한국전산구조공학회
1992년도 가을학술발표회 논문집

경계면 요소를 이용한 철근콘크리트 접촉면의 응력해석
Applications of Interface Elements to Contact Problems in Reinforced Concrete Structures

최 완철* 정 일영**
Choi, Oan Chul Jung, Il Young

ABSTRACT

경계면 요소를 이용하여 철근콘크리트 구조물의 접촉면 문제를 유한요소법으로 해석하는 기법에 대하여 연구한다. 본 연구에서는 경계면 요소의 수치해석의 이론과정을 전개하고, 실험 관찰된 부착 시험체에 적용하여 이형철근과 콘크리트 부착기구의 접촉면을 해석한다. 경계면은 특별한 연결요소를 이용하여 재현하며 Mohr-Coulomb의 마찰 이론을 응용한다. 해석의 주요점으로 하중상태에 따라 변화되는 경계면의 접촉상태, 즉 고정(stick), 미끄러짐(slide), 분리(separation)를 묘사하여 경계면 재료의 비선형 거동을 관찰한다. 부착모델의 해석결과는 실험실의 결과와 대체로 일치되며 따라서 철근콘크리트 접촉면의 응력해석을 위해 경계면 요소가 활용될 수 있음을 보여준다.

1. Introduction

Loading may cause parts of a structure to come in contact or to separate. Contact areas may change in size as loads change and weak layers may crack and allow slip, or separation. The layers behave with nonlinear response from the inelastic properties of the interfacial material. Special techniques are thus needed for the analysis of the inelastic interface behavior.

Many finite element analysis problems in structural engineering include interfaces between two or more bodies which may or may not be mechanically joined. Example problems for material interfaces include soil-structure interaction, a friction-type bolted connection, composite structures and many classical contact problems in engineering mechanics.[6]

Interface elements can be applied to solve the contact problems in reinforced concrete structures. Concrete-reinforcing bar interface can be modeled to examine the bond between the two different materials.[1],[3] The behavior of joints in precast large panel structures can be studied using nonlinear spring interface elements.[8]

The developments of finite element models for interface are presented in this paper. An application of interface elements to the analysis of reinforced concrete structures is described. Specifically, the results of the finite element analysis conducted to study the role of interface on the bond between reinforcing bars and the surrounding concrete are discussed.

* 숭실대학교 건축공학과 조교수
** 서울대학교 건축학과 교수

2. Simple Gap Model

Interface problems can be best explained with a simple gap model.[4] Consider two structures, separated by a gap that contains an elastic bumper spring. Before loading, the spring has a certain length of the gap. After closure of the gap, contact is made, then the bumper adds its stiffness to the existing structure stiffness. This situation can be handled by means of the following single d.o.f. element.

As shown in Fig. 1, K is the structure stiffness and k is the bumper stiffness. The force F in spring k is

$$F = 0 \qquad \text{if} \quad u < g \tag{1}$$

$$F = k\,(u - g) \qquad \text{if} \quad u > g \tag{2}$$

So the structure stiffness equation is

$$Ku = P \qquad \text{if} \quad u < g \tag{3}$$

$$Ku + k\,(u - g) = P \qquad \text{if} \quad u > g \tag{4}$$

or

$$(K + k\,(u - g)/u\,)u = P \tag{5}$$

The response of u is nonlinear because the stiffness is a function of u as in Eq.5. Incremental iterative procedure can be used for the solution of this nonlinear problem. The nonlinear load versus displacemant curve for the model is shown in Fig. 2.

3. Interface Model

3.1 Link Element

In the interfacial model forces are transfered from one body to another across an interface by normal stresses and tangential or shear stresses. Interface can be represented using a two-dimensional link element (Fig.3) placed at the contact surface across which slip occurs. These link elements have no physical length, but each element is assumed to act over a specified segment of the interface boundary denoted as the contact length and behaves as if it has a unit length and a unit width. The elements have a one degree of freedom tangent to the interface and one degree of freedom normal to the interface. Three nodes are needed to define the position and orientation of the elements. Nodes 1 and 2 are attached, respectively, to either side of the interface. Node 3 is a coordinate point that is used to define the orientation of the element. The coordinates of nodes 1 and 2 can be coincident, such as may be obtained with a zero thickness interface, or can be separated to represent a finite interfacial dimension.

3.2 Mohr-Coulomb Slip Surface

A key aspect of the interfacial model is the slip surface which defines the combination of normal and tangential stresses which results in movement across the interface. The interface can be represented by a Mohr-Coulomb slip surface (Fig.4). This model relates the normal stress, σ_n, to the shear stress, σ_s, across the interface as

$$|\sigma_s| = c - \sigma_n \tan\phi \tag{6}$$

in which c and ϕ are the cohesion and the angle of friction, respectively.

The behavior of contact problems can be classified into three distinct modes or states, a stick or nonslip, where both normal and tangential displacements are continous: a slip state, where normal and shearing stresses are related according to the specified slip surface; and a separation state, where the surfaces move apart. In the stick state, the magnitude of the tangential stress is lower than the limiting value, and there is no relative movement along the surface. While in the slip state, the magnitude of the shear stress has reached the limiting value on the slip surface corresponding to the current normal stress and that point on the surface, and the surface moves along the contact surface. The separation state, no normal contact force between the bodies exists, occurs as a result of tension and results in a gap between the surfaces.

The three behavior states for the interface are defined as follows:

Contact/stick

$$|\sigma_s| \leq c - \sigma_n \tan\phi \qquad (7)$$

Contact/slip

$$|\sigma_s| > c - \sigma_n \tan\phi \quad \text{and} \quad \sigma_n \leq \varepsilon \qquad (8)$$

Separation

$$|\sigma_s| > c - \sigma_n \tan\phi \quad \text{and} \quad \sigma_n > \varepsilon \qquad (9)$$

The parameter ε is a small tensile stress used to insure that Eq.9 is selected only when tension exists at the interface.

3.3 Constitutive matrix

The constitutive matrix of the interface element is defined for each of the three possible material states. It can be assumed that there is no volume change due to the shearing strains, if the relatively smooth crack surface exists between two different materials. Then, the tangential and normal components of deformation are uncoupled making them straightforward to model. The stiffness matrices corresponding to the three states of contact/stick, contact/slip, and separation are represented as

Contact/stick

$$K_{stick} = \begin{bmatrix} K_n & 0 \\ 0 & K_s \end{bmatrix} \qquad (10)$$

Contact/slip

$$K_{slip} = \begin{bmatrix} K_n & 0 \\ 0 & \mu K_s \end{bmatrix} + \begin{bmatrix} \alpha K_n & 0 \\ 0 & \alpha K_s \end{bmatrix} \qquad (11)$$

Separation

$$K_{sep} = \begin{bmatrix} \alpha K_n & 0 \\ 0 & \alpha K_s \end{bmatrix} \quad (12)$$

The parameter α maintains numerical stability by providing a small separation stiffness and a non-singular slip stiffness.

4. Reinforcing Bar-Concrete Interface

4.1 Bond Model

Finite element analysis is conducted to study the effects of interfacial properties on the bond strength of deformed reinforcing bars to concrete. The beam-end specimen (Fig.5) used in the experimental study[2),5)] is modeled in this study (Fig.6). The deformed bar-concrete interface is represented with the special link elements using the Mohr-Coulomb surface to match the stiffness and friction properties of the interfacial material.

The elastic properties of the interface can be adjusted. Before slippage, relative movement is resisted by the interface link element, and the relative movement is minimized using a large value of stiffness of the link element. Thus, the normal stiffness and tangential or shear stiffness defined as large value to preclude such slippage prior to reaching the failure surface.

4.2 Load-slip Response

The performance of the analytical model is examined on the basis of load-slip response. That response, as can be seen in load-slip curves, passes through different stages, corresponding to different material states of the steel-concrete interface.

As the applied load increases, the interface elements change their material states progressively. Innitially, all elements are in a stick state, but elements progress into slip or separation states depending on the location of the element along the deformation of the reinforcing bar. Fig.7 shows a typical load-slip curve and the progressive loss of tangent stiffness. Elements change their material states and become softer as load increases. Fig.8 illustrates the progressive change of the material states along the interface between the concrete and reinforcing bar. Sliding initiates in the front interface elements and advances toward the back. Separation follows in a similar way. Finally, all link elements separate, except for the elements on the compression side of the rib which remain in the slip state.

There are several components to movement along the interface including sliding, relative tangential displacement; offset, relative normal displacement (Fig. 9); and the absolute normal displacement due to compression of the concrete. In reality, the value of the offset should be zero. The relative movement normal to the interface can be minimized using a large value of stifnesses for the link elements as discussed before. Fig.10 shows the movement of the interface from the initial load to the peak load for the model. The offset is 0.00043 cm (0.00017 in.), which is small compared to 0.0094 cm (0.0037 in.) and 0.0127 cm (0.0050in)., the normal and the sliding movements, respectively.

Interfacial properties control the bond performance from the very beginning. Cohesion is lost in this stage. Friction along the compression side of the ribs mainly contributes to the bond force.

The material states no longer change as the load is increased further. The elements in a slip state continue to slide and the other elements remain in separation. The complete load slip curve reveals the change in nonlinear tangent stiffness up to the failure of the confined concrete.[1),3)]

5. Conclusions

Interface elements are applied to contact problems in reinforced concrete structures. The interface is represented with special link elements to transfer forces by shear and normal stresses. Mohr-Coulomb slip surface is used to define the combination of normal and shear stresses and the three material states of interface. Deformed bar-concrete interface is modeled to study the bond response. The model successfully simulates the progressive change of the interfacial material state and predicts the overall effects of the surface properties on the bond performance.

6. References

1) 최 완철, 비선형 유한요소법에 의한 에폭시 피막된 철근의 부착에 관한 연구, 한국콘크리트학회, 학술발표논문집, 1991, 5.

2) Choi, Oan Chul, Hadje-Ghaffari, H., Darwin, D., McCabe, S.L. "Bond of Epoxy-Coated Reinforcement to Concrete :Bar Parameters," ACI Material Journal, 1991, March, pp 207-217

3) Choi, Oan Chul.,"Bond Strength of Epoxy-Coated Reinforcement to Concrete, "Ph.D. Dissertation, University of Kansas, Lawrence, Kansas, 1990, July, 217 pp.

4) Cook,Robert D.,"Concepts and Application of Finite Element Analysis," John Wiley & Sons, pp. 363-366.

5) Darwin, D., McCabe, S.L., Choi, O.C., "Evaluation of Bond Performance of Epoxy-Coated Reinforcing Steel Using Nonlinear Finite Element Analysis," Proceeding, ASCE Material Congress, Denver, CO, 1990, August, pp.135-144.

6) Herrmann, L.R., "Finite Element Analysis of Contact Problems," Journal of the Engineering Mechanics Division, ASCE, Vol.104, No.EM5,1978, October, pp. 1043-1057.

7) Lopez,L.A., Dodds, R.H.Jr., Rehak, D.R.and Schmidt, R.J., Polo-Finite :A Structural Mechanics System for Linear and Nonlinear Analysis. A technical report by the University of Illinois at Urbana-Champaign, 1989.

8) Schricker,V.and Powell,G.H.,"Inelastic Seismic Analysis of Large Panel Buildings," U.C. Berkeley, EERC Report No.80-38, September, 1980.

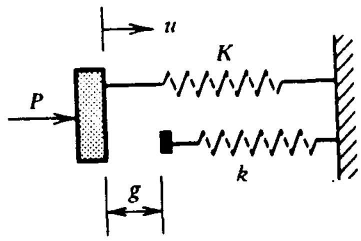

Fig. 1 Simple Gap Model (Ref. 4)

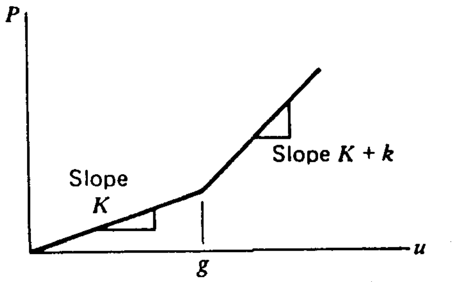

Fig. 2 Nonlinear Load versus Displacement Curve (Ref. 4)

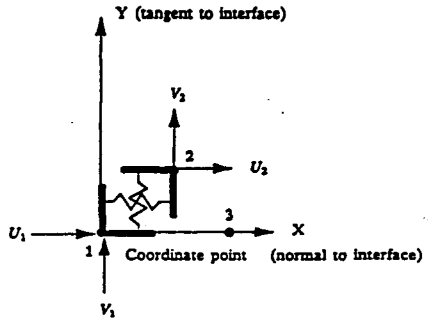

Fig. 3 Two-dimensional Link Element (Ref. 7)

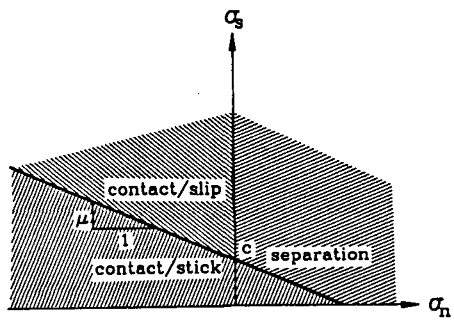

Fig. 4 Mohr-Coulomb Slip Surface

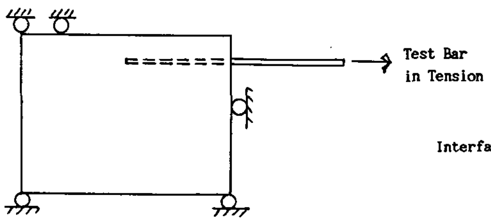

Fig. 5 Beam-end Specimen for Bond Test

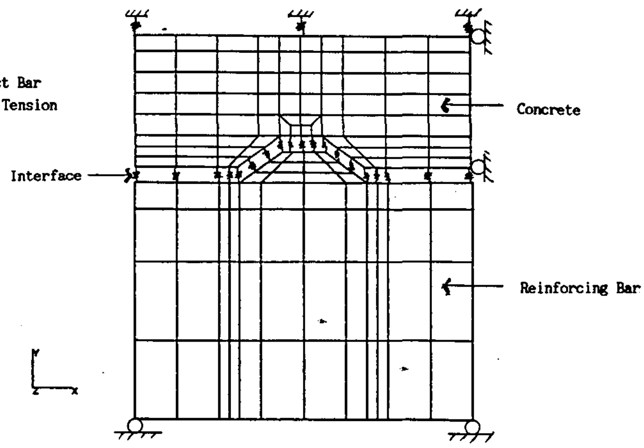

Fig. 6 Deformed Bar-concrete Interface Model

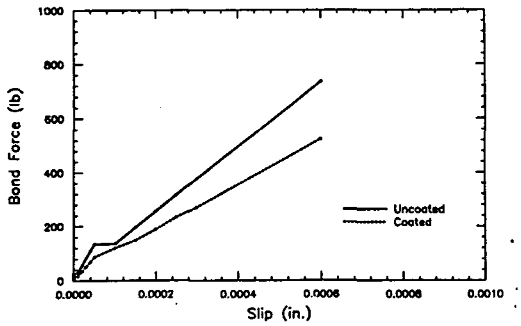

Fig. 7 Bond Force versus Slip Curve

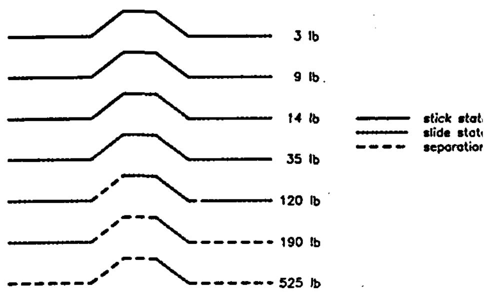

Fig. 8 Progressive Change of Material State along Interface

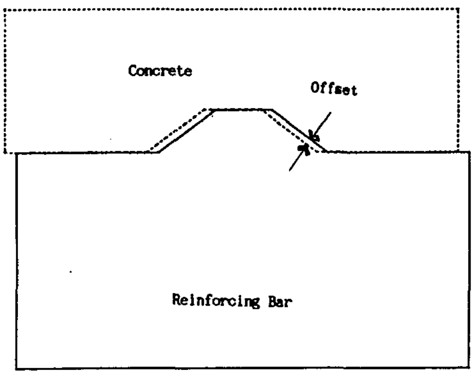

Fig. 9 Offset: Relative Normal Displacement to Interface

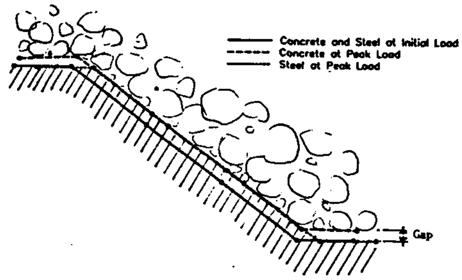

Fig. 10 Movement of Interface between Bar and Concrete