BOND BEHAVIOR BETWEEN REINFORCEMENT AND CONCRETE WITH ASR EXPANSIVE CRACK ARTIFICIALLY INDUCED USING EXPANSIVE CONCRETE

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Abstract

Sufficient restriction of expansion due to alkali-silica reaction (ASR) rarely reduces the load-carrying capacity of reinforced concrete (RC) structures. However, fracture of stirrups in ASR-affected RC structures has been recently reported in Japan. Degradation of the mechanical properties of the concrete and reinforcing steel bars reduces the load-carrying capacity of the RC structure. In this study, a pull-out test was conducted on a reinforcing steel bar embedded in concrete. An ASR expansive crack was artificially induced using expansive concrete, to clarify the influence of ASR expansive crack on the bond behavior of the reinforcing steel bar. The expansive crack reduced the resistance of concrete around the reinforcing steel bar and, consequently, the bond strength of the reinforcing steel bar. Furthermore, the bond strength of the reinforcing steel bar embedded ASR-affected concrete was estimated by assuming that the crack induced by ASR degrades the concrete tensile strength around the steel bar.

KEYWORDS: alkali-silica reaction, expansive crack, bond strength, splitting failure, pull-out test

1 INTRODUCTION

It is essential to form an adequate bond between reinforcing steel bars and concrete in order to achieve sufficient load-carrying capacity in reinforced concrete (RC) structures. One of the basic assumptions in the analysis of RC structures is that the strains in the concrete and reinforcing steel bars are equal at the location of the reinforcing steel bar, implying complete bonding between these two elements. However, fracture of reinforcing steel bars in some RC structures that have deteriorated due to the alkali-silica reaction (ASR) has been discovered in Japan. Cracks induced by ASR expansion reduce the bond strength between the reinforcing steel bar and the concrete. Moreover, degradation of the anchorage bond between the fractured reinforcing steel bar and the concrete affected by ASR may lead to a reduction in the load-carrying capacity of the RC structure.

In the present study, in order to clarify the effect of ASR expansive cracks on the bond behavior between a reinforcing steel bar and concrete, a pull-out test was performed on reinforcing steel bars embedded in a concrete specimen in which cracks were artificially induced using expansive concrete.

2 EXPERIMENTAL PROCEDURE

2.1 Test specimen

Figures 1 and 2 show the shape and dimensions of pull-out test specimens. They consist of a rectangular concrete cross-section in which deformed reinforcing steel bars are embedded.

There are two types of specimens. One has four deformed bars (D19, yield strength: 375 N/mm^2) positioned in the corners of the rectangular cross-section with 25 mm of cover, giving a cover to bar diameter ratio of 1.31, assuming that the longitudinal reinforcing steel bar is fractured in the anchorage region in the RC member. In this specimen, based on Eq. 1 (which is from Section 4.3 in Ref. [1]), failure due to corner splitting is expected to occur prior to pull-out failure or yielding of the reinforcing steel bar.

The other type of specimen has two deformed bars (D10, yield strength: 357 N/mm^2) at the top and bottom sides of the rectangular cross-section with 25 mm of cover, giving a cover to bar diameter ratio of 2.62, assuming that the stirrup at its bent regions is fractured. In this specimen, the

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reinforcing steel bar is expected to yield prior to splitting failure, based on the development length equation given in the Japanese Standard specifications for concrete structures [2]. These reinforcing bars were embedded in sound (neither reactive nor cracked) concrete with a water-to-cement ratio (W/C) of 0.63.

2.2 Test parameters

Table 1 lists the experimental parameters, including the pull-out test results, which will be described later.

Artificially induced expansive crack

Figure 3 shows the cross-section of the specimen, in which an expansive crack was artificially induced by the following procedure. The concrete around the reinforcing steel bars subjected to the pull-out load was cast using a form of expanded polystyrene in the center of the section, which had a cross-section of 100 × 150 mm. After demolding, the expanded polystyrene was removed. An expansive crack was induced by grouting the expansive concrete (W/(C+E)=0.63, E/(C+E)=0.25, E: expansive cement) in the hollow section. Slits of thin aluminum foil were then placed in the corner (D19 specimen) or the center of the short side (D10 specimen) of the hollow cross-section, in order to lead the expansive crack to the concrete close to the reinforcing steel bar used in the pull-out test.

The difference between an artificially induced crack produced by the above-described method and a crack that forms as a result of ASR expansion remains somewhat unclear. Cracks induced by ASR are usually finer in the core section than in the cover region because the expansion in the core section is restrained by the reinforcing steel. On the other hand, the confinement due to the reinforcing steel also causes longitudinally oriented cracking. Since such cracks dramatically affect the mechanical behavior of the bond between reinforcing bars and concrete, artificially induced cracks were employed in the present study.

Transverse reinforcement

The transverse reinforcement (stirrup) enhances the bond strength of the longitudinal reinforcing steel bar. The transverse reinforcement of the D19 specimen was provided by a deformed (D6) stirrup at the center of the specimen in the longitudinal direction. The transverse reinforcement ratio, $A_w/b_w/s$ (A_w: the cross-sectional area of the stirrup, b_w: the width of the specimen, s: the spacing of the stirrup) is 0.0018. Furthermore, in order to investigate the effect of inadequate confinement due to fracture in the bent region on the bond strength of the longitudinal reinforcing bar, the stirrup was also provided by an assembly of deformed (D6) bars, which reflects a stirrup that is discontinuous in the bent regions, as shown in Fig. 1.

Embedment length of reinforcing steel bars

The longitudinal reinforcing steel bars subjected to the pull-out test in the D10 specimen had embedment lengths of 200, 300, and 400 mm; these embedment lengths were used to determine the development length, in which the reinforcing steel bar yields as a result of the pull-out force.

2.3 Pull-out loading test procedure and measurements

Figure 4 shows the eccentric pull-out test equipment. The specimen was set up so that a horizontal tensile force was applied to its reinforcing steel bar. Two reinforcing steel bars at the top and bottom side were pulled out one by one. Steel plates were directly welded to the end of the reinforcing steel bar to transmit the hydraulic jacking force to the reinforcing steel bar. The reinforcing steel bar was loaded by controlling the load end slip. The applied pull-out load, the load end slip, and the free end slip at the opposite side of the load end were measured at every increase in load end slip of 0.05 mm.

3 RESULTS

Table 1 shows the expansive crack width and the pull-out test results. The crack width was measured at seven points separated by a spacing of 50 mm on the crack along the longitudinal reinforcing steel bar. The crack width given in Table 1 is the mean of these seven width measurements. The bond strength was defined as the maximum pull-out load divided by the surface area of the reinforcing steel bar along the embedment length.

No cracks appeared on the bottom surface of the specimen because the expansion on the bottom of the specimen was restrained by the friction between the bottom of the specimen and the floor of the curing location. Moreover, the splitting crack damage to the specimens, which had two reinforcing bars at the top, was so extensive as to extend to the other untested bar, and it was not possible to test both the reinforcing steel bars. Consequently, only the test results of one reinforcing bar at the top side of the specimen are shown in Table 1.

3.1 Expansive crack before pull-out test

Figure 5 shows the extent of the expansive crack in the D19 specimen with a discontinuous stirrup before the pull-out test. A large expansive crack generally propagated along the longitudinal reinforcing steel bar, while some fine cracks branched from the main longitudinal crack. The width of the crack in the specimens with the discontinuous stirrup (D19 specimen only) and without the stirrup (D19 and D10 specimen) was more than 5 mm, except for the D19 specimen without stirrup. The crack width in the D19 specimen with the discontinuous stirrup was larger than that with the stirrup.

3.2 Pull-out test results

Bond behavior and failure mode of D19 specimen

Figures 6 and 7 show the relationship between the pull-out load and the free end slip in the D19 specimens. Figure 8 shows the state of the splitting crack after the failure. All D19 specimens failed in a brittle manner by corner splitting of the concrete [3] prior to the yielding of the reinforcing steel bar. Although the specimen with the artificially induced crack failed in the same manner, its maximum load was significantly reduced. The maximum load of the specimen with the stirrup was approximately the same as that without the stirrup. However, the maximum load of the specimen with the discontinuous stirrup was smaller than that of the specimens with or without the stirrup.

Bond behavior and failure mode of D10 specimen

Figures 9 and 10 show the relationship between the pull-out load and the free end slip in the D10 specimens. The specimen with the expansive crack resulted in pullout failure prior to the yielding of reinforcing steel bar with no splitting crack, while all of the reinforcing bars of the sound specimen (without the expansive crack) yielded.

4 DISCUSSION

4.1 Expansive crack

The width of the expansive crack in almost all of the specimens both with the discontinuous stirrup and without the stirrup exceeded 5 mm. However, the expansive crack occurred on the vertical side of D19 specimen without the stirrup. Therefore, since the expansive force has disappeared, the width of the expansive crack in D19 specimen without the stirrup is relatively small. From the viewpoint of only crack width in the RC structure that was actually affected by ASR [4], damage in which the crack width exceeded 5 mm may correspond to the condition of an RC structure that is significantly affected by ASR. However, the artificially induced crack, that is intentionally directed toward the discontinuous region of stirrup, developed over the full embedment length, while an actual ASR crack may partially develop over the embedment length. Moreover, a part of the artificially induced cracks also occurred on the inside of the reinforcing bar subjected to the pull-out force, as shown in Fig. 5. Hence, the artificially induced crack may cause a larger reduction in the bond strength than an actual ASR expansive crack.

4.2 Bond behavior and failure mode

D19 specimen

The maximum load of the specimen with the artificially induced expansive crack was significantly reduced, because the confining capacity of the concrete around the reinforcing steel bar subjected to the pull-out force was reduced due to the expansive crack. Therefore, the crack along the reinforcing steel bar due to ASR expansion can be considered as a reduction of the concrete strength around the embedded reinforcing steel bar. However, as mentioned in Section 4.1, since the artificially induced crack affects the bond behavior of the reinforcing steel bar more than the actual ASR expansive crack, the reduction of the maximum load in the present study may be too large.

The maximum load of the specimen with the stirrup was approximately the same as that without the stirrup. Although the transverse reinforcement ratio of 0.0018 was generally moderate, the single stirrup, which was provided by the stirrup, was not able to effectively prevent the splitting cracks from propagating. Therefore, the bond strength of the specimen with the stirrup was not increased. On the other hand, the maximum load of the specimen with the discontinuous stirrup was smaller than that with or without the stirrup. It is estimated that the concentration of splitting cracks on the discontinuous corner due to the insufficient confinement at the corner of the discontinuous stirrup brought the large reduction of the bond strength in the specimen with the discontinuous stirrup.

D10 specimen

The D10 specimen with the expansive crack resulted in pullout failure because the crack width of the D10 reinforcing steel bar was larger than that of D19. Therefore, the maximum load of the specimen with the expansive crack decreased dramatically. However, no relationship between the embedment length and the expansive crack width was found, because the specimens for all of the embedment lengths of the reinforcing bar resulted in pullout failure.

4.3 Method for estimating the bond strength of reinforcing steel bar embedded in concrete affected by ASR expansive crack

Calculation procedure

In this section, a method for estimating the bond strength for the corner splitting failure, which takes the effect of the expansive crack into account, is discussed. Eq. 1 shows the bond strength for corner splitting failure [1].

$$\tau_{max} = \left(0.307b_i + 0.427 + 24.9\left(\frac{A_w\sqrt{2}}{s \cdot N \cdot d}\right)\right)\sqrt{\frac{100f'_c}{9.8}} \quad (1)$$

where b_i is the coefficient for evaluating the splitting crack mode. In the present specimen, the coefficient, b_i is 4.12, which corresponds to the corner splitting mode, A_w and s are defined in Section 2.2, and N is the number of reinforcing steel bars.

As mentioned in Section 4.2, the crack along the reinforcing steel bar can be considered as a reduction of the concrete strength around the embedded reinforcing steel bar. Therefore, the bond strength was calculated using Eq. 1, in which the concrete compressive strength derived from the following two procedures was substituted for the component of f'_c expressing the compressive strength. Table 2 shows the concrete strengths used for calculating the bond strengths.

1. The compressive strength that was derived from the relationship between the residual rate of concrete compressive strength [5] and the expansion rate was substituted for f'_c. The cylindrical compressive strength for sound concrete with no expansion was 37.4 N/mm^2.
2. The tensile strength that was derived from the relationship between the residual rate of concrete tensile strength [5] and the expansion rate was transformed into the compressive strength using the relationship $f'_c = (f_t/0.23)^{3/2}$. Substituting $f'_c = (f_t/0.23)^{3/2}$ into Eq. 1 gives:

$$\tau_{max} = \left(0.307b_i + 0.427 + 24.9\left(\frac{A_w\sqrt{2}}{s \cdot N \cdot d}\right)\right)\sqrt{\frac{100(f_t/0.23)^{3/2}}{9.8}} \quad (2)$$

The sound concrete tensile strength with no expansion was calculated using the same relationship between f'_c and f_t with a sound compressive strength of 37.4 N/mm^2.

Calculation results and discussion

It has been reported that the reduction in the tensile strength is larger than that of compressive strength in concrete affected by ASR expansion [6]. The compressive strength derived from the tensile strength with a small residual rate is smaller than the compressive strength with a large residual rate using the relationship between the compressive and tensile strength for sound concrete. However, the suitability of the relationship between the compressive and tensile strength, expressed as $f'_c = (f_t/0.23)^{3/2}$ for the concrete affected by ASR, must be confirmed.

Figure 11 shows the relationship between the calculated bond strength and the expansive crack width, along with the experimental bond strength. Since the bond strength was calculated using the expansion rate due to ASR, the expansion rate was transformed into the crack width. The crack width of w_{cr}, which appears on the top surface (width: 200 mm) of the specimen along the reinforcing steel bar, is equal to the expansion rate of $w_{cr}/200$ mm, assuming that a single crack occurs and dissipates the expansive force.

The experimental bond strength decreased dramatically, even for moderate crack widths. There was good agreement between the bond strength calculated using the compression strength derived from the tensile strength and the experimental bond strength. Thus, the bond strength between the reinforcing steel bar and the concrete affected by ASR can be estimated, assuming that the crack induced by ASR expansion degrades the concrete tensile strength around the reinforcing bar.

5 CONCLUSIONS

The main results obtained in the present study are summarized as follows:

1. Expansive cracks reduce the resistance of the concrete around the reinforcing steel bar subjected to a pull-out force and, consequently, the bond strength of the reinforcing steel bar. Thus, a crack lying along the reinforcing bar due to ASR expansion can be considered as a reduction of the concrete strength around the embedded reinforcing bar.
2. The excessive expansive crack width for the bar diameter causes pull-out failure prior to the yielding of the reinforcing steel bar with no splitting crack, whereas the reinforcing steel bar is designed to yield at the sound state. However, no relationship between the development length and the expansive crack width was found since all the specimens underwent pullout failure for all of the embedment lengths of the reinforcing steel bar.
3. The bond strength between the reinforcing steel bar and the concrete affected by ASR can be estimated, assuming that the crack induced by ASR expansion degrades the concrete tensile strength around the reinforcing bar.

There are some differences in the crack width, position and distribution between the artificially induced crack in this study and a crack that forms as a result of actual ASR expansion. Therefore, a pull-out test should be conducted on a specimen with a smaller expansive crack, because in this study an excessively large crack generally developed in the specimen. In addition, a pull-out test should be conducted on a specimen with an actual ASR expansive crack.

6 REFERENCES

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TABLE 1: Test parameters and pull-out test results

Expansive crack	*Bar diameter (mm)*	*Cover / bar diameter*	*Transverse reinforcement*		*Embedment length (mm)*	*Crack width (mm)*	*Maximum pull-out load (kN)*	*Bond strength (N/mm²)*	*Failure mode*
			Ratio (%)	*Condition*					
No	19 (2*-D19)	1.31	0.00	No	300		84.9	4.72	Split
			0.18	Continuous			84.5	4.69	
			0.18	Discontinuous			74.9	4.16	
	10 (1*-D10)	2.62	0.00	No	200		31.3**	---	Yield
					300		26.6**	---	
					400		29.2**	---	
Yes	19 (2*-D19)	1.31	0.00	No	300	0.71	34.9	1.94	Split
			0.18	Continuous		0.55	40.4	2.24	
			0.18	Discontinuous		6.25	22.5	1.25	
	10 (1*-D10)	2.62	0.00	No	200	5.71	10.4	1.73	Pullout
					300	7.30	6.60	0.73	
					400	5.20	10.6	0.88	

*: The number of the reinforcing bar at the top side of the specimen.
**: Since the finished point of the pull-out test in every specimen was different, the strain reached the stage of the strain hardness. Therefore, the different maximum pull-out force was found.

TABLE 2: Concrete strength used for calculating the bond strength.

Expansion rate (%)	*Compression*		*Tension*		
	Residual rate	*Cylindrical compressive strength (N/mm²)*	*Residual rate*	*Tensile strength (N/mm²)*	*Compressive strength‡ (N/mm²)*
0.00	1.00	37.4	1.00	2.57	37.4
0.25	0.70	26.2	0.60	1.54	17.3
0.50	0.70	26.2	0.45	1.16	11.3

‡: Compressive strength by using the relationship of $f'_c=(f_t/0.23)^{3/2}$

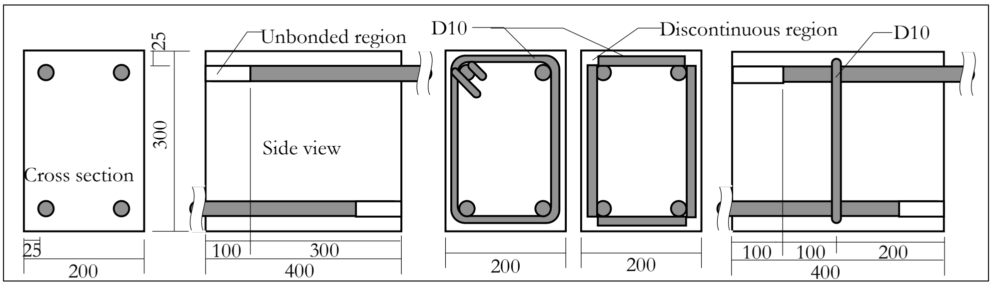

Figure 1: Shape and dimensions of D19 pull-out specimen (dimensions in mm).

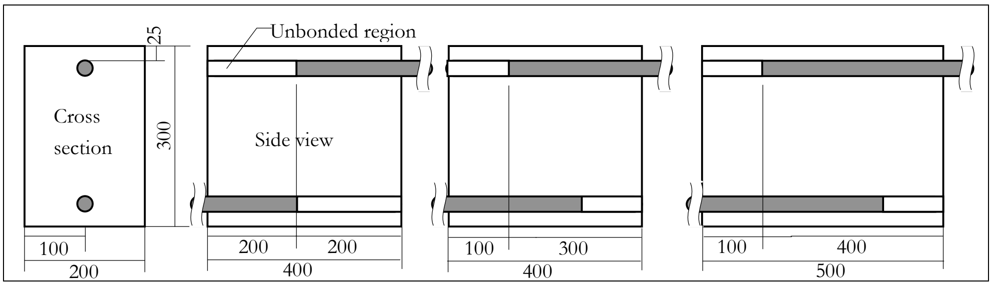

Figure 2: Shape and dimensions of the D10 pull-out type test specimen (dimensions in mm).

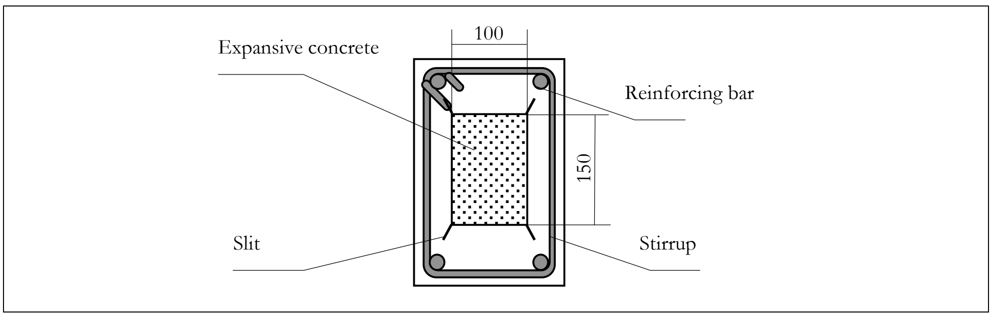

Figure 3: Cross-section of specimen, in which expansive crack was artificially induced using expansive concrete.

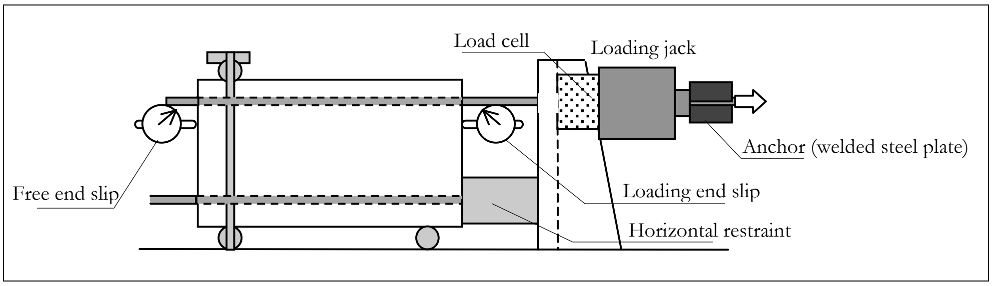

Figure 4: Pull-out test equipment.

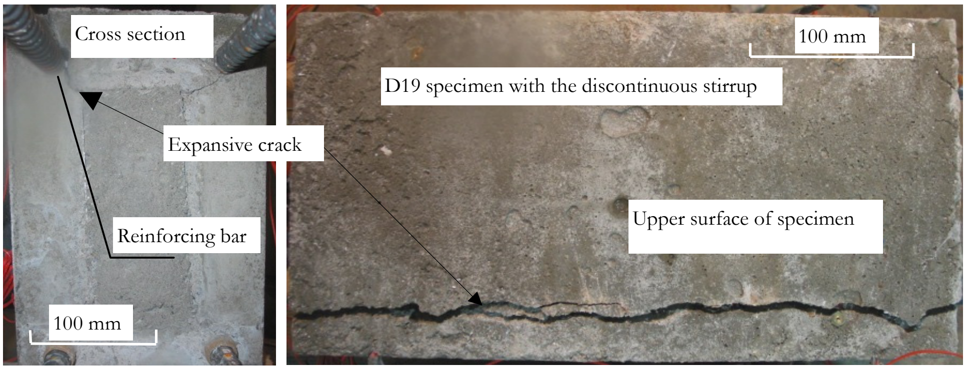

Figure 5: Extent of expansive crack in D19 specimen with discontinuous stirrup before the pull-out test.

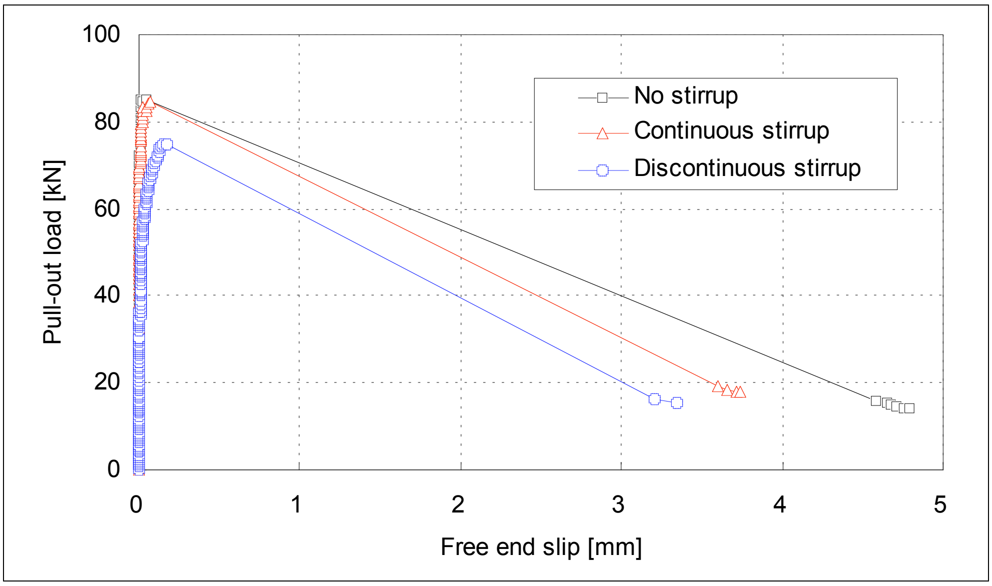

Figure 6: Relationship between pull-out load and free end slip in D19 specimens without expansive crack (the sound specimen).

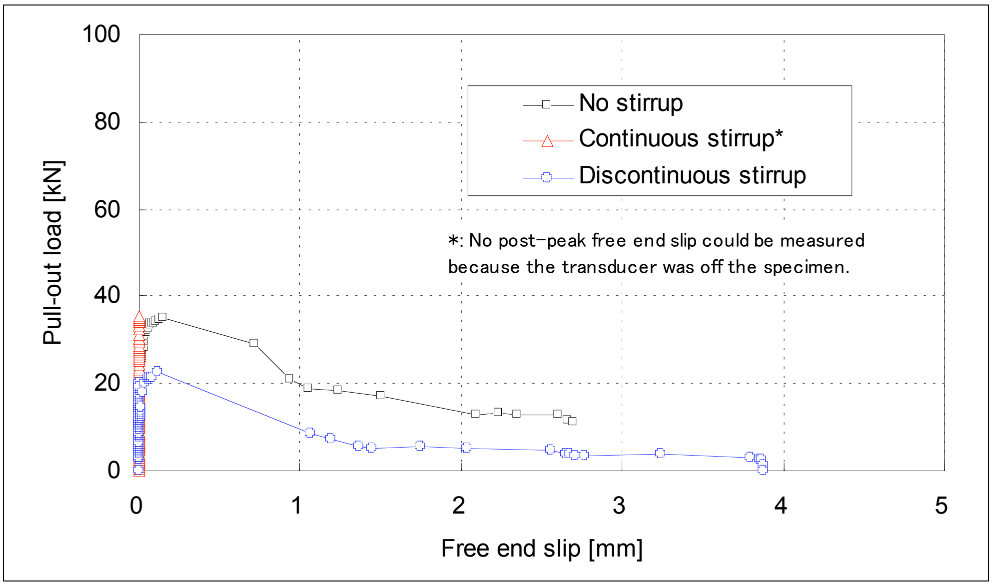

Figure 7: Relationship between pull-out load and the free end slip in D19 specimens with expansive crack.

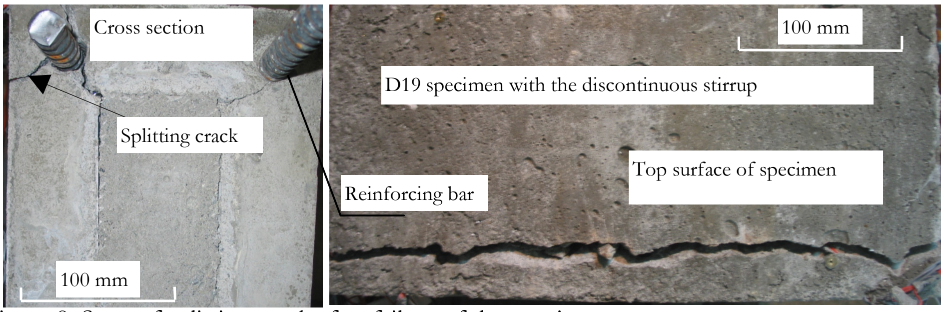

Figure 8: State of splitting crack after failure of the specimen.

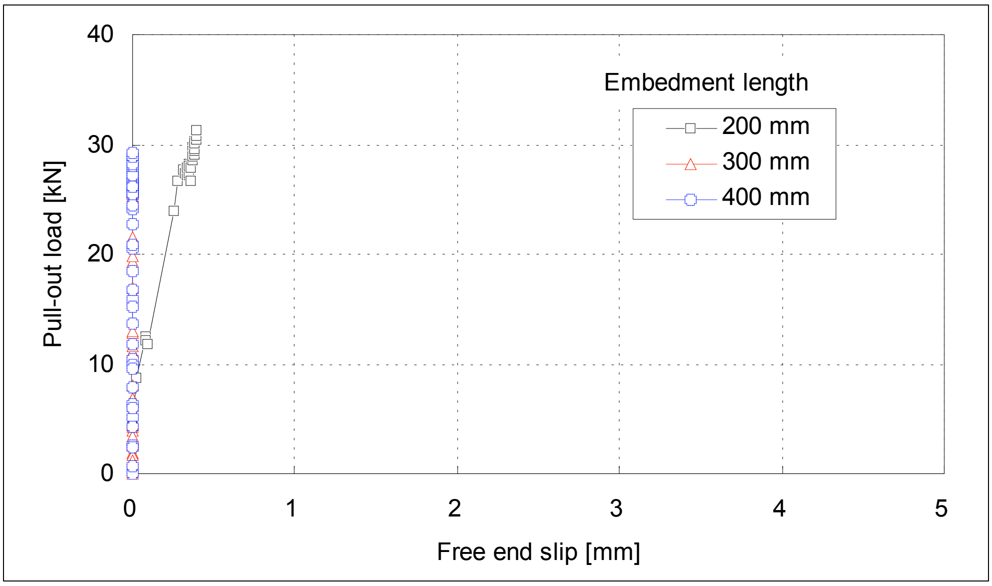

Figure 9: Relationship between pull-out load and free end slip in D10 specimens without expansive crack (the sound specimen).

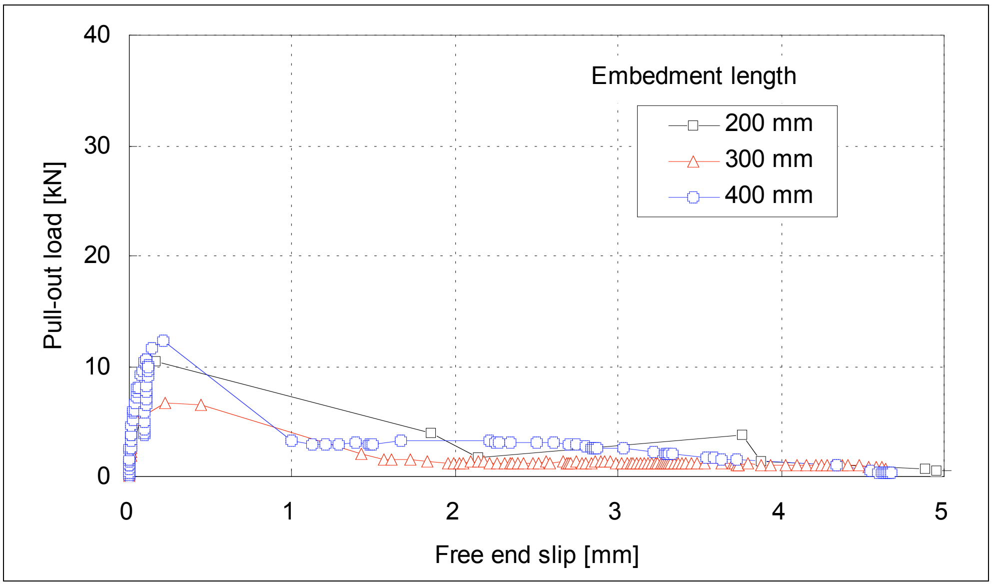

Figure 10: Relationship between pull-out load and free end slip in D10 specimens with the expansive crack.

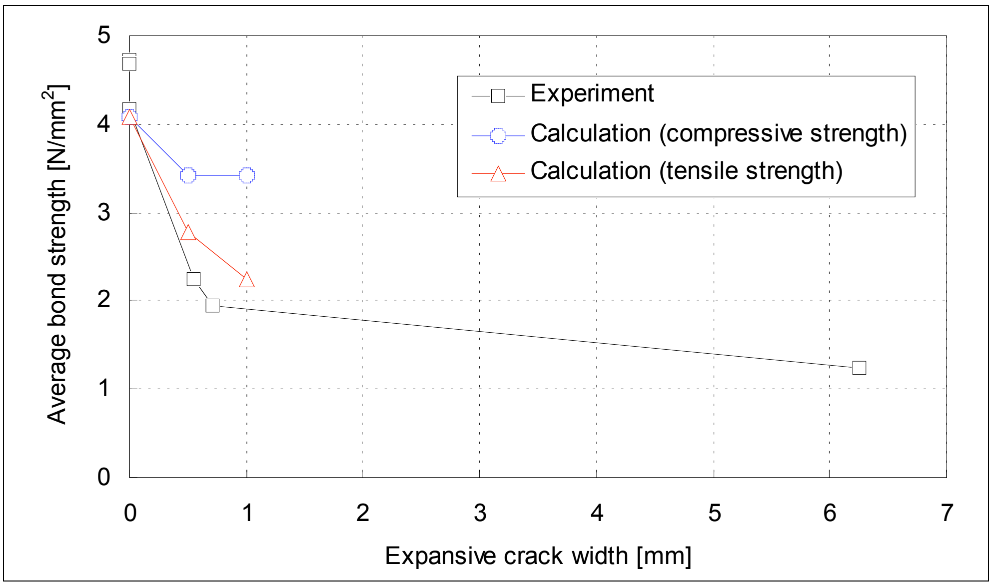

Figure 11: Relationship between calculated bond strength and expansive crack width, along with experimental bond strength.