his theory in this chapter as following.

2.2 Structural Concrete

The term *structural concrete* indicates all types of concrete used in structural applications. It may be plain, reinforced, prestressed, or partially prestressed concrete. Structural concrete is one of the materials commonly used to design all types of buildings. It involves two components materials which are concrete and steel. These two materials work together to form structural members that can resist many types of loadings (Nadim Hassoun M., 2002).

In addition concrete is used in composite design. Composite design is used for any structural member, such as beams or columns, when the member contains a combination of concrete and steel shapes.

Generally, the design of different structures is achieved by performing two main steps which are:-

i. Determining the different forces acting on the structures using proper methods of structural analysis
ii. Proportioning all structural members economically, considering the safety, serviceability, stability, and functionality of the structure.

2.2.1 Structural Concrete Elements

Structural concrete can be used for almost all buildings, whether single story or multistory. The concrete building may contain some or all of the following main structural elements (Nadim Hassoun M., 2002).

i. *Slabs* are horizontal plate elements in building floors and roofs. They may carry gravity loads as well as lateral loads. The depth of slab is usually very small relative to its length or width.

ii. *Beams* are long horizontal or inclined members with limited width and depth. Their main function is to support loads from slabs.
iii. *Columns* are members that support loads from beams or slabs. They may be subjected to axial loads or axial loads and moments.
iv. *Frames* are structural members that consist of a combination of beams and columns or slabs, beams and columns. They may be statically determinate or statically indeterminate frames.
v. *Footings* are pads or strips that support columns and spread their loads directly to the soil.
vi. *Walls* are vertical plate elements resisting gravity as well as lateral loads as in the case of basement walls.

2.2.1.1 Beam

The structural element used in this project is beam. Generally beams carry vertical gravitational forces but can also be used to carry horizontal loads (i.e., loads due to an earthquake or wind). The loads carried by a beam are transferred to column, walls, or girders, which then transfer the force to adjacent structural compression members. Beams are characterized by their profile (the shape of their cross-section), their length, and their material. In contemporary construction, beams are typically made of steel, reinforced concrete, or wood.

Internally, beams experience compressive, tensile and shear stresses as a result of the loads applied to them. Typically, under gravity loads, the original length of the beam is slightly reduced to enclose a smaller radius arc at the top of the beam, resulting in compression, while the same original beam length at the bottom of the beam is slightly stretched to enclose a larger radius arc, and so is under tension. The same original length of the middle of the beam, generally halfway between the top and bottom, is the same as the radial arc of bending, and so it is under neither compression nor tension, and defines the neutral axis. Above the supports, the beam is exposed to shear stress. There are some reinforced concrete beams in which the concrete is entirely in compression with tensile forces taken by steel tendons. These beams are known as prestressed concrete beams, and are fabricated to produce a compression more than the expected tension under loading conditions. High strength steel tendons are stretched while the beam is cast over them. Then, when the concrete has cured, the tendons are slowly released and the beam is immediately under eccentric axial loads. This eccentric loading creates an internal moment, and, in turn, increases the moment carrying capacity of the beam. They are commonly used on highway bridges.

2.3 Ready-Mixed Concrete

Ready-mixed concrete is a processed material which in a plastic and unhardened state, is sold as a finished product ready for use. Its quality depends on the ingredients, their proportions, and the thoroughness with which they are combined. Ready-mixed concrete will not remain in the plastic and unhardened state beyond a limited time, the exact period of which depends upon circumstances. Responsibility for the final quality of concrete produced as ready-mixed concrete is divided. The producer delivers it to the user who places it in the work and gives it whatever subsequent treatment it receives. Therefore, all tests which measure the acceptability of fresh concrete at the point where the responsibility for its handling passes from the producer to the user are of special significance. Furthermore, all tests, of any kind, of concrete as a material become of a particular importance because of the nature of the contractual relations involved (ASTM, 1956).

Concrete’s natural color is gray and its favored uses are utilitarian. It is very ubiquity causes it to blend into the background. But ready-mix concrete does have one remarkable characteristic: other than manufactured ice, perhaps no other manufacturing industry faces greater transport barriers. The transportation involved is the truck as shown in Figure 2.1. The transportation problem arises because ready-mix concrete both has a low value-to-weight ratio and is highly perishable. It absolutely must be discharged from the truck before it hardens (Figure 2.2). These transportation barriers mean ready-mixed concrete must be produced near its customers. For the same reason, foreign trade in ready-mixed concrete is essentially nonexistent (Syverson C., 2008).

Figure 2.1: Ready-mixed concrete truck (www.supergeotek.com)

Figure 2.2: Ready-mixed concrete from truck (www.concretenetwork.com)

2.3.1 Slump Test

The first test commonly made on a sample of freshly mixed concrete is one for slump. Slump is generally a basis for acceptance. In spite of its apparent lack of refinement, it is good tool and an excellent measure of water content. The slump test as shown in Figure 2.3 is used not only as an acceptance test but also as a measure of the thoroughness and uniformity of mixing and agitating; it is required that samples taken at approximately the one-quarter and three-quarter points of the load shall differ in slump by not more than 2 in. The permissiveness of using non-agitating equipment for transportation is determined in a similar fashion.

The method for slump test provides an excellent measure of water content, but in order for it to function and be reproducible; the procedures must be followed carefully (ASTM, 1956).

Figure 2.3: Slump test

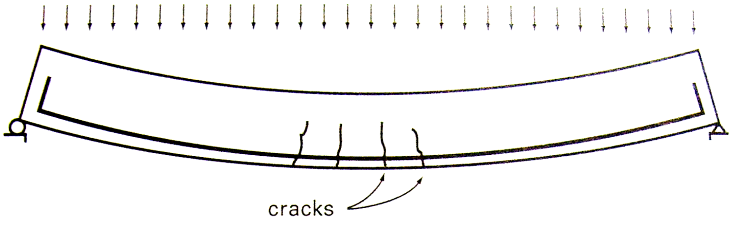
2.4 Curing Concrete

Curing is any procedure that maintains proper moisture and temperature to ensure continuous hydration. It was indicated hydration (reaction between compounds of cement and water) sets off when cement grains come into contact with water and proceeds until all the grains are hydrated, which takes a very long time. The rate of hydration is rapid in the beginning but continues rather slowly for an indefinite period of time. (Shan Somayaji, 2001)

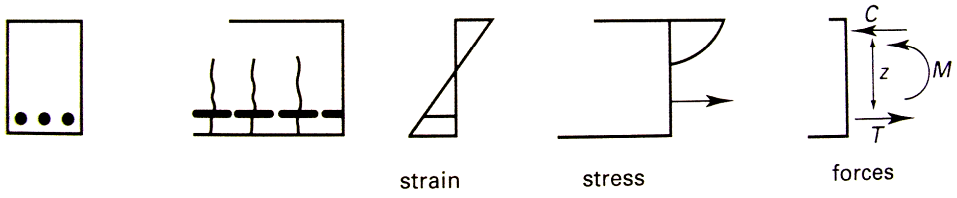
2.5 Reinforced Concrete

Although concrete is widely used in construction industry, it has most serious deficiency which is lack of tensile strength. This problem can be solved by incorporating steel reinforcement, usually in the form of thin bars, in the regions where tensile forces have to be carried. The concrete and steel reinforcement bond well together and a composite structural material is achieved which can be used to construct a wide variety of elements and structures (Warner RF, et al., 1998).

In reinforced concrete, the structural properties of the component materials are put to efficient use. It means that the concrete carries compression and the steel reinforcement carries tension. Figure 2.4 shows the structural action of simple reinforced concrete beam. The load induces tension in the lower part of the beam, and the concrete cracks. However, the steel in the cracked region carries the tensile force, so that in the section shown in Figure 2.4 (b) the steel tensile force T and the concrete compressive force C form a couple to resist the moment M.



(a) flexural behaviour
(deflections exaggerated)



(b) conditions at a cracked section

Figure 2.4: Reinforced concrete beam in bending (Warner RF, et al., 1998)

2.6 Steel Reinforcement

Reinforcement is usually in the form of steel bars. It is placed in the concrete member, mainly in tension zone, to resist tensile forces resulting from external load on the member. Reinforcement is also used to increase the member's compression resistance. Steel costs more than concrete, but it has yield strength about 10 times the compressive strength of concrete.

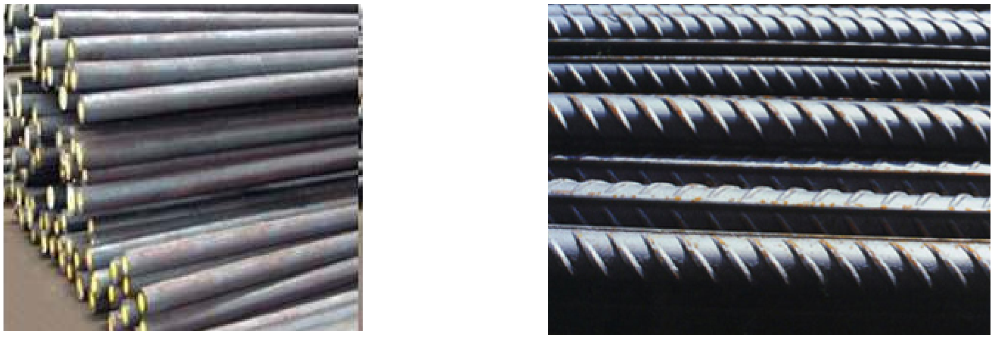
Longitudinal bars taking either tensile or compression force in a concrete member are called *main reinforcement*. Additional reinforcement in slabs, in a direction of perpendicular to the main reinforcement, is called *secondary* or *distributed reinforcement*. In reinforced concrete beams, another type of steel reinforcement is used, transverse to the direction of the main steel and bent in a box or U shape. These are called *stirrups*. Similar reinforcements are used in columns, where they are called *ties* (Nadim Hassoun M., 2002).

2.6.1 Types of Steel Reinforcement

Nadim Hassoun M., (2002) stated there are different types of steel reinforcement are used in various reinforced concrete members. These types can be classified as follows:-

2.6.1.1 Round Bars

Round bars are used mostly for reinforced concrete. It is available in a large range of diameters, from 6 mm to 36 mm, plus two special types, 45 mm and 57 mm. Round bars can be divided into two types which it is depending on their surfaces. There are either plain (Figure 2.5 (a)) or deformed bars (Figure 2.5 (b)). Plain bars are used mainly for secondary reinforcement or in stirrups and ties. Deformed bars have projections or deformations on the surface. It is to improve the bond with concrete and reducing the width of cracks opening in the tension zone.



(a) Plain bars (www.stainlesssteelpipeflange.net)

(b) Deformed bars (www.traderscity.com)

Figure 2.5: Round bars

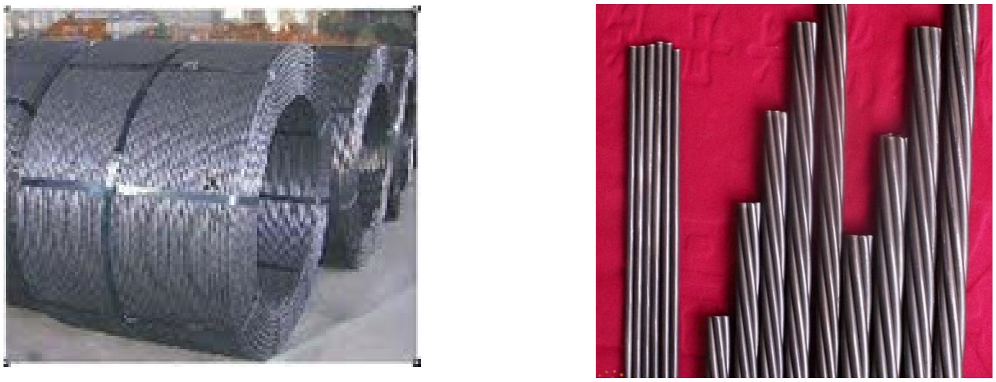
2.6.1.2 Welded Fabrics and Mats

Welded fabrics and mats consist of a series of longitudinal and transverse cold-drawn steel wires, generally at right angles and welded together at all points of intersections (Figure 2.6). Steel reinforcement may be built up into three-dimensional cages before being placed in the forms.

Figure 2.6: Welded fabrics and mats (www.flynnenslow.com)

2.6.1.3 Prestressed Concrete Wires and Strands

This type of steel reinforcements are use special high-strength steel (Figure 2.7). High-tensile steel wires of diameters 5 mm and 7 mm are used to form the prestressing cables by winding six steel wires around a seventh wire of slightly larger diameter. The ultimate strength of prestressed strands is 1,723.75 N/mm^2 or 1,861.65 N/mm^2.



(a) Prestressed wires (www.tootoo.com) **(b) Strands (www.sz-wholesaler.com)**

Figure 2.7: Prestressed concrete wires and strands

2.7 Heavy Reinforcement

Heavy reinforcement is also known as over-reinforcement. Over-reinforced concrete means that the tension capacity of the tension steel is greater than the combined compression capacity of the concrete and the compression steel (over-reinforced at the tensile face). An over-reinforced element will fail suddenly, when the concrete fails brittle and crashes before yielding of tension steel.

Mostly for the design of concrete structures, there are limits for maximal reinforcement ratio in a tensile zone, in order to avoid the brittle failure of concrete. It is known that the compressive failure of reinforced concrete member is a brittle failure, even if the concrete of normal strength (more ductile than the high strength concrete) is used. In the compression failure of reinforced concrete beams, concrete crushes before steel yields. This type of beam is said to be over-reinforced. Concrete of over reinforced beam reaches ultimate stress, but steel does not reach the yield strain (Ivana Kesegić et. al., 2009). The over-reinforced concrete beam has reinforcement ratio of 3% (Belgin C. M. and Sener S., 2007).

In context of cost, an over-reinforced section is always uneconomical because of the increase in the moment resistance is not proportion to the increase in the area of tensile reinforcement. Furthermore, the concrete having reached maximum allowable stress cannot take more additional load without adding compression steel (Punmia B.C., Ashok Kumar Jain, et al, 1992).

2.8 Development Length of Reinforcing Bars

The joint behavior of steel and concrete in a reinforced concrete member is based on the fact that a bond is maintained between the two materials after the concrete is hardened. If a straight bar of round section is embedded in concrete, a certain force is required to pull the bar out of the concrete. If the embedded length of bar is long enough, the steel bar may yield and it will leave some length of the bar in the concrete. The bonding force depends on the friction between steel and concrete. It is influenced mainly by the roughness of the steel surface area, shrinkage, the concrete mix, and the concrete cover. Deformed bars give a better bond than plain bars. Rich mixes have greater adhesion than weak mixes. Ultimate bond stress of a steel bar can be improved by the increasing in the concrete cover (Nadim Hassoun M., 2002).

Generally, the bond strength is influenced by the following factors:-

i. Yield strength of reinforcing bars, f_y. Longer development length is needed with higher f_y.

ii. Quality of concrete and its compressive strength, f'_c. The increasing of f'_c reduces the required development length of reinforcing bars.

iii. Bar size, location and spacing in concrete section. Horizontal bars placed with more than 304.8 mm of concrete below them have lower bond strength due to the fact that concrete shrinks and settles during the hardening process. Wide spacing of bars also can improve the bond strength. It gives an adequate effective concrete area around each bar.

iv. Concrete cover to reinforcing bars. A small cover may cause the cracking and spalling of the concrete cover.

v. Confinement of bars by lateral ties. Adequate confinement by ties or stirrups prevents the spalling of concrete around bars.

2.9 Tensile Force Behavior at Support

Generally, tensile force is the passive force developed from a body or system, resulting in separation in the longitudinal direction of the applied force. When the diagonal shear crack occurs in the shear span of a simply supported reinforced concrete beam, a certain amount of tensile force developed at the support. Due to this phenomenon, longitudinal reinforcement must be embedded by a certain distance known as additional anchorage length. This length is passed through the support to avoid failure of bond-splitting (Thamrin R. and Kaku T., 2007).

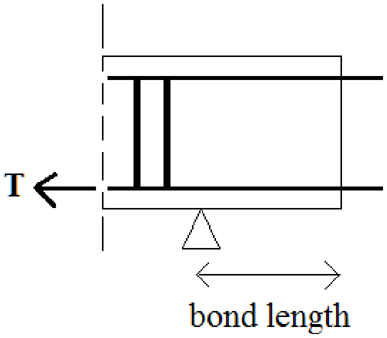


Figure 2.8: Tensile force at support

2.10 Analytical Study on Bond

Bond stress develops when the tension force, T occur between reinforcement bar with the surrounding concrete as shown in Figure 2.9 below. The bond stress between the reinforcing bar and its surrounding concrete is depends on both the length and the surface type of the reinforcement (Kankam C. K. et al., 1997).

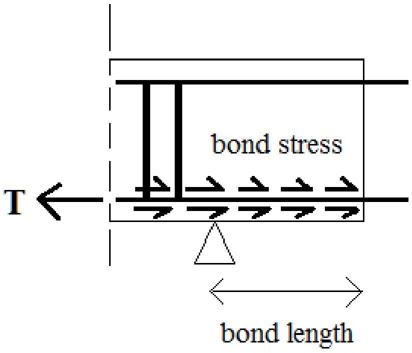


Figure 2.9: Bond stress at support zone

When the tensile stresses become large enough to overcome the low tension capacity of concrete, splitting of the concrete along the axis of the bar will occur, unless there is adequate confinement provided to resist the tensile forces. Confinement is provided by both transverse reinforcement and/or additional concrete surrounding the reinforcement which reduces the tensile stresses below the tensile modulus of rupture. Transverse reinforcement is typically provided in the form of shear and torsion stirrups in beams, which surround the longitudinal bars being developed. The transverse reinforcement enables more ribs on the bar in tension to carry the load, creating a more uniform bond stress distribution over the bar and a higher bond strength overall (Darwin D., 2005).

2.11 Bond Stress

In reinforced concrete, a good bond between the reinforcement and the concrete is required for an optimal interaction of these two materials. Without this property, reinforced concrete is not thinkable in its present-day applications. A reinforcement bar bonds to the surrounding concrete by means of the bond stress (τ_d). This is so much the more important as the roughness of the bar increases. It is known that the bond stress depends on the quality of the concrete, the way the concrete was poured (parallel or perpendicular to the axis of the reinforcement), and the position of the bar in the concrete (upper- or under-reinforcement) and the cover and the diameter of the bar (Vandewalle L. and Mortelmans F., 1988).

Furthermore, the selection of a proper type of specimen for bond strength evaluation is of great importance as it significantly influences the bond characteristics. The selection of a proper specimen is still a matter of controversy and until now no test specimen has been devised which fully represents the actual bond behavior. In reinforced concrete beams or slabs, the concrete surrounding the tensile reinforcement is in tension, whereas the concrete in this test is in compression, which not only eliminates tension cracks in the specimen but also increases the bond strength. Moreover, during the test, a small load causes a slip and the peak bond stress moves in front of the slip (Abdullah A. Almusallam et. al., 1995).

2.12 Local Bond Stress - Slip Model

Bond plays a significant role in reinforced concrete elements response and its mechanical behavior system. The phenomenon has the duty to transfer the stresses form the reinforcement bars to surrounding concrete.

“Perfect bond” can be used for first stages of analysis when perfect compatibility for concrete and reinforcement nodes` displacement can be assumed. After this stage, as the load is increasing, inevitably bond-slip takes place due to the occurrence of cracks. This affects the stress transfer between reinforcement and concrete. Due to this reason, different displacements are observed in the steel and, on the other hand, in the concrete. At the cracks, local strain of the bar is many times higher than the average strain (strain localization).

Bond-slip occurs for two principal causes which are slip due to damage in concrete adjacent to bars exhibited by cracking and crushing, and slip on the interface between steel bar and surrounding concrete. The mechanism manifests in two different ways: tension stiffening, and an increase of flexibility at member ends, due to bar pull-out at the interface node connection. These effects are extremely noticeable under hysteretic loads when bond is lost and high strains and damages occur. The connection between reinforcement bar and concrete is considered perpendicular. When a bar is pulled out, besides the tangential stresses parallel with the bar direction, radial stresses normal to the bar direction are generated. The interaction between these two kinds of stresses appear either directly, due to the shear stresses from the concrete element in areas close to reinforcement or indirectly, due to higher bond stresses caused by larger ribs (CEB-FIP 1990).

Figure 2.10 below shows the CEB-FIP Model 1990 which is the graph between bond stress versus slip. τ_1 is corresponding to s_1 and τ_3 is corresponding to s_3.

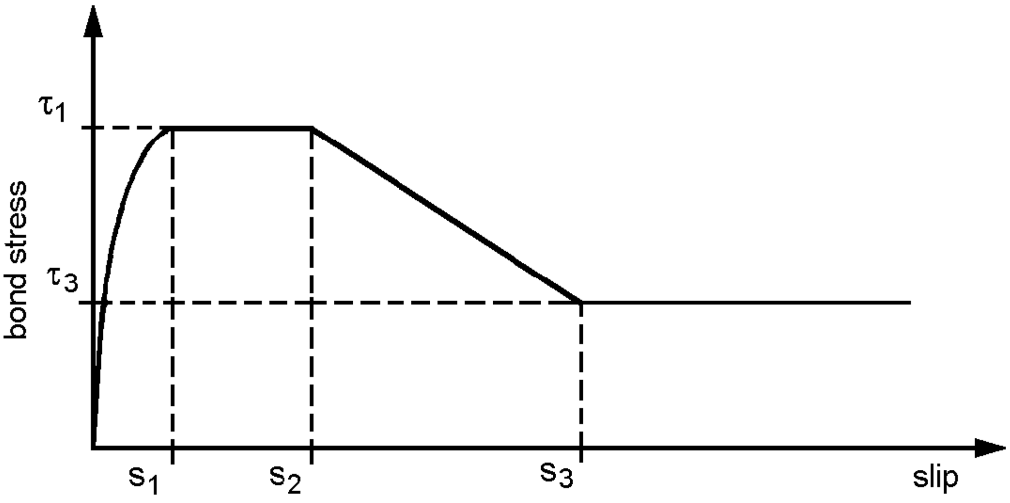


Fig 2.10: CEB–FIP Model Code 1990 (Ciampi et al., 1981; Eligehausen et al., 1983)

This value of s_1, s_2, and s_3 are taken from the table in CEB-FIP Model Code 1990 as shown below.

$$s_1 = 0.6 \text{ mm}$$
$$s_2 = 0.6 \text{ mm}$$
$$s_3 = 1.0 \text{ mm}$$

The value of α, τ_{max} and τ_f are also taken from the CEB-FIP 1990 as shown below.

$$\alpha = 0.4$$

$$\tau_{\max} = 2.0\sqrt{f_{cu}} \quad \text{.......................................} \quad \text{Eq. 1}$$

$$\tau_f = 0.15\tau_{\max} \quad \text{.......................................} \quad \text{Eq. 2}$$

According to CEB-FIP Model 1990, there are four zones for local bond stress-slip relationship. Bond stress in each zone can be calculated using the following equations:-

$$\tau = \tau_{\max} \left(S / S1 \right)^{\alpha} \qquad \text{for} \quad 0 \le S \le S1 \qquad \text{.............................} \quad \text{Eq. 2 (a)}$$

$$\tau = \tau_{\max} \qquad \text{for} \quad S1 \le S \le S2 \qquad \text{.............................} \quad \text{Eq. 2 (b)}$$

$$\tau = \tau_{\max} - \left(\tau_{\max} - \tau_f \right) \left(\frac{S - S2}{S3 - S2} \right) \qquad \text{for} \quad S2 < S \le S3 \qquad \text{.............................} \quad \text{Eq. 2 (c)}$$

$$\tau = \tau_f \qquad \text{for} \quad S3 < S \qquad \text{.............................} \quad \text{Eq. 2 (d)}$$

2.13 Bond Theory

Bond stress and slip occurred in infinite short length of the pull-out specimen can be presented in Figure 2.11 below. It is assumed that the problem is in one dimensional. The forces acting on specimen of length, L, can be seen in Figure 2.11(a) while Figure 2.11(b) shows the specimen with slip, S_x, and equilibrium conditions for a bar of length, dx.

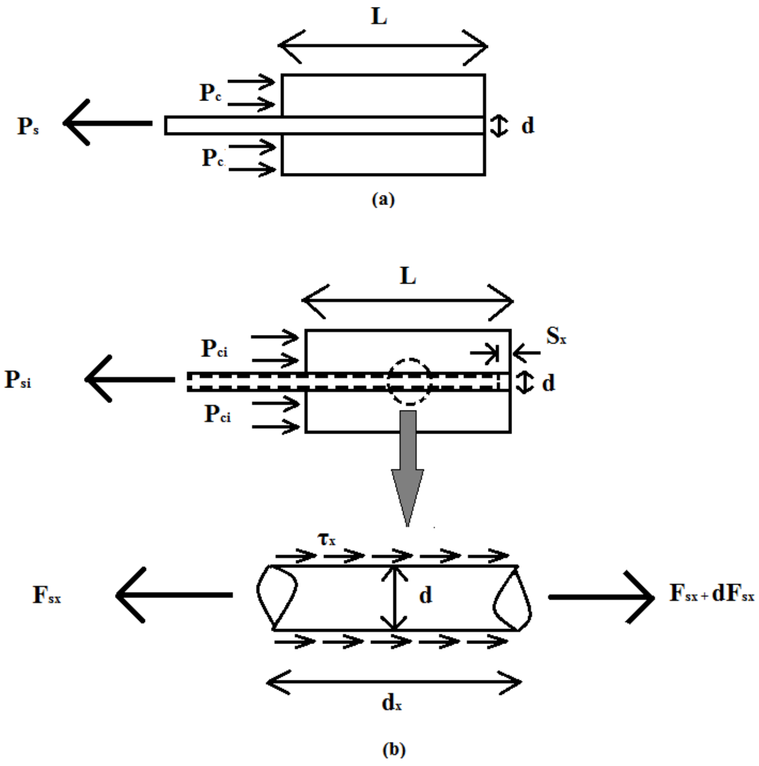


Figure 2.11: Bond stress and slip acted in an infinite short length of the pull-out specimen

The slip, S_x, at a distance x along the reinforcement bar is defined as the relative displacement between the bar and the concrete, that is:

$$S_x = u_{sx} - u_{cx} \qquad \text{.............................. Eq. 3 (a)}$$

or

$$S_x = \int_0^x \varepsilon_{sx} dx - \int_0^x \varepsilon_{cx} dx \qquad \text{.............................. Eq. 3 (b)}$$

where:- u_{sx} = displacement of the bar at point x

u_{cx} = displacement of the concrete at point x

ε_s = bar strains

ε_c = concrete strains

By differentiating Eq. 3, the increase of the local slip *ds* within an infinitesimal bar length *dx* at the location *x* can be determined.

$$\frac{dS_x}{dx} = \varepsilon_s - \varepsilon_c \qquad \text{.............................. Eq. 4}$$

The strains in the bar and concrete at each section along the prism can be written as:

$$\varepsilon_{sx} = \frac{F_{sx}}{E_s A_s} \quad , \quad \varepsilon_{cx} = \frac{F_{cx}}{E_c A_c} \qquad \text{.............................. Eq. 5}$$

we have; $$\frac{dS_x}{dx} = \frac{F_{sx}}{E_s A_s} - \frac{F_{cx}}{E_c A_c} \qquad \text{.............................. Eq. 6}$$

The total force at each cross section along the concrete prism is always constant as can be seen in Figure 2.12. It is determined by using the general equilibrium of forces.

Thus, we have;

$$F_{sx} + F_{cx} = F_{s0} + F_{c0} = \text{Constant}$$
.... Eq. 7

Therefore;

$$\frac{dF_{sx}}{dx} + \frac{dF_{cx}}{dx} = 0$$
.... Eq. 8

$$\frac{dF_{sx}}{dx} = -\frac{dF_{cx}}{dx}$$
.... Eq. 9

From the equilibrium of forces acted on an infinitesimal element of the bar of length *dx* (as shown in Figure 2.11 (b)).

$$F_{sx} + dF_{sx} = F_s + \phi\tau_x dx$$
.... Eq. 10

we have;

$$\frac{dF_{sx}}{dx} = \phi\tau_x$$
.... Eq. 11

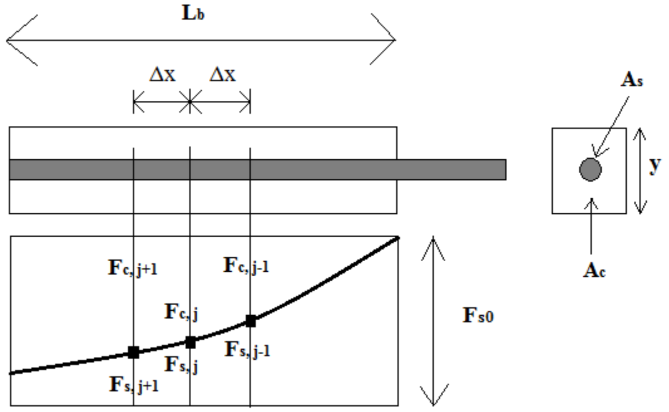


Figure 2.12: Force distribution in a concrete prism

The general second order differential equation for bond slip is found as follows by substituting Eq. 11 into Eq. 6 and differentiating with respect to *x*:-

$$\frac{d^2 S_x}{dx^2} = \left[\frac{(1+n\rho)}{E_s A_s} \right] \phi \tau \qquad \text{....................................} \quad \text{Eq. 12}$$

where $n = \frac{E_s}{E_c}$ and $\rho = \frac{A_s}{A_c}$

2.14 Second Order Runge-Kutta Method

In order to solve second order differential equation of bond stress-slip relationship (Eq. 12), Second Order Runga-Kutta was applied in this study. Only first order ordinary differential equations can be solved by using the Runge-Kutta second order method. The Second Order Runge-Kutta method is a numerical technique used to solve an ordinary differential equation of the form:-

$$\frac{dy}{dx} = f(x, y), y(0) = y_0$$

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