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THE ROLE OF REINFORCEMENT BOND ON ENERGY DISSIPATION AND DAMAGE

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ABSTRACT

This study presents the reconstruction of relationships between the dissipated bond energy and the typical parameters which may determine the prediction of generalized excitation bond-slip behavior. The analytical model used is developed for cyclic local bond stress-slip relationship of a reinforcement anchorage between constant amplitude slip. This model, developed according to experimental bond-slip tests for well-confined concrete, is represented by three major resistance components which appear to control the behavior and act, changing their influence, at various loading stages. The results predicted by that model are compared with experimental results and show good correspondence.

1 INTRODUCTION

This study presents the first stage of a long term research program at the Technion for developing practical design provisions for anchorage of steel reinforcement bars embedded in reinforced concrete joints and subjected to lateral cyclic loadings. The local bond stress-slip relationship is the common means to determine the steel-concrete interfacial mechanical properties. A simple analytical model for the local bond stress-slip relation in confined concrete has been developed during a previous study by Farhey (1986), and Yankelevsky, Adin & Farhey (1992). The work is inspired from experimental work which had been performed by several groups, and mainly based on experimental observations of the tests carried out at the University of California, Berkeley, by Eligehausen, Popov & Bertero (1983), Viwathanatepa, Popov & Bertero (1979), and Filippou, Popov & Bertero (1983). This model proposes continuous functions of the reduced envelopes as well as of the monotonic envelope. These envelopes are derived from a common mathematical model which enables to produce the complete constant-amplitude cyclic bond stress-slip history with high correspondence with experimental data. The model may follow the deterioration and therefore the reduced resistance of the bond mechanism, depending on the slip amplitude and number of cycles. The model assumes to represent the bond-slip curve by the sum of its major resistance components which control its behavior throughout the loading history. The predicted curves are smooth and in very good agreement with the experimental ones. The proposed analytical model can be helpful in advanced analysis of reinforced concrete elements. Other bond stress-slip relationships govern the behavior through various exhaustive process rules. Those multi-linear complicated models are not sufficient to treat general loading histories and non-monotonic general laws are required.

Based on the local model, analysis has been carried out for the reconstruction of relationships between the absorbed and dissipated bond energy, and parameters which dominate the cyclic behavior of the anchorage. Those relationships are useful for the development of a real general model for the prediction of bond-slip of an anchored bar, subjected to general cyclic excitation. Such a model is important for obtaining conclusions and recommendations considering practical earthquake-design.

2 BOND-SLIP MODELING

The local bond stress-slip relationship which determines the steel-concrete interfacial mechanical properties is described by its envelope and is idealized according to the separate ascending, descending, and ultimate loading stages. The bond stress-slip relationship is usually described by piecewise linear analytical models (Morita & Kaku 1974, Tassios 1979, Viwathanatepa, Popov & Bertero 1979, and Yankelevsky 1985) or by combination of linear branches with multi-degree functions (Eligehausen, Popov & Bertero 1983 and Filippou, Popov & Bertero 1983) using cumbersome techniques which link the branches. The latter two analytical models are based on the results of an intensive experimental program performed by Eligehausen, Popov & Bertero (1983). The monotonic envelope is composed of a non-linear curve representing the first ascending branch and a tri-linear curve which represents the descending branch. The reduced envelopes are piecewise linear curves composed of five linear parts. The determination of the reduced envelope and its parameters is based on damage parameters obtained experimentally for increasing number of cycles within various loading amplitudes.

Inspired from the experimental work which had been performed at Berkeley, a simple analytical model was developed by the authors. This model considers the general cyclic loading behavior of the whole range as composed of the major resistance components and proposes continuous curves of the reduced envelopes as well as of the monotonic envelope. These envelopes are derived from a common mathematical model which enables to produce the complete cyclic bond stress-slip history. The model may follow the deterioration and therefore the reduced resistance of the bond mechanism, depending on the slip amplitude and number of cycles.

The proposed model provides a general formulation to the typical bond stress-slip curve at the N-th cycle of an amplitude s_{max} as shown in Fig. 1, which represents both the monotonic curve and the family of cycle dependent curves which follow.

The bond-slip curve, shown in Fig. 1, is assumed to represent the result of three major resistance components:

2.1 The steel-concrete bond component

This is the resistance component obtained by the gradual shearing off of the concrete keys between the lugs, which is only possible in well-confined concrete (Fig. 2(a)):

$$\tau_1 = C\ (s+s_1)^D \exp[-\alpha\ (s+s_1)] \qquad (1)$$

where:

C = parameter depending on fundamental characteristics of the sample;
s = slip;
s_1 = slip value at which the lug is reattached with the concrete;
D = deterioration parameter depending on the slip amplitude s_{max};
α = parameter depending on fundamental characteristics of the sample.

2.2 The cyclic friction component

This is the friction resistance component between the reinforcing bar and the surrounding concrete, which becomes active upon unloading and reloading (Fig. 2(b)):

$$\tau_2 = \frac{(s+s_r)\ K\ \tau_f(N)}{(s+s_r)\ K + \tau_f(N)} \qquad (2)$$

where:
s_r = slip at zero bond stress;
K = slope of the first unloading or reloading branch;
τ_f = cyclic friction stress.

2.3 The virgin friction component

This is the potential additional friction resistance component when the displacement exceeds the previous certain slip in this direction (Fig. 2(c)):

$$\tau_3 = \tau_f + \frac{(s-s_{max})\ (\tau_u-\tau_f)}{(s-s_{max}) + B\ (\tau_u-\tau_f)} \qquad (3)$$

where:
s_{max} = reversed peak slip value, amplitude of cyclic loading;
τ_u = ultimate value of the virgin friction component;
B = factor of virgin friction component.

The total resistance to slip is the combination of these three components which yields a full range, smooth and continuous bond stress-slip resistance curve as shown in Fig. 2(d). A reduced envelope is obtained by a gradual decrease or increase of the characteristic parameters which govern the behavior.

Comparison of the proposed expressions with the cyclic series 2 test data of Eligehausen, Popov & Bertero (1983) are shown in Figs. 3 to 5. Except for slight deviations, the predicted continuous curves, both monotonic and cyclic loading envelopes, are in good agreement with the experimental ones, keeping in mind the unavoidable substantial scatter of ±15% observed in tests.

3 BOND ENERGY DISSIPATION

As the latter model closely follows observed experimental bond records, it may also be used for advanced analysis of quantitative damage evaluation, energy dissipation, and their use for general model development of reinforced concrete elements, where realistic bond stress-slip relationships are required. Nevertheless, this model is suitable only for constant amplitude slip loading history and not for a general loading history with arbitrary excitations. The authors are convinced that the model generalization to predict arbitrary excitations should be based on considerations of energy dissipation (as had also been stated by Eligehausen, Popov & Bertero (1983)). As a basic step towards the formulation of the damage mechanisms, the mathematical model which has been described above has been used to examine energy dissipation aspects. Although the results are based on constant amplitude harmonic tests, it may be assumed that the general energy dissipation behavior follows similar rules for generalized excitations as for constant amplitude slip loading. The area under the bond-slip curve is considered as the dissipated bond energy up to the reached slip value.

The variation of the energies of the steel-concrete bond resistance alone in two following half cycles ($E_G(N+1)/E_G(N)$) as a function of numbers of half loading cycles (N), in one direction, is given in Fig. 6, for various values of slip amplitude of cyclic loading (s_{max}). It may be observed that severe deterioration occurs at larger amplitudes and low number of cycles. All the curves representing different slip amplitudes follow a similar trend and may therefore be represented by a single mathematical expression. Accordingly, a similar relationship may be shown for the total energy.

The variation of the maximum bond stress of the steel-concrete bond resistance alone in two following half cycles ($\tau_G(N+1)/\tau_G(N)$) as a function of the steel-concrete bond resistance energies in the same two following half cycles ($E_G(N+1)/E_G(N)$) is given in Fig. 7, for various slip amplitudes. Once the energy ratio between two successive half cycles has been determined, the maximum bond stress (τ_{max}) and the corresponding slip ($s_{\tau max}$) may be obtained. Figs. 7 and 8 show these relationships which follow a trend being almost independent of slip amplitude and number of cycles. With these two parameters the mathematical expression for the bond stress-slip, in the following half cycle, is known and analysis may proceed.

The figures shown above indicate that general relationships independant of slip amplitude and number of cycles may be obtained. The mathematical tool provides the quantitative relationships between the major parameters and the bond-slip deterioration mechanism, being expressed by energy ratios as shown above.

4 CONCLUSIONS

Assuming resemblance of energy dissipation relationship in an arbitrary cyclic loading compared with constant amplitude cyclic reversed loading, the analytical work, presented in this paper, proposes energetical relationships with the characteristic parameters which govern the behavior.

These energy dissipation relationships control the general behavior throughout the loading history for the prediction of generalized cyclic bond-slip behavior for well-confined concrete.

More experimental and analytical work is needed for the development of a general model, based on the mechanisms of the resistance components, for an arbitrary non-monotonic loading.

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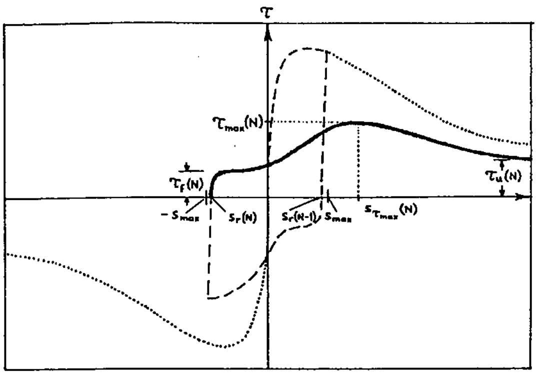

Fig. 1 - Typical result of local bond stress slip relationship for confined concrete

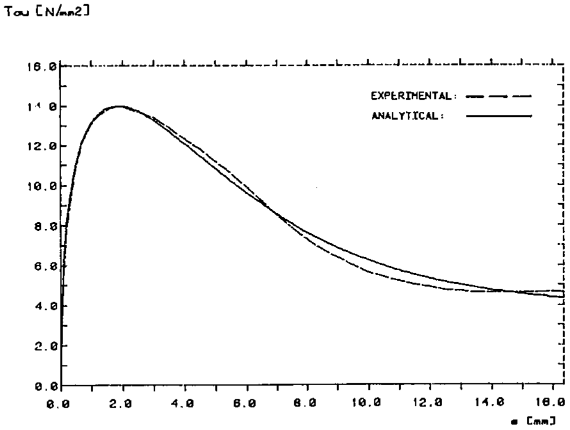

Fig. 3 - Comparison of experimental and analytical results for bond stress-slip relationship under monotonic loading

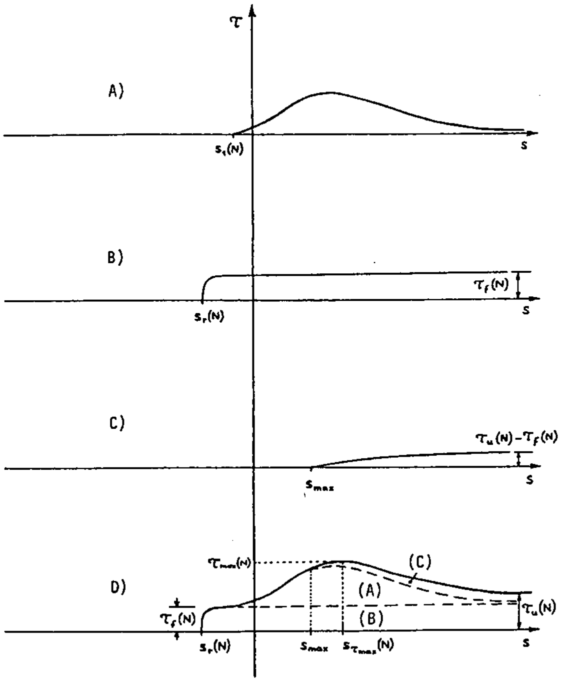

Fig. 2 - Components of bond-slip resistance:

(a) Steel-concrete bond resistance;

(b) Frictional resistance;

(c) Differential frictional resistance;

(d) Total curve

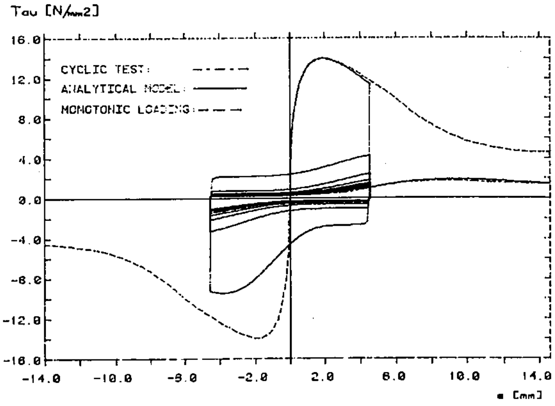

Fig. 4 - Comparison of experimental and analytical results for bond stress-slip relationships for s_{max} = 4.57 mm, after ten cycles

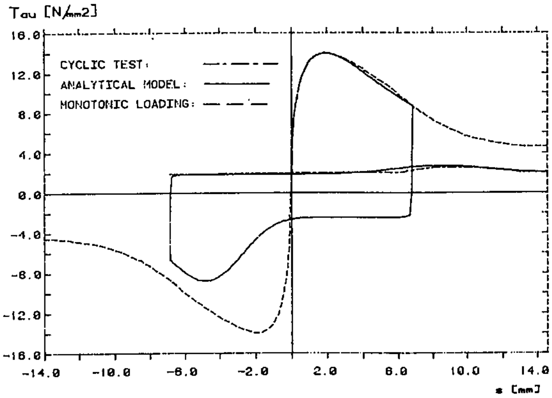

Fig. 5 - Comparison of experimental and analytical results for bond stress-slip relationships for s_{max} = 6.86 mm, after one cycle

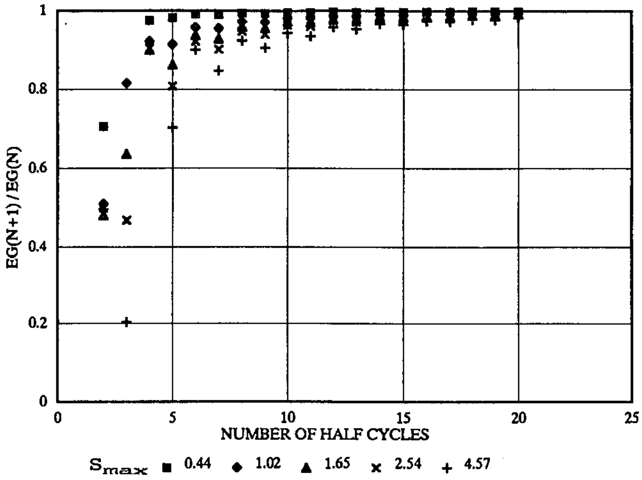

Fig. 6 - Variation of energy of steel-concrete bond resistance versus number of half loading cycles (N)

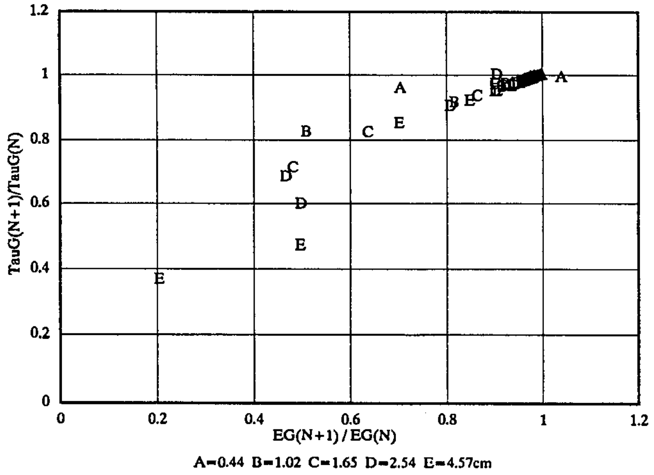

Fig. 7 - Variation of maximum bond stress of steel-concrete bond resistance alone (τ_G) versus variation of steel-concrete bond energy

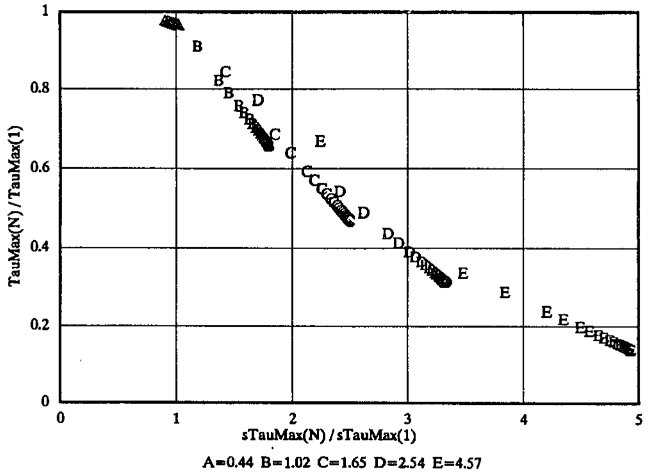

Fig. 8 - Maximum bond stress ratio versus ratio of slip value of maximum bond stress