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Scientific paper

Investigation on the Pull-out Behavior of Deformed Bars in Cracked Reinforced Concrete

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Abstract

Pull-out tests and numerical analyses for deformed bar were performed on test specimens having cracks in concrete along the axial direction of the bar. The parameters for the experiment and analysis were: the maximum width of the initial crack, the presence or absence of a mechanical anchorage, the presence or absence of bond on either side of the deformed bar, and the presence or absence of a transverse bar. In both the experiments and the analyses, the pull-out load was applied at the end of the deformed bar after introducing the initial cracking by means of preloading. The results showed that the pull-out performance was greatly reduced by cracking along the axial direction of the bar. Also, it was seen that cracking along the deformed bar tended to occur only on one side of the bar. In the particular case of mechanical anchorage it was found that bending stresses occurred near the anchorage due to eccentric loading. The transverse bar increases the residual crack width when the same initial crack width was generated before unloading and also inducing spalling of the concrete cover due to cracking of the bond, resulting the reduction in pull-out strength.

1. Introduction

After the occurrence of major damage due to a large earthquake such as the Loma Prieta earthquake (1989: USA), the Great Hanshin Earthquake (1995: Japan), and the Jiji Earthquake (1999: Taiwan), etc., each time design standards are amended, and the seismic performance of the structures is enhanced. In recent years, in the case of RC structures, the quantity of shear reinforcement required has been increased significantly in order to achieve higher seismic performance. However, when the quantity of reinforcement is significantly increased the problem of reinforcement congestion is observed. If the quantity of reinforcement is excessive, its assembly is not only expensive and time consuming, but also defects occur during placement of the concrete. This problem is particularly significant at beam-column joints where the arrangement of reinforcement from the column, the reinforcement from the beam, and the hook anchorage of the reinforcing steel is complex (**Fig. 1**).

One method to resolve reinforcement congestion is to use mechanical anchorages. With a mechanical anchorage, a projecting steel member is provided at the end of the reinforcement instead of a conventional hook an-

chorage (**Fig. 2**), which enables the anchorage length to be reduced while maintaining the anchorage performance. It is considered that if hook anchorages can be eliminated in this way, reinforcement congestion can be greatly reduced. The testing and analysis of Takeyama *et al.* (Takeyama *et al.* 2008) is an example of previous research on the anchorage performance of reinforcement in concrete using mechanical anchorages. Takeyama *et al.* carried out static and fatigue pull-out tests using the embedded length to the mechanical anchorage as a parameter, and confirmed that mechanical anchorages have sufficient pull-out resistance compared to hook anchorages. Several types of mechanical anchorages have already been developed, and design recommendations have been published by the Japan Society of Civil Engineers (JSCE 2007).

However, at present the use of mechanical anchorages is limited to comparatively massive concrete only. This is because there is little knowledge regarding the performance of mechanical anchorages in concrete with small cover thickness. Oomori *et al.* (2009) investigated the anchorage performance of reinforcement using mechanical anchorages in cases with comparatively small cover thickness, and reported that bearing pressure from the mechanical anchorages caused cracking, fracture and spalling of side surface of the concrete cover, leading to ultimate failure, but the anchorage performance was not quantitatively evaluated. Murakami *et al.* (1997) conducted pull-out loading tests of mechanical anchorages focusing on the effect of concrete strength, cover depth and transverse reinforcement ratio. Also, Nakazawa *et al.* (2002) conducted pull-out loading tests of mechanical anchorages focusing on the failure mode such as cone failure and side cover spalling. However, the failure mechanism has not been sufficiently clarified yet because it is difficult to evaluate the stress state around the

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anchorage plates in experiments. Adachi *et al.* (2011) conducted finite element analysis (FEM) of Nakazawa *et al.*'s experiment and investigated the failure process. However, continuous element analyses such as FEM cannot reproduce the effect of localized cracks. Also, the JSCE recommendations (JSCE 2007) do not define the use of mechanical anchorages for the main reinforcement of beams or beam-column joints. This is may be due to the fact that when cracking occurs in the concrete near a bearing or joint due to impact loading or seismic loading (Fig. 3), the anchorage performance is unclear. Chun *et al.* (2007), Lee *et al.* (2009), Tadokoro *et al.* (2009) and Yoshitake *et al.* (2011) carried out loading tests on test specimens using mechanical anchorages in beam-column joints, and investigated their usefulness, but the relationship between the various types of cracking that occurred due to the loading and the anchorage performance

of each reinforcement was not clarified.

The bond of deformed bars with concrete is mainly due to the transmission of force from the knots, but it is known that this transmitted force acts at an inclination to the bar axis (Goto 1971). So-called "bond splitting cracking" is cracking along the axis of the deformed bar that occurs by the component of the force transmitted from the knots in the direction normal to the axis of the bar pushing out the concrete cover. Conversely, if a crack is induced along the axis of the deformed bar in the concrete cover from the beginning, the resistance of the concrete cover to the component of force transmitted from the knots in the direction normal to the axis of the bar is reduced, hence it is expected that the bond force of the deformed bar will be reduced. Considering the splitting and cracking in the cover concrete in the research by Oomori *et al.*, there is a high possibility that there is a similar mechanism in operation with mechanical anchorages, and that the anchorage performance is reduced by cracking along the axis of the deformed bar. Hence it is possible that that the cracking along the axis of the deformed bar particularly affects the bond performance of the deformed bars and the anchorage performance of mechanical anchorages. But at present there has been almost no research on this matter, and the situation is yet not clear. Delhomme *et al.* conducted pull-out tests of steel anchors with a plate anchorage embedded in concrete having initial cracks (Delhomme *et al.* 2015). They reported that the initial cracks affect the pull-out performance of the anchors, however, the failure mechanism

Fig. 2 Mechanical anchorage.

Fig. 1 Congestion of steel bars in beam-column joints.

Fig. 3 Possibility of initial damages in concrete structures.

Table 1 Specimens in the experiment and analysis.

Specimen name	Compressive strength of concrete (N/mm ²)	Presence of the mechanical anchorage	Removing friction and adhesion	Removing the transverse bar	Target maximum width of the initial crack (mm)
S-0.0-B-T(1)	52.4	No	No	No	-
S-1.6-B-T		No	No	No	1.6
M-0.0-B-T(1)		Yes	No	No	-
M-1.0-B-T(1)		Yes	No	No	1.0
M-2.8-B-T		Yes	No	No	2.8
S-0.0-B-T(2)	24.9	No	No	No	-
S-0.0-NB-T		No	Yes	No	-
S-0.0-B-NT		No	No	Yes	-
M-0.0-B-T(2)		Yes	No	No	-
M-0.0-NB-T		Yes	Yes	No	-
M-0.0-B-NT		Yes	No	Yes	-
M-1.0-B-T(2)		Yes	No	No	1.0
M-1.0-B-NT		Yes	No	Yes	1.0

Table 2 Mix proportion of concrete.

f_c' (N/mm ²)	W/C (%)	$G_{\max}$ (mm)	S/a (%)	Unit quantity (kg/m ³)				
				W	C	S	G	AE
52.4	51	20	44.9	177	350	775	969	0.874
24.9	59	20	47.1	164	278	880	1007	3.058

f_c' : compressive strength of concrete, $G_{\max}$: maximum size of coarse aggregate, S/a : fine aggregate ratio, W : water, C : cement, S : fine aggregate, G : coarse aggregate, AE : AE water reducing agent.

has not been clearly investigated yet because the internal stress condition cannot be observed in the experiment.

In this research pull-out load tests on test specimens with cracking induced by preloading (hereafter referred to as initial cracking) and numerical analyses were carried out in order to determine the effect of cracking along the axis of the deformed bar on the bond behavior of deformed bars and the anchorage performance of mechanical anchorages for cases with a comparatively small cover thickness. In the tests, the pull-out resistance of the deformed bars, the pull-out displacement, the strain distribution, and the cracking properties were investigated with the initial crack width, the presence or absence of bond on one side of the deformed bar, and the presence or absence of a transverse bar as parameters. In the numerical analysis, the effect of the various factors such as cracking patterns in the concrete, properties of the deformed bar deformation, etc., on the pull-out failure mechanisms was investigated. In this study, a 3-dimensional meso-scale discrete analysis method, which enables to simulate the mechanical behavior in local regions around cracks and bearing forces from steel elements in a 3-dimensional space, was used.

2. Outline of the experiment

2.1 Specimens

Figure 4 and Table 1 show an outline of the test specimens and a list of the test cases respectively. There were a total of 13 test specimens, and the experimental pa-

rameters were: the presence or absence of a mechanical anchorage, the target maximum width of the initial crack, the presence or absence of bond on one side of the deformed bar, and the presence or absence of a transverse bar. The deformed bar used in the pull-out loading tests was a thread knot deformed bar with a nominal diameter of 25.4 mm (D25). The anchorage lengths in cases where a mechanical anchorage was not used and in cases where a mechanical anchorage was used were 450 mm and 200 mm respectively. The anchorage length (450 mm) in the cases where the mechanical anchorage was not used was determined using the equation by Orangun *et al.* (1977). Also, the anchorage length (200 mm) in the cases where the mechanical anchorage was used was calculated by deducting 10D ($10 \times 25 = 250$ mm) from the value calculated by the equation by Orangun *et al.*, in accordance with the JSCE recommendations (JSCE 2007). However, in order to prevent localized failure in each test specimen, an unbonded region was provided 150 mm from the loaded end. As shown in Figs. 4(a) and (b), transverse bars were placed at a 100 mm pitch within the cover concrete, immediately above the deformed bar that was subjected to pull-out. However, as described later, for the cases where the transverse bar was excluded, the transverse bar was excluded at the position closest to the mechanical anchorage. Note that in order to investigate the influence of concrete strength, two specimens were prepared for S-0.0-B-T, M-0.0-B-T, and M-2.8-B-T. Table 2 shows the concrete mix proportions, and Table 3 shows the material properties of the deformed bar and

transverse bar. For the test specimens with f'_c of 52.4 N/mm², pull-out rebar (1) and transverse bar (1) were used, and for test specimens with f'_c of 24.9 N/mm², pull-out rebar (2) and transverse bar (2) were used.

The following is a description of the operating procedures for each of the test parameters.

Table 3 Material properties of steel bars.

Name	Designation by JIS	D (mm)	f_y (N/mm ²)	E_s (N/mm ²)
Pull-out rebar (1)	D25	25.4	547	190
Pull-out rebar (2)	D25	25.4	534	190
Transverse bar (1)	D13	12.7	397	190
Transverse bar (2)	D13	12.7	391	190

D : nominal diameter, f_y : yield strength, E_s : Young's modulus.

(a) Specimens without mechanical anchorage

(b) Specimens with mechanical anchorage

(c) Prior loading to induce initial crack

(d) Pull-out loading

i) Specimens without mechanical anchorage

ii) Specimens with mechanical anchorage

Fig. 4 Outline of the experimental specimens.

2.1.1 Method of inducing the initial crack

Preloading was carried out on the test specimens so as to induce the initial crack prior to applying the pull-out load on the deformed bar. This initial crack represents a crack along the rebar induced by external loadings such as earthquakes and impact loadings as shown in Fig. 3. Since the cracking mechanism is different from that induced by only a pull-out loading, the initial crack is expected to affect the pull-out behavior of the deformed bars. Figure 4(c) shows an overview of the preloading. As shown in Fig. 4(c), a bending load was applied with an arrangement having the deformed bar that was to be pulled out, at the center of the span, and by embedding a 1 mm thick 10 mm height Teflon sheet in the concrete cover directly below the deformed bar, for inducing the bending crack. In order to control the crack width, wire displacement gauges were installed on the bottom surface of the test specimens at positions 175 mm and 50 mm respectively from the free end or the mechanical anchorage, and when the set maximum initial crack for each specimen was reached the bending load was stopped and unloading was carried out. In this study, crack widths were controlled to induce initial damages considering that, in general, crack appearances at the outer surface are evaluated in visual inspection of structures. That is, this study compares the effect of mechanical anchorage under the same deterioration grade of existing structures.

2.1.2 Unbonding one side of the deformed bar

As described later in Section 3, cracks induced by preloading through bending tends to propagate around one side of the deformed bar, and when the pull-out load is acting, an eccentric load effect is applied. Therefore the effect of the initial crack propagation pattern was investigated by eliminating the bond on one side of the deformed bar. In this study, the total bond of deformed bars is assumed to consist of bearing forces from knots, friction, and adhesion. As shown in Fig. 5, by applying a polyethylene wrap which retained the knot shape of the deformed bar, the friction and adhesion between the steel and the concrete was eliminated. Note that in this paper, as shown in Fig. 5, when the concrete cover side is on the bottom surface, and in a top surface view in which the point of application of the pull-out load is downward, the

right side of the deformed bar is referred to as the "right side" and the left side is referred to as the "left side". Unbonding using the polyethylene wrap was carried out on the right side only.

2.1.3 Presence of transverse bars

As reported by Oomori *et al.* (2009), it is known that mechanical anchorages generate bearing stress in the off-axis direction of the reinforcement, and in particular case of small thickness of concrete cover the constraint forces are small, so cracking by splitting can easily occur. Providing reinforcement in the transverse direction with respect to the reinforcement within the cover concrete can potentially reduce cracking by splitting and concrete spalling, and affect the pull-out properties. Therefore in this research, test specimens were prepared in which a transverse bar was eliminated, focusing particularly on the effect of the transverse reinforcement near the mechanical anchorage.

2.1.4 Measurement instruments

The measurement items in these tests were the bending load (during preloading), the initial crack width (during preloading and during pull-out loading), the pull-out load (during pull-out loading), the pull-out bar strain (during pull-out loading), and slip at the free end or the anchorage end (during pull-out loading). As shown in Fig. 4(e), strain gauges with a 2 mm measurement length were applied to both sides of the pull-out bar, to measure the strain. A contact type displacement meter was used to measure the slip at the free end or the anchorage end. As shown in Fig. 4(d), by installing the base of a displacement meter on a bearing plate, the relative displacement between the loading point side concrete and the free end or the anchorage end was measured.

3. Results of the experiment

3.1 Induction of the initial cracks by preloading

Table 1 shows the values of the maximum initial crack widths actually induced by preloading and the initial crack widths when unloaded. The induced maximum crack widths were all maintained within a maximum 11% error band from the target values (1.0 mm, 1.6 mm and 2.8 mm). Since over 3 mm crack width was observed in the previous study (Yoshitake *et al.* 2011) on the loading tests of beam-column joints in the post peak, the target maximum crack widths were set so that they represent damages induced by comparatively severe earthquakes. Figure 6 shows the load-initial crack width relationship during preloading. As shown in this figure, even though the maximum initial crack widths before unloading were the same, the slope of the unloading curve differed depending on the presence or absence of the transverse bar, and the residual crack width tended to be larger in the cases with the transverse bar. The effect on the pull-out behaviors of the deformed bar is described later in Section 3.2.4.

Fig. 5 Method for removing bond at the one side of steel bars.

Table 4 Result of the experiment and analysis.

Specimen name	Width of the initial crack (mm)				Max pull-out load (kN)		Failure mode	
	Exp.		Ana.		Exp.	Ana.	Exp.	Ana.
	Max	Unload	Max	Unload				
S-0.0-B-T(1)	-	-	-	-	258.9	286.5	Yielding	Splitting
S-1.6-B-T	1.75	1.18	1.58	1.27	185.5	188.0	Splitting	Splitting
M-0.0-B-T(1)	-	-	-	-	270.1	274.6	Cone	Cone
M-1.0-B-T(1)	1.04	0.63	0.97	0.72	247.4	247.1	Cone	Cone
M-2.8-B-T	2.76	2.34	2.75	2.44	182.7	183.6	Cone	Cone
S-0.0-B-T(2)	-	-	-	-	205.4	204.9	Splitting	Splitting
S-0.0-NB-T	-	-	-	-	136.3	135.6	Splitting	Splitting
S-0.0-B-NT	-	-	-	-	217.9	220.3	Splitting	Splitting
M-0.0-B-T(2)	-	-	-	-	184.6	181.8	Cone	Cone
M-0.0-NB-T	-	-	-	-	139.2	143.6	Cone	Cone
M-0.0-B-NT	-	-	-	-	194.7	195.3	Cone	Cone
M-1.0-B-T(2)	1.11	0.81	1.07	0.91	145.2	139.9	Cone	Cone
M-1.0-B-NT	1.06	0.61	0.93	0.69	184.5	183.3	Cone	Cone

3.2 Pull-out test results

Table 4 shows the pull-out load capacity and failure mode for each test specimen. Also, Fig. 7 shows the relationship between the pull-out load and the pull-out displacement of the free end or the anchorage end. The following is an explanation of the effect of each test parameter.

3.2.1 Effect of the mechanical anchorage

The pull-out load capacity of S-0.0-B-T(1) and S-0.0-B-T(2) in which a mechanical anchorage was not used was 259 kN and 205 kN respectively, and in contrast the pull-out load capacity of M-0.0-B-T(1) and M-0.0-B-T(2) in which a mechanical anchorage was provided was 254 kN and 185 kN respectively. The pull-out load capacity was slightly reduced even though the anchorage length in the cases that used a mechanical anchorage was based on the JSCE guidelines. This is considered to be because the concrete cover was comparatively small in the tests. Figure 8(b) shows the failure state of M-0.0-B-T(1). Inclined cracking occurred in the concrete cover at the position of the mechanical an-

chorage, and the bearing force from the mechanical anchorage in the off-axis direction of the reinforcement pushed the cover concrete out in a cone shape, thereby causing pull-out failure.

3.2.2 Effect of initial crack width

Figure 9 shows the relationship between the maximum initial crack width and the pull-out load capacity. For both the cases that did not use a mechanical anchorage and the cases that did use a mechanical anchorage, as the maximum initial crack width increased, the pull-out load capacity was reduced. However, the slope of the approximated straight lines in the figure is smaller in the cases using a mechanical anchorage, so it is considered that the effect of the initial crack can be reduced by using a mechanical anchorage.

Figures 8(a) and (c) show the failure states for S-1.6-B-T and M-1.0-B-T(1). In S-1.6-B-T which had no mechanical anchorage, pull-out failure occurred by splitting failure by enlargement of the initial crack width along the deformed bar. On the other hand in M-1.0-B-T(1) which had a mechanical anchorage, cone

(a) Different target of maximum crack widths

(b) Effect of transverse bar

Fig. 6 Load-initial crack width relationships in the prior loading.

Fig. 7 Pull-out load-slip at the free end or anchorage relationships.

Fig. 8 Pull-out failure pattern of deformed bars with/without mechanical anchorages in thin cover concrete.

failure occurred together with enlargement of the initial crack width. However, by comparison with M-0.0-B-T(1) which had no initial crack, the angle of the inclined crack that caused the cone failure was smaller.

Figure 10 shows the relationship between the pull-out load and the right side and left side strain in the cases that did not use a mechanical anchorage. In S-0.0-B-T(1) in which an initial crack was not induced, there was almost no difference between the right side and left side strains regardless of the distance from the loaded end. In contrast in S-1.6-B-T in which the initial strain was induced, a slight difference was found between the right side and left side strains. This is inferred because as shown in **Fig. 11**, the initial crack is formed so that it goes around the reinforcement to the left or the right, so the bond between

Fig. 9 Effect of the maximum initial crack width on pull-out capacity.

the reinforcement and the concrete differs between the left and right. It is inferred that when there is an initial crack along the reinforcement, the reinforcement subjected to the pull-out load is not in a pure uniaxial stress state, and deformation is produced in the off-axis direction.

Figure 12 shows the relationship between the pull-out load and the right side and left side strain in the cases that did use a mechanical anchorage. It can be seen that there is a large difference between the right side strain and the left side strain particularly at the position near the mechanical anchorage. Also, it can be seen that in the cases where the initial crack was induced, the relationship of magnitude between the right side and left side strains tends to be reversed in accordance with distance from the anchorage.

This is considered because the mechanical anchorage resists not only the pull-out load in the axial direction of the reinforcement, but also a bending moment, and the boundary condition resembles that of a fixed end, so a large bending moment is produced.

3.2.3 Effect of the presence or absence of bond on one side of the reinforcement

To verify the production of deformation in the off-axis direction due to the elimination of bond on one side of the reinforcement as described in Section 3.2.2, and to

investigate the relationship between the bond elimination position and the off-axis direction deformation, test specimens were produced that were unbonded on one side. Comparing S-0.0-B-T(2), S-0.0-NB-T, M-0.0-B-T(2), and M-0.0-NB-T as shown in **Table 4**, it can be seen that regardless of the presence or absence of a mechanical anchorage, the pull-out resistance has been greatly reduced by unbonding. **Figure 13** shows the changes in right side and left side strains. For S-0.0-NB-T which did not use a mechanical anchorage a significant difference between the right side and left side strains was not produced, but for M-0.0-NB-T which did use a mechanical anchorage, the right side and left side strains were different, so deformation in the off-axis direction was found. Focusing on the unbonding position, unbonding was carried out only on the right side, and at $x = 50$ mm and 100 mm which were comparatively close to the loading point, it can be seen that the right side strain is greater than the left side strain. On the other hand, at the positions $x = 150$ mm and 200 mm which were close to the mechanical anchorage, this trend was reversed, and the left side strain was greater than the right side strain. This is considered because of the effect of the mechanical anchorage behaving as a fixed end. This deformation behavior is explained in detail in Chapter 5 using the results of numerical analysis.

Fig. 10 Load-strain of pull-out bar relationships in the cases without mechanical anchorage (x = distance from the loaded end).

Fig. 11 Pattern of initial cracks around the steel bars.

Fig. 12 Load-strain of pull-out bar relationships in the cases with mechanical anchorage (x = distance from the loaded

Fig. 13 Effect of bond at the one side of steel bar on the strain development (x = distance from the loaded end).

3.2.4 Effect of the presence or absence of transverse reinforcement

Figure 7(d) shows the pull-out load - slip relationship at the free end or the anchorage end for the cases where the transverse bar was removed near the mechanical anchorage (S-0.0-B-NT, M-0.0-B-NT and M-1.0-B-NT) and the cases where the transverse bar was provided (S-0.0-B-T(2), M-0.0-B-T(2) and M-1.0-B-T(2)). It can be seen that when an initial crack was not induced, the effect of the transverse bar on the pull-out load resistance was small, regardless of the presence or absence of the mechanical anchorage. On the other hand, in the cases where the initial crack was induced, clear differences were found, with the pull-out load being greater when the transverse bar was omitted. This is considered to be because in the cases where the transverse bar was removed, the residual initial crack width was smaller, as shown in Fig. 6. When the maximum values of the initial crack widths experienced previously are compared under the same conditions, as in this research, if the transverse reinforcement is yielded and residual strain occurs in the transverse reinforcement, crack closure is obstructed by the transverse reinforcement during unloading, so the residual initial crack width is increased, and this is considered to decrease the constraint of the concrete cover on the deformed bar or the mechanical anchorage.

4. Outline of the numerical analysis

4.1 Objective

In the tests described up till the previous section, the pull-out behavior was investigated while using mechanical anchorages with small concrete cover with an initial crack width and presence and absence of transverse reinforcement. However, in the tests the stress distribution within the test specimens, the state of the cracking, and the state of deformation of the reinforcement was not clear, so it was not possible to investigate the failure mechanisms in detail. Therefore in this research a 3-dimensional numerical analysis was also carried out, to confirm the validity of the analysis model and to investigate the failure mechanisms. Numerical analysis was carried out for all the test cases shown in Table 1.

4.2 Method of the analysis

In this research a meso-scale analysis was carried out using the Rigid Body-Spring Model (hereafter, RBSM). RBSM is one method of discrete analysis developed by Kawai, in which the object under consideration is modeled by dividing it into multiple rigid elements, and connecting the rigid elements with springs (Kawai *et al.* 1978). Crack extension and enlargement of the crack width are represented by separation of adjacent elements. In the case of a 3-dimensional model, one normal direction spring and two shear direction springs are provided between adjacent rigid elements, as shown in Fig. 14(a).

As shown in Fig. 14(b), in the meso-scale analysis carried out in this research, the cross-section of the deformed bar was divided into many elements, and the shape of the knots was also modeled. In the normal finite element method, the bond of reinforcement is represented by spring elements, etc., arranged in the direction of axis of reinforcement between the reinforcement and the concrete elements, and the bond-slip relationship of the spring element does not take into consideration those stresses which are in the off-axis direction of the reinforcement. Therefore, the relationship between the bond behavior of the deformed bar and the stresses in the off-axis direction of the bar, as pointed out by Goto (1971), cannot be taken into consideration. As a result it is not possible to investigate the effect of spalling of concrete due to bond failure, and the constraint effect of the concrete cover on the bond behavior. By modeling the shape of the knots, as in this research, it is possible to obtain the magnitude and direction of the forces from the knots through the results of the analysis, as pointed out by Goto. The shape of the knots affects the cracking behavior around the deformed bars. In the previous study (Hayashi *et al.* 2013) in which shape of the knots is modeled same as that in this study, crack development around the deformed bars was verified by conducting pull-out analysis of cylindrical specimens. It was confirmed that the model of deformed bars can reproduce conical shape of cracking pattern as observed by Goto (1971). The authors also have confirmed that it is possible to reproduce the effect of transverse reinforcement on the spalling of cover concrete due to bond failure of deformed bars using this analysis method (Hayashi *et al.*

Fig. 14 Concept of RBSM (3D).

2013).

A random shape using Voronoi diagram was adopted for the concrete element meshing, so that the crack directions were not dependent on the element meshing. The dimensions of the concrete elements were 10 mm^3 to 20 mm^3 , taking into consideration the maximum size of the coarse aggregate. **Figure 15** shows the analysis model. The loading plate and the bearing plate during preloading were modeled as rigid elements regardless of the presence or absence of a mechanical anchorage, and by applying a forced displacement in the vertical direction to the loading plate, the initial crack was induced in the center of the span. The loading plate and the bearing plate were pin hinged, and the bearing plate was free in the horizontal direction. During pull-out loading, a forced displacement was applied to the element at the end of the deformed bar that was being pulled out. By fixing the concrete elements in the pull-out direction on the front side in the figure, the reaction was provided. It

is to be noted that the definitions of right side and left side are the same as for the experiments.

4.3 Constitutive models

4.3.1 Concrete

Figure 16 shows the concrete stress-strain model. For the spring in the normal direction, elastic behavior was taken into consideration on the compression side, and tension softening on the tension side. At the meso-scale, the characteristic of this analysis model is that the concrete does not fail under compressive stresses, based on the concept that the failure of concrete observed at the macro-scale occurs due to the accumulation of tensile failure and shear failure (Nagai *et al.* 2004). From the model used in the previous study (Hayashi *et al.* 2013), the tension softening branch shown in **Figs. 16(a)** and **18** was changed to bilinear model to reproduce the fracture energy of concrete under bending.

For the shear direction springs, it is assumed that the behavior is elastic until the failure criterion is reached and after the failure criterion is reached $\tau = \tau_{\max}$, as shown in **Fig. 16(c)**. However, in order to represent the reduction in interlocking effect due to crack opening, τ is reduced in association with deformation of the normal direction spring, as shown in **Fig. 16(d)**.

4.3.2 Steel

Figure 17 and **Eqs. (1), (2) and (3)** show the stress-strain model of the reinforcement. The model of Shima *et al.* (1987) was adopted for the stress-strain relationship of the normal direction spring in the hardening region. However, the initial strain of strain hardening was 1.5%. Also, the stress-strain relationship during unloading and reloading followed the initial slope. On the other hand, the shear direction spring always exhibited elastic behavior.

$$\sigma = E_s \varepsilon \quad \varepsilon < \varepsilon_y \quad (1)$$

$$\sigma = f_y \quad \varepsilon_y < \varepsilon < \varepsilon_{sh} \quad (2)$$

$$\sigma = f_y + (1 - e^{\varepsilon_{sh} - \varepsilon/k}) (1.01 f_u - f_y) \quad \varepsilon > \varepsilon_{sh} \quad (3)$$

where,

$$k = 0.032 (400/f_y)^{1/3} \quad (4)$$

σ is reinforcement stress (N/mm^2), E_s is reinforcement Young's modulus (N/mm^2), ε is reinforcement strain, f_s is reinforcement yield stress (N/mm^2), f_u is reinforcement tensile strength (N/mm^2), and ε_{sh} is initial strain of strain hardening ($= 1.5\%$).

4.3.3 Steel-concrete interface

The bond behavior of the reinforcement-concrete interface is subject to the effects of breathing, etc., and it is difficult to directly model it from the test results. Therefore in this research the concrete stress-strain

Fig. 15 Analytical models.

model was used for the stress-strain relationship of the reinforcement-concrete interface. However, the tensile strength f_t was reduced to 50%. It was confirmed in past research that the pull-out behavior of deformed bar can be appropriately reproduced with this model (Hayashi *et al.* 2013).

5. Result of the numerical analysis

5.1 Verification of the analytical model

5.1.1 Initial cracks

Table 4 shows the maximum initial crack widths and the residual initial crack widths induced during preloading. As in the experiments, the maximum initial crack widths induced in the analysis were virtually the same as the target values. Also, although the analysis values of the residual initial crack widths during unloading were slightly large, the residual crack width in the presence of transverse reinforcement was increased, so the same trend as that of the experiments, was obtained (see M-1.0-B-T(2) and M-1.0-B-NT). It can be seen that the

effects of, the bond of the deformed bar, the crack opening behavior, and the transverse bar, on the crack closing behavior was reproduced well.

5.1.2 Relationship between pull-out load and free end or anchorage end slip

Figure 19 shows the relationship between the pull-out load and the free end or anchorage end slip obtained in the analysis. For comparison, the experimental results are also shown. The analysis results generally agree with the experiment, so it is considered that the effect of the presence and absence of the mechanical anchorage, the initial crack, and the transverse reinforcement has been appropriately reproduced. In addition, the pull-out load capacity values from Table 4 are also shown, and in all cases the difference from the experimental results was maintained to within the range of 10%.

5.1.3 Failure properties

Figure 20 shows an example of the state of the model at failure obtained in the analysis. The analysis results of

Fig. 16 Constitutive models of concrete.

Fig. 17 Constitutive model of steel (normal spring).

Fig. 18 Constitutive model of interface (normal spring).

Figs. 20(a), (b) and (c) correspond to **Figs. 8(a), (b) and (c)** respectively. In the analysis, in the cases using a mechanical anchorage, cone cracking occurred in the cover concrete near the anchorage, resulting in ultimate failure. Also, in the cases where the initial crack was induced, it can be seen that the angle of the inclined cracks generated from the mechanical anchorage tended to be smaller. It is inferred that the bearing force in the off-axis direction of reinforcement generated from the anchorage, is reproduced.

5.1.4 Strain distribution in the pull-out bar

Figure 21 shows the changes in the strain distribution of the pull-out deformed bar, obtained from the analysis. For comparison, the experimental results are also shown. For both the experiment as well as analysis, the strains

shown in the figure are the average values of the right side and the left side. There is a general agreement between the analysis results and the experiment results, hence the bond and slip behavior of the deformed bar associated with the increase in pull-out load was reproduced well.

From the above it has been confirmed that the pull-out behavior of deformed bars in RC with small cover can be reproduced well with this analysis model.

5.2 Investigation of the mechanism of pull-out failure

5.2.1 Effect of eliminating the bond on one side

Figure 22 shows the cracking pattern at the maximum load during preloading. As shown in **Fig. 11**, the phenomenon of forming the initial crack so that it passes

Fig. 19 Comparison of pull-out load-slip at the free end or anchorage relationships in the experiment and analysis.

Fig. 20 Failure pattern in the analyses (deformation $\times 20$).

around one side of the reinforcement has been reproduced in the analysis. In this analysis, the initial crack passed around the left side in S-1.6-B-T, and passed around the right side in M-1.0-B-T(1) and M-2.8-B-T.

Figure 23 shows the curvature distribution and de-

formed state under the maximum load of the pull-out deformed bar for M-1.0-B-T(1) and M-2.8-B-T as obtained in the analysis. The curvature at each position has been calculated from the strain on the right side and left side, and the direction in which the strain on the left side

Fig. 21 Comparison of strain distribution in the experiment and analysis.

Fig. 22 Pattern of initial crack in the analyses (deformation $\times 10$).

is in tension, is taken to be the positive value. In the case of M-1.0-B-T(1) and M-2.8-B-T in which the initial crack passed around the right side, it can be seen that the curvature in the region near the loading point is positive, and in the region near the mechanical anchorage is negative. This is the same trend as the experimental result for M-0.0-NB-T which was unbonded on the left side as shown in **Fig. 16**. The deformed state exhibits a wave form shape corresponding to the curvature distribution. Near the anchorage the reinforcement is extended in the vertical direction in the figure, but below that it is curved to the left side, and near the loading point it is again extended in the vertical direction. It is considered that this is because the mechanical anchorage is behaving as a fixed point, as stated in Section 3.2.3.

By forming the initial crack, so that it passes around the reinforcement on one side as described above, a large curvature tends to be produced particularly near the mechanical anchorage, causing concern for over stress concentration problems, etc., when the fatigue loads are acting.

5.2.2 Effect of transverse reinforcement

Figure 24 shows the changes in the strain distribution of the transverse bar arranged near the mechanical an-

chorage. It is to be noted that the strain shown in the figure is for an element in the center of the cross-section of the transverse bar. Since the strain induced by the bending load was significantly larger than that induced in the pull-out loading, those two strain distributions look almost the same in the figure. When the initial crack was induced by preloading, it can be seen that, the larger the maximum initial crack width, the greater the area over which, the strain in the transverse bar exceeds the yield strain. **Figure 25** shows the deformed state of the transverse bar, provided near the mechanical anchorage at the maximum pull-out load. With M-0.0-B-T(1), in which the initial crack was not induced, the transverse bar deformed over a comparatively local range, and in contrast with M-1.0-B-T(1) and M-2.8-B-T in which the initial crack was induced, the transverse bar deformed over a comparatively wide range. This is to be considered because, during preloading the bond of the transverse bar was reduced. In particular with M-2.8-B-T, the strain at positions where the bending cracking did not occur, during preloading, also greatly exceeded the yield strain. Hence it is inferred that the bond failure was significant, and there is a high possibility of occurrence of bond cracking around the reinforcement. It is inferred that, since the thickness of the cover was comparatively small,

Fig. 23 Curvature distribution and deformation of the pull-out steel bars with mechanical anchorage obtained in the analysis.

Fig. 24 Change of strain distribution in transverse bar near the mechanical anchorage.

while inducing the initial crack, the cover concrete was already in a state in which spalling could easily occur, due to the bearing stress from the knots in the off-axis direction of the reinforcement. The fact that a crack along the pull-out deformed bar is also seen in the cross-sectional view along the pull-out deformed bar in **Fig. 25** indicates that the crack is formed on a plane surface. When the pull-out load was acting, a large bearing force acted on the concrete cover, particularly near the mechanical anchorage. One possible reason that can be considered is that the pull-out load capacity was reduced by the transverse reinforcement, particularly for the cases having the mechanical anchorage. Even though cover concrete was already in a state in which spalling could easily occur, the bond of the transverse bar seems to be still remaining according to the residual crack width shown in **Table 4**. Larger residual crack in the case with the transverse bar indicates that the remaining bond

generates the restraint effect of the rebar on crack opening and closing.

The decrease of pull-out resistance due to the transverse reinforcement as described above is considered to be caused by the reduction of the constraint effect of the cover concrete due to bond failure of the transverse reinforcement, in addition to the increase in the residual initial crack width as described in Section 3.2.4.

6. Conclusions

In order to investigate the effect on the behavior of pull-out failure, of initial cracking along deformed bars in concrete, with comparatively small cover thickness, experiments and numerical analyses were carried out in the presence or absence of a mechanical anchorage, the initial crack width, the presence or absence of bond on one side of the deformed bar, and the presence or absence

of transverse reinforcement as parameters. The conclusions obtained from this research were as follows.

- 1) The 3-dimensional meso-scale discrete analysis using Rigid Body-Spring Model can reproduce the pull-out behavior of deformed bars with and without mechanical anchorages in cracked reinforced concrete. Crack patterns, deformation of the deformed bars, as well as the pull-out capacities and load-displacement relationships can be well predicted.
- 2) As the initial crack width is increased, the pull-out capacity of the deformed bars is reduced. However, this reduction in the pull-out capacity, due to initial cracking can be minimized slightly by the use of mechanical anchorages.
- 3) The initial cracking along the reinforcement is generated so that the crack passes around one side of the reinforcement. Therefore when the pull-out load is acting, the tensile stress generated within the cross-section of the reinforcement is not uniform. In particular when a mechanical anchorage is used, the anchorage is fixed in the rotational direction, and it behaves as a fixed end, so a large bending stress is generated near the anchorage.
- 4) For the same maximum value of initial crack width experienced previously, transverse reinforcement tends to reduce the pull-out load capacity of the deformed bars. This is to be considered because the residual value of the initial crack width is increased, and the concrete cover can easily spall due to yielding of the transverse reinforcement and the loss of bond.

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