Interface modeling between concrete and reinforcing-bars in RC members

Industrial Technology of Nihon University ○ Ming-Chien HSU
Tetukazu KIDA; Tadashi ABE
Toshiaki SAWANO; Yoshitaka OZAWA

1. Introduction

Finite Element Method (hereon; called the "FEM") is a way to simulate tests that done in laboratory. Also, the FEM is a way to help researchers to understand the internal part of the test specimens. Therefore, using the FEM to find out the bonding between concrete and reinforcing-bars (Hereon; called the "re-bars") would be suitable. This would help researchers to understand the bonding or interface relationship between the concrete and re-bars.

The authors created a three dimensional model of RC beam with the parameters from the standard specifications for concrete structures [1], CEB-FIP Mode Code 90 [2], and Diana manual [3]. Furthermore, the parameter of the interface elements and model structural would be the mean focus in this paper.

2. Test Materials, Specimen Sizes, and Test Method [4]

(A) Test Materials

Ordinary Portland cement and coarse aggregate with a maximum size of 20 mm were used for the concrete test specimens. The D16 re-bars of SD 295A type were used. The physical properties of concrete and re-bars are listed in Table 1.

(B) Specimen Sizes

The span of the RC beam test specimens was 2000mm and the overhangs were 400mm on each side that the total length was 2800mm. The width was 300mm, and the height was 210mm. Three D16 re-bars were placed at the tensile side and two D16 re-bars were placed at the compression side. The effective depth of the tension re-bars were 172mm. There was no shear re-bars in the test specimens. Fig. 1 shows the RC beam test specimens.

(C) Test Method (Static-Load Test)

Fig. 1 shows the location of the static-load test that was performed by the wheel-load (diameter 400mm and width 250mm) and stopped at the center of the test specimens. The load was increased from 0.0kN with 5.0kN increments until the test specimen broke. The deflection and the strain of the concrete and re-bars were measured at each loading.

3. Specimen Model and Material Properties and Analysis Procedure for FEM [3]

(A) Specimen Model for FEM

The three-dimensional of RC beam's model was created by DIANA that was half of the test specimens. Re-bars and interface were included in the model, as well. There were five layers of RC beam model that was one layer of concrete elements, one layer of interface elements, and so on. Each layer of concrete elements would be connecting with one layer of interface elements that shows in Fig. 2. A twenty-node isoparametric solid brick element was used for the concrete elements. The interface was an eight-by-eight nodes (plane quadrilateral) interface element between two planes in the three-dimensional configuration.

(B) Material Properties for FEM

For the concrete cracking, the Smeared-cracking modeling [1, 5 and 8] would be used that deals macroscopically with cracks and re-bars by expressing the average stress and average strain relationships in an element. The plasticity used for the concrete was Drucker-Prager [1 and 6] that is a smooth approximation of the Mohr-Coulomb yield surface, and is a conical surface in the principal stress space. The re-bars' plasticity was Von Mises [1, 6 and 7] that is a circular cylinder in the principal stress space.

RC部材におけるコンクリートと鉄筋の界面モデル

徐　銘謙、
木田　哲量、阿部　忠、澤野　利章、小澤　善隆

Table 1 Properties of concrete and re-bars [4]

Test Specimen	Concrete compressive strength (N/mm^2)	Reinforcement Bar (SD295A / D16) Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Young's modulus (kN/mm^2)
	38.5	368	568	200

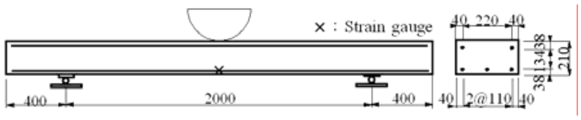


Fig. 1 Specimen size and arrangement of re-bars [4]

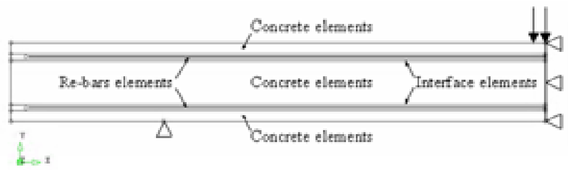
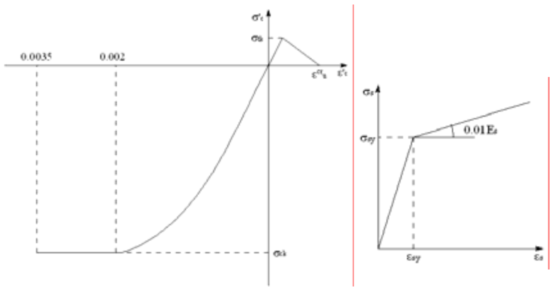
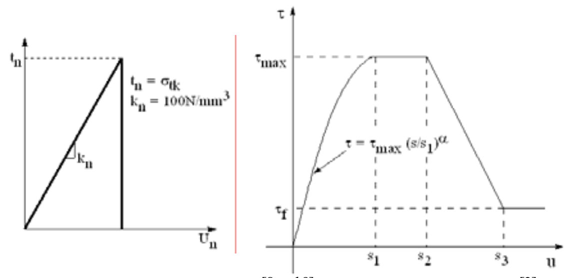


Fig. 2 RC beam model and mesh



(a) Concrete's stress-strain (b) Re-bars' stress strain

Fig. 3 Stress and strain relationship [2]



(a) Discrete cracking model [8 and 9] (b) Bond-slip model [3]

Fig. 4 Stress-relative displacement relationship for interface elements [3, 8 and 9]

$$\sigma_{tk} = 0.23\sigma_{ck}^{2/3} \qquad (1)$$

Where,

σ_{tk}: Tensile strength (N/mm^2);

σ_{ck}: Compression strength (N/mm^2).

$$\varepsilon_u^{cr} = 2G_f / \sigma_{tk} h_{cr} \qquad (2)$$

Where,

ε^{cr}_u: Ultimate strain,

G_f: Fracture energy (Eq. 5; N/mm);

h_{cr}: Crack band-width (mm).

$$\sigma'_c = \sigma_{ck} * \frac{\varepsilon'_c}{0.002} * \left(2 - \frac{\varepsilon'_c}{0.002}\right) \qquad (3)$$

Where,

σ'_c: Stress for compression (N/mm^2);

ε'_c: Strain for compression (≤ 0.002).

$$\tau = \tau_{max}(S/S_1)^\alpha \qquad (S \leq S_1) \qquad (4)$$

Where,

τ: Bond stress (N/mm^2);

τ_{max}: Maximum bond stress ($=2.0(\sigma_{ck})^{1/2}$; N/mm^2);

τ_f: $0.15\tau_{max}$ (N/mm^2);

α: 0.4;

S: slip (S_1=0.6; S_2=0.6; S_3=1.0; mm).

$$G_f = 10(d_{max})^{1/3} \sigma_{ck}^{1/3} \qquad (5)$$

Where,

d_{max}: Aggregate size (mm).

(1) Concrete parameter

(a) Tension strength

The tension strength was calculated from the compression strength, and shows in Eq. 1 that was from the Standard Specifications for Concrete Structures. [2] For the concrete tension softening curve, the linear tension softening was chosen from DIANA's manual [1]. The ultimate tension strain in the softening curve is shown in Fig. 3 (a), and Eq. 2 is the calculation for the ultimate strain in the tension softening curve. The shear retention should also consider into the cracking modeling, and the full shear retention was used in the modeling of concrete cracking. In the other hand, the shear modulus did not reduce in the calculation.

(b) Compression strength

The uniaxial compression test had been done in the laboratory. The compression strengths are list in the Table 1 for the RC beams. However, the characteristic of the compression curve need to be adopted from the Standard Specifications for Concrete Structures. The equations and compression curve are listed in Eq. 3 and Fig. 3 (a), respectively. The Young's modulus and yield strength, was 1/3 of compression strength, were found in the Standard Specifications for Concrete Structures, too.

(2) Re-bars' parameter

The strain-stress curve of re-bar was bi-linear and embedded in interface elements. After the re-bars' yield strength, the slop of 0.01Es would be used. Fig. 3 (b) shows the properties of re-bars.

(3) Interface parameter

There were two parameters for the interface elements that were discrete cracking model and bond-slip model. Fig. 4 shows both parameters. For the linear stiffness modules, there were two stiffness modules that were normal stiffness and shear stiffness. The normal stiffness was between the normal traction and normal relative displacement. The shear stiffness was between the shear traction and the shear relative displacement. Moreover, the both normal and shear stiffness (k_n) would be set as 100N/mm^3 [8 and 9].

(a) Discrete cracking model

The relationship between the tensile strength (t_n) of discrete cracking and the displacement (u_n) is shown in Fig 4(a). The discrete cracking, is based on a total deformation theory, was used for the cracking modeling in the interface elements. The tensile strength (t_n) was same as the concrete tensile strength (σ_{tk}). The brittle behavior was used after the cracking developed. The shear criterion that used in the crack development stage was setup to be zero.

(b) Bond-slip model

The Bond stress-slip relationship was used for the interface elements between the concrete elements and the re-bars' elements. Moreover, the bond-slip model was splitting of concrete cover condition that the failure was due primarily to the tensile redial stresses caused by the lug-bearing forces. Therefore, the bond-slip parameter [3] used in this modeling was unconfined concrete with good bond conditions. Fig. 4 (b) shows the relationship for the bond stress (τ) and the slip distance (S). Eq. 4 shows the calculation of the bond stress-slip curve.

(C) Analysis Procedure

The load steps were used for the non-linear analysis calculation, and the increment for the step was 5kN. For the iteration processing, Quasi-Newton method [1], uses the information of previous solution vectors and out-of–balance force vectors during the increment to achieve a better approximation, would be used with displacement and force norms for convergence criteria. Ten interactions would be used for each load steps, and convergence tolerance would be 0.001.

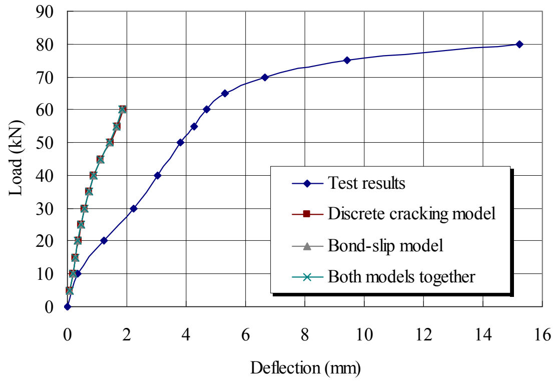


Fig. 5 Deflection and load relationship

4. Test and the modeling Results

The results for the test would be three test specimens' average and the deflection at the center of the span was been measured. The results for test and modeling are show in Fig. 5.

(A) Test Results

The test specimens failed around 80kN. The re-bars reach its yield point around 65kN to 70kN. The compression re-bars started to turn into tension when the loading was around 55kN. The initial cracks started between 10kN to 20kN.

(B) Modeling Results

The interface model had included the re-bars, and also, had connected two layers of concrete elements. By considering the interface parameter, authors tried to combine the discrete cracking model and the bond-slip model together. Therefore, there were three inputs for the parameters that were discrete cracking model, bond-slip model, and combine discrete cracking and bond-slip models together. Moreover, in the Specification [2], the failure strain of the concrete compression strength is -3.5×10^{-3} at the ultimate limit state. Therefore, the stop criterion was set at the maximum principal strain of -3.5×10^{-3} in the integration points of concrete elements [1 and 2].

All three models stopped the calculation at 60kN which means that one of the mesh concrete elements had reached to the maximum principal strain. The concrete element that reached to the maximum principal strain was located near at the support. The tensile re-bars reached to its yield between 40.0kN and 50.0kN for all three inputs. The tensile strength was reached when the loading over 50.0kN for all three inputs. At the end, all the inputs had the re-bars strength of 5.737E-03.

5. Conclusion

(1) The model of the RC beam was 5 layers which had one layer of concrete element, one layer of interface element, and so on. In this case, the linear stiffness modules that used in the interface elements will affect the calculation. It is because the higher of the stiffness would let the interface elements become more stiffens. That was why the deflections were small in the modeling.

(2) The stop criteria for the modeling were based on the maximum principal strain of -3.5×10^{-3} in the integration points of concrete elements. The mesh concrete element that reached this stop criterion was located near at the support. It is because the model was set up to be on layer of concrete elements, one layer of interface elements, and so on. This would let the Diana treated the lower layer of concrete elements as one full section that connect with the middle section of the concrete elements by using interface elements.

(3) The interface modeling for the re-bars should be setup around the re-bars instead of a full layer in the model. It was because the parameter for the interface elements between the concrete and the re-bars was bond-slip relationship. However, the interface elements in this modeling was included the re-bars in it and connected two separate layers of concrete elements. Therefore, the interface modeling should just focus on the relationship between concrete and re-bars or the relationship between concrete and concrete as crack developed.

(4) All the results for the modeling were stop at 60kN and similar to each other. The deflection was less than the test results. This means that the linear stiffness in the interface elements was too stiffening. Therefore, the deflection was increase nearly in a straight line. Moreover, the interface elements should not be a full layer that included the re-bars and connected two layers of the concrete elements together. Again, the interface should be around the re-bars and use bond-slip model or simulated as cracks in the concrete by using discrete cracking model.

(5) The three input parameters for the interface were failure at same loading and had same displacement results. These results showed that the both normal and shear stiffness of the interface were too high. It should be reduced, so that, the results of the three input parameters would be different.

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