- Technical Paper -

EFFECTS OF EXPANSION OF CONCRETE AND FRACTURE OF REINFORCEMENT ON SHEAR BEHAVIOR OF RC BEAMS

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ABSTRACT

To clarify the load-carrying behavior change of RC beam caused by the expansion of concrete, the fracture of reinforcement or the expansive crack along the longitudinal reinforcement, experimental study was carried out. From the experimental investigation, the shear resistance and structural deformation were highly influenced by fractured stirrups. However, in case of no expansive crack, the effect of the fractured longitudinal reinforcement to the load-carrying behavior was not obvious. Moreover, the effect of expansive crack to the increase of deformation capacity was observed.

Keywords: expansion of concrete, fractured reinforcement, expansive crack, shear behavior

1. INTRODUCTION

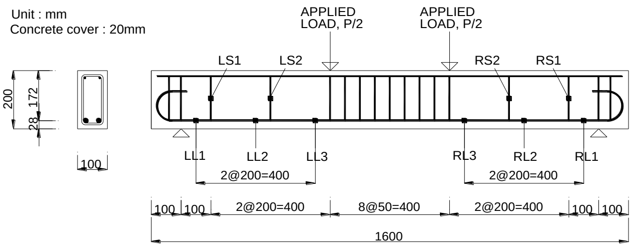
The alkali silica reaction (ASR) sometimes produces not only the degradation in the mechanical properties of concrete and the interaction between concrete and reinforcing steels but also the damage of the reinforcing steels [1]. The fracture of the reinforcing steel in its anchorage or bent region has recently been reported [2]. Therefore, it is important to understand the load-carrying behavior and capacity of reinforced concrete (RC) members deteriorated by ASR expansion. Especially, the relation between the shear resisting mechanism and the fractured reinforcement holds a great significance for the structural deformations related with the safety and serviceability of RC structures.

The aim of this paper is to clarify the load-carrying behavior change of RC beam caused by the expansion of concrete, the fracture of reinforcement and the expansive crack along the longitudinal reinforcement in RC beams.

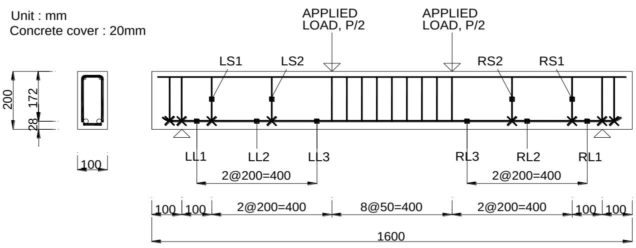
2. EXPERIMENTAL PROGRAM

2.1 Test specimens

The specimen details are shown in Fig. 1. The test specimens were RC beams with the rectangular section. All specimens had a span length of 1,400mm (whole length of 1,600mm) and 100 x 200mm rectangular cross section. Longitudinal tension reinforcement consisted of two D16 (SD345) bars with yield strength of 388.5N/mm^2, so as to be a tensile reinforcement ratio of 0.023. Longitudinal compression reinforcement consisted of two D6 (SD295A) bars with yield strength of 320.9N/mm^2. D6 (SD295A) stirrups were arranged by the spacing of 200mm in longitudinal direction of the specimens, so as to be a shear reinforcement ratio of 0.32. LS, LL,



(a) N01 and E01



(b) E04

Fig. 1 Specimens

Table 1 Mix proportion of concrete

Specimen	Concrete (unit mass)								
	G_{max}, mm	Slump, cm	Air, percent	W/C, percent	Water, kg	Cement, kg	Expansive additive, kg	Fine aggregate, kg	Coarse aggregate, kg
N01 to 10	15	12.0	4.0	62	179	288	0	913	910
E01 to 04						202	86		

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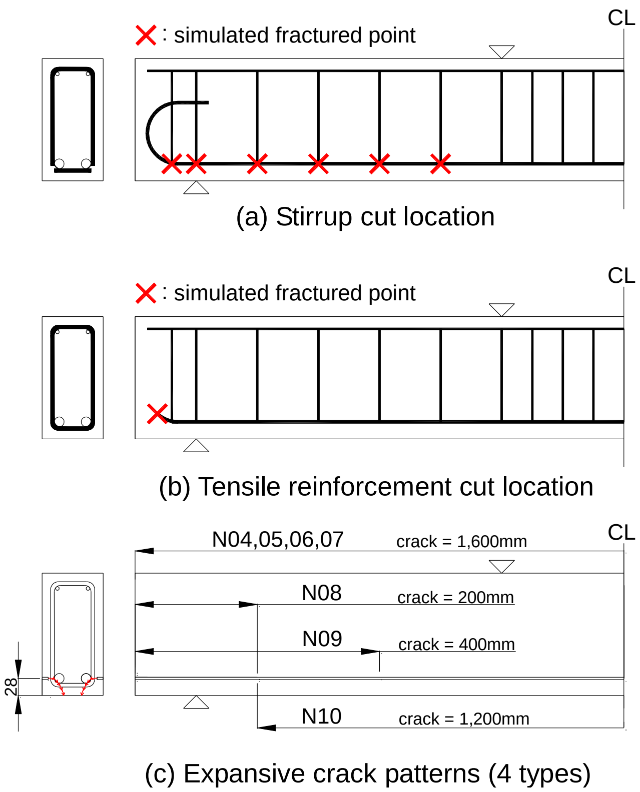


Fig. 2 Test parameters

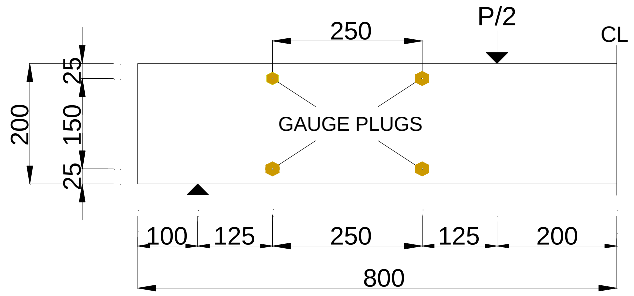


Fig. 3 Measurement of expansion (unit: mm)

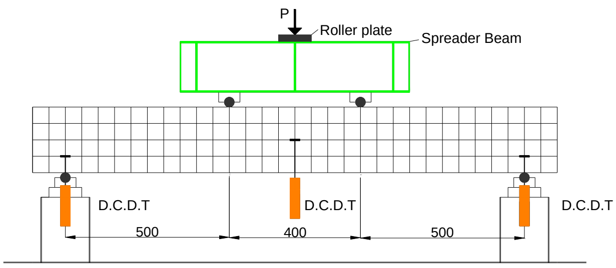


Fig. 4 Loading test setup (unit: mm)

RS, RL denoted in Fig. 1 show the strain gauges which adhered to reinforcement. Total number of test specimens was fourteen.

The mix proportions of concrete used in test specimens are shown in Table 1. Water-cement ratio is 0.62 with a cement content of 288kg/m^3. The proportion of E series consisted of specimens using expansive additive. The cement mass of 30% were replaced by the expansive additive. This proportion was designed to ensure the adequate expansion in a reasonable time period. The specimens were cast and cured under controlled conditions in the laboratory room for 28 days.

2.2 Test parameters

Table 2 describes the detail of test specimens and the test parameters including the test results.

(1) Expansion of concrete

Concrete expansion was produced by using the expansive additive with the proportion as mentioned above. Further discussion must be needed regarding the difference between the expansion by ASR and the expansive additive in the expansion mechanism and its result in the mechanical property of concrete. However, this research only focused on the effect of the compressive stress induced by the restraint of reinforcement. Then, the difference in the expansion mechanism is not mentioned.

(2) Fracture of reinforcement

Although the mechanism of this fracture in ASR affected structures is not completely obvious, the influence of the fracture on the load-carrying capacity of RC structures is quite significant. The bent region of the stirrups and the anchorage region of the longitudinal reinforcement were cut, as shown in Fig. 2 (a), (b) respectively. All fractured reinforcement was artificially cut and embedded prior to casting. It should be noted that cutting stirrup is not continuous completely in its two bent regions of bottom side, while the compressive and tensile reinforcements are connected each other by stirrups.

(3) Expansive crack and its length

An expansive crack along the direction of longitudinal reinforcement must degrade the bond strength at the longitudinal reinforcement, and consequently, bring the change on the load-carrying behavior. Four types of crack lengths were arranged as shown in Fig. 2 (c). The artificial notches were provided on the side surface in the height of 28mm from the bottom of the specimen by using an electric blade for concrete, whose width of the blade was 3mm. The depth of the notch from concrete surface is 10mm, judging from concrete cover (20mm) and diameter of tensile reinforcement (D16). After inducing the notch, static demolition agent (W/E=27%) was put into the notch to propagate the expansive crack toward the location of the tensile reinforcement in the RC cross section.

As shown in Fig. 2 (c), 1,600mm (crack length) indicates the crack induced along the whole length of tensile reinforcement. 200mm (crack length) and 400mm (crack length) indicate the cracks induced in each anchorage region. On the other hand, 1,200mm (crack length) indicates the crack induced in only the portion of 1,200mm of the central span.

The crack width in the specimens (N04 to N09) which induced the expansive crack was measured at the open section of both ends of the specimen. Crack was usually propagated from the artificially induced notch to the bottom side of the specimen via the location of the longitudinal tension reinforcement in the section as shown in Fig. 2 (c). The range of crack width was from 0.05 mm to 1.0 mm. The smaller

Table 2 Beam details and test results

Specimen *1	Test parameters: Reinforcement cut, Long.*2	Stirrup*3	Crack length*4 (mm)	f'_c (N/mm^2)	Calculation(kN): Flexure P_u	Shear V_c	V_s	V_y	Test result (kN) P_{max}	Failure mode *5	Expansion rate(%)*6 Hori.	Vert.
N01	N	N		32.0	88.4	21.6		36.8	103.8	DT		
N02	N	Y		40.0	91.7	23.2		38.4	69.1	ST		
N03	Y	N		40.0	91.8	23.3		38.5	96.4	DT		
N04	N	N	1,600	32.0	88.4	21.6		36.8	108.1	FT		
N05	N	Y	1,600	40.0	91.7	23.2		38.4	68.1	ST		
N06	Y	N	1,600	40.0	91.8	23.3	15.2	38.5	104.5	ST		
N07	Y	Y	1,600	42.4	92.6	23.7		38.9	67.3	ST		
N08	Y	Y	200	42.4	92.6	23.7		38.9	63.6	ST		
N09	Y	Y	400	40.9	92.1	23.5		38.6	69.7	ST		
N10	Y	Y	1,200	40.9	92.1	23.5		38.6	84.6	ST		
E01	N	N		8.16	37.6	13.7		28.9	101.6	FT	0.16	0.68
E02	N	Y		8.16	37.6	13.7	15.2	28.9	65.4	ST	0.17	0.79
E03	Y	N		8.16	37.6	13.7		28.9	110.2	FT	0.14	0.72
E04	Y	Y		8.16	37.6	13.7		28.9	53.8	ST	0.14	0.89

*1-N01-10: normal concrete, E01-04: expansive additive mixed
*2&*3 - Y: cut, N: no cut
*4-crack length as shown in Fig. 2 (c)
*5-Failure Mode (FT: flexural tension, DT: diagonal tension, ST: shear tension)
*6-Hori- horizontal expansion rate, Vert.-vertical expansion rate

crack widths are observed in the closer position of the longitudinal reinforcement.

2.3 Measurement of concrete expansion

The expansion of the specimen with the expansive additive was measured in the early stage after demoulding. Contact gauge method (1/1000 mm) is applied for the measurement of concrete expansion. 8 gauge plugs were embedded in the cover concrete of each specimen as shown in Fig. 3. Before the loading test, horizontal and vertical length changes between 2 gauge plugs were measured. An expansion rate was calculated by dividing the measured length change with each base length. As shown in Fig. 3, horizontal and vertical base length is 250 and 150 mm respectively.

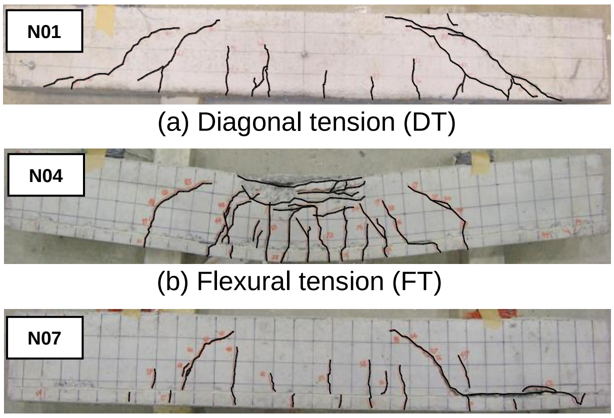
2.4 Loading test procedure

The loading test setup is shown in Fig. 4. Load was applied using 2000kN universal testing machine. The beams were loaded in two symmetrical points so that the flexural span was 400mm and overall span being 1,400mm. Direct current displacement transducers (DCDT) were placed at the center of the span and both support points to measure deflections. Strains in the longitudinal reinforcement and stirrup were measured by electrical resistance strain gauges. Stirrup gauges were attached on the stirrup at the center of the height, as shown in Fig.1. In addition, the crack propagation was observed.

3. Test results and discussion

3.1 Cracking behavior and failure modes

Fig. 5 (a) through (c) show the typical failure



(a) Diagonal tension (DT)

(b) Flexural tension (FT)

(c) Shear tension (ST)

Fig. 5 Typical failure crack patterns

crack patterns. Three different failure modes were observed, while the sound RC beam (N01) failed in the diagonal tension failure (DT). Table 2 includes the failure mode of each specimen. First failure mode is the diagonal tension failure (DT). Two specimens (N01, N03) were observed to fail in diagonal tension failure according to the design. N03 showed the diagonal tension failure after yielding of the beam, while N01 showed the failure prior to the yielding. Second one is the flexural tension failure (FT). Three specimens (N04, E01, E03) were observed to fail in flexural tension. The final one observed in the remaining specimens is shear tension failure (ST) with the bond splitting crack. Specifically, all specimens with the fractured stirrup failed in this mode. So, it can be said that when stirrup is fractured, structural performance is changed and shear tension failure dominated the beam behavior.

3.2 Effect of the fracture of the longitudinal reinforcement in the anchorage region

Fig. 6 shows the load-deflection curves of the specimens with or without the fractured longitudinal reinforcement in the anchorage region. The test

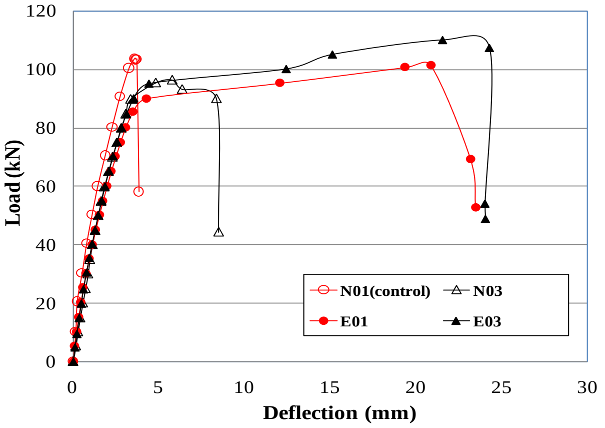


Fig. 6 Load - deflection curves

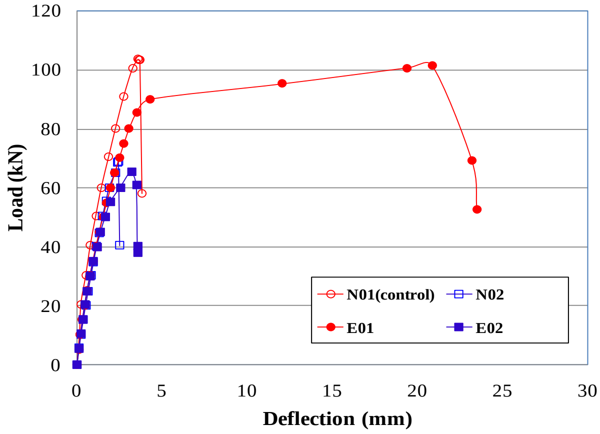


Fig. 9 Load - deflection curves

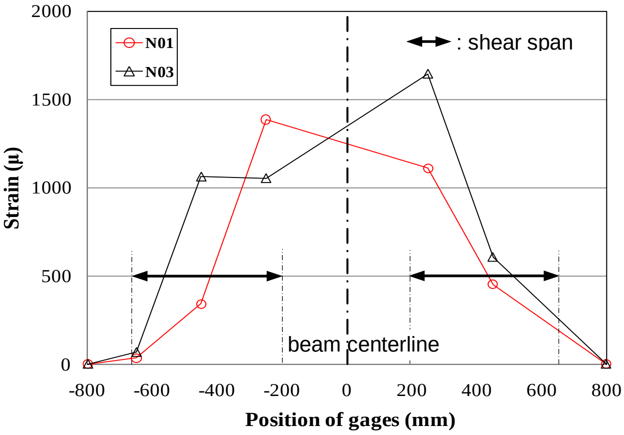


Fig. 7 Strain distribution in tensile reinforcement at load 60kN

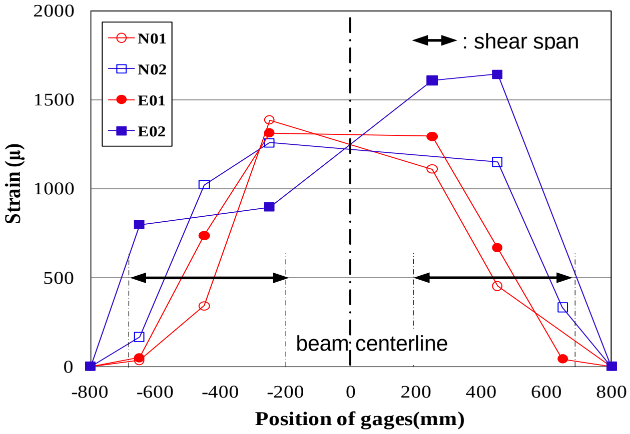


Fig. 10 Strain distribution in tensile reinforcement at load 60kN

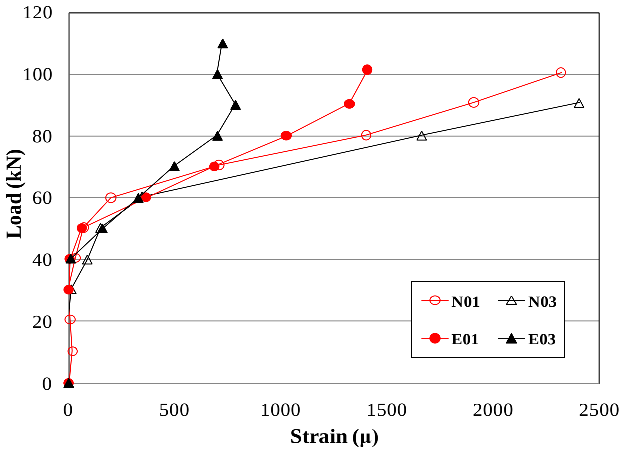


Fig. 8 Load - strain curves of stirrups

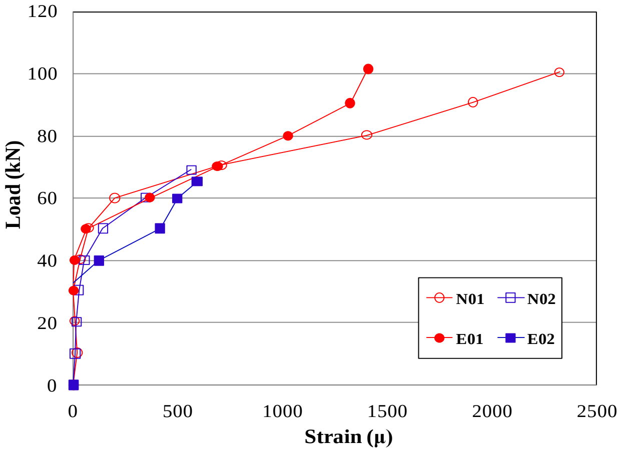


Fig. 11 Load - strain curves of stirrups

specimens N01, N03 were observed to fail in DT. However, N03 with the fracture of the longitudinal reinforcement showed the DT after yielding. Fig. 7 shows the distribution of the strain in the longitudinal reinforcement at the load of 60kN. The strain in the shear span of N03 was larger than that of N01. This is attributed to the slip of the fractured longitudinal reinforcement due to the inadequate anchorage. Consequently, an arch action in the shear resisting mechanism brought a little increment of the deformation capacity.

Based on the above result, it can be said that the fracture of longitudinal reinforcement in its anchorage region, in case of no expansive crack along the longitudinal reinforcement, scarcely change the shear resisting mechanism in the RC beam designed to fail in DT.

E01 and E03 specimens which induced the expansion of concrete showed the flexure tension failure and the higher deformation capacity than specimen N01. Fig. 8 shows the load-strain curve in stirrup. E01 and E03 specimens had smaller strains in stirrups than N01 or N03. This is because the diagonal tension crack development and propagation were

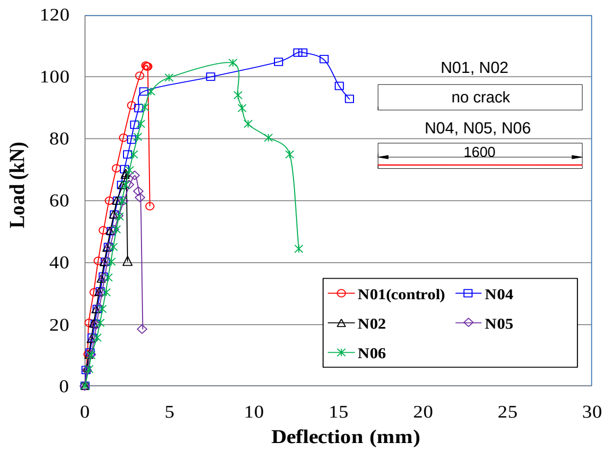


Fig. 12 Load - deflection curves

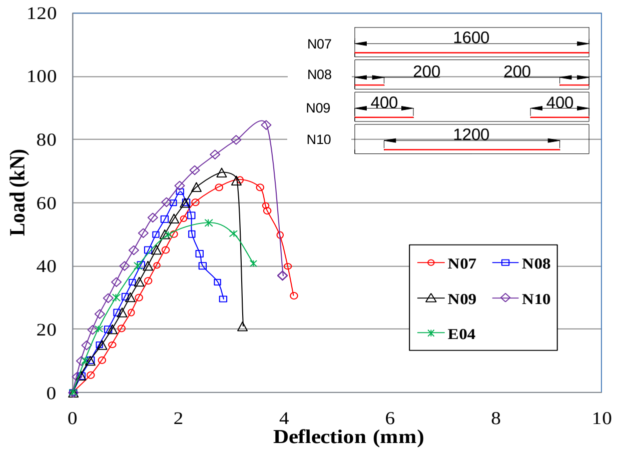


Fig. 14 Load - deflection curves

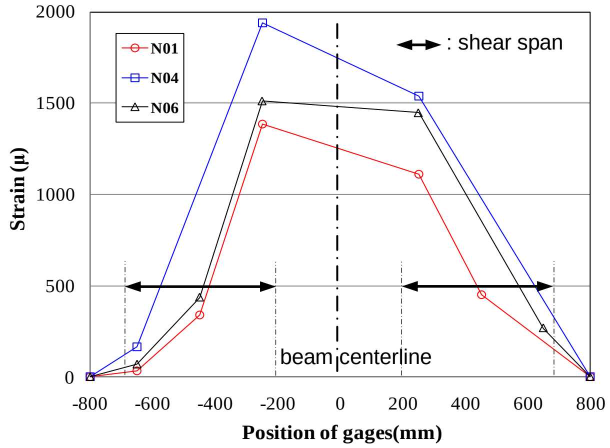


Fig. 13 Strain distribution in tensile reinforcement at load 60kN

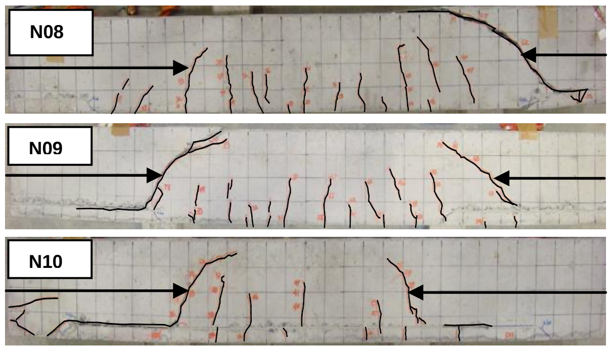


Fig. 15 Crack propagation of N08, N09, N10

restricted by the compressive stress induced by the restraint of expansion. And also, the compressive strain of the concrete in the flexural compression zone might be easy to get to the ultimate strain, because of the compressive stress induced by the restraint of the expansion.

3.3 Effect of fractured stirrups at its corner region

Fig. 9, 10 and 11 show the load-deflection curves, the distribution of the strain in the longitudinal reinforcement at the load of 60kN, and the load-strain curve in stirrup of the specimens with or without the fractured stirrup at its corner, respectively.

No matter the expansion of concrete, the specimens (N02 and E02) with the fractured stirrups were observed to fail in ST. The fractured stirrups decrease the resistance against bond splitting crack caused by the dowel action of the longitudinal reinforcement after the development of diagonal crack. And then, the shear tension failure with the sudden splitting crack propagation occurred before yielding.

As shown in Fig. 10, the strain in shear span close to the anchorage region of N02 specimen with the fractured stirrup was larger than that of N01 specimen. The slip of the longitudinal reinforcement seems to occur due to the inadequately enclosed stirrup in the N02 specimen. On the other hand, in the N01 specimen, the beam action was able to be maintained from the occurrence of the diagonal crack up to just before the DT failure, because of the adequate confinement of stirrup. Those facts indicate that the fracture of stirrups causes the reduction of the resistance to the slip of the tensile reinforcement and then shear tension failure with the splitting cracks.

The E01 specimen with the non-fractured stirrup showed the large deformation after yielding owing to the compressive stress induced by the restraint of the expansion. However, the E02 specimen with the fractured stirrups resulted in the shear tension failure. As shown in Fig. 11, the bond splitting cracks in the E02 specimen seemed to be propagated before the stirrup sufficiently resisted to the diagonal cracks due to the fractured bent region of bottom side. Although the diagonal crack propagation at the web region of shear span around the neutral axis was restricted by the compressive stress induced by the restraint of expansion, the resistance to the bond splitting crack due to vertical tension stress caused by the dowel action was not able to be exhibited. This may be attributed that the compressive stress around the location of the longitudinal reinforcement is mainly active not to the vertical direction, but to the horizontal direction along the longitudinal reinforcement.

The E02 specimen is almost the same as the N02 in the maximum load. This value is much larger than calculated one by using compressive strength from the cylinder test with free expansion. It should be noted that the decrease of material strength in the RC beam due to the expansion of concrete is smaller than the strength of cylinder concrete specimen with free expansion. So, the appropriate concrete strength should be considered for the accurate calculation of shear resisting capacity in RC beams subjected to ASR expansion.

3.4 Effect of expansive crack (in case of length 1600mm)

Fig. 12 and Fig. 13 show the load-deflection curves and the distribution of the strain in the longitudinal reinforcement at the load of 60 kN of the specimens with or without the expansive crack in the whole span length, respectively. The N04 specimen with the expansive crack showed the flexural tension failure, while the N01 failed in diagonal tension failure. As shown in Fig. 13, the strain in the shear span of N04 was larger, because the expansive crack led the slip of the longitudinal reinforcement. Consequently, the arch action in the shear resisting mechanism brought the large deformation capacity. Although the similar mechanism was also produced in the N06 specimen, the arch action collapsed due to the fracture of the longitudinal reinforcement at its anchorage region.

On the other hand, when fractured stirrups were embedded at its corner, the sudden shear tension failure was observed regardless of expansive crack. This is because the slip of the longitudinal reinforcement due to the inadequately enclosed stirrup caused the bond splitting crack, as mentioned in 3.3. It should be noted that expansive crack along the location of the longitudinal reinforcement at the fractured corner of the stirrups can change the shear resisting mechanism and cause the drastic reduction of the load-carrying capacity.

3.5 Effect of expansive crack lengths

Fig. 14 shows the load-deflection curves of the specimens with some types of the expansive crack lengths. Fig. 15 shows the crack pattern of N08, N09 and N10 specimens.

All specimens resulted in the shear tension failure regardless of the expansive crack length and its location. This is because the fractured stirrups degraded the resistance against the bond splitting crack, as mentioned in 3.3. However, the N10 specimen which induced the crack length of 1,200mm at the central span of specimen, the biggest maximum load was observed. From the observation of cracking during the test, N10 showed the smallest range of cracking in span direction as shown in Fig. 15. Some arch action seemed to be produced because of the relatively better condition in bond at the anchorage region. On the other hand, N08 which induced the crack length of 200mm in the only anchorage region showed the largest range of cracking and the most cracks. From these results, it can be said that the expansive crack which occurred around the anchorage region of the longitudinal reinforcement is significantly related with shear resisting mechanism.

4. CONCLUSIONS

In this paper, the effects of the expansion of concrete, the fracture of longitudinal tensile reinforcement, fractured stirrups and expansive crack on the load-carrying behavior of RC beam, which was designed to fail in the diagonal tension failure at the sound state, were investigated.

The following conclusions can be obtained.

(1) The fracture of longitudinal reinforcement in it anchorage region, in case of no expansive crack along the longitudinal reinforcement, scarcely change the shear resisting mechanism in the RC beam designed to fail in diagonal tension failure.

(2) Every specimen with the fractured stirrups was observed to fail in shear tension failure. The fractured stirrups can degrade the resistance against bond splitting crack caused by the dowel action of the longitudinal reinforcement. Therefore, the effect of the fractured stirrups on the shear resistance was significant.

(3) The expansive crack along the longitudinal reinforcement at the fractured corner of the stirrups can change the shear resisting mechanism and cause the drastic reduction of the load-carrying capacity. Moreover, the expansive crack which occurred around the anchorage region of the longitudinal reinforcement is significantly related with shear resisting mechanism.

ACKNOWLEDGEMENT

This research was greatly supported by the Hanshin Expressway Management Technology Center and JIP Techno Science Corporation. The cast of specimens and experiment work were supported by W, Yang who was graduate student. The authors wish to express their sincere gratitude to above members.

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