NUMERICAL SIMULATION ON LOCAL BOND-SLIP BETWEEN STEEL AND CONCRETE WITH EXPERIMENTAL VERIFICATION

Xilin Lu[1], Yuguang Dong[2]

ABSTRACT

The bond stress vs. slip relationship is one of the basic constitutive properties required in the nonlinear finite element analysis of SRC structures, unfortunately, research focused on this field is not enough. This article presents a new model of local bond-slip of SRC structures under monotonic pullout loading. In order to verify this model, a new type pullout experiment was designed to test bond-slip relationship between steel and concrete. Then the simulation curve derived from the proposed model was compared with experiment results, which agreed with each other well.

In order to put the bond-slip model into use in simulating SRC structure, A SRC wall was tested by monotonic horizontal loading, and simulated by 3D nonlinear finite element method with the help of program ANSYS. In this simulation, appropriate steel model and concrete model were input, and the bond-slip model under monotonic loading developed in this study was considered. Then the numerical simulations were compared with SRC wall test. The comparison demonstrates that the numerical analysis considering bond-slip relationship is more coincident with experiment results than that without bond-slip relationship.

KEY WORDS

Bond-slip, Mechanic model, Simulation, Monotonic loading, Cyclic loading, SRC wall

INTRODUCTION

Steel reinforced concrete (SRC) structures built with structural steel encased in reinforced concrete are widely used in high-rise buildings and other systems requiring a large lateral-load resistance and considerable strong axial load capacity.

SRC structure is a composite structure made up of two materials with different characteristics, namely, concrete and steel. Since external load is very rarely applied directly to the steel reinforcement, the structural steel can receive its share of load only from surrounding concrete.

[1] Professor, State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, 200092, China, *lxlst@mail.tongji.edu.cn*

[2] Ph. D. Candidate, State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, 200092, China, *Plasticity@sohu.com*

"Bond stress" is the name assigned to shear stress at the steel interface which, by transferring load between the structural steel and the surrounding concrete, modifies the steel stress. This bond, when efficiently developed, enables the two materials to form a composite structure. When the bond stress is large enough, such as structures under strong earthquake, bond failure will occur at the interface, at the same time, slip will also appear between the structural steel and the concrete. In this stage, bond-slip between the two materials would describe the relations that how structural steel and concrete transfer stress, and modify deformation each other. In fact, the structural steel and concrete interacts in a complex way through bond-slip and dowel action. However, in previous time that digital computer is under developed, these complex phenomenons cannot be considered with an accurate way, and engineers have to rely heavily on empirical formulas for the design of concrete structures, which were derived from numerous experiments.

Recent years, with the development of computer calculation, it has become possible to simulate SRC structure in a more accurate way by considering more real effects such as bond-slip relations. In this way, it is very helpful for us to know the mechanism of SRC structure further more. Unfortunately, there is little study about the experiment and the model of bond-slip relations between structural steel and surrounding concrete, which significantly restricts the development of computer simulation of SRC structures.

The authors of this article analyzed a lot of articles about bond-slip property of reinforced concrete, and at this basis, had a special experiment to test the local bond-slip relationship between structural steel and concrete, and proposed a numerical model of bond-slip. Then, a SRC shear wall was tested, and simulated with the help of finite element program ANSYS. In simulations, two different analysis models were built. In one of the models, bond-slip relationship proposed in this article was considered, in the other, perfect bond that no slip would exist between steel and concrete was assumed.

LOCAL BOND-SLIP EXPERIMENT

TEST SPECIMENS

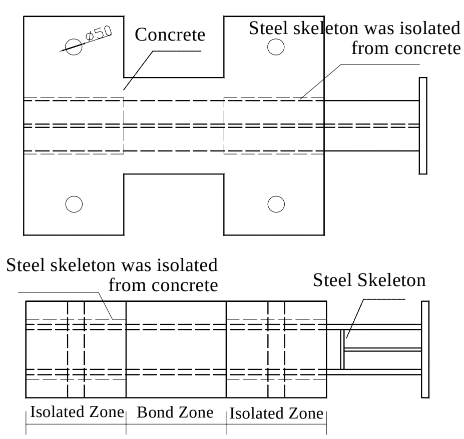

Fig.1 Local Bond-Slip Specimen of SRC Structure

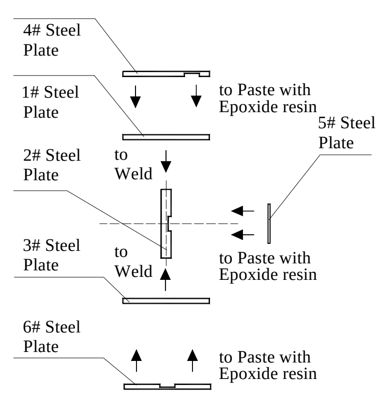

Fig.2 Assembly of Structural Steel

Two series of tests were carried out for specimens with different parameters under monotonic and cyclic pullout loading. These parameters are concrete strength, volume ratio of stirrup reinforcement, bond length respectively. In addition, in order to analyze different bond effect of different position of structural steel, three partially bond specimens were designed, in these three specimens, flange inside and web plate of steel skeleton were isolated from concrete. Detail of specimens is shown in Table 1. Mechanical property of concrete and steel is shown in Table 2 and Table 3 respectively.

In order to measure the strain of steel, these structural steels were assembled with steel plates by welding and pasting. Grooves were milled on some steel plate to paste strain gauges, just as shown in Fig.2.

Table 1 Detail of Specimens

Specimen	Bond length (mm)	Grade of Concrete	Stirrup of Specimen	Partially bond	Loading
LBS-01	200	C30	$\phi 6@100$	no	monotonic
LBS-02	200	C45	$\phi 6@100$	no	monotonic
LBS-03	200	C60	$\phi 6@100$	no	monotonic
LBS-04	200	C45	$\phi 4@100$	no	monotonic
LBS-05	200	C45	$\phi 8@\ 50$	no	monotonic
LBS-06	100	C45	$\phi 6@100$	no	monotonic
LBS-07	300	C45	$\phi 6@100$	no	monotonic
LBS-08	200	C45	$\phi 6@100$	yes	monotonic
LBS-09	100	C45	$\phi 6@100$	yes	monotonic
LBS-10	200	C45	$\phi 6@100$	no	monotonic
LBS-11	200	C30	$\phi 6@100$	no	cyclic
LBS-12	200	C45	$\phi 6@100$	no	cyclic
LBS-13	200	C60	$\phi 6@100$	no	cyclic
LBS-14	200	C45	$\phi 4@100$	no	cyclic
LBS-15	200	C45	$\phi 8@\ 50$	no	cyclic
LBS-16	100	C45	$\phi 6@100$	no	cyclic
LBS-17	200	C45	$\phi 6@100$	no	cyclic
LBS-18	200	C45	$\phi 6@100$	yes	cyclic

Table 2 Mechanical property of concrete

Grade of concrete	Compressive strength σ_c (N/mm2)	Tensile strength σ_t (N/mm2)	Young's modulus E (N/mm2)
C30	28.5	2.4	3.31e4
C45	50.4	3.3	3.85e4
C60	64.3	3.8	4.17e4

Table 3 Mechanical property of steel

Specimen of Material	Young's Modulus (N/mm^2)	Yield Stress f_y (N/mm^2)	Tensile stress f_u (N/mm^2)
10mm steel plate	2.08e5	343	429
6mm steel plate	2.12e5	355	438
Φ4 bar	2.11e5	294	387
Φ6 bar	2.38e5	362	435
Φ8 bar	2.03e5	387	458

TEST SET-UP

To test the local bond-slip specimens, a special loading set-up with two kinds of screw bolts was designed, the first kind with two screw bolts pushes specimen at the end of it, and the other kind with four screw bolts presses specimens on the top of it. In this way, the specimen can be fixed rigidly onto the loading set-up without any slide, so, many kinds of loading mode including monotonic loading and cyclic loading can be realized.

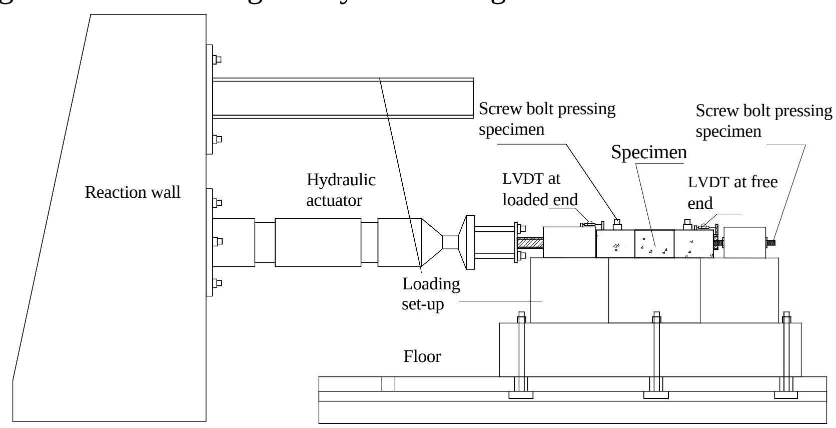

Fig.5 Setup of experiment

Some strain gauges were pasted in the grooves of steel plate to measure the strain of structural steel, as shown in Fig.3. In addition, the specimens were instrumented with Linear Variable Differential Transducers (LVDT) for slip measurement. A LVDT was placed horizontally at the end of specimen to measure the specimen slip of free end, and another was placed horizontally at the tip of specimen to measure the specimen slip of loaded end. The set-up of the experiment is shown in Fig.5.

TEST RESULTS AND NUMERICAL MODEL

The specimens were tested with monotonic pull-out loading or cyclic pull-push loading. After loading, no apparent crack or split was founded at the load end or surface of specimens, just shown in Fig.5 and Fig.6, So the bond failure on interface between the structural steel and surrounding concrete was realized in this experiment. At the same time, the concrete splitting failure or concrete crushing failure of specimens were avoided. A typical force-slip curve under monotonic loading is shown in Fig.7.

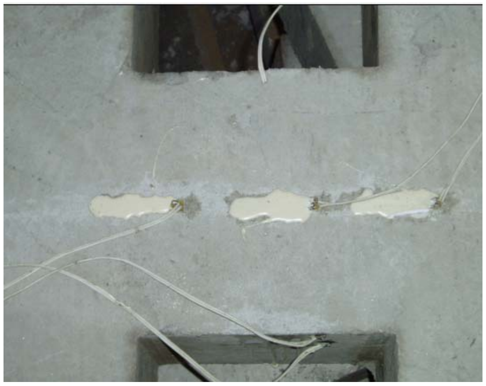

Fig.5 No Apparent Crack on the Load End of Concrete after Experiment

Fig.6 No apparent Crack on the Surface of Concrete of Bond Zone after experimrnt

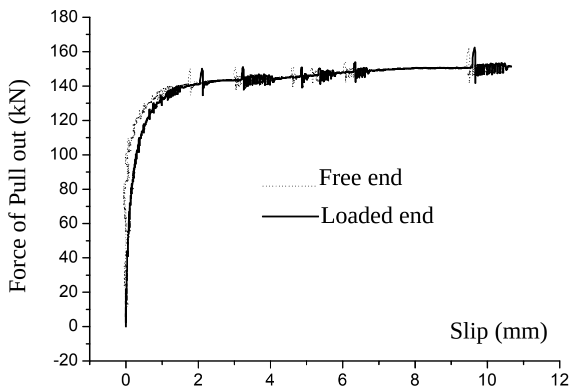

Fig.7 Typical Force-Slip Experiment curve

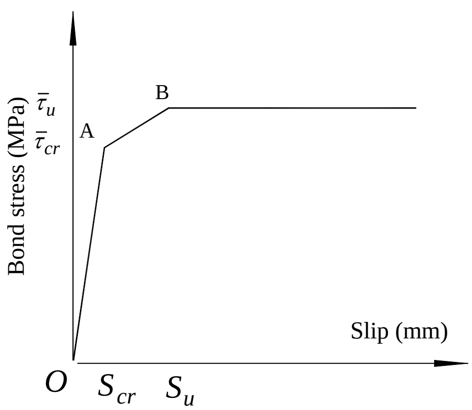

Fig.8 Trilinear local bond-slip model of SRC curve under monotonic loading

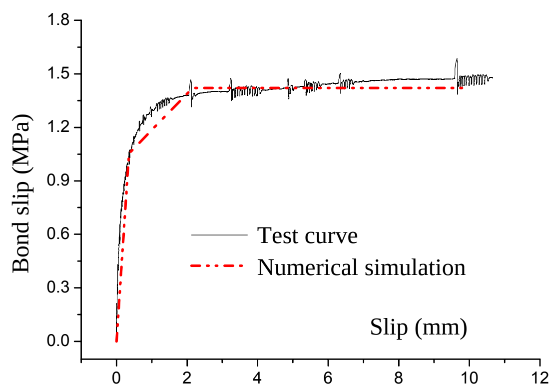

Fig.9 Comparison between test and numerical simulation

Based on the experiment results of these specimens, numerical constitution model of bond-slip of steel reinforced concrete under monotonic loading was proposed. As showed in Fig.8, the model is a simple trilinear curve, which is defined by two points, A ($\bar{\tau}_{cr}$, S_{cr}) and B ($\bar{\tau}_u$, S_u). The numerical value of $\bar{\tau}_{cr}$, S_{cr} , $\bar{\tau}_u$, S_u is shown in formula from (1) to (4).

$$\bar{\tau}_{cr} = 0.028 f_{cu} + 0.026\rho_{sv} + 0.111 \quad (1)$$

$$\bar{\tau}_u = 0.047 f_{cu} + 0.159\rho_{sv} - 0.160 \quad (2)$$

$$S_{cr} = 0.151Le/100 + 0.054 \quad (3)$$

$$S_u = (0.117\rho_{sv} + 0.867)Le/100 + 0.633 \quad (4)$$

where f_{cu} (MPa) is the compressive strength of concrete, ρ_{sv} (%) is the volume ratio of stirrup reinforcement, Le (mm) is the bond length of specimen.

The cross-section of structural steel is more complicated than that of steel bar, so the different positions of cross-section such as outside of flange plate, inside of flange plate, web plate have different bond property. In order to analyze the discrepancy, two specimens that isolated the bond of inside of flange plate and web plate to concrete was designed. According to experiment result, the bond stress of outside of flange plate is higher than that of inside of flange plate and web plate, and the ratio is 2.566. So the bond stress of flange plate and web plate can be concluded, as formula (5) and (6) showed.

$$A_{of}\tau_{of} + A_{if}\tau_{if} + A_w\tau_w = \bar{\tau}\left(A_{of} + A_{if} + A_w\right) \quad (5)$$

$$\tau_{of} = 2.566\tau_{if} = 2.566\tau_w \quad (6)$$

Where A_{of} , A_{if} , and A_w are the area of outside of flange plate, the area of inside of flange plate, and the area of web plate respectively, and τ_{of} , τ_{if} , and τ_w are the bond stress of outside of flange plate, inside of flange plate, web plate respectively, $\bar{\tau}$ is average value of whole cross-section of structural steel, which can be got from curve of Fig.8. In addition, the hypothesis that every positions of cross-section have the same slip is taken in this model.

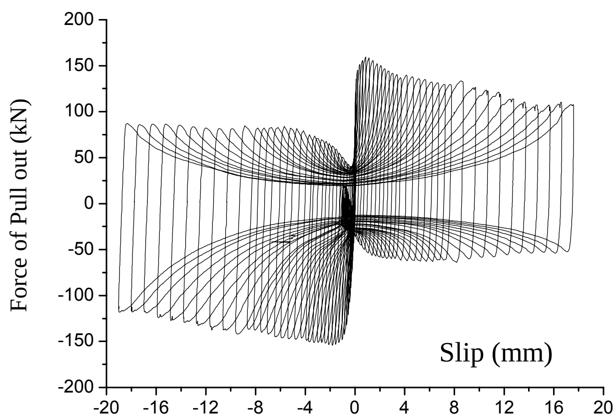

Fig.10 Typical Load-Slip Experiment Curve under Cyclic Loading

To verify this model, specimen numbered LBS-06 was analyzed with the proposed bond-slip model, and simulation result was derived. Consequently, simulation and experiment result of this specimen were compared. As showed in Fig.9, the simulation coincided with experiment curve well. So, the monotonic bond-slip model is accurate enough to simulate the real bond property of specimen.

Bond-slip property between steel and concrete under cyclic loading was also investigated in this article, and the force versus slip curve is shown in Fig.10. It shows a typical response for bond in cyclic loading. Experiment results and bond-slip model of cyclic loading will present in subsequent articles.

BOND-SLIP MODEL IN NUMERICAL SIMULATION OF SRC STRUCTURE AND EXPERIMENT VERIFICATION

INTRODUCTION OF SRC WALL EXPERIMENT

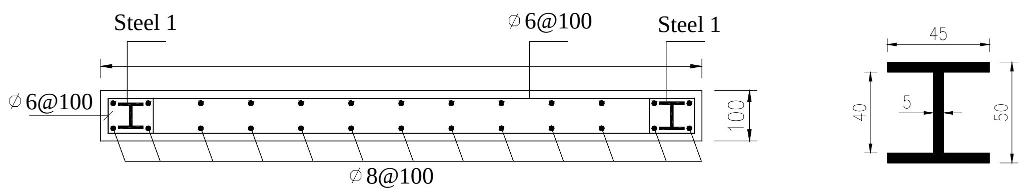

Fig. 11 Cross Sections and Detail of SRC Wall

In order to verify the proposed analytical model of bond-slip suitable for the SRC walls, a SRC wall was tested under monotonic loading. The cross sections and details of reinforcement are shown in Fig. 11.

The height of the SRC wall was 3000 mm, the concrete strength of the wall was 50.1 MPa, and concrete Young's modulus was 35503 N/mm^2. The mechanical property of structural steels and steel bars were tested and showed in table 4.

The wall were fixed on laboratory strong floor by means of high-strength steel bolts, axial load of 30t was applied slowly by five hydraulic jacks, which pushed against a stiffened reaction beam, and remained constant throughout the test. The horizontal monotonic loading was applied using a servo hydraulic actuator, and velocity of loading was controlled at 0.667 mm/minute.

Table 4 Mechanical property of steel

Steel specimens	Yield Strength (N/mm^2)	Ultimate Strength (N/mm^2)	Young's Modulus (N/mm^2)
5mm Steel plate	312.62	450.02	2.01e5
Φ6 bar	307.11	441.53	2.19e5
Φ8 bar	265.92	389.27	2.02e5

NUMERICAL SIMULATION METHOD

From previous article, two basically different elements, namely the bond-link element and bond-zone element, have been proposed to date for inclusion of the bond-slip effect in the finite element analysis of concrete structures. In detailed studies where the detailed local behavior is of interest, continuous bond elements such as bond-zone elements are most appropriate. In practice cases, however, where the overall structural behavior is of primary interest, the bond-link element provides a reasonable compromise between accuracy and computational efficiency.

In this article, Program ANSYS was selected to simulate monotonic loading test of SRC wall with 3D finite element analysis.

concrete

The response of a structure under load depends on the stress-strain relationship of the constituent materials and the magnitude of stress to a large extent. Many mathematical models of concrete are currently used in the analysis of reinforced concrete structures. Among those models, the monotonic envelope curve introduced by Kent and Park was adopted in this study, as Fig.12 showed. This model assumes that concrete is linearly elastic in the tension region. Beyond the tensile strength, the tensile stress decreases linearly with increasing principal tensile strain, and ultimate failure is assumed to take place by cracking.

structural steel and reinforced steel

Structural steel and reinforcement bars are modeled as nonlinear strain hardening material with yield stress σ_y, as showed in Fig.16. As the behavior of concrete structure is greatly affected by the yielding of reinforcement bar and structural steel, it is essential to take advantage of the strain-hardening behavior of steel in improving the numerical stability of the solution.

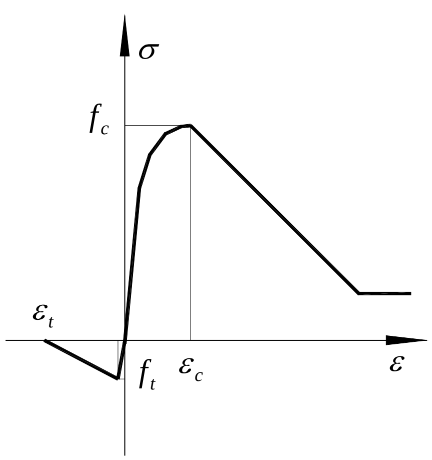

Fig. 12 Stress-Strain Curve of Concrete

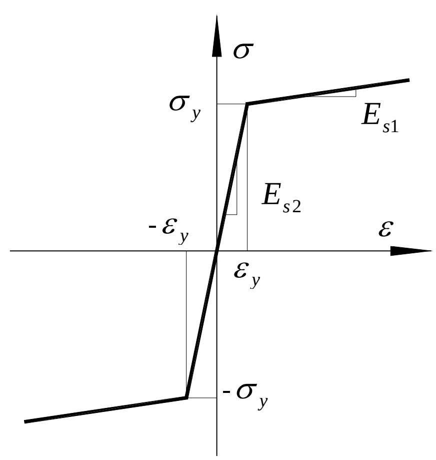

Fig. 13 Stress-Strain Curve of Steel

bond-slip between structural steel and concrete

Bond-link element was applied for its computational efficiency. The numerical model of local bond-slip relationship between structural steel and concrete under monotonic loading provided by this article was applied, as showed in Fig.8. The bond-slip between reinforcement bars and concrete was ignored in this study because the reinforcement bars have more effective bond property than that of structural steels.

COMPARISON BETWEEN SIMULATION RESULTS AND EXPERIMENT RESULTS

In order to analyze the effect of bond-slip to the SRC structure, the SRC wall was analyzed with two different analysis models in this article. In one of the two models, bond-slip property was ignored that two materials kept perfect-bond. In the other model, bond-slip relationship was considered, and the bond-slip constitute relationship proposed in this article was utilized.

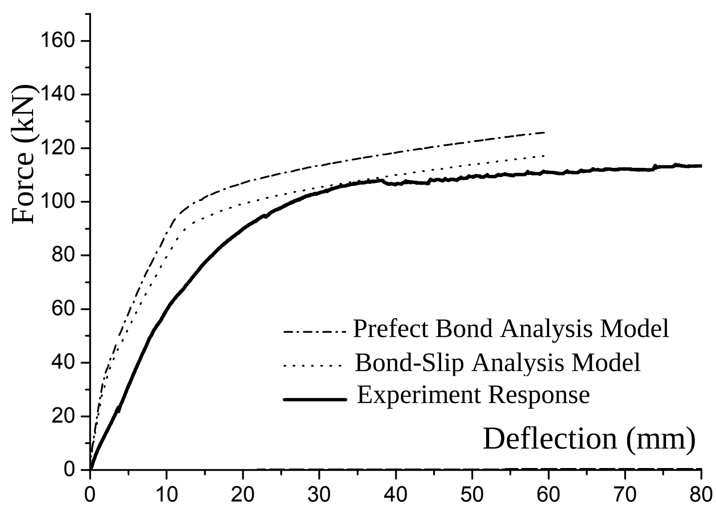

Fig.14 Load-Deflection Relationships of Simulation and Experiment of SRC Wall

Fig.14 showed the two analytical results and the measured load-displacement of loading point of SRC wall. The figure showed the effect of bond slip to the force-deflection response of the specimen. The initial discrepancy between analysis and experiment came from the fact that the specimen slide at loading, and the sliding motion between specimen and floor might cause the reducing of stiffness of experiment results. From Fig.14, it is clear to find that result of analysis model considering bond-slip relationship is more closer to measured response than that of the model assuming perfect bond.

CONCLUSIONS

18 specimens of bond-slip between structural steel and concrete under monotonic pullout loading and cyclic loading were tested in this article. Based on the tests, a new bond-slip model of monotonic loading was presented, and the model agreed with experiment well.

In order to verify the proposed analytical model of bond-slip under monotonic loading suitable to SRC walls, a SRC walls were tested under monotonic loading, and the SRC wall was analyzed by 3D nonlinear finite element method. Two different simulation models were used to analyze the SRC wall. In one of the two models, bond-slip property between structural steel and concrete was ignored so that two materials kept perfect-bond. In the other model, bond-slip relationship proposed by this article was considered.

According to the comparison with experiment, the simulation model considering bond-slip relationship agreed with the measured response better than the model assuming perfect bond. So as a conclusion, simulation model considering bond-slip is more accurate than traditional perfect bond simulation model. It is essential to study the bond-slip relationship for grasping the mechanical property of SRC wall furthermore.

ACKNOWLEDGEMENT

The authors would like to acknowledge the support of the National Natural Science Foundation of China through grant 50321803. In addition, the support of Tongji University, State key Laboratory for Disaster Reduction in Civil Engineering is also appreciated.

REFERENCE

Bartos P. (1982). "Bond in Concrete." Applied Science Publishers, London.

Kwak H.G., Kim S.P. (2001). "Bond-Slip Behavior under Monotonic Uniaxial Loads. " *Engineering Structures*, 23 298-309.

Kayali O., Yeomans S.R. (2000). "Bond of Ribbed Galvanized Reinforcing Steel in Concrete. " *Cement & Concrete Composite*, 22 459-467.

Fang C., Lundgren K., and Chen L. (2004). "Corrosion Influence on Bond in Reinforced Concrete." *Cement and Concrete Research*, 34 2159-2167.

Lundgren K. (2000). "Pull-out Test on Steel-Encased Specimens Subjected to Reversed Cyclic Loading. " *Materials and Structures*, 33 450-456.

Keuser M., Mehlhorn G. (1987). "Finite Element Models for Bond Problems. " ASCE, Journal of Structure Engineering, 113(10) 2160-2173.

Scott B., Park R., and Priestley M. (1982). "Stress-Strain Behavior of Concrete Confined by overlapping Hoops at Low and High Strain Rates." *Journal of ACI*, 79(1) 13-27.