

Prediction of Bond Between Steel and Concrete by Numerical Analysis

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Abstract: This paper presents the results of subtask dealing with the bond behavior study of the reinforcement systems under monotonic loading pull-out tests. This numerical method is based on the slip and the bond stress distributions through the anchored length of the bar in the concrete block. The work refers, especially to the implementation of reinforcing bars and bond-slip models between steel and concrete in the developed finite element program. For the application of the proposed method, three analytical expressions of bond-slip relationship are selected. The obtained results are presented and commented with the fundamental characteristics of plain concrete and reinforced concrete members. The bond models in contribution with concrete and reinforcing steel provide a relatively good representation of bond-zone system responses.

Keywords: Bond-slip relationship, Pull-out test, Calibration, Embedment length, RC members, Bond stress distribution, Perfect model, Cohesive model.

INTRODUCTION

A reinforced concrete is a composite material made up of two components with different mechanical behavior and physical features. In general, the load is already applied to concrete and the reinforcing bars receive its part from the surrounding concrete by bond. In composite structures, the bond between different components of reinforced concrete member has a primordial role and its negligence conducted to weedy structural response. In the past, this complex phenomenon has led engineers to take empirical formulas for the design of reinforced concrete structures. For these reasons, the incorporation of bond is considerably carried out in recent works.

To calibrate the bond behaviour, experimental studies widely known as pull-out or push-out tests were performed [1]. Numerous researchers have already investigated the anchorage behavior of reinforcing bar and a number of analytical bond-slip models have been developed. Ones of the most widely used bond stress-slip relationship is proposed by Ciampi *et al.* [2] and Eligehausen *et al.* (1983) [3]. More, many researchers have developed analytical and numerical models yielding to stress-slip response and bond stress distribution of reinforced concrete members [4-13]. The common object is to have a reliable analysis that takes into account the effective behavior of the composite reinforced-concrete structures.

Although significant improvements in the experimental domain as well as in the theoretical aspects of steel-concrete interface behavior have been achieved, which most of them assume a perfect bond. Particular attention is paid to stress variation in steel and to the force transfer between steel and surrounding concrete. In this context, the gradual deterioration of the interface will be considered between the extremes cases [13]: the perfect bond and the no bond cases in which reinforcing bars can slip.

To accomplish this task, the interface is considered as a separate material with a proper behavior and the constitutive modeling is derived using an energetic approach. For more realistic simulations, non-linear laws with several branches which mark different stages in the overall behavior during a progressive loading were taken up.

In this way, there are two distinct kinds of analytical models based on force equilibrium principle of pull-out problem (1) the full perfect model and (2) the cohesive (contact) interface model. The principal difference between these approaches is that in the first case a perfect interface is assumed; no slip between reinforcing bar and surrounding concrete is allowed and displacement field is assumed as continuous at the interface region. The displacement continuity requirement is abandoned when the interface is considered to be cohesive. In this study, these two models are considered.

To reach our goal, the finite element method, well known as a robust tool in structural mechanics modeling is used for reinforced concrete analysis. Primordial parameters have a great influence on the response of reinforced concrete tensioned members such as: the progressive cracking, the tension stiffening effect, the non-linear material properties and the bond effect at the concrete-steel interface which can be used to improve the members' response.

This article is a partly task of a group research work on non-linear behavior of reinforced concrete structures: modeling and analysis. The computational system has for base a finite element program which has already conceived for this object. This work refers to the implementation of different representations of reinforcing bars and to quantify the contribution of bond between concrete and steel.

REINFORCEMENT FINITE ELEMENT MODELS

In finite element modeling of reinforced concrete structures, there are three different alternative representations of reinforcement: smeared, embedded and discrete reinforcement models. The first one is rarely used and therefore it depends on the nature of used structure. The discrete and embedded representations are formulated and introduced in the developed program.

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Discrete Reinforcement Representation

The discrete modeling of steel reinforcement is the first approach used in finite element analysis of reinforced concrete structures [14]. The discrete representation of reinforcement uses one dimensional truss elements and it is the only way for accounting for bond slip and dowel action effects in Fig. (1).

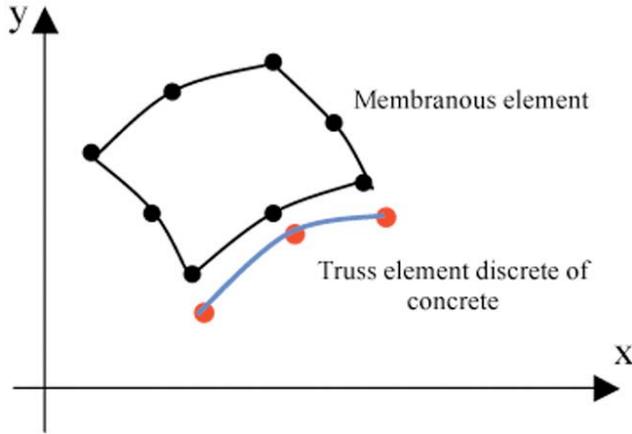


Fig. (1). Discrete representation of steel bars.

A significant advantage of discrete representation is that it can account for possible displacement of the reinforcement with respect to the surrounding concrete. The bond effects are usually related with this representation and the bond-link or cohesive models can be used to connect the steel and concrete nodes in order to considerate this effect. The main disadvantage is that the finite element mesh patterns are only restricted by the location of reinforcement and consequently the increase of the number of concrete elements and the degrees of freedom. In this way, Lagrange or Serindipity iso-parametric concrete elements are used and a line three node truss elements is used to represent the steel and the compatibility between concrete and steel must be guaranteed.

Embedded Reinforcement Representation

In this representation, the reinforcement bar is considered as an axial member incorporated in the concrete element such that its displacements are consistent with membranous concrete elements and bond lost can be considered in Fig. (2).

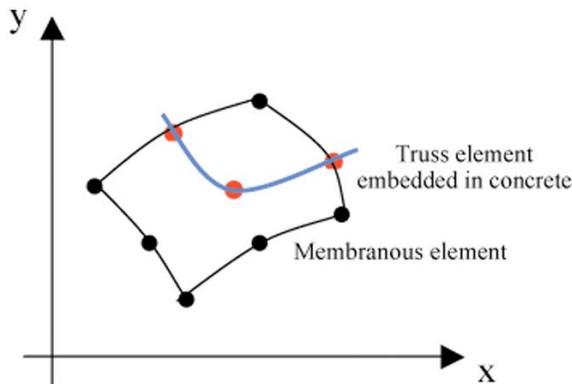


Fig. (2). Embedded representation steel bars.

In this scope, many works have been presented different formulations for this model [15-17]. Embedded models al-

low for an independent choose of concrete mesh. So the same number of nodes and degrees of freedom are used for both concrete and steel. The disadvantage of this procedure is that additional degrees of freedom increase the computational and numerical treatment.

BOND FINITE ELEMENT MODELS

In this strategy, two distinct procedures of the bond lost were studied: (1) the bond-link model also known as shear-lag model and (2) the cohesive model as presented bellow. These elements are associated with the discrete reinforcement model, which has the advantage of representing different material properties more precisely. Afterwards other bond conditions at different nodes can be easily represented.

To describe the bond behavior between concrete and steel, the vertical and horizontal relative displacement between concrete and steel in the local coordinates can be considered. The same type of iso-parametric elements having no physical dimension in the transverse direction is considered. It uses linear, quadratic or cubic interpolation functions corresponding to the nodes number of used finite element. In linear analysis, the vertical relative displacements are too small compared to the horizontal displacement, which means that concrete and steel common nodes have the same degrees of freedom in local vertical axis while they have different degrees of freedom in horizontal axis.

Perfect Bond Analysis

This element can be conceived as two orthogonal springs [14] that connects the concrete nodes to its same of steel nodes (Fig. 3). For each spring an appropriate stress-strain relation is defined. In linear analysis, it is assumed that the steel nodes are perfectly bonded to those of concrete and no slip is then assumed. This means that concrete and steel having the same nodes and consequently having the same degrees of freedom.

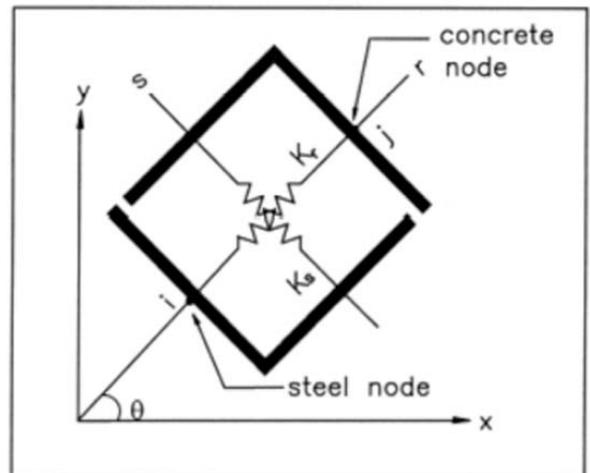


Fig. (3). Bond-link model.

The bond effect is assumed as an interaction between reinforcing bars and surrounding concrete. When the change of stresses in concrete and steel occurs, the effect of bond begins and becomes more pronounced at the end anchorages of reinforcing bars and in the vicinity of cracks. To evaluate the bond stress-slip relationships, many studies have been published taken the perfect bond in consideration.

Cohesive Bond Analysis

The concrete-steel interface behavior must be described from stress-strain laws. Many constitutive relationships are presented in the literature. In this element, the behavior of the interface continuum between concrete and steel is described by a proper law which considers the specific properties of the bond. The contact element provides a continuous connection between reinforcing bars and concrete [18-19], the authors showed the bond-link element cannot represent adequately the stiffness of bond.

Analysis Without Bond

In this case, the stiffness matrices of the steel elements are computed in local axis at the nodes of non bond. The concrete element stiffness matrices are calculated in the global axis and they are transformed steel local axes at common nodes. In y-direction, concrete and steel have the same degree of freedom but having different degree of freedom in x-direction at common nodes.

LOCAL BOND-SLIP RELATIONSHIP

In the following section, it is assumed that the bond characteristics of reinforcing bar are analytically described by a local relationship of bond $\tau=\tau(s)$, in which τ is the shear stress acting on the contact surface between bars and concrete and s is the corresponding slip; that is the relative displacement between steel bar and concrete. Once the relation $\tau=\tau(s)$ is known and using equilibrium equation and compatibility relations, the second differential equation governing the slip can be defined as:

$$\frac{d^2s}{dx^2} - \frac{\pi D}{E_s A_s} \tau(s) = 0 \tag{1}$$

which D is the diameter, A_s is the cross sectional area, E_s is the Young's modulus of the reinforcing bars and $s(x)$ is the slip between concrete and steel abscissa x .

Using the Eq. (1), important phenomena can be observed such as: the anchorage length evaluation, the determination of the tension stiffening effect and cracks spacing and opening. These problems can be solved once the boundary conditions of the specific problems are specified and this observation reinforces the importance of a consistent local bond-slip relationship.

Analytical Expression of Bond- Slip Relationship

Two alternative basic hypothesizes have been used in the past: in one bond stress is considered to be linear function [3], while in the other it is considered to be a non-linear relationship between bond stress and slip. Analytical expressions for the local $\tau=\tau(s)$ relationships have already been developed. In this work, two $\tau=\tau(s)$ relationships are selected as examples to simulate the bond-slip behavior between reinforcing bar and surrounding concrete.

a) The relationship established by Eligehausen [3] is expressed by the following non-linear function as:

$$\tau(s) = \tau_0 \left(\frac{s}{s_0}\right)^{0.4}, \quad 0 \leq s \leq s_1 \tag{2a}$$

$$\tau(s) = \tau_0, \quad s_1 \leq s \leq s_2 \tag{2b}$$

$$\tau(s) = \tau_0 - (\tau_0 - \tau_f) \frac{s - s_2}{s_3 - s_2}, \quad s_2 \leq s \leq s_3 \tag{2c}$$

$$\tau(s) = \tau_f, \quad s \geq s_3 \tag{2d}$$

With $s_1 = 1$ mm, $s_2 = 3$ mm, $s_3 = 10.5$ mm $\tau_f = 5.00$ MPa and $\tau_1 = 13.50$ MPa (Fig. 4).

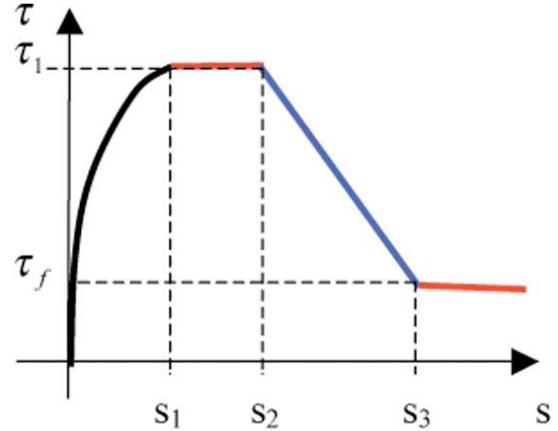


Fig. (4). Exponential bond-slip model.

b) The simple bi-linear bond stress-slip model is selected and the parameters of the model are derived from the experiment data corresponding to material features of each specimen (Fig. 5).

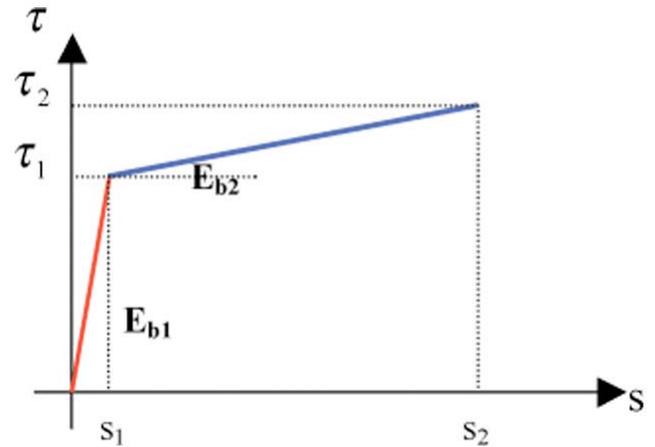


Fig. (5). Bi-linear bond stress-slip.

To represent the bond-slip effect, the ultimate bond stress is considered the same for the used relationships.

$$\tau_1(s) = E_{b1} s \quad s \leq s_1 \tag{3a}$$

$$\tau_2(s) = \tau_1 + E_{b2}(s - s_1) \quad s_1 \leq s \leq s_2 \tag{3b}$$

$s_1 = 2$ mm, $s_2 = 10.5$ mm, $\tau_1 = 10.55$ MPa and $\tau_f = 13.50$ MPa.

The local relationship; $\tau=\tau(s)$ must be introduced in Eq. (1) for the solution of the structural problem and it can be proved that when the slips are small, the analytical expressions are the same laws and having the same structural responses.

Interpretation of Pull Out Tests

In this section, an approach to calibrate a given local bond slip; $\tau=\tau(s)$ relationships of pull-out test results, is described. It consists of the numerical solution of Eq. (1). Useful relationship involving the pull-out tests between the loaded end and the zero-slip point can be determined by using an energy approach. The external forces work acting along the transfer length:

$$W_{ext}=\pi D \int_0^x \left(\int_0^{s(x)} \tau(s) ds \right) dx \tag{4}$$

The elastic energy in the bar along x of length is:

$$W_{int}=\frac{1}{2} \int_v \{ \sigma \} \{ \epsilon \} dv \tag{5}$$

From Eqs. (4-5) in the one-dimensional problems, it's possible to obtain:

$$\pi D \int_0^x \left(\int_0^{s(x)} \tau(s) ds \right) dx = \frac{A_s}{2E_s} \int_0^x \sigma^2(x) dx \tag{6}$$

and it leads to;

$$\int_0^x \left\{ \pi D \int_0^{s(x)} \tau(s) ds - \frac{A_s}{2E_s} \sigma^2(x) \right\} dx = 0 \tag{7}$$

The Eq. (7) must be satisfied for each value for x ($0 \leq x \leq l_{an}$: which l_{an} is the transfer length), the above relation can be expressed as:

$$\pi D \int_0^{s(x)} \tau(s) ds - \frac{A_s}{2E_s} \sigma^2(x) = 0 \tag{8}$$

For the particular value of $x = l_{an}$, which corresponds to the anchorage length,

$$\pi D \int_0^{s_{an}} \tau(s) ds - \frac{N^{*2}}{2E_s A_s} = 0 \tag{9}$$

The corresponding total load is generated along the transfer length by:

$$N^* = \pi D \sqrt{\frac{1}{2} D E_s \int_0^{s_{an}} \tau(s) ds} \tag{10}$$

which s_{an} is the slip at the loaded end.

When a local relation of bond is chosen, the Eq. (10) represents the applied load-slip relation.

Determination of Anchorage Length

Consider a bar of pull-out test and application of the proposed method. The local bond-slip relationship is described by the relations by the relations (2) and (3) with its parameters. Let $D = 12$ mm is the diameter, $A_s = \frac{\pi D^2}{4} = 113.04$ mm² is the cross area and $E_s = 2.10^5$ MPa is the longitudinal Young's modulus of the bar. The bar is embedded in concrete block (Fig. 6), the minimum anchorage length, l_{an} ,

needed to obtain no-slip at the free end when the nominal load $N^* = 10$ KN, is applied to the bar, is chosen.

For the same problem, it is necessary to compute the minimum anchorage length l_{an} and the corresponding load N^* . Therefore to resolve the problem, it must be providing two equations to be established.

The first step consists of determining the maximum pull-out load N^* , for each relationship of bond $\tau=\tau(s)$, the general solution $s(x)$ of the differential equation (Eq.1) can be expressed as:

$$s(x) = g(x) \tag{11}$$

where $g(x)$ is the function solution.

Using the boundary conditions for both ends of the reinforcing bar to determining the integration constants:

Table 1. Boundary Conditions

free end : $x = 0$	loaded end : $x = l_{an}$
$\epsilon_s(x=0) = 0$	$\epsilon_s(x=l_{an}) = \frac{N^*}{A_s E_s}$
$S(x=0) = 0$	$s(x=l_{an}) = s_{an}$
$\frac{ds(x=0)}{dx} = 0$	$\frac{ds(x=l_{an})}{dx} = \epsilon_s(l_{an})$

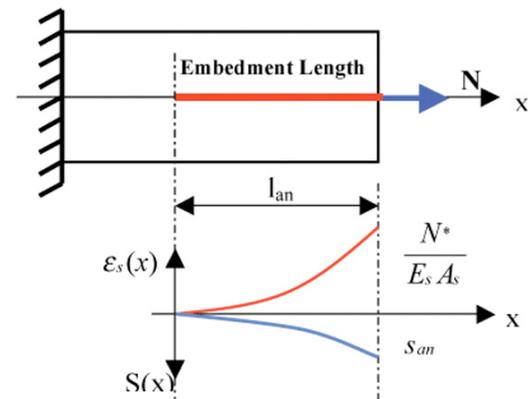


Fig. (6). The pull-out test: strain and slip repartitions.

The numerical solution $s(x)$ of Eq. (1) with boundary conditions (Table 2) corresponding to either local bond-slip relationship (2) or (3). The value of x to which N^* is needed anchorage length.

NUMERICAL EXAMPLES

In order to test the proposed approach, the response of anchored reinforcing bars under monotonic pull-out load is studied. The specimen is an anchored # 12 bar in a well confined block of concrete of 300*75.31*75.31 mm witch corresponds to anchorage length of 12.5 bar diameters.

In studied cases, the concrete was modeled by eight-node Serendipity plane stress elements with 2*2 Gauss integration points and the reinforcement bar was modeled by three-node truss elements.

The material proprieties of materials are shown in Table 1. and one of bond are described in section 4 indifferently for the selected relationships.

Table 2. Material Characteristics

Material properties	Values
Concrete compressive strength	35 MPa
Concrete tensile strength	3.5 MPa
Concrete E_c modulus	20909 MPa
Poisson's coefficient	0.30
Steel E_s modulus	210000 MPa

To calibrate the bond slip effect between concrete and steel, three distinct models are selected, such as: (1) full perfect, (2) Eligehausen model [3] and (3) bi-linear model. These models are introduced in finite element program and the collected results are analyzed and discussed in the next section.

The distribution analysis of normal and shear stresses for plain concrete member (Fig. 7) and along anchored bar where the full-perfect bond is assumed, in this case, the transmission of stresses is carried out in the integral way relative to the contact nodes (Fig. 8).

The above Figs. (8-10) showed the concentration and the dissipation of stresses in the interface zone for full-perfect model, exponential model and bi-linear model respectively. When the degradation of bond starts in certain nodes (localized stresses), there will be a total re-reduction of the stresses between reinforcing bars and concrete by the intervention of bond.

The comparison between distinct bond models, it is possible to record in presence of the interaction, the stress stresses are much concentrated in loaded end and they propagated inside of the structure. Thereafter the damage continues proportionally to the degradation of the bond characteristic and growth of concrete stresses.

From obtained results, it can be noted that the incorporation of the interface in a numerical simulations makes possible to reproduce in a more satisfactory way the rational observations, due to the transmission stresses between concrete and reinforcing bars.

According to the normal and shear stress curves (Figs. 8-10), it is possible to appreciate how the connection influences the transmission of the efforts from steel bar towards the concrete and vice versa. From the figures, it can be seen that analytical results of two kinds of elements (linkage and contact) are almost identical but the full-perfect model underestimates the bond strength.

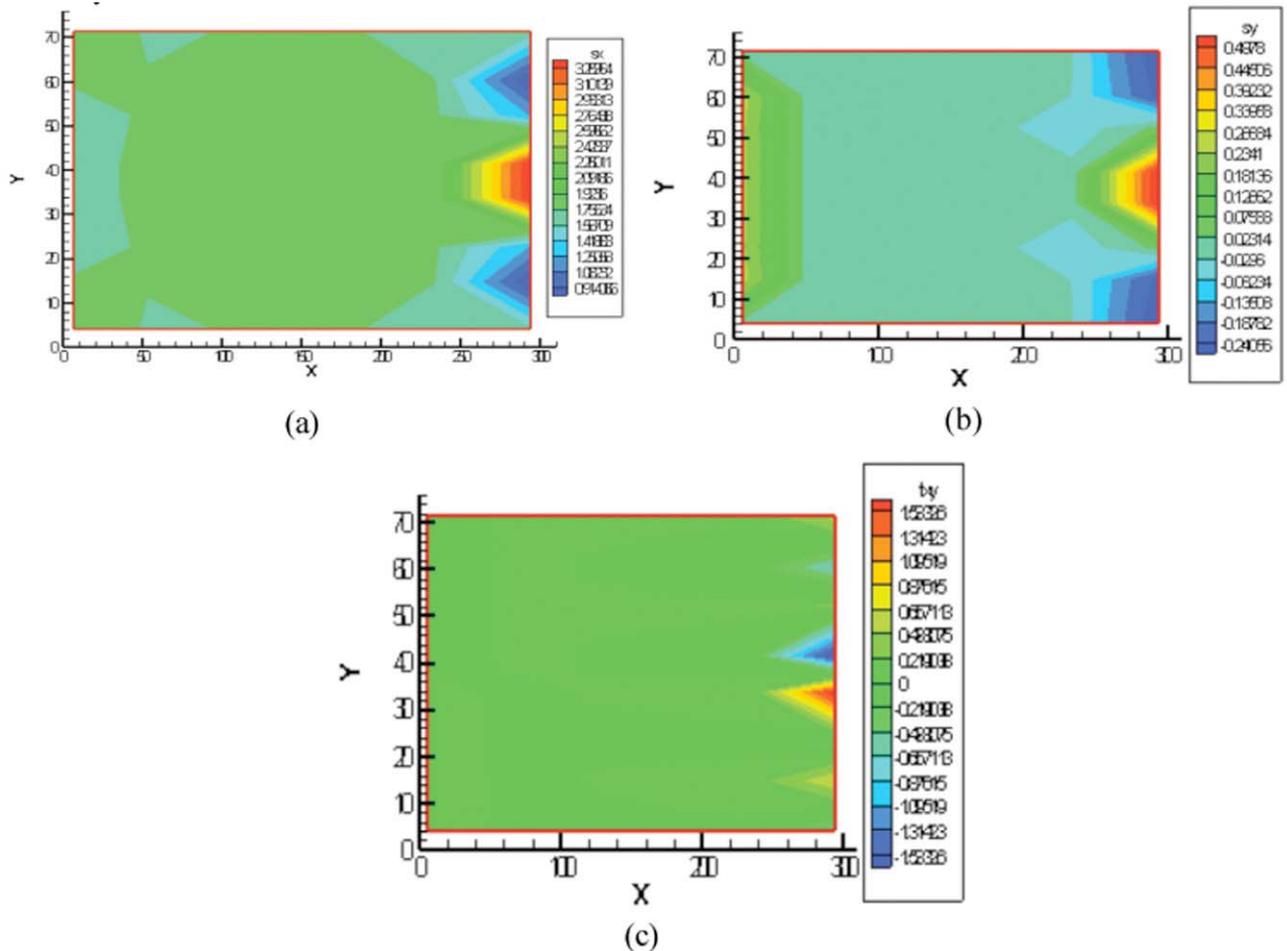


Fig. (7). Stress distributions in plain concrete member (a) σ_x , (b) σ_y , (c) τ_{xy} .

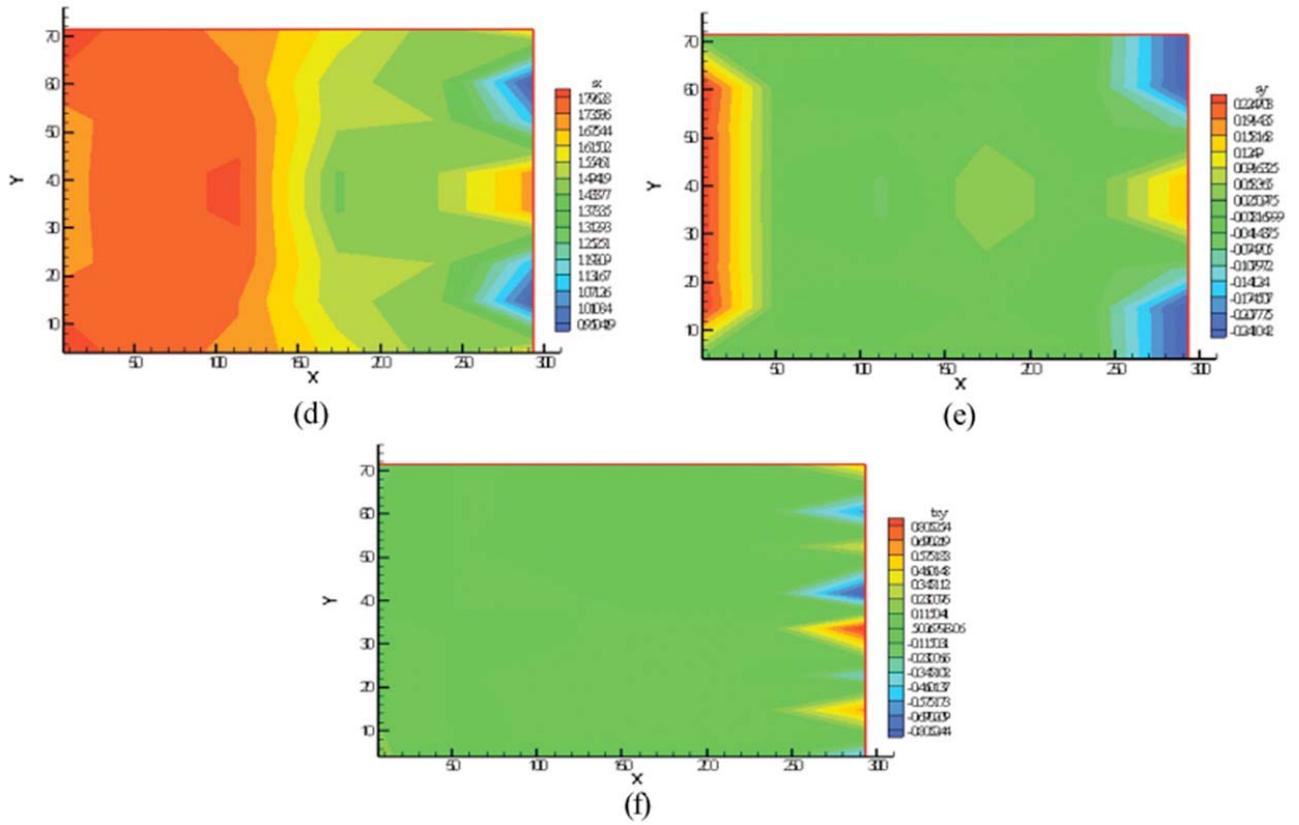


Fig. (8). Stress distributions in RC member with perfect bond, (d) σ_x , (e) σ_y , (f) τ_{xy} .

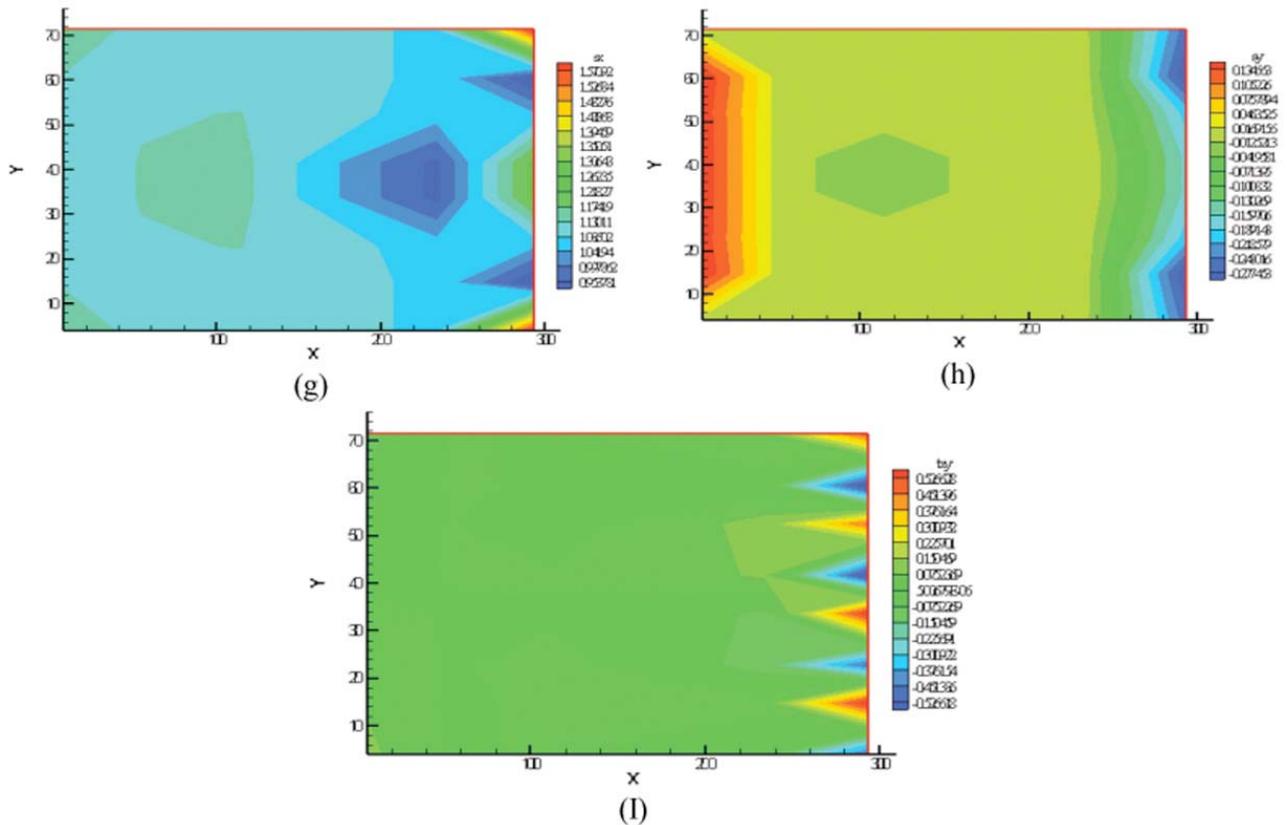


Fig. (9). Stress distributions in RC member with Eligehausen Model (g) σ_x , (h) σ_y , (I) τ_{xy} .

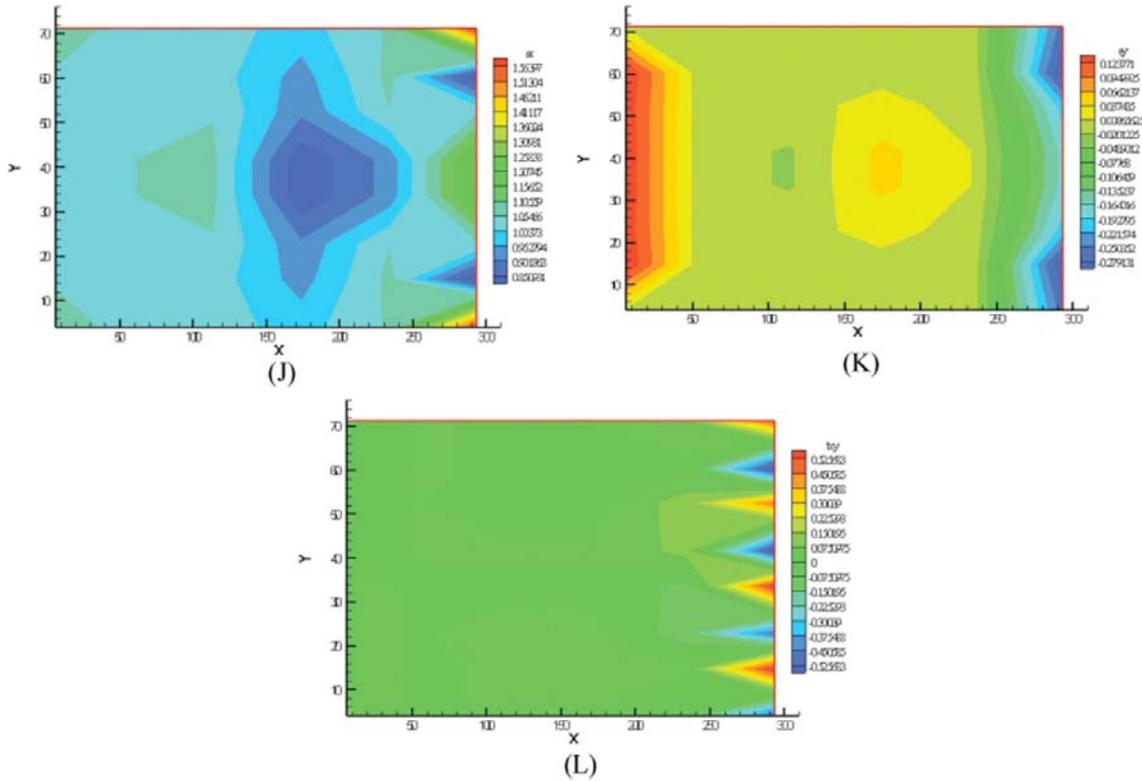


Fig. (10). Stress repartition in RC member with Bi-linear law of bond (J) σ_x , (K) σ_y , (L) τ_{xy} .

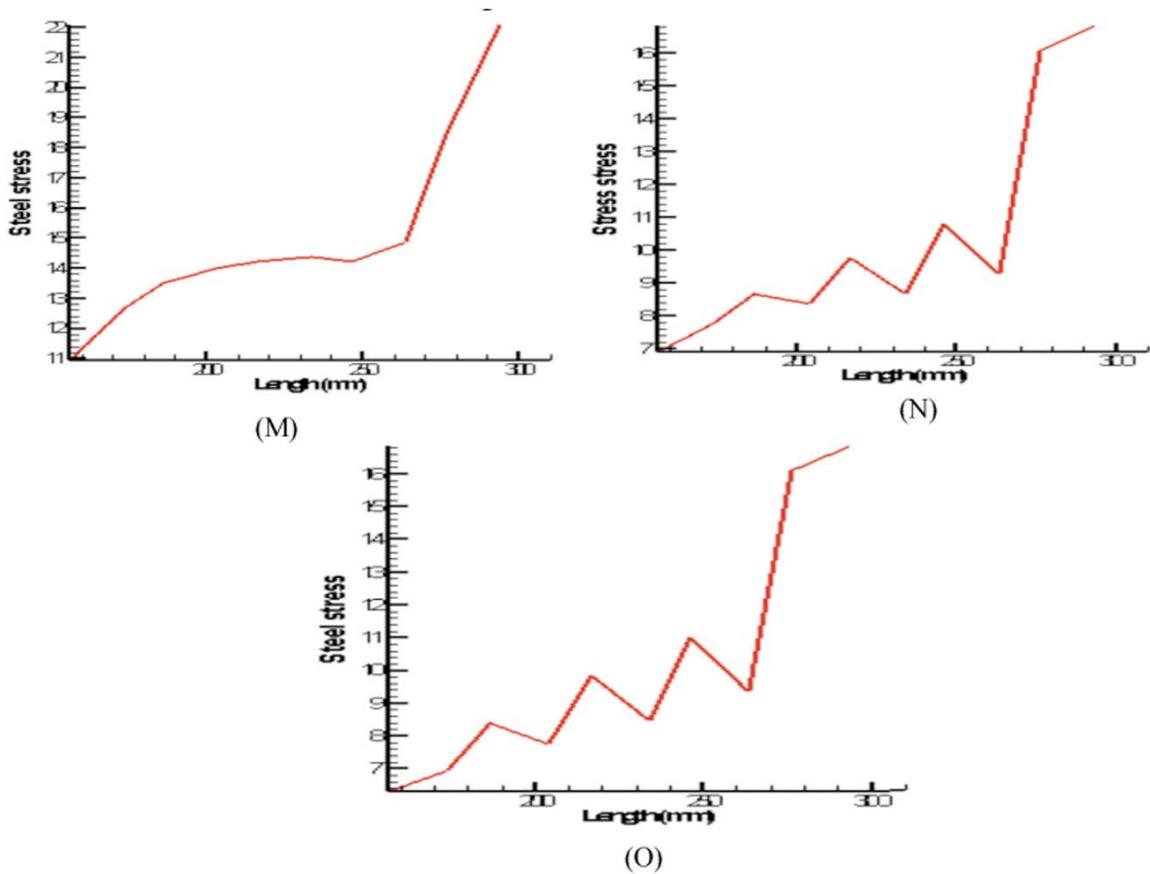


Fig. (11). Steel stress along the anchorage length; (M) Perfect model, (N) Exponential law, (O) Bi-linear law.

The Fig. (11). shows the steel stress repartitions along the reinforcing bar; in this case, the predicted steel load computed the full-perfect model is over-estimated the steel load and it is 31 % higher than ones calculated by contact models.

CONCLUSIONS

The paper studied the calibration of bond-slip behavior under monotonic loading. It presents the analysis and the incorporation for perfect bond and contact bond models for use in finite element analysis. These formulations were conducted to the following conclusions: (1) The improvement of finite element models of composite material, it is necessary to use not only the constitutive laws of concrete and steel but also one of the interface, (2) The stress distribution in the steel bar of pull-out tests may principally be influenced by the properties of the interface, (3) The transfer length depends of the bond stress relationship, (4) It appears that the full bond model under-estimates the strength bond and analytical response computed using contact element match slightly better than those calculated using linkage element.

Although this study is restricted to 2-D problems, for the efficiency and reliability of the proposed demarche, the bond-slip can easily be adopted to 3-D problems and added to 3-D finite element program.

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