NEW RC PANEL ELEMENT WITH BOND-SLIP EFFECT

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ABSTRACT

A new panel element combining concrete and reinforcement panels with bond interface is introduced. Unlike classical contact element, reinforcement is distributed to the whole panel instead of concentrated on a line. In the new element, each concrete and reinforcement panels have 8 nodes and bond effect is modelled between the panels. The model combines the advantages of smeared crack model and bond zone element. The analysis of concrete and reinforcement panels is based on fixed-crack angle theory, and the bond-slip effect is described between concrete and smeared reinforcement panels. The effect of steel strain is included in the bond slip relationship between concrete and reinforcement. Verification of simple cases such as pull out test, and axial tension have been carried out. The results agree well with experimental data. The effect of element size was also studied in the case of pull out test. Through the comparison of results from different kind of meshes, it is proved that relatively few elements are necessary to simulate the case. This new panel element can be applied to include the bond-slip behaviour in the analysis of reinforced concrete elements.

1 INTRODUCTION

The bond between concrete and reinforcement is the basis of composite action between the concrete and reinforcement. In well-designed structures, the bond has enough strength to transfer the forces and the slip is very small, but for certain cases such as in gravity load-designed structures subjected to lateral loads, the strength and deformation of the structure may be determined by bond slip behaviour.

ACI 408 committee [1] listed 12 mains factors affecting the bond performance and several bond-slip models have been proposed (Ueda, et. al. [2], Eligehausen, et. al. [3], Okamura and Maekawa [4]). Among these models, Okamura and Maekawa's model can be applied to the post-yield range because of the introduction of the local steel strain in the relationship.

Two different elements have been typically proposed to include the bond-slip effect in the

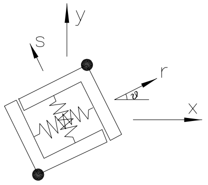


Figure 1 Bond link element

(Keuser and Mehlhorn [5])

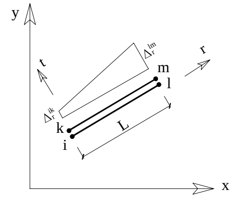


Figure 2 Bond zone element

(Keuser and Mehlhorn [5])

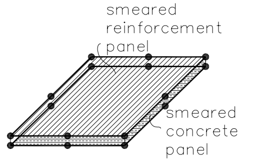


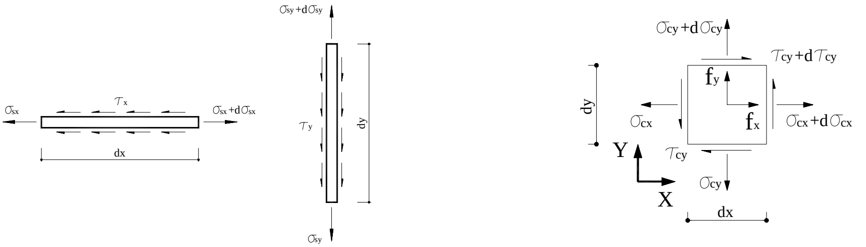
Figure 3

The new RC element

finite element analysis of RC structures. One is bond link element and the other is bond zone element as also known as contact element (Keuser and Mehlhorn [5]). Bond-link element consists of two orthogonal springs which connect and transmit shear and normal forces between a reinforcing bar node and an adjacent concrete node (Figure 1). Since the link has no physical dimensions, the two connected nodes originally occupy the same location in the finite element of undeformed structure. In the bond zone element, the contact surface between reinforcing bars are modeled by using a constitutive law, which represents the properties of the bond zone (Figure 2).

2 ANALYTICAL MODLE

Bond failure can be either splitting failure or pull-out failure. The new element is a 2D element and hence can not include the out-of-plane confinement. It only considers pull-out failure. The element has 8 nodes for each concrete and reinforcement panels, and these 16 nodes are also used to represent the bond effect between concrete panel and reinforcement as indicated in figure 3. In this paper, the bond-slip-strain relationship proposed by Okamura and Maekawa [4] is adopted.



Reinforcement in x-direction

Reinforcement in y-direction

Two-dimensional equilibrium of forces in the concrete

Figure 4 Two-dimensional equilibrium of forces in the reinforcing bars and concrete

2.1. Strong form

From the free bodies of reinforcing bars and concrete panel shown in figure 4, the equilibriumequations can be developed as

$$\frac{d\sigma_{cx}}{dx} + \frac{d\tau_{cxy}}{dy} + \frac{4}{d_{bx}}\rho_x \tau_x = 0 \qquad (1)$$

$$\frac{d\sigma_{cy}}{dy} + \frac{d\tau_{cxy}}{dx} + \frac{4}{d_{by}}\rho_y \tau_y = 0 \qquad (2)$$

$$\frac{d\sigma_{sy}}{dx} - \frac{4}{d_{by}}\tau_y = 0 \qquad (3)$$

$$\frac{d\sigma_{cy}}{dy} + \frac{d\tau_{cxy}}{dx} + f_y = 0 \qquad (4)$$

The constitutive laws include three parts: the constitutive laws for concrete, reinforcement and bond interface. All the constitutive laws are adopted from Okamura and Maekawa [4] based on fixed-crack angle theory.

2.2. Weak form

Equilibrium equations can be expressed in matrix form as

$$\partial_{tt}\sigma + EQ \cdot \tau = 0 \qquad (5)$$

where $\sigma = \{\sigma_{cx} \quad \sigma_{cy} \quad \tau_{cxy} \quad \rho_x \sigma_{sx} \quad \rho_y \sigma_{sy}\}^T$ $\qquad \tau = \{\tau_x \quad \tau_y\}^T$

$$\partial_{tt} = \begin{bmatrix} \frac{1}{\partial x} & 0 & \frac{1}{\partial y} & 0 & 0 \\ 0 & \frac{1}{\partial y} & \frac{1}{\partial x} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{\partial x} & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\partial y} \end{bmatrix} \qquad EQ = \begin{bmatrix} \frac{4\rho_x}{d_{bx}} & 0 \\ 0 & \frac{4\rho_y}{d_{by}} \\ -\frac{4\rho_x}{d_{bx}} & 0 \\ 0 & -\frac{4\rho_y}{d_{by}} \end{bmatrix}$$

Weighted integration method is introduced and the equation can be be simplified as

$$(K_{sc} - K_b)u = P \qquad (6)$$

where $K_{sc} = t \cdot \int_\Omega B^T \cdot D_{cs} \cdot B \cdot d\Omega$ $\qquad K_b = t \cdot \int_\Omega N^T \cdot EQ \cdot D_b \cdot T_s \cdot N \cdot d\Omega$

$$D_{cs} = \begin{bmatrix} E_{cx} & 0 & 0 & 0 & 0 \\ 0 & E_{cy} & 0 & 0 & 0 \\ 0 & 0 & G_c & 0 & 0 \\ 0 & 0 & 0 & \rho_x E_{sx} & 0 \\ 0 & 0 & 0 & 0 & \rho_y E_{sy} \end{bmatrix} \qquad D_b = \begin{bmatrix} E_{bx} & 0 \\ 0 & E_{by} \end{bmatrix} \qquad B = \partial_{tt}^T N$$

$$T_s = \begin{bmatrix} -1 & 0 & 1 & 0 \\ 0 & -1 & 0 & 1 \end{bmatrix}$$

$$\partial_{tt} = \begin{bmatrix} \frac{1}{\partial x} & 0 & \frac{1}{\partial y} & 0 & 0 \\ 0 & \frac{1}{\partial y} & \frac{1}{\partial x} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{\partial x} & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\partial y} \end{bmatrix} \qquad EQ = \begin{bmatrix} \frac{4\rho_x}{d_{bx}} & 0 \\ 0 & \frac{4\rho_y}{d_{by}} \\ -\frac{4\rho_x}{d_{bx}} & 0 \\ 0 & -\frac{4\rho_y}{d_{by}} \end{bmatrix}$$

3 VERIFICATION

3.1 Pull out test and axial tension test

3.1.1 Pull-out test by Ueda et. al. [2]

Four pull-out test specimens from Ueda et. al. [2] were used to check the performance of the new element. The data of the specimens can be seen in Table 1.

The specimen was modeled with 4 elements (Figure 5). Restraints were applied on the concrete panel, and uniformly distributed load was applied on the reinforcement panel. The relationship of load and slip at the loading end was compared with analytical results.

3.1.2 Axial tension by Doerr (Keuser and Mehlhorn [5])

In the axial tension test by Doerr, the embedded length of the specimen is 508 mm, the diameter of the bar is 16 mm, concrete strength is 37.2 MPa and yield strength of rebar is 420 MPa. The specimen was modeled with 13 elements as shown in figure 7. Restraints were applied on the concrete panel, and uniformly distributed load was applied on the reinforcement panel in Figure 6. The distribution of bar forces at load T=20kN, 40kN and 70kN from experiment was compared with analytical results (Figure 8).

Table 1– Test data

	Embedded length (mm)	Concrete strength (MPa)	Bar size (mm)	Yield strength of rebars (MPa)
S101	610	19.9	32	414
S107	610	18.2	32	331
S61	406	23.8	19	469
S64	610	28.7	19	438

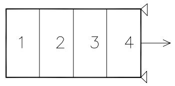


Figure 5. Modeling of pull out test

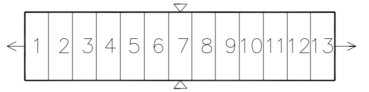
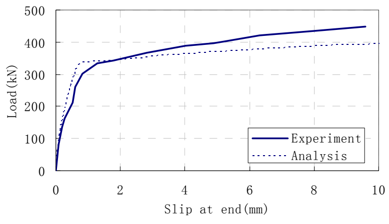
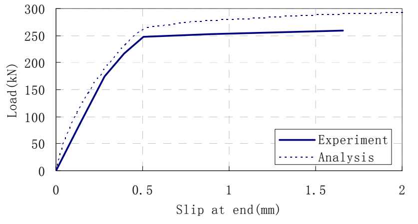


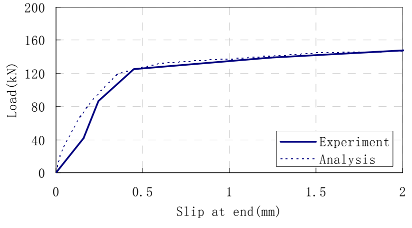
Figure 7. Modeling of pull out test



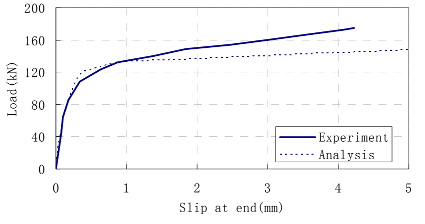
(a) Specimen S101



(b) Specimen S107



(c) Specimen S61



(d) Specimen S64

Figure 6. Comparison of experimental and analytical results for different specimens

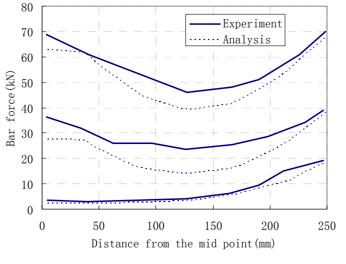


Figure 8. Comparison of bar forces between experiment and analysis

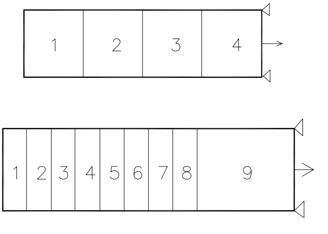


Figure 9. Two different meshes

3.2 Effect of element size

To study the effect of element size, the specimens were divided into different element number, and then the analytical results from two different meshes were compared. In pull-out test by Filippou (Soroushian et. al. [6]), the embedded length is 635 mm, the diameter of bar is 25.4 mm, concrete strength is 30 MPa and yield strength of rebar is 450 MPa.

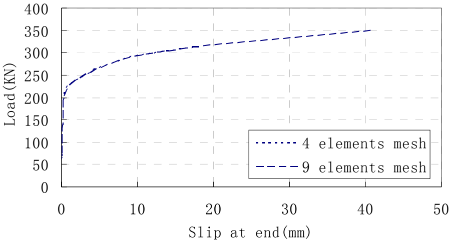


Figure 10. Comparison of two meshes

The specimen was modeled by 4 elements and 9 elements separately in figure 9. Restraints were applied on the concrete panel, and uniformly distributed load was applied on the reinforcement panel.

The simulated results from 4-element model and 9-element models were compared as shown in figure 10. It shows that 4 elements is enough to simulate the case of pull out test.

4 CONCLUSION

The paper presents a new reinforced concrete panel element with bond-slip effect. In the new element, double node is applied to simulate smeared concrete and smeared reinforcement panels separately, and the bond-slip effect are modelled between the two panels. The advantage of the element is to combine the advantage of smeared RC model and bond contact model. Through numerical verifications, it is proved that the new element can simulate bond problems such as pull out and axial tension tests quite well. The new element can also simulate the bond problem with realtively few elements.

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