EFFECT OF RUPTURE OF SHEAR REINFORCEMENT ON SHEAR CAPACITY OF ASR DAMAGED REINFORCED CONCRETE BEAMS

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Abstract

In recent years, it is reported in Japan that stirrups, as well as longitudinal steels, in T-shaped beams of bridge piers were ruptured at their bent corners mainly due to large ASR expansion. Therefore, it is essential to make clear the shear resistant mechanism of the beams, in which the stirrups are ruptured at the bent corner, in order to evaluate their residual shear capacity.

In this study, the effects of expansion of concrete as well as bond and anchorage characteristics of stirrups on shear behaviour are investigated. Bond strength of ASR damaged concrete is also examined in order to evaluate the bond and anchorage characteristics of ruptured steels.

From the test results, it is found that rupture of stirrups has relatively large influence on shear capacity of reinforced concrete beams. However, the degree of the influence depends largely on the anchorage characteristics of ruptured stirrups in ASR damaged concrete.

Keywords: rupture of stirrups, shear capacity, ASR expansion, bond and anchorage characteristics, bond strength

1 INTRODUCTION

In recent years, it is reported in Japan that stirrups, as well as longitudinal steels, in T-shaped beams of bridge piers were ruptured at the bent corner or butt joints. In order to make clear the causes of this rupture, vigorous research works has been done after the finding of the rupture in existing reinforced concrete structures. Up to the present, it is recognized that this phenomenon occurred not only due to excessive ASR expansion but also under complex combinations of several factors, such as mechanical properties and surface shape of reinforcing bars, bending or welding methods of reinforcing bars, corrosive atmospheres and so on [1]. As for the load carrying capacity of damaged structures, on the other hand, it is indicated that in most cases structural safety of damaged members is guaranteed at the present stage as far as the anchorage of ruptured steels is maintained by the bond between concrete and reinforcing bars based on the site inspection of the damaged structures as well as some experimental and analytical investigations [1]. However, it is essential to make clear the shear resistant mechanism of ASR damaged beams, in which stirrups are ruptured at their bent corners, in order to evaluate the residual shear load carrying capacity.

In this study, bond strength of ASR damaged concrete as well as normal and expansive ones is examined in order to evaluate the bond and anchorage characteristics of ruptured steels. In addition, the effects of rupture of stirrups as well as concrete expansion on load carrying behaviour of reinforced concrete beams are investigated by beam loading tests.

2 BOND STRENGTH TESTS

2.1 Objectives

In order to evaluate the effects of rupture of stirrups on shear capacity of reinforced concrete members, it is essential to make clear the bond and anchorage characteristics of ruptured reinforcing bars in ASR damaged concrete. Therefore, the bond strength tests were carried out in order to obtain fundamental data on bond and anchorage characteristics of ruptured stirrups in damaged concrete.

2.2 Specimens

Specimens for the bond strength tests were concrete cubes of 100×100×100mm, in the center of which a reinforcing bar (length: 1000mm) was embedded as shown in Figure 1. Bond length of the embedded reinforcing bars was set as 4D (D: bar diameter) for normal and expansive concrete according to JSCE-G503 "Test method for bond strength between reinforcing steel and concrete by pull-out test [2]", while 5D was selected for ASR damaged concrete. The rest part outside the bond

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length, the bond between concrete and reinforcing bar was eliminated by using grease and masking tape.

2.3 Test variables

The main test variables were kind of concrete and diameter of reinforcing bars.

Mix proportions of normal, expansive and ASR damaged concrete are listed in Table 1. In the expansive concrete, 38% of unit cement weight was replaced by expansive admixture (calcium sulfo alminate). Reactive fine and coarse aggregates, which are categorized as one of andesite and judged as "not harmless" by JIS A 1145 "Method of test for alkali-silica reactivity of aggregates by chemical method [3]", were used in the pessimum (approximately 50% by weight) for the ASR damaged concrete. Sodium Chloride (NaCl) was also added so that total alkali contents might become 8kg/m^3. This relatively high dosage of NaCl in the mix might have initiated corrosion of reinforcement. However, corrosion of the reinforcing bars was not discriminated after the loading tests.

Material properties of each concrete at the bond strength test are listed in Table 2. Free expansion of the expansive concrete was approximately 1.2% at the age of 5 days, while that of the ASR concrete was about 0.33% at the age of 491 days under exposure in natural environment. In both of the expansive and the ASR concrete specimens, expansive cracks were observed at the time of the bond strength tests. In the ASR concrete, however, less but large cracks up to the width of 0.3mm were observed compared with the expansive concrete, in which the maximum crack width was at most 0.15mm. This suggests that expansion mechanism of concrete is different between ASR concrete and expansive one.

As for the diameter of reinforcing bars, 6(D6), 10(D10), 13(D13) and 16mm(D16) were selected for normal and expansive concrete, while D10 and D13 for ASR damaged concrete. Mechanical properties of these reinforcing bars are shown in Table 3. Note that the shapes of ribs and lugs of D6 bars are different from those of the others.

Details of the specimens for the bond strength tests are indicated in Table 4. The number of specimens for each combination of test variables is 6 for normal and expansive concrete, while 2 for ASR damaged concrete.

2.4 Loading tests

Loading tests were carried out according to JSCE-G503 [2] as shown in Figure 2. During the loading tests, the applied loads and pull-out displacements were recorded. From these results, the average maximum bond stress as well as the stress at the pull-out displacement of 0.002D was calculated by using Equation 1.

$$\tau = \frac{\alpha P}{\pi L D} \qquad (1)$$

where, τ : bond stress, P : applied load, L : bond length, D : bar diameter, α : modification factor considering the effect of compressive strength ($\alpha = 29.4 / f'_c$), f'_c : compressive strength at 28days (N/mm^2).

2.5 Test results and discussions

In Table 4 are listed the average bond stress at the pull-out displacement of 0.002D, the average maximum bond stress and final failure mode. Some examples of the relationship between the average bond stress and pull-out displacement are also shown in Figure 3.

Failure mode

The observed failure modes of the specimens are divided into two patterns, that is, 1) pull-out of reinforcing bar from the concrete, in which the applied load decreased gradually with increasing the pull-out displacement and 2) splitting failure of concrete due to the hoop tension stress generated by the bearing stress at the face of the lugs, which accompanied a sudden drop in load carrying capacity and a large increase of the pull-out displacement (See Figure 3). As listed in Table 4, the final failure mode of the normal and expansive concrete specimens shifted from pull-out of reinforcing bar to splitting failure of concrete as the bar diameter increased. This is mainly due to that the hoop tension stress becomes larger with increasing the bar diameter, which resulted in premature splitting failure of concrete. In ASR damaged concrete specimens, the observed failure mode was only the splitting of concrete irrespective of the diameter of reinforcing bars. This implies that the pre-existing ASR cracks reduce the resistance against the hoop tension stress.

Average maximum bond stress

Figure 4 shows the relationship between the maximum average bond stress and the diameter of reinforcing bars. In the normal concrete specimens, the maximum average bond stress became smaller with increasing the diameter of reinforcing bars, except for the case of D6 which had a different shape of lugs and ribs. The same tendency was observed in the ASR damaged concrete specimens. In the expansive concrete specimens, on the other hand, remarkable difference in the average maximum bond stress due to the diameter of reinforcing bars could not be observed. In addition, the average maximum bond stress was significantly small compared with those in the normal and ASR concrete ones. In case of the expansive concrete, the inside minute cracks due to expansion deteriorated the whole of cement matrix and this might cause the significant reduction in bond strength between concrete and reinforcing bars. As for the ASR damaged concrete, on the other hand, the reduction in the average maximum bond stress is at most 5% compared with the normal concrete. From these results, significant deterioration in bond characteristics due to ASR could not be observed in this case except that the final failure mode tends to shift from pull-out of reinforcing bar to splitting failure of concrete due to the existence of expansive cracks. However, the authors' another tests on the bond strength of ASR damaged concrete (compressive strength: 28.4N/mm^2, elastic modulus: 8.5kN/mm^2, free expansion: 0.49%) [4] indicate that the reduction in the bond strength of the ASR damaged concrete becomes lager up to 25-36% compared with the normal concrete when the cover thickness is less than 4.5 times of the reinforcing bar. These are similar to the results reported by Chana [5]. Therefore, further investigations should be necessary on the effects of cover thickness, bar diameter and so on in the different expansion conditions in order to evaluate the bond characteristics of ruptured reinforcing bars in ASR damaged concrete.

3 BEAM LOADING TESTS

3.1 Objectives

Load carrying behaviour of ASR damaged concrete structures is affected by many factors, for examples, degree of ASR deterioration (expansion, cracks, etc.), magnitude of introduced chemical prestress and, of course, with or without rupture of longitudinal and/or shear reinforcement. Many of past researches indicated that reduction in load carrying capacity due to ASR is not so serious if an excessive expansion causing yielding or rupture of reinforcing bars did not occur. In addition, shear capacity of ASR damaged members becomes rather higher than that of non-damaged ones due to the introduced chemical prestress [6]. However, researches on residual load carrying capacity of ASR damaged members with ruptured stirrups and/or longitudinal steels scarcely exist at the present stage. The objectives of the beam loading tests are to investigate the effects of concrete expansion, rupture of stirrups and bond deterioration on shear capacity of reinforced concrete beams, and then to evaluate structural safety of ASR damaged members.

3.2 Specimens and test variables

The beam loading tests are divided into two series, Series-A and Series-B, according to their main objectives.

Series-A

In Series-A tests, relatively small reinforced concrete beams with width × full depth × total length of 100 × 200 × 1800mm were used. The main test variables are i) with or without concrete expansion and ii) bond and anchorage characteristics of stirrups. In this case, ASR expansion was imitated by using expansive concrete. As for the bond and anchorage of stirrups, four deferent conditions were considered as shown in Figure 5, that is, no deterioration (Condition 1), deteriorated bond but no rupture (Condition 2), with rupture but no bond deterioration (Condition 3) and both of rupture and bond deterioration (Condition 4). Deteriorated bond condition was made by using grease and vinyl tape. In case of Condition 2, the bond between a stirrup and concrete was eliminated along its whole length. In case of Condition 4, on the other hand, the bond was eliminated in the length of 60mm (=6D, D: bar diameter) from the ruptured point.

As for the concrete, normal and expansive concrete with the same mix proportions as the bond strength tests were used (see Table 1). Two D13 deformed bars were used for main reinforcement, while D6 stirrups were used as shear reinforcement. As for the spacing of stirrups, 100mm (shear reinforcement ratio p_w =0.63%) and 140mm (p_w =0.45%) were selected. Material properties of concrete and mechanical properties of reinforcing bars are listed in Table 5 and Table 6, respectively. The stirrups were cut at their bent corner in the tension side of the cross section in case of Condition 2 and 4.

According to the combination of test variables, totally 16 beams were fabricated and the details of these beams are shown in Table 7. All of the beams tested under the Condition 1 were designed to fail in flexure according to the JSCE Standard Specifications for Concrete Structures [7].

Series-B

Series-B tests were carried out in order to investigate the effects of practical ASR expansion and rupture of stirrups on load carrying behaviours. In this series, totally three reinforced concrete beams with width × full depth × total length of 300 × 300 × 2000mm were used. Two of them were made by the same ASR concrete as used in the bond strength tests, while the other one was made by normal concrete. The mix proportions of these concrete are listed in Table 1. Five D19 reinforcing bars (f_{sy} =378N/mm^2, reinforcement ratio p =1.84%) were used for longitudinal reinforcement and D10 (f_{sy} =330 N/mm^2) stirrups were used for shear reinforcement. The spacing of stirrups was 120mm (p_w =0.40%), and the bent corners of these stirrups were cut in the tension side of the cross section in one of the two ASR concrete beams (the beam H-5) as shown in Figure 6.

These tested beams were exposed to sun and rain but off the ground for about 18 months after casting of concrete. In this case, they were simply supported and subjected to the stress caused by their dead load. The temperature range was -2.8 to 38.4°C and the average was 16.2°C, while the average relative humidity was 61%. During the exposure, changes in the strain of concrete, longitudinal bars and stirrups were measured. Material properties of normal and ASR concrete at the loading tests are shown in Table 8. The details of Series-B beams are listed in Table 9. These beams were designed to fail in shear in order to evaluate the effectiveness of stirrups within ASR damaged concrete.

3.3 Loading tests

All of the test specimens were loaded under symmetrical two-point loads monotonously up to failure. The shear span – effective depth ratio (a/d) in Series-A was set as 3.53, while in Series-B as 2.0 so that the effect of shear force might become dominant. During the loading tests, applied load, deflections at the mid span and the loading points, changes of the strains in longitudinal steels and stirrups were recorded. In addition, the propagation of cracks during loading was observed.

3.4 Test results and discussions

Series-A

Results of Series-A tests are summarized in Table 7. In addition, some examples of final failure mode of the specimens are shown in Figure 7.

In the expansive concrete beams, chemical prestress due to the restraint of expansive strain was introduced. The average value of this restraining strain in the longitudinal bars was approximately 230×10^{-6} and the resultant introduced chemical prestress was about 2.8N/mm^2. The initial cracking pattern due to the concrete expansion was somewhat different according to the bond and anchorage condition of the stirrups, and longitudinal cracks along with the main reinforcement were observed in the expansive concrete beams with the ruptured stirrups.

As seen in Table 7, the measured maximum load carrying capacity of the expansive concrete beams which failed in flexure was approximately 20% smaller than that of the corresponding normal concrete beams. This is mainly due to the significant reduction in compressive strength of concrete caused by concrete expansion, which is inferred from the fact that the failure mode of the expansive concrete beams was flexural compression failure without yielding of longitudinal bars while that of the normal concrete beams was flexural tension failure. In this case, however, the measured maximum loads of the expansive concrete beams were considerably larger than the calculated ones which were estimated by using cylinder strength under expansion restrained condition (see Table 5). This implies that the practical deterioration of concrete inside the beams might be smaller compared with the values obtained from cylinder specimens. Therefore, it is essential to consider this when evaluating the load carrying capacity of ASR damaged members.

The measured maximum load of the beams under Condition 2 (deteriorated bond but no rupture) was almost the same as that of the corresponding Condition 1 (no bond deterioration and no rupture) beams irrespective of concrete types. From these results, it is suggested that shear capacity of the beams in which the bond between concrete and stirrups are deteriorated does not decrease significantly as long as the stirrups were tightly anchored into core concrete by acute-angled hook, although the propagation of diagonal cracks becomes somewhat remarkable in the normal concrete beams as seen in Figure 7 due to the stiffness reduction in section height direction.

As for the beams tested under Condition 3 (with rupture but no bond deterioration) and 4 (both of rupture and bond deterioration), final failure mode was different according to the used concrete. In the expansive concrete beams (B100T, B140T, B100FT, B140FT), premature shear bond failure occurred. Bond strength of expansive concrete itself is considerably small compared with that of normal concrete as mentioned section 2, and the estimated necessary bond length which guarantees the yielding of stirrups was approximately 100mm (17D). In the expansive concrete beams, therefore, enough bond length of stirrups could not be secured and the stirrups could not display their strength. Small bond strength also affects the resistance against the dowel force of longitudinal reinforcement. As shown in Figure 7, significant shear bond cracks were observed in the beams B100T and B100FT, resulting in the premature shear bond failure. As for the normal concrete beams, on the other hand, the beam N100T showed flexural tension failure, while the other three beams (N140T, N100FT, N140FT) showed diagonal tension failure. These results seemed to be related to the relationship between shear force carried by each stirrup and bond strength of concrete. In case of the beam N100T, the shear force carried by each stirrup was relatively small compared with that of the beam N140T with smaller shear reinforcement ratio, and well transferred by the bond between a stirrup and concrete. In the other three beams, it seemed that the truss mechanism was also formed at first. However, debonding between concrete and stirrups occurred at relatively early stage after the diagonal cracking and this resulted in the diaconal tension failure.

In Figure 8 are shown some examples of the relationship between the strain in stirrups and the allied load. In the normal concrete beams, the stirrup strains in the beam N100 was much larger than those of the beams N100F and N100T which also showed flexural tension failure. This was related to the bond and anchorage condition of stirrups in concrete. In the beam N100F, the strain in a stirrup was averaged along with its legs due to no bond, and this resulted in smaller values of stirrup strain and larger value of diagonal crack width as seen in Figure 7 compared with the beam N100. The stirrup strains in the beam N100T was smaller than those in the beam N100F, and this is mainly due to that the stirrups were ruptured at the bent corners and anchored only by bond, also the truss mechanism was formed and the beam failed finally in flexure. In the beam N100FT, the increase in the stirrup strain stopped at the applied load of about 40kN due to slip, and resulted in diagonal tension failure. In the expansive concrete beams, on the other hand, significant increase in the stirrup strains could not be observed. In the beams B100 and B100F, diagonal cracks were scarcely observed and concrete crushing occurred before diagonal cracking because of the effects of introduced chemical prestress and reduced compressive strength of concrete in the compression zone as well as no rupture of stirrups. In the beams B100T and B100FT, on the other hand, the bond slips occurred at early of loading due to small bond strength and this led to the shear bond failure without increase in the stirrup strains.

Figure 9 shows some examples of the load-deflection relationships. As for the normal concrete beams, significant deference in the maximum load and the deformation characteristics after the maximum load could not be observed among the beams which failed in flexure, although the flexural stiffness of the beams N100F and N100T up to the maximum load was somewhat smaller compared with that of the beam N100. In case of the beam N100FT, the flexural stiffness was furthermore reduced. From these results, it is supposed that the rupture as well as the bond deterioration of stirrups have an influence on the flexural stiffness. This tendency was also observed in the expansive concrete beams.

Series-B

In Table 9 is shown the summary of Series-B loading tests. Figure 10 shows the crack maps of ASR damaged concrete beams before loading and Figure 11 shows the cracking pattern and the failure mode after the loading tests.

At the time of the loading tests, random cracks due to ASR expansion were observed in both of the ASR damaged beams especially in the upper side of them. In the beam H-5 with ruptured stirrups, however, longitudinal cracks along with the tensile reinforcing bars were also observed. This implies that the restraining force against the expansion in the vertical direction was reduced in the beam H-5 due to the rupture of stirrups. The maximum crack width due to ASR expansion was 1.0mm in the beam H-1, while 1.5mm in the beam H-5. The average restraining strain in the tensile reinforcing bars was approximately 0.0003 in the beam H-1 and 0.00055 in the beam H-5. These values correspond to the introduced chemical prestress at the tension fiber of 3.0N/mm^2 and 5.5N/mm^2, respectively.

The normal concrete beam N-1 showed diagonal tension failure, and this coincided with the predicted failure mode although the measured maximum load was approximately 20% higher than the estimated value. In the ASR damaged beams, on the other hand, flexural tension failure occurred although some cracks which had already existed before the loading tests extended to diagonal cracks with increasing the applied load. This is mainly due to the effect of introduced chemical prestress as indicated in the past research [6]. In the beam H-5, however, shear bond cracks along with the tensile reinforcing bars were observed as seen in Figure 11 because of the rupture of stirrups, and the maximum load of the beam H-5 was somewhat smaller than that of the beam H-1 without the rupture of stirrups. From these results, it is recognized that the effect of the introduced chemical prestress, which had a role to increase the concrete shear capacity, was rather larger than the negative effect of the deterioration of concrete and the rupture of stirrups, which reduce the shear capacity of the beams, in case of the deterioration level observed in the tested beams. From the bond strength tests, the required bond length which guarantees the yielding of the stirrups was approximately 5D (=50mm, D: bar diameter), and it is supposed that the ruptured stirrups still worked well due to the combined effect of the chemical prestress which increased the bond strength between concrete and stirrups.

In Figure 12 are shown the relationships between the stirrup strain and the applied load. As seen in this figure, the stirrup strain in the beam N-1 began to increase after the diagonal cracking at about 200kN, and reached the yield strain at the final stage of loading. This implies that the truss mechanism was formed and the beam failed finally in shear due to the yielding of stirrups. In the ASR damaged beams, on the other hand, the stirrups did not reach their yield strain even at the final stage of loading. This fact implies that the introduced chemical prestress increased the concrete shear capacity and restrained the opening of the diagonal cracks. Comparing among the ASR damaged beams, however, the stirrup strain at the final stage of the beam H-5 was approximately 50% of that of the beam H-1. In the beam H-5, shear bond cracks as seen in Figure 11 became significant with increasing the applied load. These bond cracks are thought to occur due to the dowel force of the longitudinal bars, and the ruptured stirrups in the beam H-5 could not restrain this force only by the bond between concrete and the stirrups, resulting in the smaller strains compared with those of the beam H-1.

Figure 13 shows the relationships between the applied load and the deflection at the loading point. As seen in this figure, the load carrying capacity of the beam N-1 decreased abruptly due to the brittle diagonal tension failure, while both of the ASR damaged beams showed ductile load-deflection relationships. Comparing among the ASR damaged beams, the flexural rigidity of the beam H-5 after the applied load of about 300kN as well as the maximum capacity became somewhat smaller than those of the beam H-1. This is mainly due to that the restraining effect of the ruptured stirrups against ASR expansion became smaller, resulting in the increase of expansive cracks as well as their width which caused the reduction of flexural rigidity.

From the results of Series-B loading tests, the influence of the rupture of stirrups on the shear capacity of the ASR damaged beams was rather small at the damage state observed in this study compared with the effect of chemical prestress. If the ASR damages become more significant, however, the rupture of stirrups might lead to the premature bond failure or the diagonal tension failure.

4 CONCLUSIONS

In this study, the effects of rupture of stirrups on shear capacity of ASR damaged beams were investigated through the bond strength tests and two kinds of beam loading tests. The main conclusions obtained are summarized as follows.

1) The reduction in the bond strength of the ASR concrete, of which the expansive strain and the maximum crack width was approximately 0.33% and 0.3mm respectively, was at most 5% compared with that of the normal concrete although the final bond failure mode tended to be the splitting of concrete rather than the pull-out of reinforcing bar due to the existence of expansive cracks. However, these results were obtained from restricted specimens and conditions. Therefore, further investigations should be necessary on the bond strength of ASR damaged concrete, especially focussing on the effects of cover thickness, bar diameter and so on in the different expansion conditions.

2) The bond characteristics of the expansive concrete used in this study were different from those of the normal and ASR damaged concrete. In the expansive concrete, the inside minute cracks due to expansion deteriorated the whole cement matrix and this might cause the significant reduction in bond strength between concrete and reinforcing bars. From these results, it is noted that attention should be paid when imitating the ASR damage by using expansive concrete.

3) In the normal and expansive concrete beams, debonding between the stirrups and the cover concrete did not have large influence on the ultimate shear capacity on condition that the stirrups were anchored well into the core concrete by the acute-angled hook, although the width of the diagonal cracks tended to become larger. The rupture of the stirrups, on the other hand, had relatively large influence on the failure mode and the ultimate shear capacity of the beams. When considering the residual shear capacity of the ASR damaged structures with ruptured stirrups, special attention should be paid on the bond strength deterioration of cover concrete due to large expansion.

4) The ASR damaged beams, in which the maximum crack width due to ASR expansion was 1.0-1.5mm, failed in flexure even when the stirrups were ruptured, while the normal concrete beam showed the diagonal tension failure. Judging from these results, the effect of the introduced chemical prestress was rather larger compared with that of the rupture of the stirrups at the damage level observed in the tested ASR beams. In the ASR damaged beam with ruptured stirrups, however, the bond cracks along with the longitudinal bars extended during the loading tests. This implies that the premature bond failure might occur in the beams with ruptured stirrups if the damage level becomes larger due to further expansion which causes the deterioration of the bond characteristics of concrete. Therefore, further investigations on the different damage levels, especially on the relationship between the outside damage profiles and the residual shear capacity, should be necessary to take rational countermeasures against the ASR damaged structures with ruptured stirrups.

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TABLE 1: Mix proportions of used concrete.

Type	G_{max} (mm)	Slump (cm)	Air (%)	W/C (%)	s/a (%)
Normal	25	8	4.0	70	46.4
Normal (Series-B)	25	12	4.5	63	45.8
Expansive	25	8	4.0	70	46.4
ASR	25	12	4.5	63	45.8

Type	Unit weight (kg/m^3)								Water Reducing Agent (cc/m^3)
	W	C	Ex	S_{normal}	$S_{reactive}$	G_{normal}	$G_{reactive}$	NaCl	
Normal	165	236	-	882	-	1020	-	-	590
Normal (Series-B)	183	290	-	840		1080	-	-	726
Expansive	165	147	89	882	-	1020	-	-	590
ASR	183	290	-	394	411	507	492	13.1	726

TABLE 2: Properties of concrete (bond strength tests).

Type	Compressive Strength f'_c (N/mm²)	Elastic Modulus E_c (kN/mm²)	Free Expansion (× 10^{-6})
Normal	28.8	27.1	-
Expansive	5.1 (14.7) *	5.1 (23.8)*	12123 (5 days)
ASR	27.7	11.6	3267 (491 days)

* the values under expansion restrained condition

TABLE 3: Mechanical properties of reinforcing bars (bond strength tests).

Diameter	Yield Strength f_{sy} (N/mm²)	Tensile Strength f_{su} (N/mm²)	Elastic Modulus E_s (kN/mm²)
D6	404	560	186
D10	325	493	194
D10 (ASR)	356	492	183
D13	308	476	182
D13 (ASR)	333	488	189
D16	337	482	201

TABLE 4: Details of specimens and results of tests (bond strength tests).

Specimen	Concrete type	Diameter of bars D (mm)	Bond length	Number of specimens	Average bond stress at 0.002D (N/mm²)	Maximum average bond stress (N/mm²)	Failure * mode
N-D6	Normal	6	4D	6	5.1	10.4	P:6, S:0
N-D10		10			8.5	18.2	P:4, S:2
N-D13		13			8.4	15.1	P:3, S:3
N-D16		16			7.3	11.0	P:0, S:6
B-D6	Expansive	6			1.2	6.3	P:6, S:0
B-D10		10			1.0	6.2	P:6, S:0
B-D13		13			2.3	8.1	P:3, S:3
B-D16		16			2.1	6.3	P:0, S:6
A-D10	ASR	10	5D	2	11.1	17.2	P:0, S:2
A-D13		13			9.9	14.9	P:0, S:2

* P: pull-out of reinforcing bar, S: splitting failure of concrete

TABLE 5: Properties of concrete of Series-A beams.

Type	Compressive Strength f'_c (N/mm²)	Tensile Strength f_t (N/mm²)	Bending Strength f_b (N/mm²)	Elastic Modulus E_c (kN/mm²)	Free Expansion (× 10^{-6})
Normal	34.5	3.15	3.91	31.4	-
Normal (N100T, N140T)	32.2	2.45	4.05	27.5	-
Expansive	2.4 (8.7)*	0.30 (0.56)*	0.68 (1.03)*	2.63 (6.27)*	27926 (7 days)

* the values under expansion restrained condition

TABLE 6: Mechanical properties of reinforcing bars used in Series-A beams.

Concrete Type	Diameter	Yield Strength f_{sy} (N/mm²)	Tensile Strength f_{su} (N/mm²)	Elastic Modulus E_s (kN/mm²)
Normal (except for N100T, N140T)	D6	382	541	196
	D13	334	534	191
Expansive (including N100T, N140T)	D6	442	586	203
	D13	338	497	199

TABLE 7: Details of specimens and results of beam loading tests (Series-A).

specimens	concrete	bond and anchorage condition	spacing of stirrups (mm)	*1 P_u (kN)	*2 V_c (kN)	*3 V_s (kN)	*4 P_s (kN)	*5 P_{max} (kN)	*6 failure mode
N100	Normal	Condition 1	100	67.5	22.1	35.8	115.8	76.2	FT
N100F		Condition 2		67.5	22.1	35.8	115.8	74.2	FT
N100T		Condition 3		66.8	21.5	39.5	122.0	73.3	FT
N100FT		Condition 4		67.5	22.1	35.8	115.8	62.5	S
N140		Condition 1	140	67.5	22.1	25.5	95.2	76.9	FT
N140F		Condition 2		67.5	22.1	25.5	95.2	76.7	FT
N140T		Condition 3		67.5	22.1	28.2	100.6	66.2	S
N140FT		Condition 4		67.5	22.1	25.5	95.2	59.3	S
B100	Expansive	Condition 1	100	35.1	13.9	39.5	106.8	61.0	FC
B100F		Condition 2		35.1	13.9	39.5	106.8	56.6	FC
B100T		Condition 3		35.1	13.9	39.5	106.8	51.7	SB
B100FT		Condition 4		35.1	13.9	39.5	106.8	41.2	SB
B140		Condition 1	140	35.1	13.9	28.2	84.2	61.0	FC
B140F		Condition 2		35.1	13.9	28.2	84.2	59.1	FC
B140T		Condition 3		35.1	13.9	28.2	84.2	50.2	SB
B140FT		Condition 4		35.1	13.9	28.2	84.2	46.1	SB

*1 calculated ultimate flexural capacity
*2 calculated shear capacity contributed by concrete (Based on JSCE Standard Specification [4])
*3 calculated shear capacity contributed by stirrups (Based on JSCE Standard Specification [4])
*4 calculated ultimate shear capacity (P_s=2V_c+2V_s)
*5 measured maximum load
*6 FT: flexural tension failure, FC: flexural compression failure, S: diagonal tension failure, SB: shear bond failure

TABLE 8: Properties of concrete of Series-B beams.

Type	Compressive Strength f'_c (N/mm^2)	Elastic Modulus E_c (kN/mm^2)
Normal	27.4	22.4
ASR	26.8	21.9

TABLE 9: Details of specimens and results of beam loading tests (Series-B).

Specimens	Concrete	Rupture of Stirrups	Spacing of Stirrups (mm)	*1 P_u (kN)	*2 V_c (kN)	*3 V_s (kN)	*4 P_s (kN)	*5 P_{max} (kN)	*6 failure mode
N-1	Normal	—	120	458	117	89	412	521	S
H-1	ASR	—		456	116(126)	89	410(430)	520	FT
H-5	ASR	○		456	116(134)	89	410(447)	487	FT

*1 calculated ultimate flexural capacity
*2 calculated shear capacity contributed by concrete (Based on JSCE Standard Specification [4])
( ) indicates the value considering the effect of chemical prestress
*3 calculated shear capacity contributed by stirrups (Based on JSCE Standard Specification [4])
*4 calculated ultimate shear capacity (P_s=2V_c+2V_s)
( ) indicates the value considering the effect of chemical prestress
*5 measured maximum load
*6 FT: flexural tension failure, S: diagonal tension failure

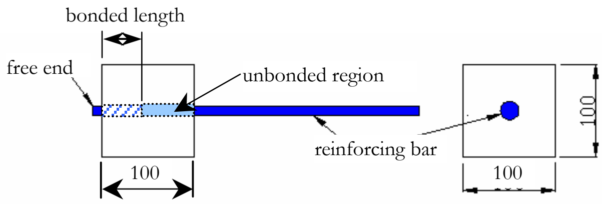

Figure 1: Test specimen for the bond strength tests.

Figure 2: JSCE bond strength test.

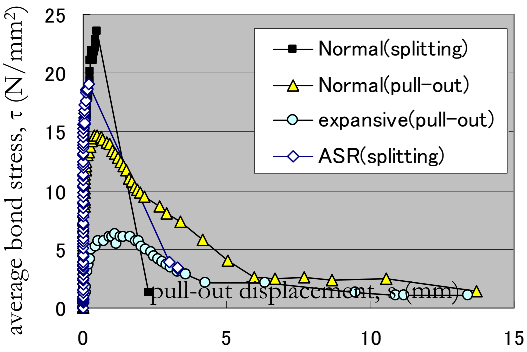

Figure 3: Examples of the relationship between the average bond stress and pull-out displacement.

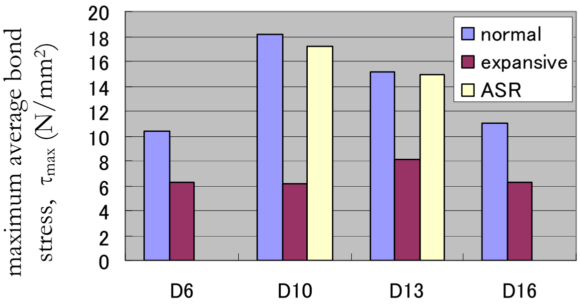

Figure 4: Relationship between the maximum average bond stress and the bar diameters.

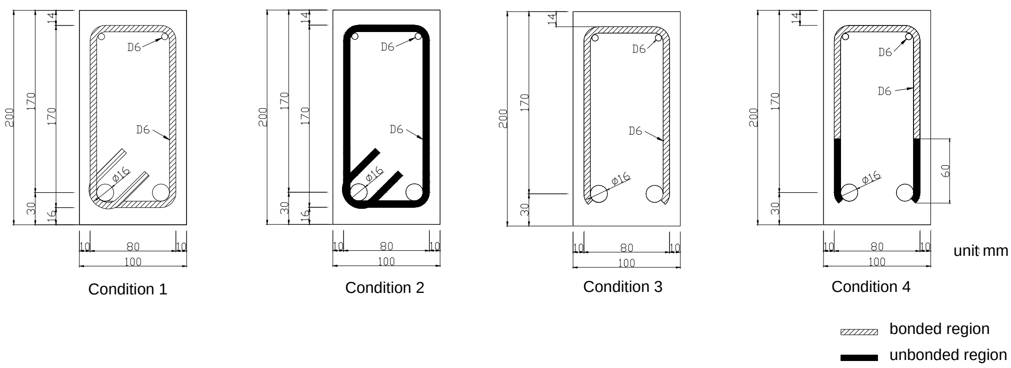

Figure 5: Cross sections of Series-A specimens and considered deterioration conditions.

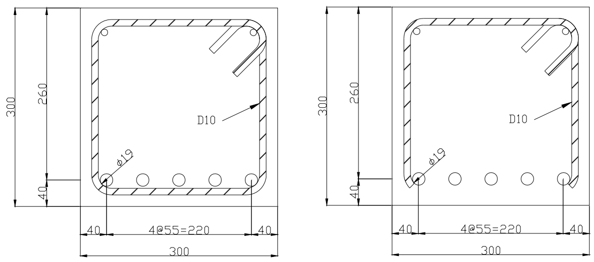

Figure 6: Cross sections of Series-B beams.

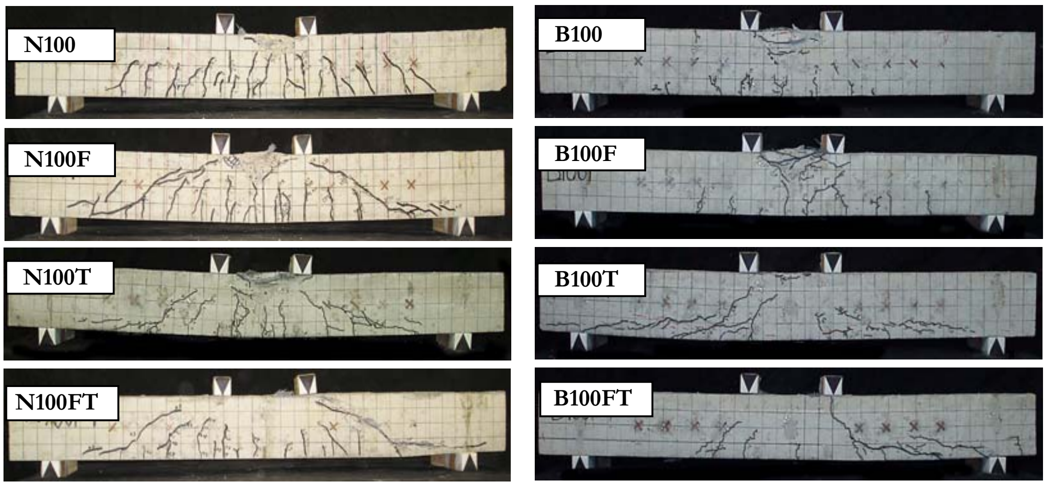

Figure 7: Final failure mode of Series-A beams (s=100mm).

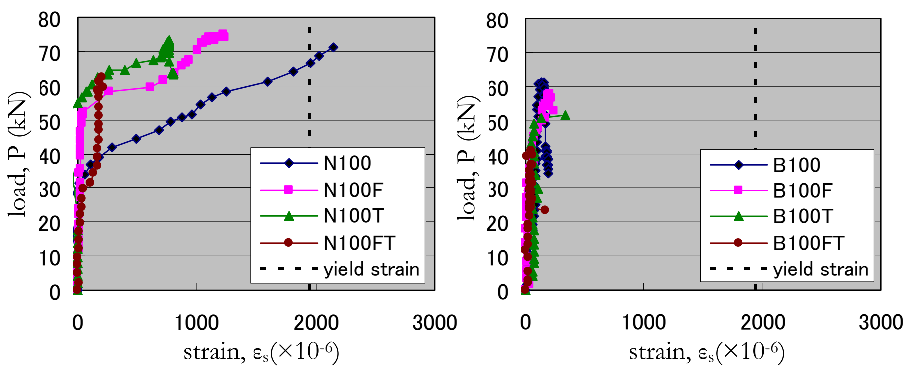

Figure 8: Examples of the relationship between the strain in stirrups and the allied load.

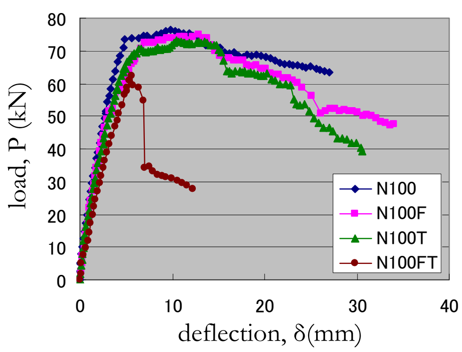

Figure 9: Load-deflection relationship (s=100mm, normal concrete).

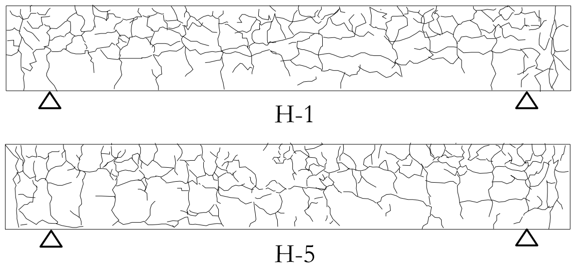

Figure 10: Crack map due to ASR expansion.

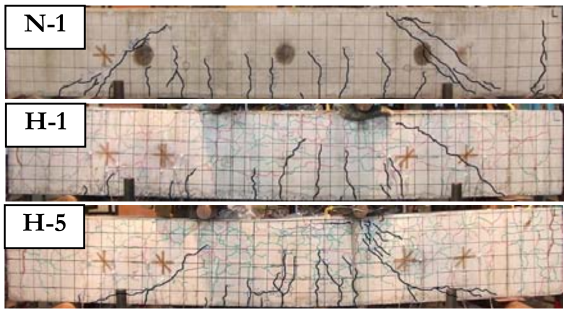

Figure 11: Final failure mode of Series-B beams.

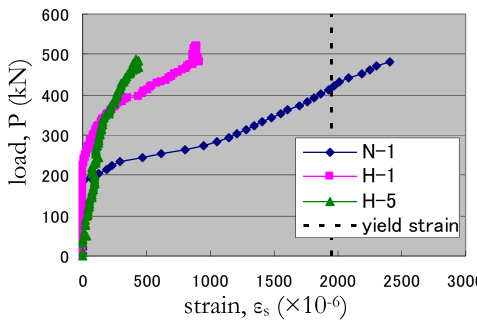

Figure 12: Relationship between stirrup strain and the applied load.

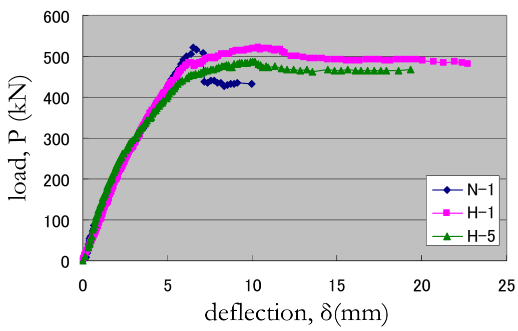

Figure 13: Relationship between the applied load and the deflection at the loading point.