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Nonlinear Analysis of Reinforced Concrete Joints with Bond-Slip Effect Consideration in OpenSees

Komeyl Karimi Moridani*[1], Panam Zarfam[2]

[1] *Department of Civil Engineering, Bandar Anzali Branch, Islamic Azad University, Bandar Anzali , Iran*
[2]*Department of Civil Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran*

*Corresponding author's Email address: karimi.k@srbiau.ac.ir

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ABSTRACT: In this study the effects of bond-slip modelling in reinforced concrete structures based on analytical equations has been investigated. TEE joint from the cap beam to the column at a location connection of the bridge is considered. The work refers, especially to the implementation of reinforcing bars and bond-slip models between steel and concrete in the developed finite element program. In order to assess the bond-slip effect, the OpenSees finite element model of the TEE joint is constructed. CEB-FIP analytical method of bond-slip is considered with nonlinear behaviour parameters from materials. Also, It is performed Nonlinear time history and pushover analysis. Based on analytical equations, the results show that taking into account the bond-slip effects in the reduction of stiffness, ultimate capacity and energy dissipation.

Keywords: Bond-Slip model, beam-column connection, OpenSees, Nonlinear analysis, Bridge

INTRODUCTION

The bond mechanism between deformed reinforcement and concrete in concrete structures has been verified by perfect bonding. The performance of reinforced concrete structures depends on the bond strength and bond-slip behaviour between the concrete and reinforcing steel (Delso et al., 2011). Nonlinear behaviour of concrete is dependent on external loading, internal factors and time-dependent factors. The slips of the reinforcement and deterioration of the bond interfaces in the beam-column connections(Pier to cap beam in bridges) and above the foundations and plastic hinge regions play a key role in describing the behaviour of reinforced concrete frames under earthquake excitations (Limkatanyu et al., 2008).

An approximate method to take in to account bond-slip effects of rebars is by reducing properly the E value or f_y of the steel material. This is more usual when modelling based on lumped plasticity. This paper presents an analytical model to describe the bond-slip behavior of reinforcing bars in well-confined concrete under two type nonlinear analysis. Analytical model of bond stress strain relationship is used based on CEB-FIP model code. CEB-FIP consider analytical model of bond-slip behaviour (Telford et al., 1990).

In this study of the interior factor of the concrete (Bond-Slip) which is often neglected in the current modelling are examined. It can be a key element for the ultimate load carrying capacity of reinforced concrete structures since it affects the anchorage of bars and the strength of lap slices (Hong et al., 2012).

In most studies it is assumed that there is perfect bonding between concrete and reinforcement at the joint. And regardless of the slip modelling. While structures such as reinforced concrete bridges, cap beam to column connections are prone to slip on reinforcement.

Then, the complete bond between concrete and reinforcing steel is not suitable assumption and shows the significant difference between the experimental and analytical responses.

In another study several currently available bond stress-slip models are focussed for steel and FRP reinforcing bars in concrete. Parametric studies are performed on the most appropriate bond-slip model to verify the effect of different surface conditions of reinforcing bars on the structural nonlinear behaviour (Zhang et al., 2014).

In the next work, bond-slip merits and demerits are discussed in terms of application limitation. Researchers proposed the analytical model on the bond-slip relationship. Their studies led to valid results against experimental studies from the literature and is shown to be simple and reliable (Long et al., 2013).

In another study, An analytical modeling approach is proposed for simulating the lateral load–deformation response of reinforced concrete columns with deficient lap splices. The modeling approach includes implementing bond versus slip springs in the formulation of a fiber-based macro models (Orakcal et al., 2012).

BOND-SLIP DEFINITION

The element of reinforcement concrete is given by the following specifications. In order to consider the effect of Bond-Slip, the axial deformation of the reinforcement is considered separately and independently of the concrete part (Figure 1) (Hashemi et al., 2012).

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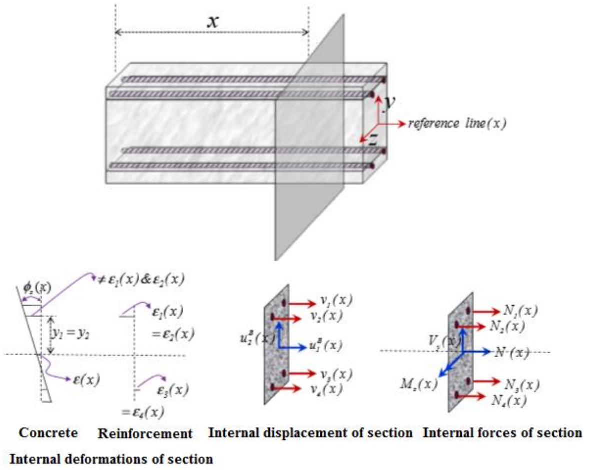

Figure 1. The forces, displacement and deformation of internal section related to element of reinforced concrete

$$dN(x) + \sum_{i=1}^{n} D_{b_{s-f_i}}(x) \times dx = 0 \qquad (1)$$

$$\frac{dN(x)}{dx} + \sum_{i=1}^{n} D_{b_{s-f_i}}(x) = 0 \qquad (2)$$

$$dN_i(x) - D_{b_{s-f_i}}(x) \times dx = 0 \qquad (3)$$

$$\frac{dN_i(x)}{dx} - D_{b_{s-f_i}}(x) = 0 \, , i = 1,2, \ldots n \qquad (4)$$

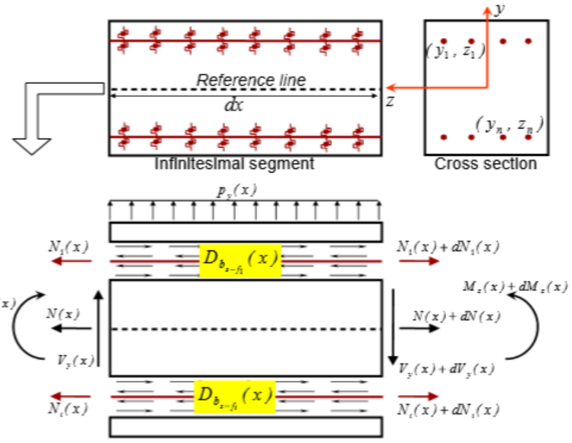

Figure 2. A length(dx) of beam-column element with bond consideration between concrete and reinforcing steel

$N(x)$ Is the axial force of reinforced concrete elements; $N_i(x)$ is an axial force in ith reinforcement; and is the number of longitudinal reinforcement and $D_{b_{s-f_i}}$ is Connection force per unit length of the reinforcement. The force is obtained by multiplying the stress bonding at the perimeter bar.

Equilibrium equation in the vertical direction is as follows:

$$dV_y(x) - p_y(x) \times dx = 0 \qquad (5)$$

$$\frac{dV_y(x)}{dx} - p_y(x) = 0 \qquad (6)$$

$dV_y(x)$ Is the shear force at the section of concrete element and $p_y(x)$ is the uniform external force along dx. Moment equilibrium equation around z is as follows:

$$dM_z(x) - V_y(x) \times dx - \frac{1}{2} p_y(x) \times (dx)^2 - \sum_{i=1}^{n} y_i \times D_{b_{s-f_i}}(x) \times dx = 0 \qquad (7)$$

$$\frac{dM_z(x)}{dx} - V_y(x) - \sum_{i=1}^{n} y_i \times D_{b_{s-f_i}}(x) = 0 \qquad (8)$$

$M_z(x)$ Is bending around the z axis at the section of concrete elements and y_i is the distance from ith reinforcement from element axis. The relationship can be summarized as follows:

$$\frac{d^2 M_z(x)}{dx^2} - p_y(x) - \sum_{i=1}^{n} y_i \times \frac{dD_{b_{s-f_i}}(x)}{dx} = 0 \qquad (9)$$

NUMERICAL ANALYSIS

Capturing the structural response and associated damage require adequate modelling of localized inelastic deformations occurring in the member end regions as identified by the shaded areas in Figure 3. The slip considered here is the result of strain penetration along a portion of the fully anchored bars into the adjoining concrete members (e.g. Joints) during the elastic and inelastic response of a structure.

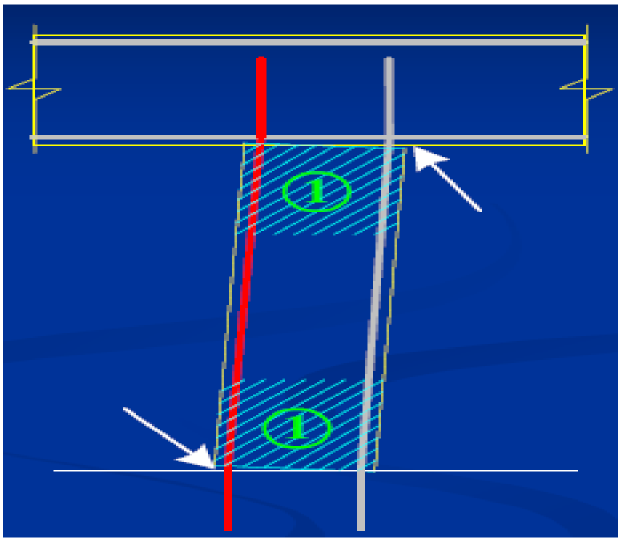

Figure 3. Expected inelastic regions at the column and wall ends (Mazzoni et al., 2006).

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In order to determine the influence of bond-slip modelling, Tee joint between cap beam and column in OpenSees is reviewed. Figure 4 demonstrates configuration of element sections, materials, and nodes in OpenSees. Element zero length section is applied in local connection for assignment of bond slip in this area.

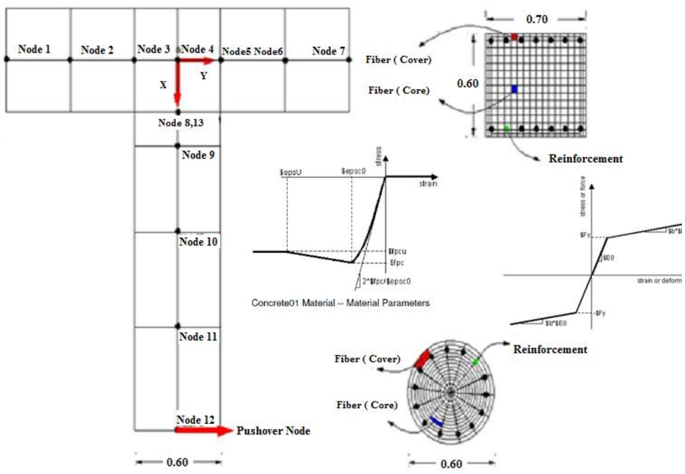


Figure 4. Tee joint detailing

MATERIALS AND METHODS

A uniaxial material model for the confined and unconfined concrete has been used. The uniaxial material model is based on Kent-Scott-Park (1971) model with degrading Linear unloading/reloading stiffness according to the work of Karsan-Jirsa (1969). No tensile stress is assumed for the concrete. A strain of 0.002 for unconfined concrete under the maximum stress and a strain of 0.006 as a limiting value are assumed.

Confined concrete has a strain of 0.005 at a stress of 6.38 Kips/inch^2 and a strain of 0.05 at a stress of 5.11 Kips/inch^2. The longitudinal reinforcements are modeled by OpenSees steel02 element and with a bi-linear stress-strain relation which accounts for strain hardening. The yield stress is 65 Kips/inch^2 and the slope of strain hardening section is assumed to be 0.01 of the initial slope. This element has a same behavior in tensile and compression.The strain-stress relation for the reinforcements is a symmetrical one [9].

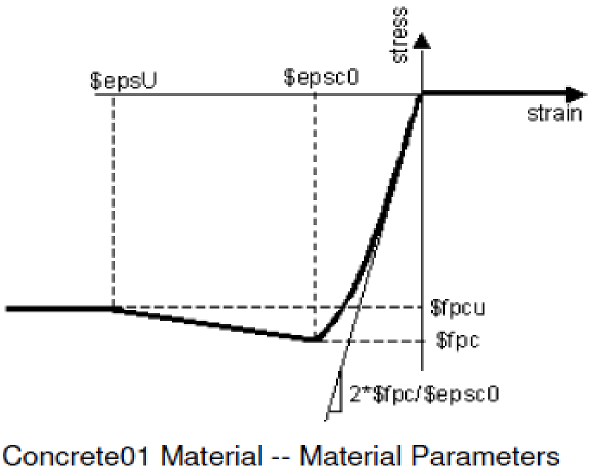


Figure 5. concrete01 model for core and cover (Mazzoni et al., 2006).

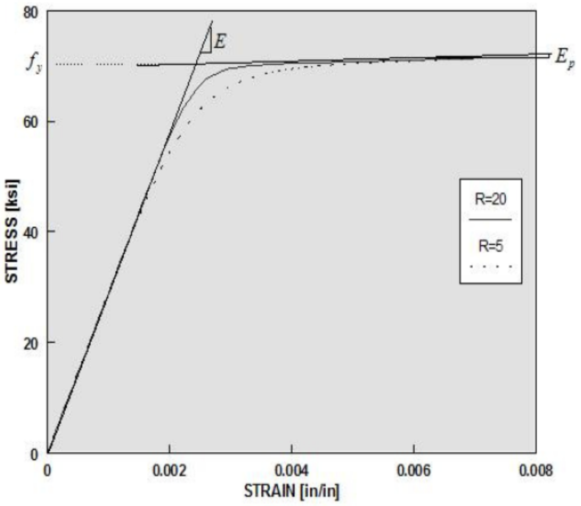


Figure 6. Steel02 model for reinforcement (Mazzoni et al., 2006).

Bond-Slip behavior model

UniaxialMaterial Bond_SP01 in OpenSees is fully anchored steel reinforcement bars. The model experience bond slip along a portion of the anchorage length due to strain penetration effects. This trend is usually the case for bridge joints such as column to bridge bent caps. Rebar slip formulation at member interface under yield stress obtained from equation 10 (Mazzoni et al., 2006).

$$\$Sy(in) = 0.1\left(\frac{d_b(in)}{4000}\,\frac{\$fy(MPa)}{\sqrt{\$fc(MPa)}}(2\alpha+1)\right)^{\frac{1}{\alpha}} + 0.013(in) \qquad (10)$$

$d_b$rebar diameter,fc concrete compressive strength of the adjoining connection member, Fy yield strength of the reinforcement steel, $\$fu$, Ultimate strength of the reinforcement steel, $\$Su$ Rebar slip at the loaded end at the bar fracture strength ($\$Su$ = (30~40)*$\$Sy$), $b Initial hardening ratio in the monotonic slip vs. bar stress response (0.3~0.5), $R Pinching factor for the cyclic slip vs. bar response (0.5~1.0) and α is parameter used in the local bond-slip relation and can be taken as 0.4 in accordance with CEB-FIP Model Code 90 [9].

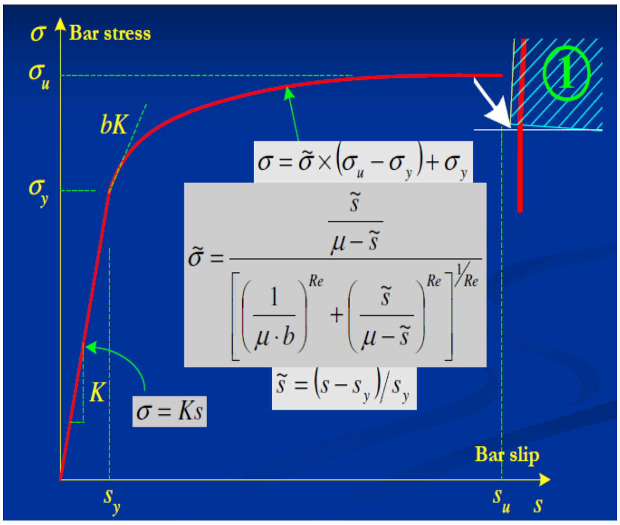


Figure7. Bond_SP01 Based on CEB-FIP Model (Mazzoni et al., 2006).

VERIFICATION AND VALIDATION OF MODEL

A model should be verified and validated to the degree needed for the models intended purpose or application. All materials and elements used in the model are based on OpenSees manual. Also, the sample of this connection modelling is given in OpenSees. (page 52-56) (Mazzoni et al., 2006). nodal Configuration of connection, degree of freedom, concrete , steel and bond-slip materials, solution system of equations, convergence tolerance, numberer, and algorithm analysis is corresponding with manual. For all materials the analytical modelling Compatible with experimental studied is assignment.

Indeed, the definition of nonlinear bond- slip model is assigned to the CEB-FIP Model Code 90. Therefore, we have used an analytical model equation for bond-sp01. Using OpenSees (open source) and link with MATLAB software, it is simplified but accurate in determining the behavior of the band- Slip in connection (Sadrossadat Zadeh et al., 2006).

RESULTS AND DISCUSSION

Selection of optimal fiber

To reduce the analysis time and accuracy is determined by computing the optimal number of fibers. Twelve of path fibers shows the optimum results. This selection of fiber number leads to the reduction of time and exact values (Correal et al., 2004).

PUSHOVER CURVE

In figure 8 the pushover diagram of beam-column joint is compared with the one obtained by the bond-slip consideration described above. Comparison of two curves presented that the yielding point of joint have a relatively little difference. It should be noted the recent result is obtained from one joint. While the results will be significant when the assessment is on the structure included several joints. Due to the slip reinforcing steel, the steel is not in strain-hardening section and slope of strain- hardening section is estimated to be very low.

The ultimate strength is less than perfect bonding. However, this difference is a few but it is very influential on the ultimate loading in structure.

Nonlinear static analysis results show that consideration of Bond-Slip estimate the yield strength and ultimate strength of concrete at the lower level. The deterioration is due to start the slip reinforcement at the joint which is associated with increased stress in section (MATLAB Ver 2007).

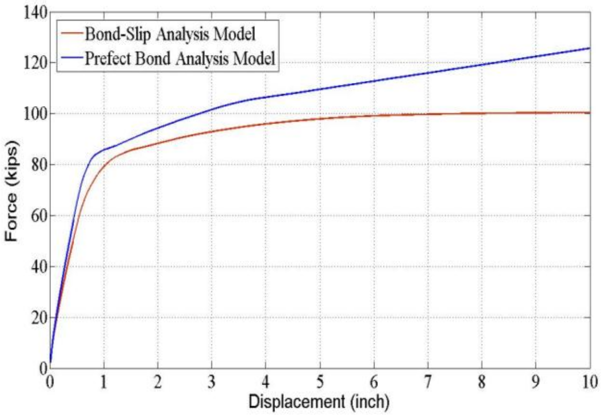


Figure 8. Effect of Bond-Slip modelling in Pushover curve.

Cyclic behavior of reinforcing steel in nonlinear time history analysis (NTHA)

Using five earthquake records according to certain conditions, the stress-strain curve of reinforcing steel is investigated in the bond-slip region. Figure 9 demonstrates the acceleration response spectra to earthquake ground motions. Thus, time history dynamic analysis was performed in TEE joint with the assumption of a perfect bond and the sliding effect.

The Stress-strain curve of four earthquake records shows the hysteresis loops fairly regular. However, the joint located in the nonlinear area. NTHA analysis of COYOTE LAKE record (EQ2) was in the dominating frequency of joint. Hence, it has caused more vulnerable to damage (See figure 9 ,10 Combined)

The results of figure 9 show that taking into account the energy dissipation estimate less than perfect bonding of the reinforcement (MATLAB Ver 2007).

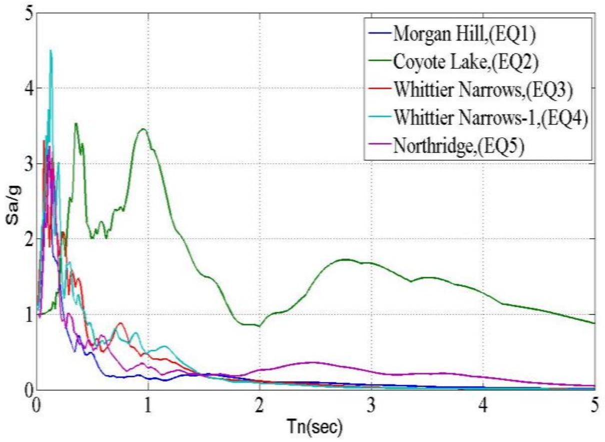
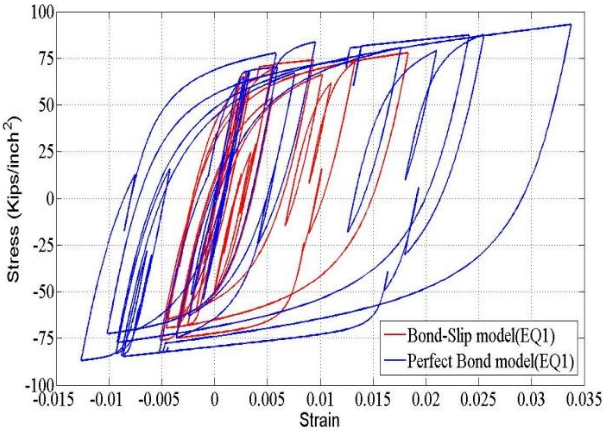
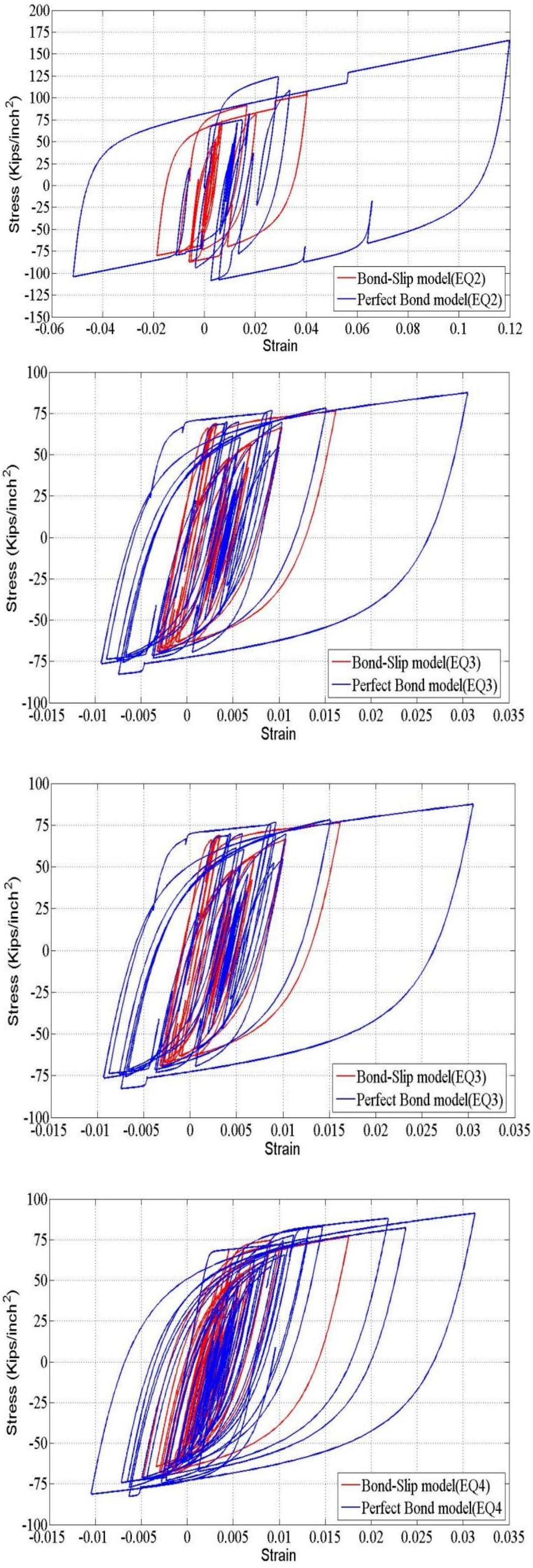


Figure 9. The pseudo acceleration response spectra to earthquake ground motions





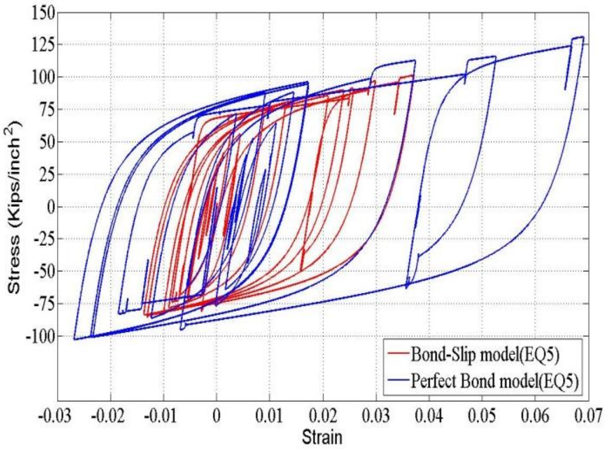


Figure 9. Effect of Bond-Slip modelling on the stress–strain diagram for reinforcing steel during nonlinear time history analysis

Earthquake records are included Morgan Hill (EQ1), COYOTE LAKE (EQ2), Whittier Narrows (EQ3), Whittier Narrows-1(EQ4), Northridge(EQ5) that was the scale of g (PEER web site).

CONCLUSION

Concrete structures such as bridges which are common in this connection for many of these types of connections are exist. The capacity curve of this structures will be affected more and cause more decrease of the capacity and energy dissipation values and estimates lower than the full bond modelling. Analytically methods can be used to specify exactly bond-slip behaviour of the RC connections. In this study, based on a nonlinear analysis of reinforced concrete, the bond-slip effect between concrete and bars along the joint elements was applied according to numerical equations. Also, to consider of the bond-slip effects in reinforcement concrete structure result in the reduction of energy dissipation and stiffness leading to the characteristic hysteretic loop. Results demonstrate that by taking this effect into the estimation of seismic damage to structures is noteworthy.

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