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EFFECT OF BOND CHARACTERISTICS OF REBARS ON LOAD-DISPLACEMENT RELATIONSHIPS FOR RC MEMBERS

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Abstract

In this paper, bond characteristics of deformed bars in reinforced concrete members will be described. Load-displacement relations of RC members subjected to cyclic excitations are expected to be spindle or fat shape with good energy dissipation. However, some members would show slip behavior or narrow shape in load-displacement relations if they had low shear capacity. The capacity for bond stress between reinforcing bars and concrete can be evaluated by considering concrete compressive strength, quantities of transverse reinforcement and dimensions of cross section of the members especially width of section and thickness of cover concrete for reinforcing bars. The average bond stress of main bars in RC beams can be calculated from yield strength of the bars and shear span of the beams. The bond margin can be defined as the ratio of bond capacity on average bond stress. On the other hand, in RC beam with slab, stress condition of main bar in lower layer would be more critical than that in upper layer for both compression and tension.

Three specimens of T shape beams with varied bond margins were tested statically in previous research. In this paper, effect of bond margins on restoring force characteristics of the previous test specimens were discussed, finite element analyses were conducted for these specimens, and the analytical results were compared with experimental ones.

In the previous test, slip phenomena which was defined as relative displacement between main bars and core concrete in longitudinal direction was observed only in specimen with lowest bond capacity, especially in lower layered bar, though in other specimens, there were no slip observed. Based on these results, three dimensional nonlinear FE analyses were conducted in this research. One of the main features of FE model in this research was bond element for main bars. The bond elements were inserted between main bars and concrete elements, which had nonlinear bond stress-displacement relations as its constitutive model.

Analytical results were compared with experimental ones by many variables, for example, deformations, flexural and shear components, equivalent viscous damping ratio, stress distributions of main bars and bond stress and slip relations. Analytical results were corresponding well to the experimental ones and slip behaviors of the specimen with lowest bond capacity were also observed analytically. One of the features of them was that, in both analytical and experimental results, it was observed that the flexural and shear components of deformation were related to bond margin. In the specimen with lowest bond margin, shear components of deformation was larger than flexural ones. And also in both analytical and experimental results, slip behaviors were observed in the flexural deformations and load and flexural deformation relationship showed narrow shape with worse energy dissipation.

Keywords: Reinforced Concrete; Bond between Rebar and Concrete; Restoring Force Characteristics; FE Analysis

1. Introduction

Load-displacement relations of reinforced concrete members subjected to cyclic excitations are expected to be spindle or fat shape with good energy dissipation as represented by TAKEDA model [1]. However, some members would show slip behavior or narrow shape in load-displacement relations if they had low shear capacity. Slip behaviors in load-displacement relations are caused by some reasons and bond characteristics between main bars and concrete might be one of the reasons.

In this paper, non-linear finite element analyses are conducted for static loading tests of RC beam with slab which has been carried out previously [2-4]. The effects of bond characteristics of main bars and concrete on hysteresis curves of RC beams with slab are examined by comparing analytical and experimental results. This paper is based on and is additional study of previous paper [5].

2. Bond Behaior and Restoring Force Characteristics

As shown in Fig. 2.1, neutral axis of T-shaped reinforced concrete section subjected to bending moment moves to slab side from the middle of the depth. Thus, stress and strain of bottom reinforcing bars become higher than those of top bars under both positive and negative bending moments. It means that, the reinforcement located opposite to slab might be subjected to high stress condition including bond.

In previous researches conducted by the authors, slip behavior in load-displacement relations of RC members with slab were observed. Figures 2.2 shows relationship between bond stress of longitudinal bars through beam-column joint and beam rotation angle observed during shaking table test of 20 story RC building [6]. “#3-2” and “#3-5” are representing shaking test cases. In the case of #3-5, largest input wave was used in the test. Although flexural yielding was observed at beam end and bond stress was lower than bond strength, the slip behaviors were observed significantly in bottom bars rather than top bars as shown in Fig. 2.2.

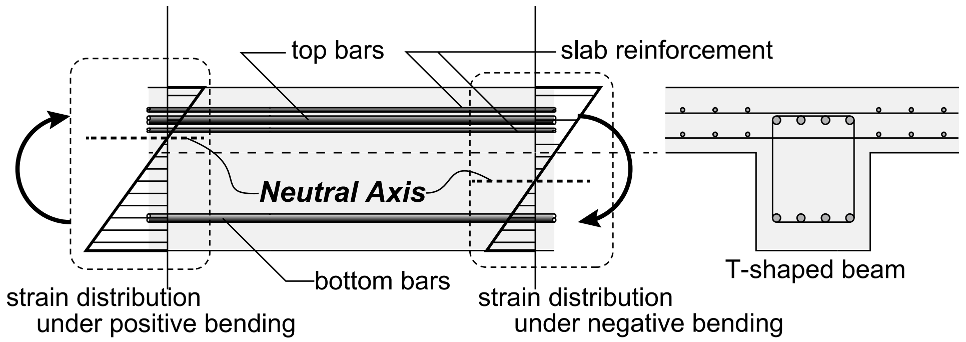
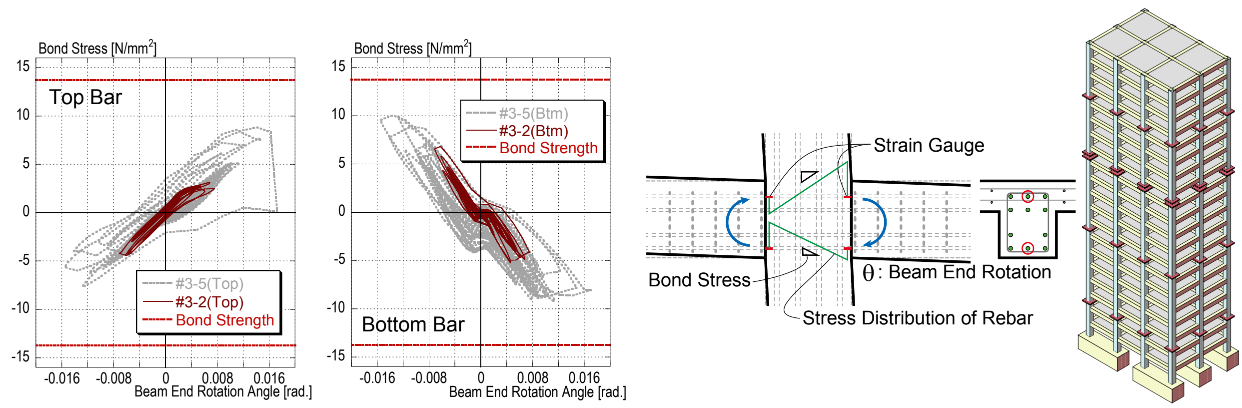


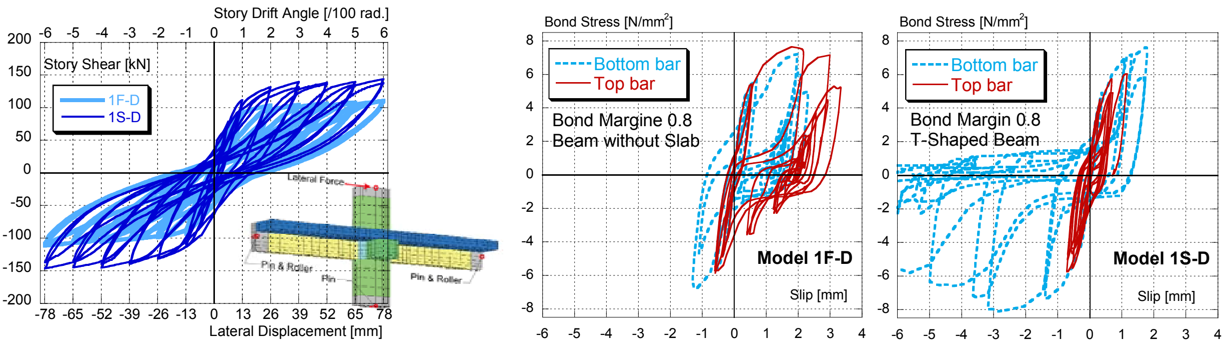
Figure 2.1 Strain Distributions at Critical Sections of T-shaped Beam under Bending



(a) Observed Bond Stress - Rotation Angle Relations (b) Diagram of Beam-Column Joint and Specimen

Figure 2.2 Bond Characteristics of Main Bars Observed during Shaking Table Test [6]

Figure 2.3 shows the restoring force characteristics and bond behaviors in the previous researches [7]. Finite element analyses were conducted for beam-column joint models with/without slab. From the analytical study, it was derived that in the model of T-shaped beam-column joint, which has slab, the bond stress and slip of bottom bars were larger than those of top bars, while in the beam-column joint without slab, there were few different between top and bottom rebar's bond characteristics.



(a) Restoring Force Characteristics (b) Relationship between Bond Stress and Slip of Main Bars

Figure 2.3 Results of Inelastic FE Analysis of Beam-Column Joint Models [7]

3. Outline of Previous Experimental Tests

In this chapter, outline of static loading tests conducted previously [2, 3, 4] is described. The static loading tests were carried out as a part of the test programs in the research project of study on seismic safety for RC structures under long period ground motions. The test specimens were modeled as RC beams with slab of intermediate story of ultra-high rise RC building.

3.1 Test Specimens

Properties of test specimens are summarized in Table 3.1, and Table 3.2 lists material properties for the specimens. Geometry and reinforcement of the test specimens, and loading system of the test are illustrated in Figure 3.1 and Figure 3.2, respectively.

Purpose of the research was to study effect of long period ground motions on RC members, and bond capacity was focused on. Six specimens with the same cross section and bar arrangement were planned. The variables of them were shear span to depth ratio and loading program. In the previous test, three level bond capacities were chosen, and two specimens were constructed for each level. These two specimens subjected to different loading cycles. One of them was 10 times loading cycles for one amplitude, and the other was twice for each amplitude. In this paper, three specimens with different shear span are studied. As shown in Table 3.1, by changing the shear span, bond margin to the flexural yielding varied from 1.0 to 1.9. One of the main features of the test was measuring relative displacement between main bars and core concrete. The relative displacement was assumed to be caused by slip behavior. As described in detail in the following chapter, at the mid span long bolts were welded to main bars and relative displacement between the bolts and another bar anchored in core concrete was measured.

Table 3.1 Properties of Test Specimens

Specimen	B3N	B2N	B1N
Beam Width [mm] × Depth [mm]	300 × 360		
Main Bars	4+2-D16(SD490) Top/Bottom		
Stirrup	4-D6@75mm(SHD685)		
Slab Thickness, Bar Arrangement	t=100mm, D6@150mm(SD295A)		
Beam Length L_0[mm]	1000	1400	1800
Shear Span to Depth Ratio	1.4	1.9	2.5
Bond Margin to Flexural Capacity	1.0	1.5	1.9

Table 3.2 Material Properties

(a) Concrete

	B3N	B2N	B1N
σ_B	62.7	65.8	61.1
Ec	34000	38800	36800
σ_T	4.14	4.28	3.73

(b) Reinforcing bars

	D16(SD490)	D6(SHD685)	D6(SD295A)
usage	main bars	stirrup	slab rein.
σ_y	536	697	409
Es	204000	192000	216000

σ_B: compressive strength, Ec: Young's modulus of concrete, σ_T: splitting strength, Unit [N/mm^2]

σ_y: yield stress, Es: Young's modulus of reinforcement

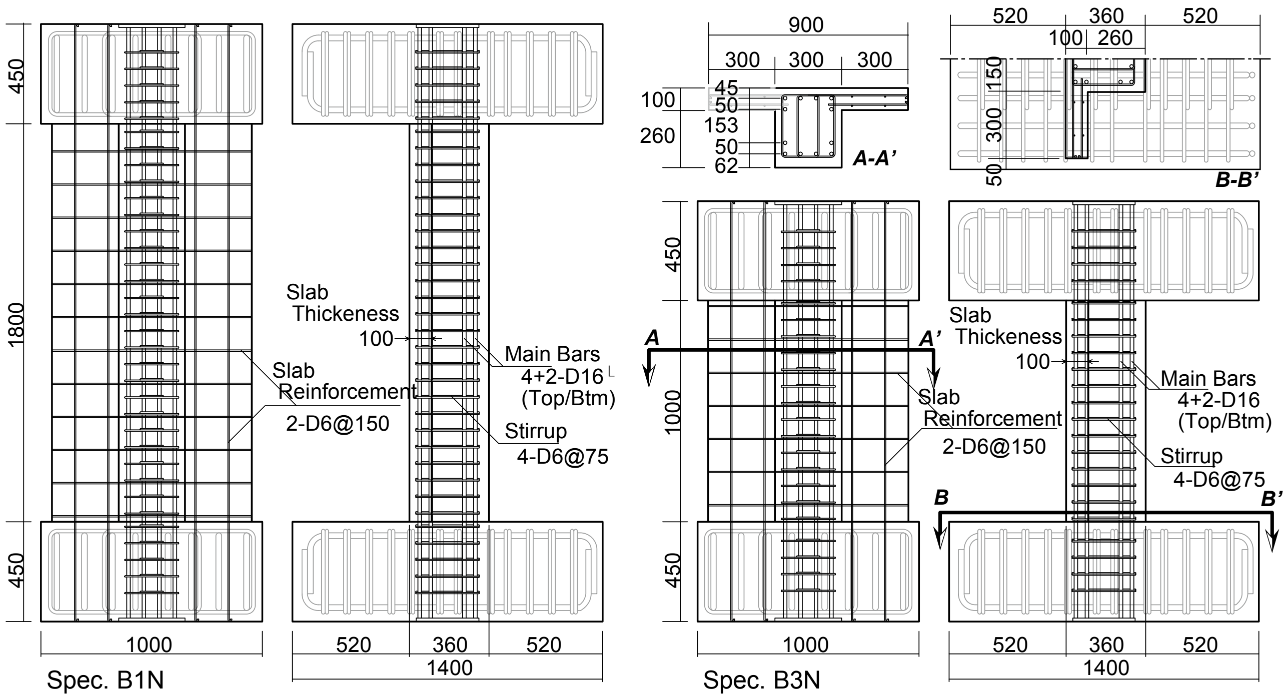
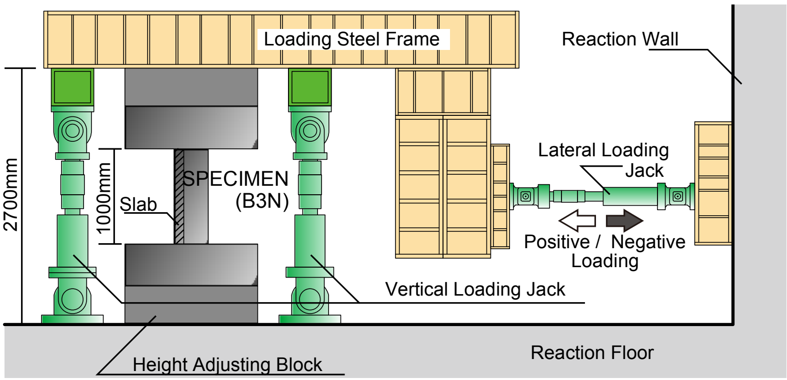


Figure 3.1 Geometry and Reinforcement of the Test Specimens



All specimens subjected to reversed cyclic lateral load by the lateral loading jack.

By controlling two vertical loading jacks, loading steel frame and reaction floor were kept parallel.

Figure 3.2 Loading System of the Test

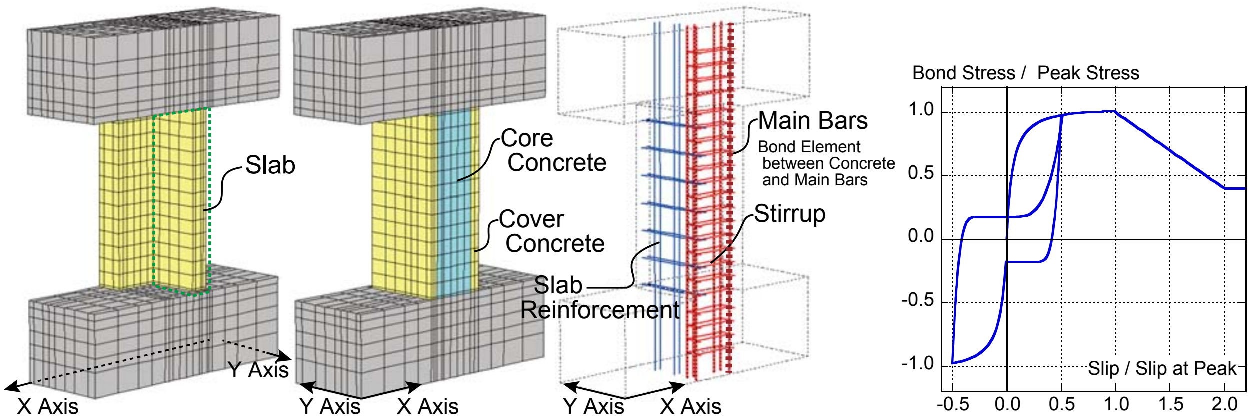
3.2 Outline of Test Results

For all specimens, tensile yielding of main bars were observed through rotation angle R=1/100 to R=1/67 cycles. In specimen B3N, splitting cracks were observed remarkably and shear capacity dropping was observed at large displacement loading cycles, while the other two specimens were stable until the end of the test. Details of the test results will be described in following chapters compared with analytical results.

4. Nonlinear Finite Element Analysis

4.1 Analytical Models

The analyses were conducted using FINAL, a finite element program developed for concrete structures [8, 9]. Figure 4.1 illustrates FE mesh and boundary conditions of analytical model. Half part of the specimen was modelled by using symmetrical condition. Concrete was modelled using six-node hexahedral elements and reinforcing bars were modelled using truss elements. Four-node joint type elements were inserted between one ridgeline of hexahedral element and truss element of main bar for the purpose of considering bond slip behavior between concrete and main bar. Example of bond stress - slip relations of joint type element are shown in Figure 4.1(b). The maximum bond stress in the beam was defined as bond splitting strength [10], and slip at peak was assumed to be 1.0mm for all elements.



(a) Element Mesh of Specimen B3N (b) Bond - Slip Relations

Figure 4.1 Analytical Model

4.2 Loading Conditions

In the experiment, specimens were subjected to reversed cyclic lateral load keeping top and bottom stab as parallel. The boundary conditions of FE analysis in this paper were same as those of experiment, i.e. the top surface of the stab was kept parallel to the bottom surface. Rotation angle R is defined as horizontal displacement at the top of the specimen δ_H divided by beam length L_0. Loading cycles in the FE analyses were almost same as the experiment except small amplitude loading cycle after larger one. For example, R=1/200 cycle after R=1/50 cycles were not calculated in FE analysis.

5. Comparisons of Test and Analytical Results

5.1 Crack Patterns and Load-Displacement Relationship

Example of crack patterns of analytical and experimental results are shown in Fig. 5.1. Experimental load - displacement relation of each specimen is compared with analytical result as shown in Fig. 5.2. For all specimens, flexural yielding at beam end was observed in both analytical and experimental results. Regarding maximum and flexural yield strength, analytical results were slightly larger than experimental ones in specimen B2N and B1N, though the analytical results of specimen B3N showed good accordance with experimental ones. For all specimens, slip behavior and changing of stiffness were observed remarkably in experiment, where those behaviors were not remarkable in analyses. From these points of view, further research must be conducted to improve accuracy of analysis.

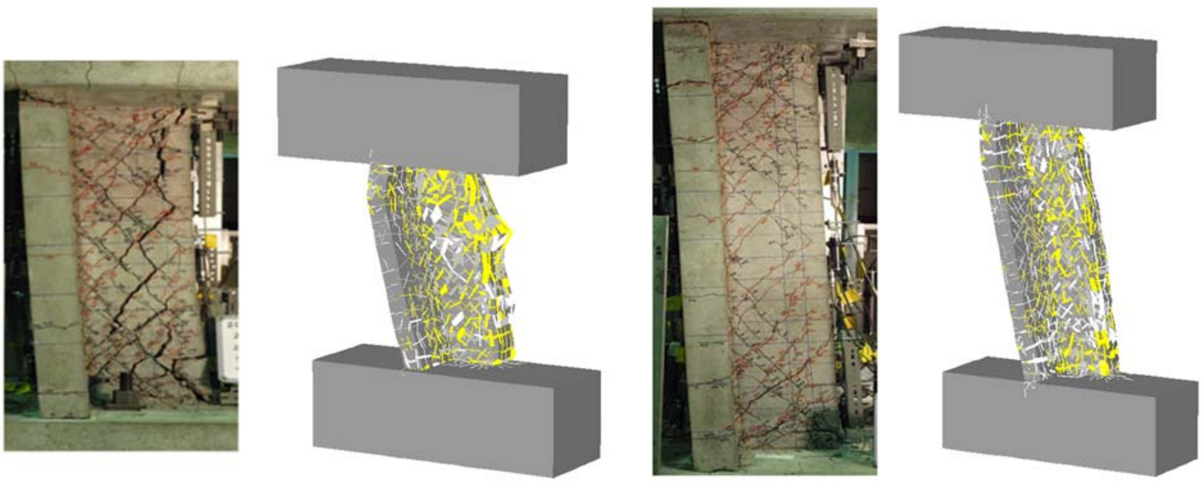
Figure 5.3 shows the comparisons of equivalent viscous damping ratio h_{eq}. Equivalent viscous damping ratio h_{eq} can be calculated by following equation. Broken and solid lines named as “TAKEDA” and “Slip” in Fig. 5.3 are representing calculation by TAKEDA model[1] and TAKEDA Slip model [11], respectively.

$$h_{eq} = \frac{1}{4\pi} \cdot \frac{\Delta W}{W_e} \quad \cdots\cdots\cdots\cdots (1)$$

where, ΔW: hysteretic energy dissipation,

W_e: elastic strain energy, $= D_m \cdot Q_m/2$

(D_m, Q_m): displacement and shear force at cycle peak as shown in Fig. 5.3(c)



(a) B3N (Exp.) (b) B3N (FEM) (c) B1N (Exp.) (d) B1N (FEM)

Figure 5.1 Crack Patterns of Specimens

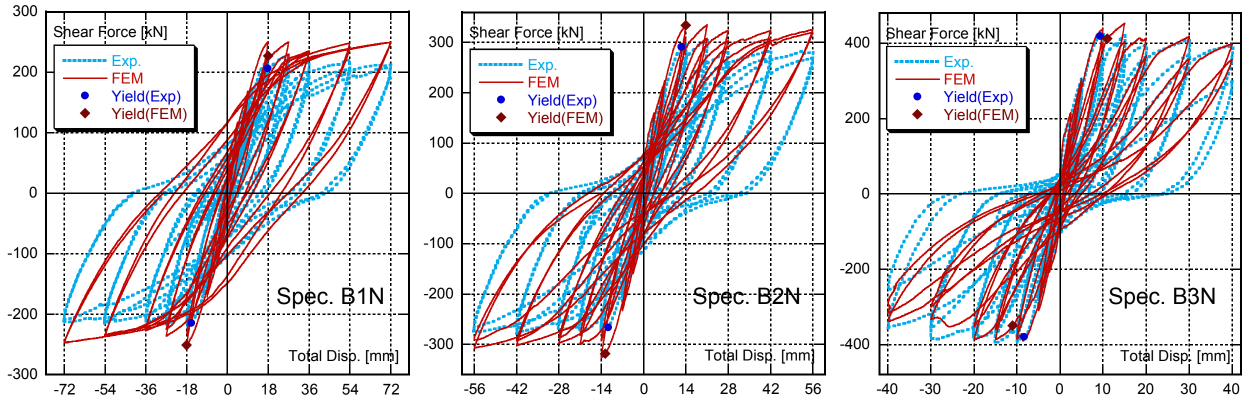
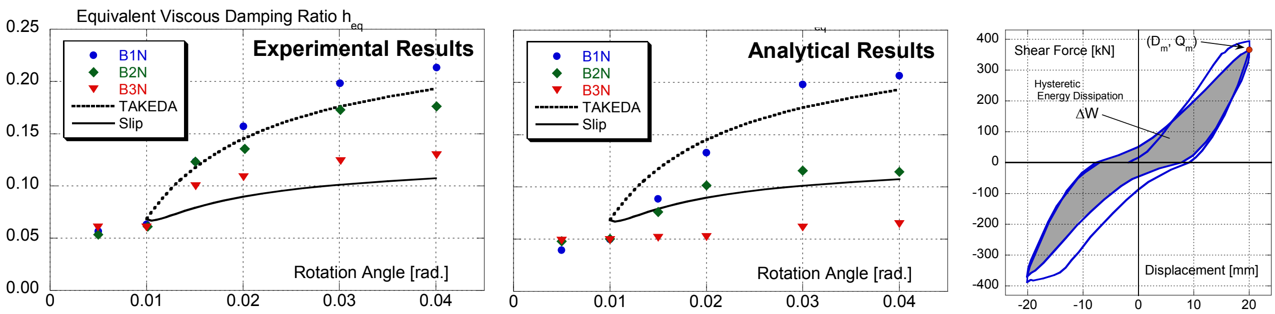


Figure 5.2 Comparisons of Load-Displacement Relations



(a) Experimental Results (b) Analytical Results (c) Example of Calculation

Figure 5.3 Transition of Equivalent Viscous Damping Ratio

Regarding specimen B2N and B3N, analytical results of h_{eq} underestimated to experimental results. Although, analytical result of specimen B1N showed good accordance with experimental result. And regarding specimen B3N, not only in analysis but also in experiment, h_{eq} is lower than TAKEDA model. It means that, the beam with low bond capacity shows low energy dissipation capacity. And these figures show that, for all specimens, FE analysis could estimate energy dissipation capacity conservatively.

5.2 Bond Characteristics

In the experiment, local strains of longitudinal bars were measured by strain gauges at from 6 to 8 points for each bar. The measured strain can be calculated to stress by using inelastic cyclic model after yielding. In this study, Menegotto-Pinto model was used [12]. Examples of stress - strain relations from the calculation by the model are shown in Fig. 5.4. Figure 5.5 shows comparisons of analytical and experimental results of main bar stress distributions for specimens B1N and B3N. The results of specimen B2N showed almost same tendency as specimen B1N. Except compression stress of specimen B1N and B2N, analytical results corresponded well to the experimental results. It is surmised that non-correspondence of the compression stress caused overestimation of shear force of these two specimens in Fig. 5.2.

Bond stress could be calculated from axial stress of two adjacent point at the middle of the span. And in the experiment, relative displacement between core concrete and main bar was measured at the center of the span as shown in Fig. 5.6. From these two series of data, bond stress - relative displacement relations were shown in Fig. 5.7. Bond stress and slip in the analysis were derived as average of some elements located almost the same area of the experiment. In the experiments, large slip behavior was observed at only bottom bar of specimen B3N at large loading cycles. In the analyses, large slip was observed in specimens B3N and B2N. Especially in B3N, slip behavior of bottom bars corresponded well to the experimental results. From the comparisons of them, bond stress conditions at bottom bars became more severe than those at top, and it caused slip these behaviors.

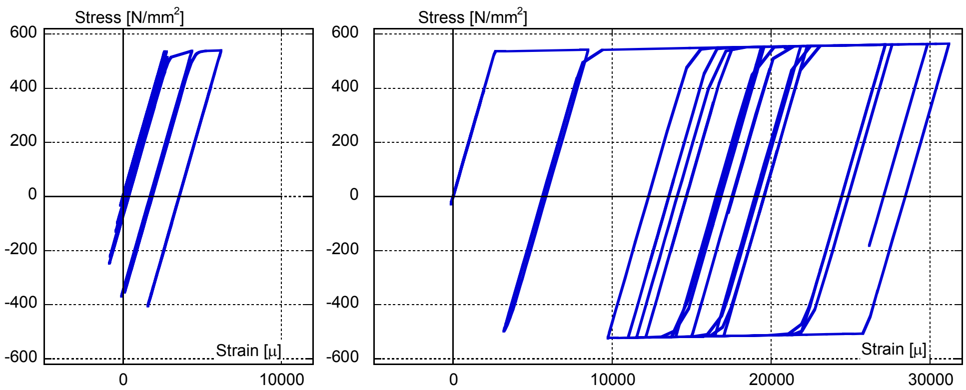
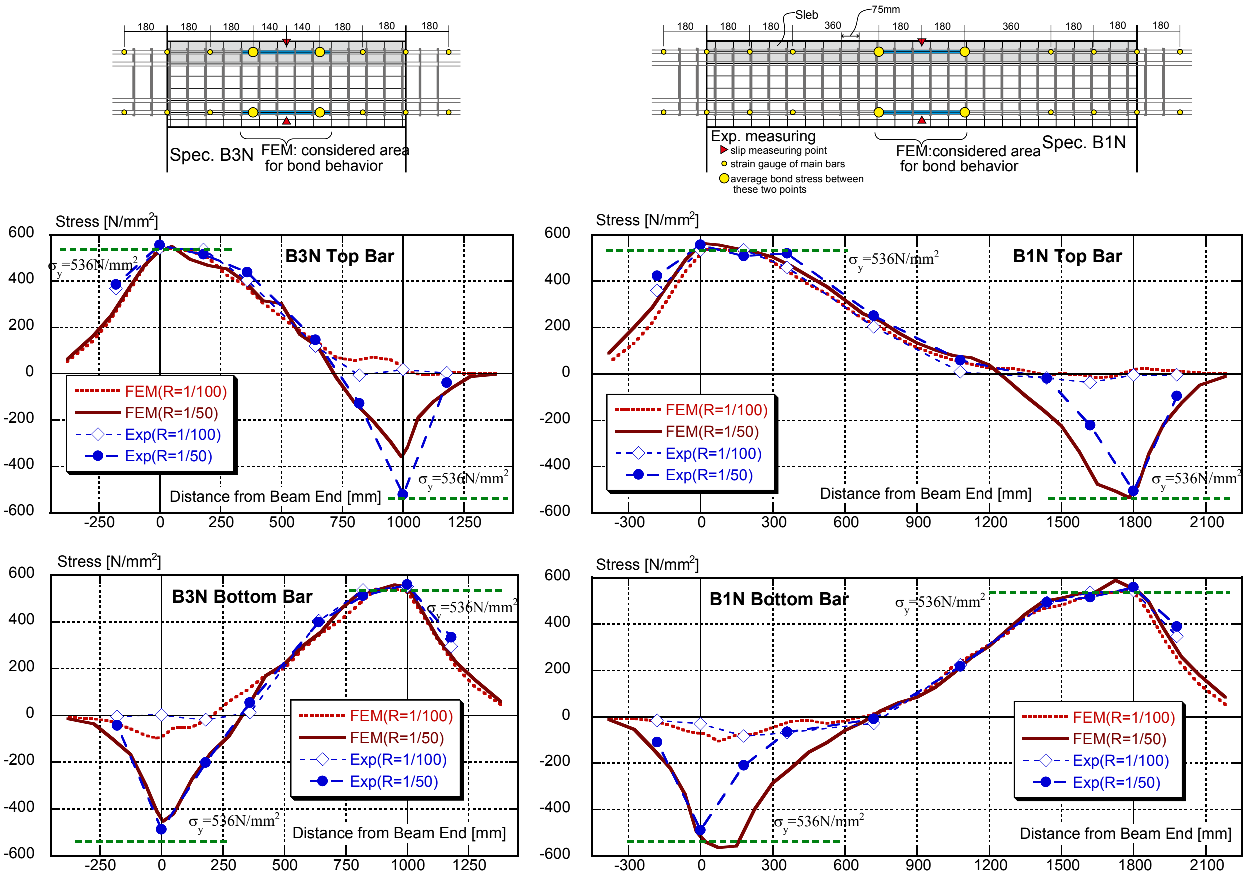


Figure 5.4 Samples of Stress - Strain Relationship



(a) Specimen B3N (b) Specimen B1N

Fig. 5.5 Comparisons of Analytical and Test Results of Stress Distribution of Main Bars

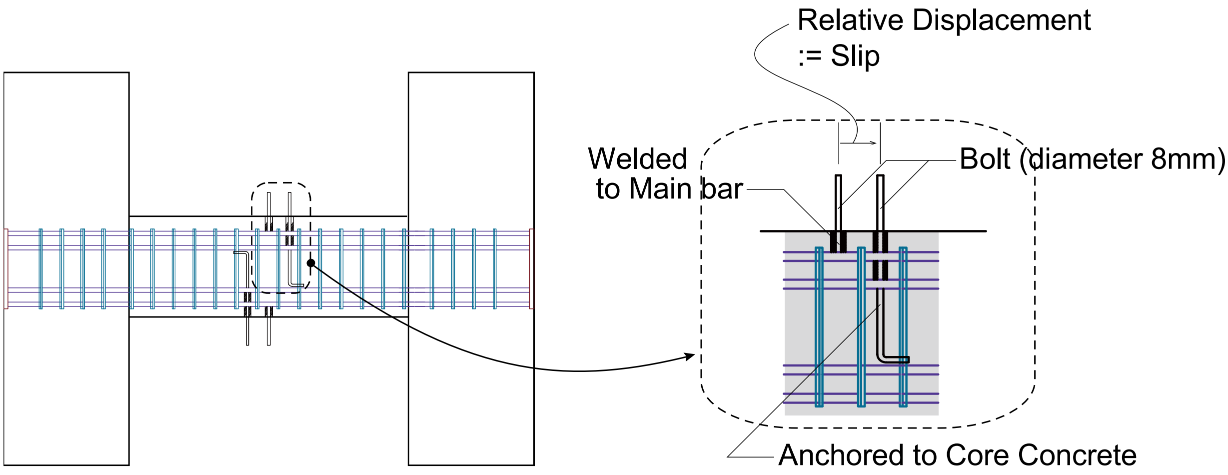
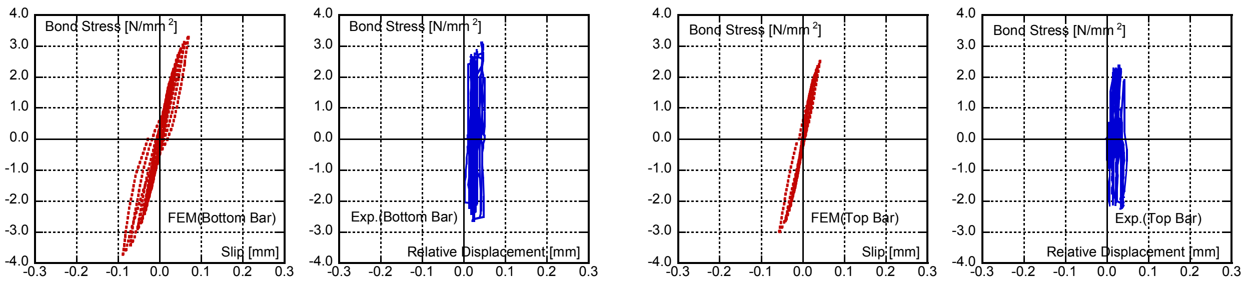
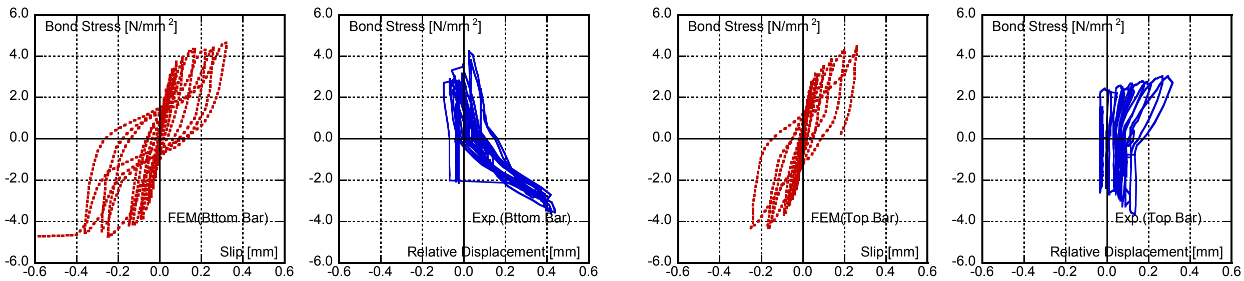


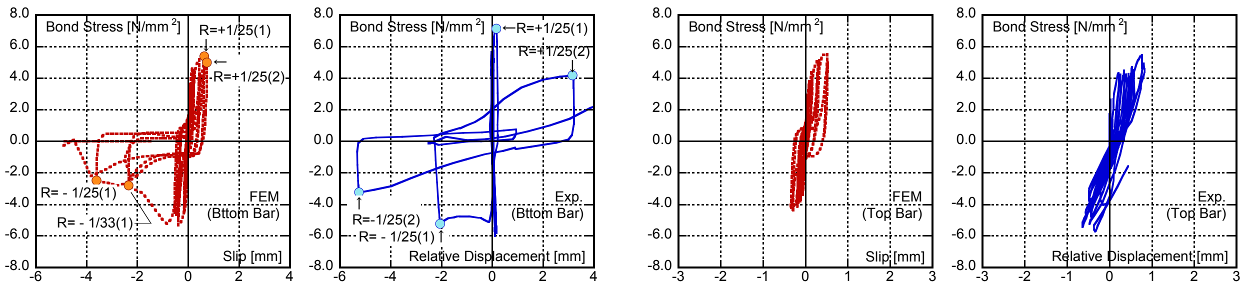
Fig. 5.6 Measuring of Slip in the previous test



(a) Bottom Bar of Specimen B1N (b) Top Bar of Specimen B1N



(c) Bottom Bar of Specimen B2N (d) Top Bar of Specimen B2N



(e) Bottom Bar of Specimen B3N (f) Top Bar of Specimen B3N

Fig. 5.7 Comparisons of Analytical and Test Results: Bond Stress Slip Relations

6. Conclusions

Nonlinear finite element analyses were carried out for previous experimental test of beam specimens with slab. Restoring force characteristic and bond slip behaviour were discussed by comparing analytical and experimental results. The findings from this study are as follows:

1) Specimen B3N, short span specimen with lowest bond margin showed slip behaviour in the restoring force characteristics and had lowest energy dissipation capacity in three specimens. These characteristics were observed in both experimental and analytical results.

2) Analytical results of stress distribution of main bars were good accordance with experimental ones except in compression zone of specimens B1N and B2N.

3) Analytical results of bond slip relations of main bars at middle of the span were compared to experimental ones. Large slip was observed at bottom bars located at opposite side from slab of short span specimen B3N in both experimental and analytical results. It was suggested that the slab at upper side affected bond behaviour of bottom main bars at the opposite from slab.

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