SHEAR RESISTING MECHANISM IN RC BEAMS WITH FRACTURED STIRRUPS

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Abstract

The fracture of stirrups due to concrete expansion has been reported on some bridge piers affected by the alkali silica reaction in Japan. RC beams with stirrups cut off at bent corners were tested to investigate their shear resisting mechanism. The test results indicated that the shear capacity of RC beams with damaged stirrups was reduced by approximately 20%; this reduction was induced by a decrease in the shear strength provided by not only stirrups but also concrete. In addition, the loss of confinement due to stirrups made it difficult to sustain the truss action, but contributed to the development of the arch action.

Introduction

The alkali silica reaction (ASR) induces cracking and volume expansion in concrete structures. This expansion has been reported to cause the fracture of stirrups on some bridge piers in Japan (Miyagawa, 2003). It is found mainly at bent corners of stirrups in RC structures, as shown in Fig. 1. The fractured stirrups not only reduce the shear strength of the RC structures but also fail to satisfy the structural details that are required to evaluate the load carrying capacity. Hence, the current safety verification methods may not be applicable to the assessment of their structural performance against the shear force.

The Japan Society of Civil Engineers (JSCE) proposed a verification method for the safety performance of RC structures with fractured stirrups, which was derived on the basis of experimental results by Regan and Reid (2004). These researchers conducted loading tests of RC beams with defective stirrups that have no hooks at bent corners. They proposed that the bond strength of stirrups without end anchorages was limited due to the loss of its development length around the diagonal crack. Based on experimental results, they concluded that

Fig. 1 Fractured stirrup

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this proposition was applicable to the evaluation of the shear capacity of RC beams with defective stirrups. By considering Regan and Reid's proposition and existing experimental data, the JSCE suggested that their shear capacity was estimated by neglecting efficiency of stirrups in 20 times diameter (20ϕ) from the fractured end (JSCE, 2005).

The JSCE's approach is based on the modified truss model, which provides the shear capacity by adding the strength contribution by concrete to that by stirrups. The concrete contribution is considered as the shear force at the commencement of the diagonal crack, while the stirrup contribution is calculated by the 45° truss equation. In the JSCE's proposition, only the latter is reduced by neglecting stirrups in 20ϕ from the fractured end. However, it is reasonable to assume that the role of stirrups is not only to contribute to the shear capacity but also to confine concrete and tensile steels to sustain the truss action. This means that the JSCE's approach may not be applicable to assess the shear resisting mechanism in RC structures with fractured stirrups. Hence, further experimental data is indispensable for discussing the adverse effect of fractured stirrups.

The aim of this paper is to reappraise the shear resisting mechanism of RC structures with fractured stirrups. RC beams that have stirrups intentionally cut off at bent corners are tested to investigate the adverse impacts on the shear capacity.

Experimental program

For evaluating the effects of fractured stirrups on the shear resisting mechanism, three types of specimens—N1, N2, and N3—were tested. Fig. 2 shows their details. N1 was a nondefective RC specimen, while N2 and N3 had defective stirrups that were intentionally damaged at bent corners. All stirrups in the shear span of N2 were cut off at the top end near the compressive steels and those of N3 were cut off at the bottom near the tensile steels. All the specimens were 290 × 410 mm in cross section and had a shear span-to-depth ratio of 3.

Table 1 shows the properties of the specimens. All the specimens contained 1.13% tensile steel with a high yield strength of 719 MPa for developing a large flexural capacity. The shear reinforcement ratio was 0.21% at a spacing of 104 mm, and its yield strength was 363 MPa. The concrete compressive strength was approximately 35 MPa; this value was obtained using three control cylinders on the day of the tests. All the specimens were simply supported at the ends and loaded by two point loads.

The JSCE's evaluation method considered the bond strength of stirrups at 20ϕ from the cutoff end to be ineffective. In order to verify this proposition, the strains in stirrups of N2 and N3 were measured at two or three points for each stirrup; these points were located at 60 mm (10ϕ) , 145 mm (24ϕ) , and 230 mm (38ϕ) from the cutoff end. Further, strain gages were attached at the same locations on N1 for comparing the nondefective and damaged stirrups.

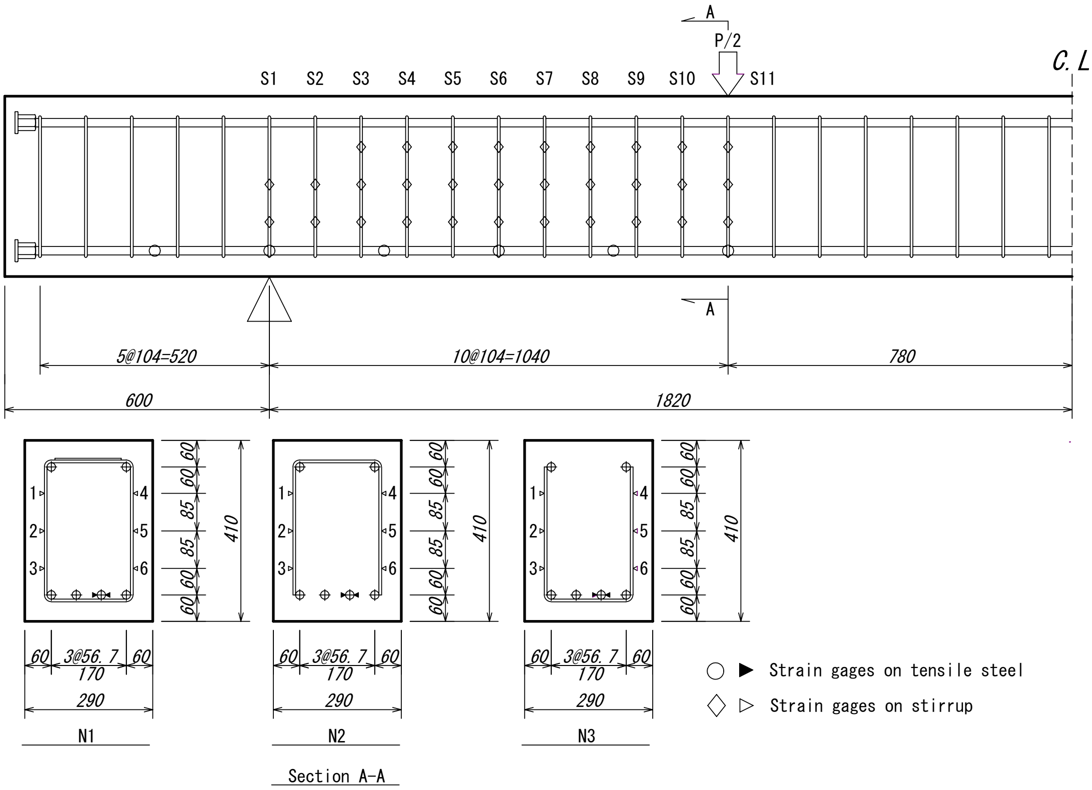


Fig. 2 Specimen details (unit: mm)

Table 1 Properties of specimens

Specimen	b, mm	d, mm	a/d	Concrete	Tensile steel			Stirrup			
				f'_c, Mpa	A_s, mm	ρ_w, %	f_y, MPa	ϕ, mm	s, mm	ρ_t, %	f_{yt}, MPa
N1	290	350	3	35.7	1134	1.13	719	6	104	0.21	363
N2				35.3							
N3				35.3							

In addition, the mechanical changes in the concrete induced by ASR were not taken into account in this experiment.

Shear capacity of RC beams with fractured stirrups

All the specimens failed in shear. Fig. 3 shows the comparison among the load-deflection relations for the specimens. The specimens exhibited similar load-deflection curves before the formation of the diagonal crack. However, the shear capacities of N2 and N3, which had damaged stirrups, were reduced by approximately 20% as compared with the nondefective specimen N1.

Table 2 shows a comparison of the shear capacities obtained from the JSCE code (JSCE, 2002), JSCE's proposition, ACI code (ACI, 2005), and test results. The JSCE and ACI codes provided conservative estimates for N1, but overestimated the shear capacity of N2 and N3 since they provided the shear capacity of nondefective RC beams. Meanwhile, the shear capacity derived from the JSCE's propositions was calculated by adding the concrete contribution to the stirrup contribution, which was reduced by neglecting stirrups in 20ϕ from the fractured end. The comparison of the estimates with the test results of N2 and N3 showed that they were in good agreement with each other. The JSCE's proposition is highly applicable to the verification of the shear capacity of RC beams with fractured stirrups.

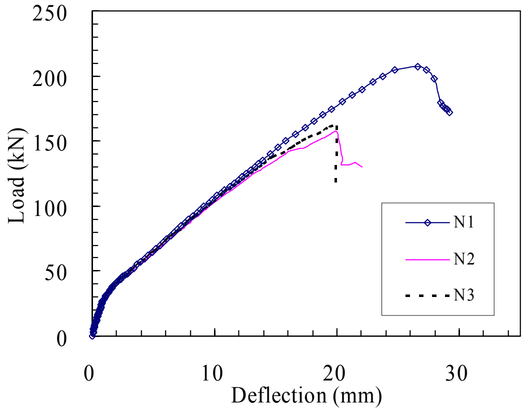


Fig. 3 Load-deflection curve

Table 2 Comparison between estimates and test results

Specimen	JSCE code					ACI code	Test results
	Vccal, kN	Vscal, kN		Vcal(=Vccal+Vscal), kN		Vcal, kN	Vexp, kN
		JSCE code	JSCE's proposition	JSCE code	JSCE's proposition		
N1	111	67	67	178 (0.86)	178 (0.86)	180 (0.87)	207
N2	110	67	46	177 (1.13)	156 (0.99)	179 (1.14)	157
N3	110	67	46	177 (1.09)	156 (0.96)	179 (1.10)	162

Values in parentheses denote Vcal/Vexp.

<u>Strains in stirrups</u>

Fig. 4 shows the strains in stirrups S1 through S11 with crack patterns at the shear failure. The stress-strain relation is defined as the bilinear model with a strain at the yield strength of $2{,}113 \times 10^{-6}$. The dominant diagonal cracks are denoted with heavy lines. By comparing their crack patterns, it is apparent that the diagonal crack angles of N2 and N3 are completely different from that of N1. The fractured stirrups might adversely affect their shear resisting mechanism.

The strains in stirrups also varied depending on whether they were cut off at bent corners or not. With regard to the stirrups of N1, yield strains are found in the local zone near the dominant diagonal crack, which means the lower points of S5 through S7, the middle of S6 through S8, and the upper points of S7 through S9. It is appropriate to assume that nondefective stirrups are beneficial in restraining the propagation of the diagonal crack and providing resistance against the shear force. On the other hand, the stirrups of N2 did not yield at 10ϕ from the cutoff end near the tensile steels, such as the lower point of S5. The stirrups of N3 also showed the same tendency in strains at 10ϕ from the cutoff end near the compressive steels, such as the upper points of S7 through S9. Hence, stirrups within 10ϕ from the fractured end were not able to develop the bond strength to resist the shear force.

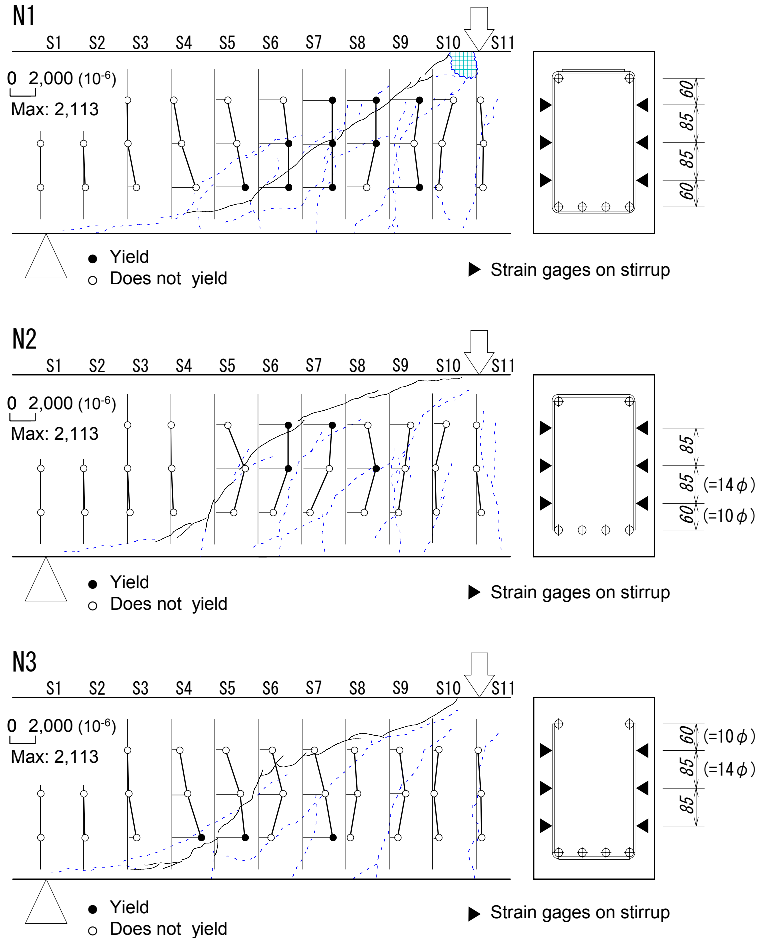
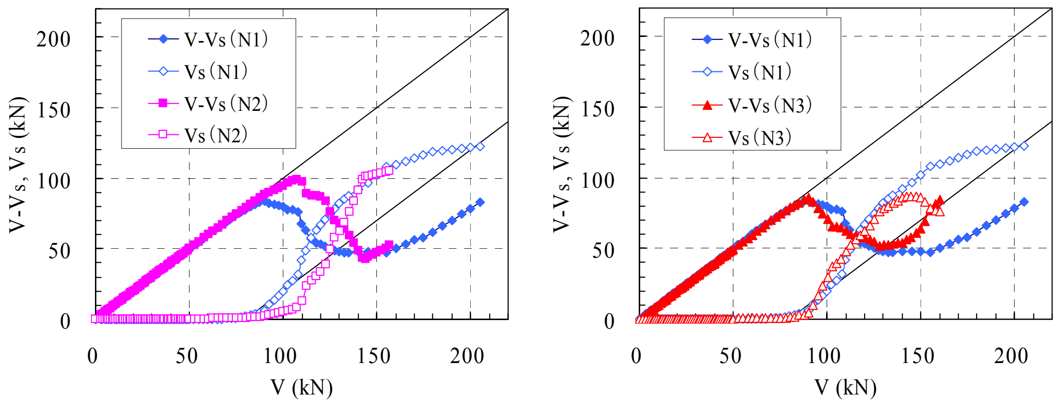


Fig. 4 Strains in stirrups with crack patterns at the shear failure

Even though stirrups from the cutoff end for N2 and N3 had the same strain pattern, the distribution of the pattern was in contrast with each other. N2 had larger strains at the upper points of S6 through S8, while N3 had larger strains at the lower points of S4 and S5. These results imply that the difference in the damaged part of stirrups between N2 and N3 is closely related to their shear resisting mechanisms.

Shear strength contribution by concrete and stirrups

Fig. 5 shows the shear strength contributions by concrete and stirrups and compares N1 with N2 and N3. The concrete contribution was deemed to be equivalent to the applied shear force minus the stirrup contribution, V–Vs. The stirrup contribution was derived by summing the shear strength provided by five different stirrups for each specimen. The shear strength provided by each stirrup was calculated by multiplying the strain near the



(a) N1 and N2 (b) N1 and N3

Fig. 5 Comparisons of the shear strength contributions by concrete and stirrups

dominant diagonal crack by the modulus of elasticity and the area. The strains employed in this procedure were as follows: the lower point of S6, the middle of S7 and S8, and the upper point of S9 and S10 for N1 and the lower point of S5, the middle of S6, and the upper point of S7 through S9 for N2 and N3.

As shown in Fig. 3, the shear capacities of N2 and N3 decreased to nearly 80% of that of N1. The major reason for this was the difference in the strength contribution provided by both concrete and stirrups. The concrete contribution of N2 remained at approximately 60% of that of N1, while its stirrup contribution increased at the same level as that of N1. It can be seen that the reduction in the concrete contribution of N2 has a large impact on its low shear capacity. Meanwhile, although the concrete contribution of N3 was nearly equal to that of N1, its stirrup contribution decreased to approximately 60% of that of N1. Hence, the reduction in the shear capacity of N3 is attributable to its low stirrup contribution.

The reason why the stirrup contribution between N2 and N3 varied was that the tensile stresses in stirrups were different due to their different locations. Fig. 6 shows the distribution of the tensile stresses in each stirrup that was employed to calculate the stirrup contribution. With regard to N2, the lower point of S5 was not able to develop the tensile stress since it was cut off at the bottom end near the diagonal crack. The upper points of S6 and S7 with nondefective hooks contributed to the

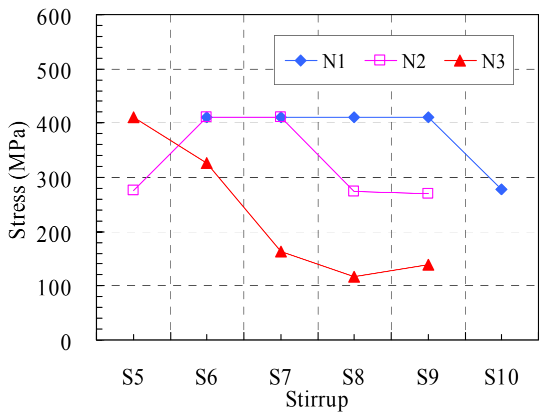


Fig. 6 Stresses in stirrups employed for their strength contribution

resistance against the shear force. Meanwhile, with regard to N3, S7 through S9 were cut off at the top end in the vicinity of the diagonal crack, which made it difficult to provide shear strength. On the basis of these findings, it is reasonable to infer that the strength contribution by concrete and stirrups varied depending on whether the stirrups were fractured at the top or bottom end.

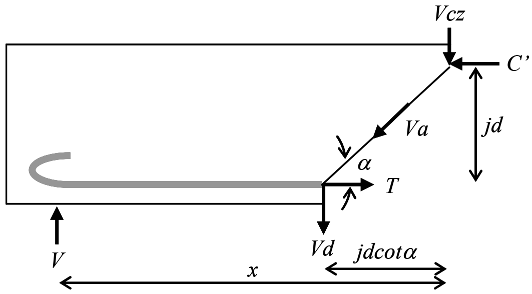


Fig. 7 Forces within the shear span of an RC beam element without stirrups

Arch and beam actions in RC beams with fractured stirrups

It is well known that RC beams without stirrups are able to resist a shear force by means of the arch and beam actions (Park and Paulay, 1975). Fig. 7 shows the forces within the shear span of an RC beam element without stirrups. If the contribution of dowel action is considered as negligible, the principal shear resisting mechanism is derived on the basis of the moment of resistance as follows:

$$M = Tjd \qquad (1)$$

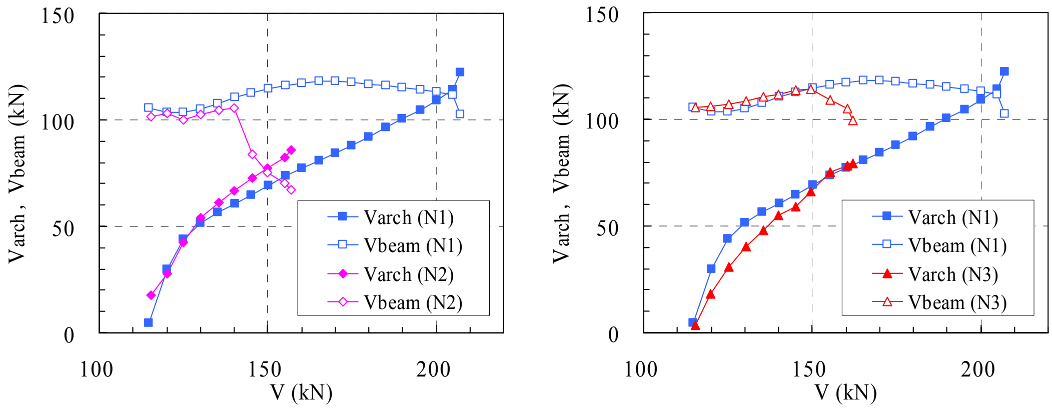
By combining this with the relationship between the shear force and the rate of change of moment along the beam, the following modes of the internal shear resistance are obtained:

$$V = jd\frac{dT}{dx} + T\frac{d(jd)}{dx} \qquad (2)$$

Eq. (2) indicates the two principal modes of the shear resistance. One of the modes is called "beam action" and is represented as $jd(\mathrm{d}T/\mathrm{d}x)$. This term implies that the internal tensile force of principal tensile steels is supposed to vary and the internal lever arm is kept constant. The other mode is called "arch action" and is expressed as $T(\mathrm{d}jd/\mathrm{d}x)$. This term implies that the internal lever arm varies depending on the distance from the beam support while the internal tensile force remains constant. The arch action contributes to the transfer of a vertical load to the beam support by means of the inclined compressive resultant.

Eq. (2) is supposed to represent the shear resisting mechanism in RC beams without stirrups. It would be difficult to resolve the applied shear force in N1, N2, and N3 into each shear resisting component and the arch and beam actions since stirrups are included. However, approximate estimates for the arch and beam actions are useful in clarifying their shear resisting mechanism after the formation of the diagonal crack.

Fig. 8 shows the shear resisting forces resulting from the arch and beam actions and compares those of N1 with those of N2 and N3. The forces were obtained by using the distribution of the internal tensile force and the internal lever arm in Eq. (2). The internal tensile force was derived from the strains in the tensile steels. The internal lever arm was calculated from the relationship between the moment and the internal tensile force in Eq.



(a) N1 and N2 (b) N1 and N3

Fig. 8 Comparison of the shear resisting forces by the arch and beam actions

(1). With regard to N1, the beam action was maintained to be virtually constant from the formation of the diagonal crack to just before the shear failure. The increase in the applied shear force was borne mainly by the arch action. These facts imply that nondefective stirrups in N1 functioned efficiently in the confinement of tensile steels, which contributed to the sustaining of the beam action. Meanwhile, the beam action of N2 and N3 decreased suddenly around an applied shear force of 150 kN since their damaged stirrups could not confine the tensile steels. In particular, it is highly probable that the reduction in N2 was due to the stirrups that were cut off near the tensile steels.

Shear resisting mechanism in RC beams with fractured stirrups

Table 3 summarizes the experimental results with regard to parameters such as the strength contribution by concrete and stirrups and the shear resisting force by the arch and beam actions at the shear failure. In comparison with N1, the concrete contribution of N2 decreased more sharply than the stirrup contribution. Meanwhile, the concrete contribution of N3 was nearly equal to that of N1, despite the stirrup contribution of the former decreasing markedly.

It should be stressed that stirrups not only contribute to the shear capacity but also sustain the arch and beam actions by confining the concrete and tensile steels. In particular, the confinement of tensile steels is beneficial in maintaining the truss action. The experimental results of N2 indicated that the stirrups cut off at the bottom end had an adverse effect on the confinement of tensile steels; this was deemed to reduce the shear resisting force resulting from the beam action. With regard to Fig. 9 that shows stresses in tensile steels at each applied shear force, the stresses in tensile steels in N2 developed to a magnitude greater than the shear span at 150 kN just before the shear failure. This implies that N2 suffered difficulties in sustaining the truss action as well as a decrease in the shear resisting force by the beam action, which resulted in the shear resisting mechanism being

Table 3 Summary of experimental results

Specimen	Vexp, kN	Vs, kN	Vc (=V-Vs), kN	V_{arch}, kN	V_{beam}, kN
N1	207	122	83	131	88
N2	157 (0.76)	105 (0.86)	52 (0.63)	97 (0.74)	58 (0.66)
N3	162 (0.78)	76 (0.62)	85 (1.02)	88 (0.67)	86 (0.98)

Values in parentheses denote the proportion relative to N1.

transferred from the truss action into the arch action.

On the other hand, N3 was able to sustain the truss action without any reduction in the concrete contribution and the shear resisting force by the beam action since their stirrups were cut off at the top end. However, these stirrups were unable to contribute to the shear strength due to the loss of bond strength near the diagonal crack, which resulted in a shear failure without increasing the stirrup contribution.

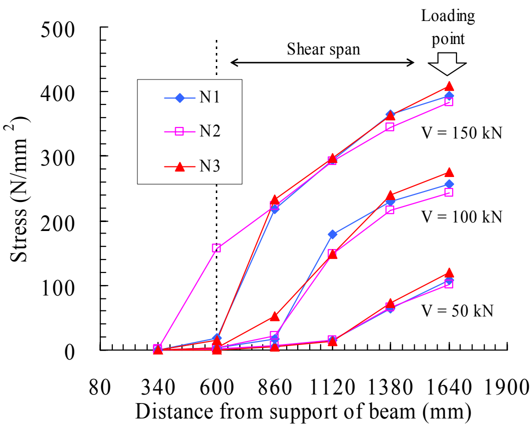


Fig. 9 Stresses in tensile steels

Conclusion

Based on loading tests of RC specimens with stirrups cut off at the bent corners, the following conclusions can be drawn.

1. The shear capacity of RC beams with stirrups fractured at bent corners was reduced to approximately 80% of that in the case of nonfractured stirrups.
2. The JSCE's proposition that considers the concrete contribution as constant but reduces the stirrup contribution is highly applicable to the verification of the shear capacity of RC beams with fractured stirrups.
3. The strength contribution by concrete and stirrups varied depending on the location of the damaged stirrups. The RC beam with stirrups fractured at the bottom end reduces the concrete contribution more sharply as compared to the stirrup contribution. On the other hand, the concrete contribution of the RC beam with stirrups fractured at the top end is nearly equal to that of the nondefective RC beam despite its stirrup contribution decreasing markedly.
4. The RC beam with stirrups fractured at the bottom end is unable to sustain the truss action due to the loss of confinement of tensile steels, which transfers the shear

resisting mechanism to the arch action.

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Notation

a	=	shear span
a/d	=	shear span-to-depth ratio
A_s	=	tensile steel
b	=	width of beam
C'	=	internal compression force
d	=	effective depth of cross section
f'_c	=	compressive concrete strength
f_y	=	yield strength of tensile steel
f_{yt}	=	yield strength of stirrup
j	=	ratio between internal lever arm and effective depth
M	=	moment
s	=	spacing between stirrups
T	=	internal tensile force due to flexure
V	=	shear force
V_a	=	strength contribution by aggregate interlock
V_{arch}	=	shear resisting force by arch action
V_{beam}	=	shear resisting force by beam action
V_c	=	strength contribution by concrete
V_{cal}	=	calculated value of shear capacity
V_{ccal}	=	calculated value of strength contribution by concrete
V_{cz}	=	strength contribution by compression zone
V_d	=	strength contribution by dowel action
V_{exp}	=	experimental value of shear capacity
V_s	=	strength contribution by stirrup
V_{scal}	=	calculated value of strength contribution by stirrup
x	=	distance from support of beam
α	=	angle of diagonal compression struts to the horizontal
ϕ	=	stirrup diameter
ρ_t	=	stirrup ratio
ρ_w	=	tensile steel ratio

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