STUDY ON THE MECHANISM OF SHEAR STRENGTH DECAY OF RC MEMBERS UNDER LOAD REVERSALS

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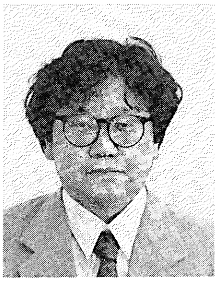

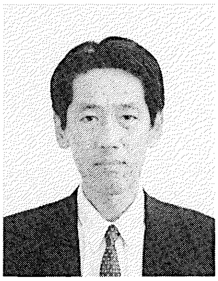

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This paper reports the results of an experimental study on the mechanism of shear strength decay of RC members under cyclic load reversals. The failure pattern of RC members was classified into two types, shear failure and bending failure, by separating the displacement components. The shear strength decay of concrete under load reversals results from a loss of concrete shear transfer capacities in the compression zone. While confinement stress is applied to the core concrete by hoops, shear strength of the concrete remains at about 40% of the shear strength of an RC member under monotonic loading. To prevent shear failure under load reversals, the tensile stress of the hoops must be maintained at a minimum of 80% of its yield strength.

Keywords: *shear strength, load reversals, shear deformation, shear reinforcement, ductility*

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1. INTRODUCTION

An important aspect of improving the seismic resistance of RC structures is to ensure adequate ductility of the RC members. This point is widely recognized, and methods of evaluating ductility have been proposed by many researchers. However, the basis of ductility evaluation in the proposed methods differs among the researchers. For example, one method uses bending strength and shear strength ratio as a parameter[1)], another calculates ultimate curvature with the stress-strain relationship of the concrete, which depends on the amount of hoop confinement[2)], and there is also a compromise method using the strength ratio while taking the stress-strain relationship of concrete confinement into account[3)], a regressional method based on experimental data[4)], and a method that focuses on the buckling of longitudinal rebars[5)], and an analytical method based on non-liner FEM calculations[6)]. One of the reasons for such a variety of methods is that the failure mechanism of RC members under cyclic loading is so complicated and has not been fully clarified as yet[7)8)]. Consequently, understanding the mechanism of strength decay of RC members under inelastic reversed cyclic loading is important to rational evaluation of RC member ductility.

Against this background, we have carried out cyclic loading tests on RC columns and discussed the mechanism of shear strength decay of RC members.

2. SHEAR STRENGTH OF RC MEMBERS UNDER LOAD REVERSALS

2.1 Previous Research

The shear strength of RC members under load reversals is different from that under monotonic loading. The usual design method for the shear load and shear strength of RC members entails evaluating the sum of concrete contribution (Vc) and the shear reinforcement contribution (Vs), as computed according to the conventional truss analogy. Vc is derived from shear loading tests on RC specimens without shear reinforcement. However, Vc is actually the shear contribution of concrete after diagonal cracking, and it includes concrete shear transfer in the compressive zone, the dowel action of longitudinal rebars, etc. Therefore, the value of Vc after diagonal cracking does not necessarily coincide with the shear strength of an RC member without shear reinforcement [9)10)].

Under cyclic reversed loading, tensile strain arises in the column axis direction in both sides of cross section near the fixed end of the column can be observed under cyclic reversed load, shear transfer through concrete in the compressive zone may be seriously damaged. Some researchers have pointed out that this may be the main reason for the reduction of Vc[11)12)]. Wight et al. carried out load reversal tests an RC specimens with an introduced axial compressive force and found that a greater axial force resulted in less decay of the shear strength[13)]. They concluded that degradation of Vc is not inevitable and that all the applied shear force should be carried by the shear reinforcement under reversed loading. Payley and Gosain et al. obtained similar conclusions[14)15)].

A calculation of shear strength that ignores Vc appears to give too conservative an estimate. Priestly et al. have also pointed out that ignoring Vc is too conservative, and proposed a reduction factor for Vc to give it a minimum value of about 1/3 of the shear strength of RC members without hoop[16)]. They derived the function of their proposed reduction factor using regression analysis, but did

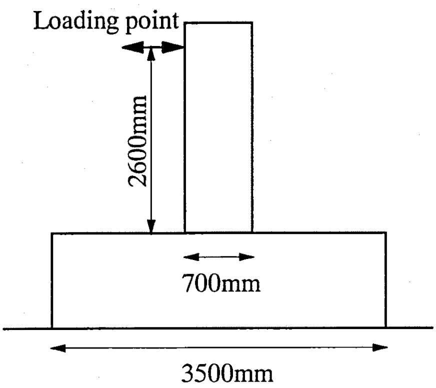


Figure 1 Dimensions of Specimen

Longitudinal rebar : D25

Cross ties included in No.701, No.702

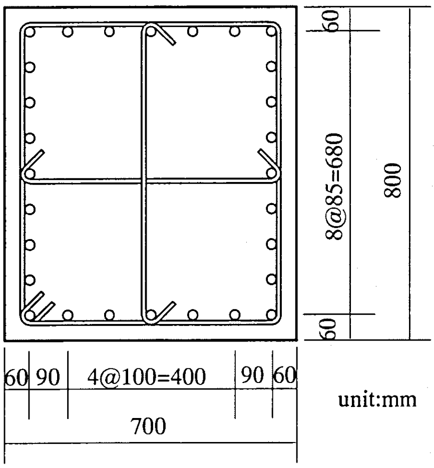


Figure 2 Cross Section of Specimen

Table 1 Definition of Specimens

No	Hoops		Loading	
	Diameter	Spacing	Loading procedure	Displacement amplitude
1	–	–	Monotonic	–
301	D6	8cm	One-Sided Cyclic	–
302	D6	8cm	Monotonic	–
303	D6	8cm	Reversed Cyclic	$\pm 3\delta y$
304	D6	8cm	Reversed Cyclic	$\pm 2\delta y$
305	D6	8cm	Reversed Cyclic	$\pm 5\delta y$
306	D6	8cm	Reversed Cyclic	$\pm 4\delta y$
501	D10	12cm	Reversed Cyclic	$\pm 3\delta y$
502	D10	12cm	Reversed Cyclic	$\pm 2\delta y$
503	D10	12cm	Reversed Cyclic	$\pm 4\delta y$
701	D10*	8cm	Reversed Cyclic	$\pm 3\delta y$
702	D10*	8cm	Reversed Cyclic	$\pm 4\delta y$

Note* : Cross ties included in No.701, No.702

not clarify the mechanical meaning.

2.2 Research Procedure
While many research reports have dealt with the relation between ductility of RC columns and shear strength, as noted above, few have mentioned the mechanism of shear strength decay. We carried out load reversal tests to clarify the mechanism of shear strength decay of RC members.

3. TEST PROGRAM

3.1 Description of Test Specimens and Loading Procedures
Loading tests were carried out on 12 cantilever RC column specimens. Test conditions for these 12 specimens are summarized in Tab.1. The cross section and longitudinal rebar arrangement of all specimens were the same. D25 (deformed bar of nominal diameter 25mm) formed the longitudinal rebars. Lateral loading was applied 2.6m above the bottom face of the column. Figure 1 shows the dimensions of the specimens. The rebar arrangement and cross section are shown in Fig.2. Cross ties were employed in specimens No.701 and No.702.
The loading programs in the tests were as follows: 1) monotonic loading, 2) one-sided cyclic loading, 3) reversed cyclic loading with fixed displacement amplitude as shown in Fig.3. Horizontal shear force only was applied, and it was imposed with a displacement-controlled actuator of capacity 750 kN. The yield displacement of specimens (δ_y) was determined as the loading tip displacement when the tensile strain of longitudinal rebars as monitored by strain gauges attached at the bottom cross section of the column reached the yield point. The concrete used for the specimens was ready mixed concrete of nominal compressive strength 30MPa. The maximum size of coarse aggregate was 20mm. Mechanical characteristics of the materials used are summarized in Tab.2 and Tab.3.

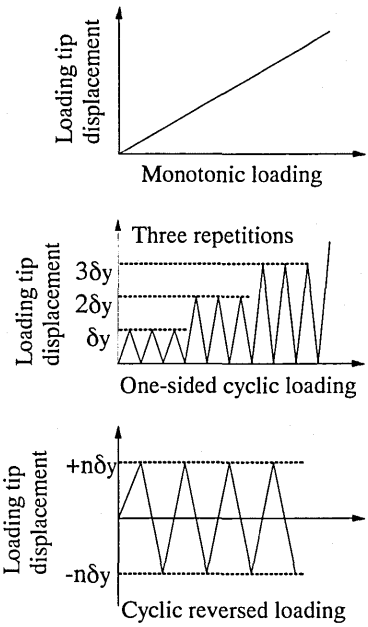


Figure 3 Loading Procedure

3.2 Measuring Instrumentation
The applied load, displacement at the loading point, relative displacement between reference points fixed in column concrete, and pullout of the longitudinal rebars from the footing were measured. Pullout of longitudinal rebars is the displacement between the top face of the footing and a reference point located 50 mm above. The location of reference points used to measure relative displacement is shown in Fig. 4.

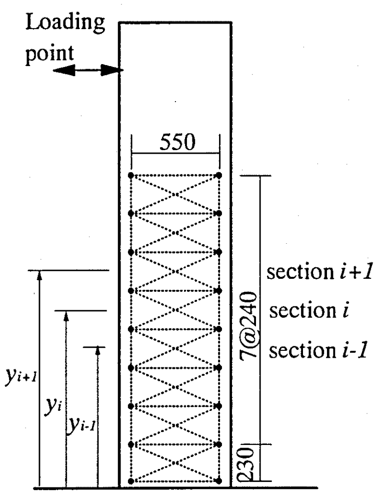


Figure 4 Relative Displacement Measuring Section (unit:mm)

Table 2 Mechanical Properties of Concrete in Loading Tests

No.	Compressive strength (MPa)	Young's modulus $*10^4$ (MPa)	Splitting strength (MPa)
1	34.3	2.9	3.0
301	41.8	3.2	2.9
302	39.8	3.0	3.1
303	40.0	3.1	2.9
304	37.9	2.9	2.9
305	38.1	2.8	2.5
306	38.9	3.0	2.5
501	32.6	2.7	3.1
502	34.4	2.8	3.0
503	40.1	2.9	3.2
701	29.4	2.6	2.5
702	34.8	2.6	3.0

Table 3 Mechanical Properties of Reinforcement

Rebar	Diameter	Yield point (MPa)	Young's modulus (GPa)
Longitudinal rebar	D25	378	187
Hoop	D6	334	181
Hoop	D10	363	185

4. TEST RESULTS

4.1 General Behavior of Specimens

Figure 5 shows examples of load-displacement hysteresis loops for specimens No.1, No.301, No.302 and No.501.

Specimen No.1 suffered typical shear failure; diagonal cracks were observed before the longitudinal rebars yielded, and load-carrying capacity was suddenly lost. Specimens No.301 and No.302, under monotonic loading and one-side cyclic loading, respectively, suffered diagonal shear cracks which extended to the compressive side of the cross section, ultimately resulting in shear compression failure of the concrete near the fixed end of the columns. Specimens under cyclically reversed loading exhibited X-shaped cracks and lost their strength gradually as the number of loading cycles increased. However specimens No.502 and No.701 showed little strength loss even after 30 loading cycles. Figure 6 shows the changes in the peak load at each loading cycle.

4.2 Decomposition of Load Tip Displacement

The load tip displacement of a specimen consists of three components: 1) flexural deformation(δ_b), 2) rotation resulting from pullout of longitudinal rebars from the footing(δ_r), and 3) shear deformation (δ_s).

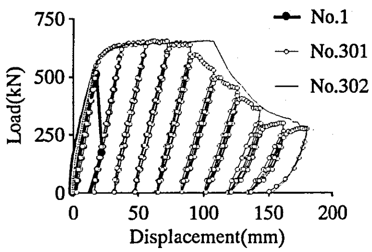
Therefore the total load tip displacement, δ, can be expressed as the sum of these components.

$$\delta = \delta_b + \delta_r + \delta_s \qquad (1)$$

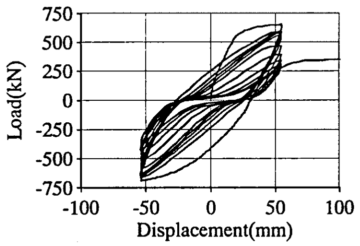
δ_b is obtained by integration of curvature along the column axis as follows:

$$\delta_b = \Sigma \phi_i \cdot (H - y_i) \cdot \Delta y \qquad (2)$$

where ϕ_i is the curvature at the i-th section in Fig.4, Δy is the



(a) Specimen No.1,No.301,No302



(b) Specimen No.501

Figure 5 Load-Displacement Hysteresis Curves

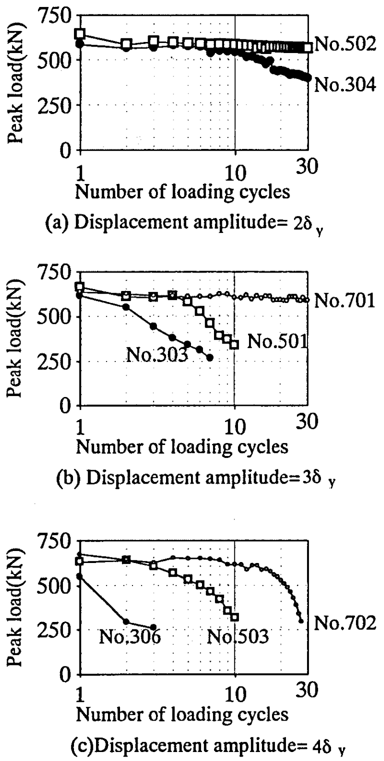


Figure 6 Relationship between Number of Loading Cycles and Peak Load

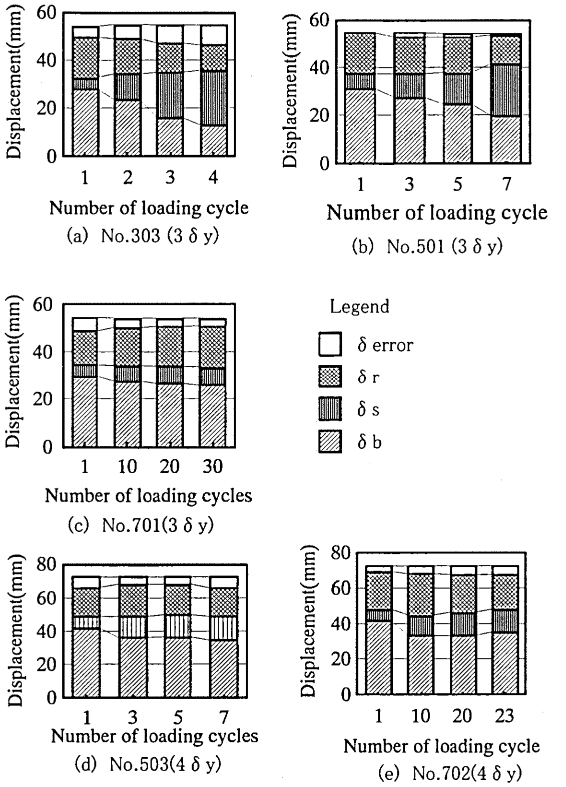


Figure 7 Variation of Displacement Components with Number of Loading Cycles

length of the i-th section, y_i is the distance of the centroid of the i-th section from the fixed end of the column, and H is the distance of the loading point from the fixed end of the column.

Rotational displacement by pullout of the longitudinal rebars from the footing can be expressed as follows:

$$\delta_r = H\theta \qquad (3)$$

where θ is the rotation angle resulting from pullout of the longitudinal rebars.

Shear deformation can be calculated by the sum of average shear strains measured at each sections.

$$\delta_s = \Sigma \gamma_i \cdot \Delta y \qquad (4)$$

where γ_i is the nominal shear strain at the i-th section.

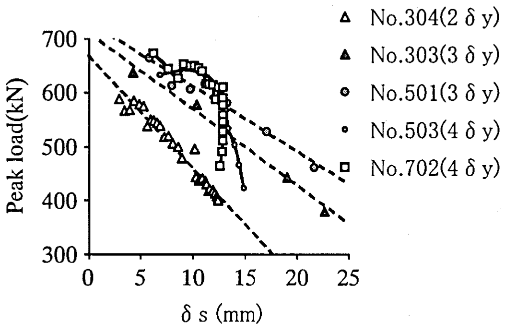


Figure 8 Relationship between Shear Deformation and Strength Reduction

Figure 7 shows the variation in each of these displacement components with number of reversed loading cycles. The errors indicated in Fig.7 are the difference between measured load tip displacement and the displacement calculated according to eq.1. The errors are relatively small, meaning that decomposition into these components was correct. Figure 8 shows the relationship between δs and peak shear load acting on specimens. Specimens No.303, No.304, and No.501 lost strength with increasing δs, which means these specimens failed in shear. On the other hand, specimen No.702 lost strength without increasing shear deformation, which means it failed in bending. Specimen No.503 shows similar behavior to No.702, but δs also increased slightly. Therefore the failure mechanism of No.503 could not be clearly judged. Table 4 summarizes the failure pattern of each specimen under reversed cyclic loading.

Table 4 Failure Mode of Specimens with Reversed Cyclic Loading

		Displacement amplitude		
		2δy	3δy	4δy
Hoop contents (%)	0.10	No.304 Gradual shear failure	No.303 Shear failure	No.306 Shear failure in a few cycles
	0.15	No.502 No failure within 30 cycles	No.501 Shear failure	No.503 Bending failure but not clear
	0.33	–	No.701 No failure within 30 cycles	No.702 Gradual bending failure

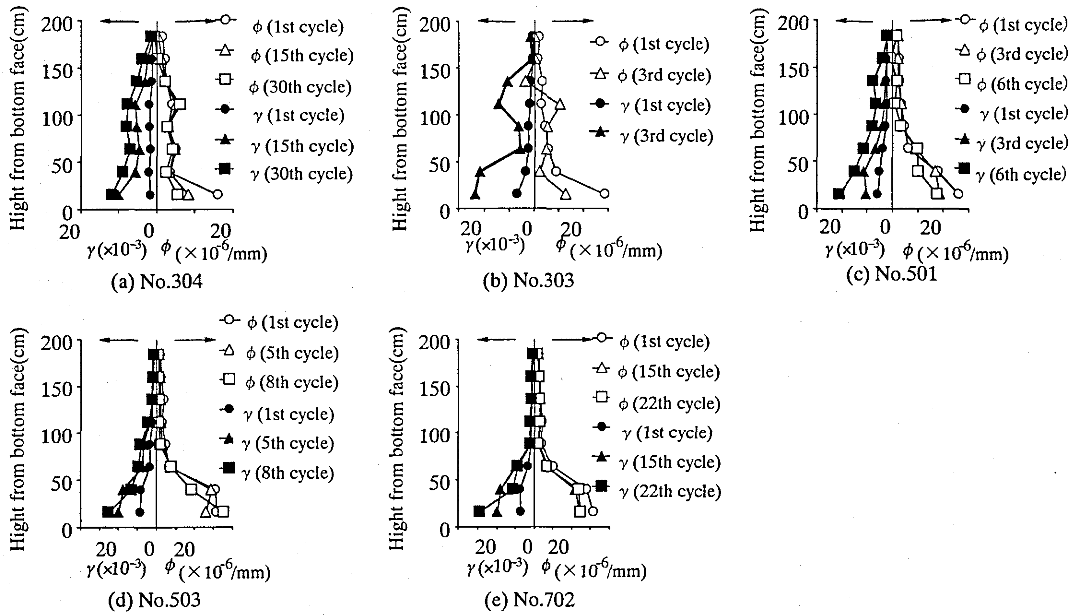


Figure 9 Curvature and Shear Strain Distribution of Reversed Loaded Specimen

4.3 Distribution of Shear Strain and Curvatures

Figure 9 shows the distributions of measured nominal shear strain and curvature along the column axis of specimens that underwent distinct strength deterioration within 30 cycles of load reversal. Figures 9(a) to 9(c) represent the shear strain distribution of specimens that failed in shear. Figure 9(e) is the distributions of the specimen which failed in bending. Figure 9(d) is that of the specimen whose failure mode cannot be clearly judged.

Characteristics common to all specimens that suffered shear failure are that the nominal shear strain increased with increasing loading cycles and that the second peak section where shear strain and curvature concentrated exists at about 1.0m to 1.5m above the bottom face of the column. On the other hand, in the case of specimens No.503 and No.702, which did not undergo shear failure, shear strain concentrated within a distance of 1.0m from the bottom face. Thus, the shear strain distribution along the column axis differs according to the failure pattern.

5. DISCUSSION OF MECHANISM OF SHEAR FAILURE

5.1 Shear Resistance Mechanism of Specimens After Diagonal Shear Cracking

The shear load applied to RC members after diagonal shear cracking occurs is transferred by a combination of shear reinforcement, concrete in the compression zone, shear resistance on the surface of the diagonal cracks, and dowel action of longitudinal rebars. It is desirable to separate the shear resistance mechanism into these components so as to understand the shear deterioration mechanism of RC members under load reversals.

We assumed a shear resistance mechanism as schematically described in Fig.10. V_{cc} denotes shear transfer by concrete in the compressive zone, V_d denotes the dowel force of longitudinal rebars, and V_{dt} denotes shear transfer across the diagonal crack surface. Causes and characteristics of deterioration of these shear resistance components are outlined below.

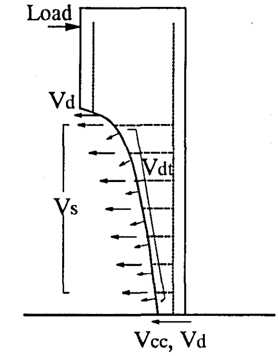


Figure 10 Assumed Shear Resistance Mechanism

There are three possible reasons for deterioration of V_{cc}: (i) compression failure of concrete, (ii) reduction in compressive stress in concrete owing to residual tensile strain through process of reversed loading, (iii) strength reduction of concrete by cracks parallel to the principal compressive stress direction. Evaluations of concrete strength reduction owing to the third reason differ among researchers. For example, according to Miyahara's results[17], concrete strength remained at 70% to 80% that of plain concrete, while, Belarbi et al. reported a more significant strength reduction[18].

V_{dt} falls as a result of increasing crack width. It has two components, one parallel to the column axis and the other orthogonal to the column axis. Therefore if V_{dt} falls, the tensile force in the column axis direction on the crack surface must also be reduced. Thus, the observed tensile stress of longitudinal rebars will exceed the tensile stress calculated from bending analysis owing to fall in V_{dt} with increasing width of diagonal cracks, which is the so-called moment shift[19].

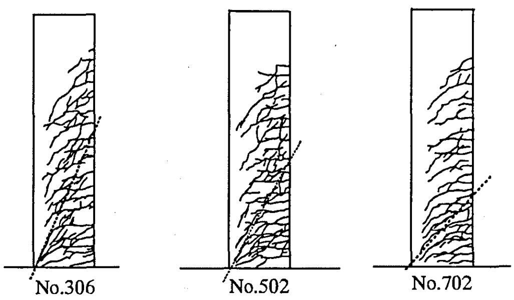


Figure 11 Shear Crack Pattern (at peak of 1st positive loading cycle)

The stiffness of dowel action also falls with cyclic loading. When the stiffness of dowel action falls, localized dowel deformation of the longitudinal rebars should be observed.

V_c, the overall shear resistance contributed by the concrete, is impossible to evaluate directly. Then, we evaluated V_c by subtracting V_s from the applied shear load. V_s is calculated from the assumption of a bilinear constitutive law for the hoops. We used the nominal strain derived from the relative displacement measurements between reference points in the transverse direction and the column axis to calculate the stress of the hoops. The angle of inclination of diagonal cracks is necessary to determine total amount of the hoops crossed by the cracks. This angle was determined by observing cracks in the column specimens at the peak of the first loading cycle, as shown in Fig.11.

5.2 Shear Strength Reduction in Monotonic Loading

Here we discuss the results of concrete and longitudinal rebar strains measured at the column fixed end so as to estimate the sectional concrete stress in the compressive zone. The location of strain measurements is shown in Fig.12. The longitudinal rebar strain, ε_c^s, is the average of measured strains obtained from four strain gauges attached to the rebars. The concrete strain, ε_c^c is the average strain obtained from relative displacements between reference points along the longitudinal rebar. Figure 13 shows the relationship between curvatures at the fixed end and applied load(V), Vc, ε_c^c, and ε_c^s. From Fig.13, it can be observed that, when Vc begins to fall, distinct difference arises between the compressive strain of the concrete and the rebars except in the case of specimen No.503 (Fig.13 (b)) where this characteristics was not clearly observed. The absolute value of rebar compressive strain rises while that of the concrete decreases. This means that the compressive force necessary to resist the bending moment at the cross section near the fixed end is supported initially by the concrete, but this gradually shift onto the longitudinal

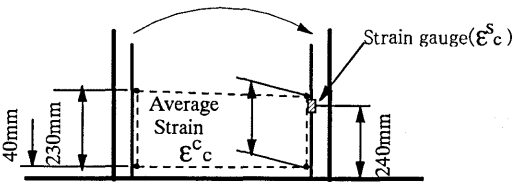
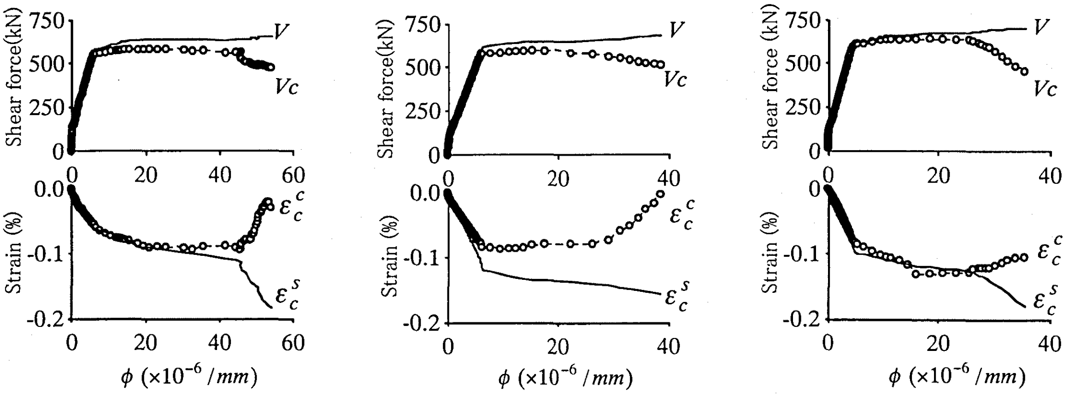


Figure 12 Location of Strain Measurement



(a) No.302 (b) No.503 (c) No.702

Figure 13 Relationship between Vc or Compressive Strain and Curvature near Fixed End of Column

rebars. Since the compressive force escerted by concrete is inclined to the column axis, the concrete can carry some horizontal force, which means shear transfer in compressive zone. However, the compressive force sustained by the longitudinal rebars is primarily vertical and little horizontal force can be carried. As shown in Photo.1 and Photo.2, the cover concrete spalls off as a result of shear compression. Thus the reduction in concrete shear resistance results from the decrease in compressive stress of the concrete.

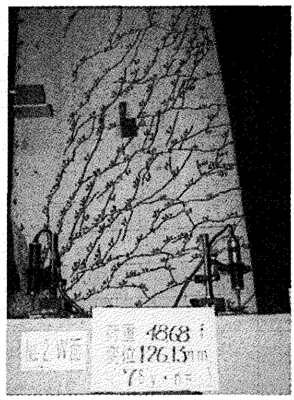


Photo.1 State of Failure of Column near Fixed End (side view)

Photo.2 State of Failure of Column near Fixed End (compressive face)

5.3 Shear Strength Reduction under One-Sided Cyclic Loading

Figure 14 compares the relationship between applied shear load and Vs for specimen No.301 under one-sided cyclic loading and specimen No.302 under monotonic loading. The dotted line represents Vs calculated using the truss analogy based on the assumptions that Vc is equal to the shear strength of specimen No.1, which did not contain any hoops.

One of the features of the hoop contribution under one-sided cyclic loading is that hoop stress is not released even when the applied load is removed as reported by Ruhnau[20]. Crack contact is said to be one of the reasons for this in ref.21. The residual stress of hoops gradually increases with the number of loading cycles. However, once the shear strength of the column decreases, the residual stress of the hoops also falls. The ratio of Vs increment to V would be 1.0 if the total shear force were carried only by the hoops. But the ratio was smaller than 1.0 under one-sided cyclic loading as the residual hoop stress increased, which means that shear contributions from other sources are still active.

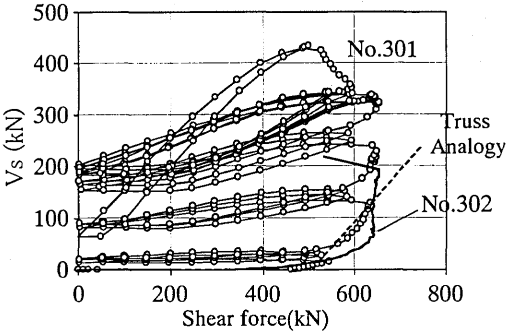


Figure 14 Relationship between Shear Load and Vs

Figure 15 shows the relationship between shear deformation and V-Vs, which means shear contribution from sources other than hoops. The curve for No.301(a) in Fig.15 is obtained simply by subtracting Vs from V. Negative values of V-Vs means that Vs exceeds V and compressive stress arises in the concrete as the result of the hoop confinement force. The diagonal cracks divide the column specimen into two structural bodies, but the hoop confinement force links these bodies and the concrete continues to transfer shear force. Therefore we have assumed the shear resistance of concrete is active under the presence of confinement by the residual hoop tensile stress. The curve for No.301(b) is modified by the addition of Vs to V-Vs when the applied load was removed in the preceding loading cycle. Comparing curves No.301(b) and No.302 for monotonic loading, they match well. Thus, though the absolute value of hoop stress is larger in the case of one-side cyclic loading, shear contribution of concrete is not substantially lower in cyclic loading.

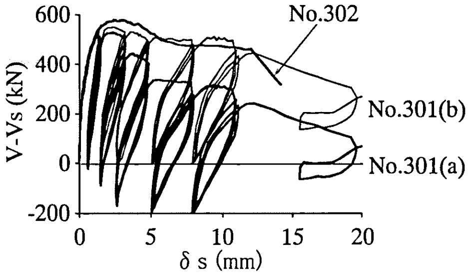


Figure 15 Relationship between Shear Deformation and V-Vs

5.4 Shear Strength Reduction under Cyclic Load Reversals

a) Loss of shear transfer of concrete in compression zone

As already mentioned, the reduction in shear strength under cyclic load reversals is governed by many factors, and it is difficult to isolate the effects of each. However by comparing the difference in shear contribution of the concrete between positive and negative loading in the first cycle, the contribution made by concrete shear transfer on the compressive side can be roughly estimated. The residual tensile strain of compressive longitudinal rebars left after the preceding cycle of positive loading may lead to loss of concrete compressive stress in the compressive zone and loss of V_{cc}, shear transfer by the concrete. Here, we discuss the reduction in V_{cc} resulting from the loading direction reversal in the first loading cycle by observation of the measured strain and deformation of specimen No.306, which suffered shear failure within the first cycle of negative loading.

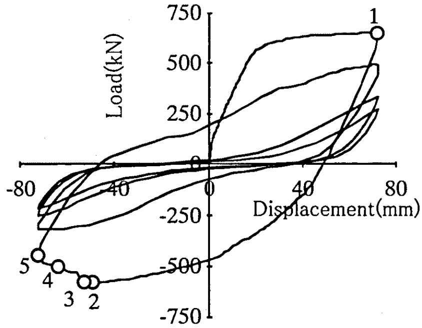


Figure 16 Load-Displacement Hysteresis Loop(No.306)

The displacement amplitude at the loading point of specimen No.306 was fixed at $4\delta_y$. The load-displacement hysteresis loop is shown in Fig.16. Figure 17 shows the relationship between load,ε_c^s, and ε_c^c from the beginning of unloading in the first positive loading cycle to the peak of first negative loading. The tensile strain arising in the compressive side of the concrete during the preceding positive loading remained even at the peak of negative loading. On the other hand, the tensile strain of longitudinal rebars changed from about 0.5% to about 0% during the negative loading cycle. Thus, compressive stress in the compressive-side longitudinal rebars during negative loading would in most cases reach the yield stress. As a result, the compressive force of the concrete considerably decreased. Figure 18 shows the deformation of the column specimen in the process. Numbers 1 to 5 in Fig.18 correspond to the points denoted in Fig.16. The scale of the displacement is magnified by ten times to allow an easy grasp of the characteristics of the deformation. Though flexural deformation is dominant at the peak of positive loading, shear distortion becomes distinct after the direction of loading changes. Figure 19 shows the relationship between shear deformation and V-Vs. Maximum value of Vc reached about 550kN during positive loading, but in negative loading it fell to about 60% of this maximum value in positive loading.

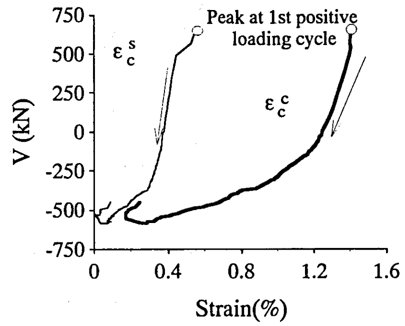


Figure 17 Compressive Strain in 1st Negative Loading Cycle

The decrease in shear transfer of concrete in the compressive zone seems to depend on the residual tensile strain of the concrete. We examined the effect of residual tensile strain on shear transfer for all specimens on which

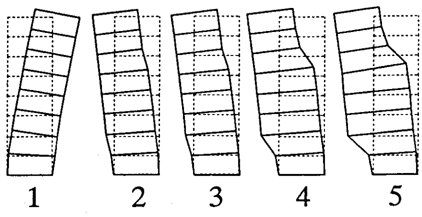


Figure 18 Deformation of Specimen No.306

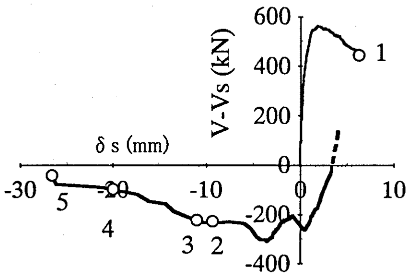


Figure 19 Relationship between δs and V-Vs in 1st Cycle of Loading

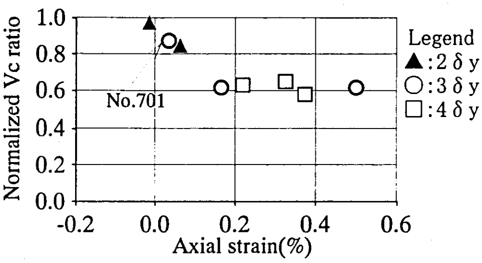


Figure 20 Relationship between Axial Compressive Strain and Normalized Vc Ratio

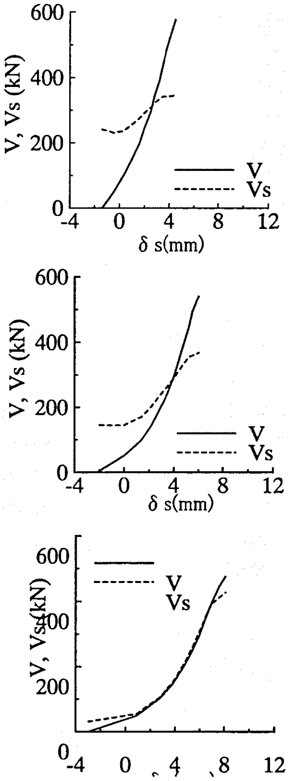


Figure 21 Relationship between Shear Deformation and Load and Vs (Top:5th cycle loading) (Middle:10th cycle loading) (Bottom:15th cycle loading)

eversed loading was carried out. Figure 20 shows the relationship between residual tensile strain of concrete and the maximum value of Vc at the peak of the first negative loading cycle. The vertical axis of Fig.20 represents the maximum of Vc normalized by concrete shear strength as obtained from the monotonic loading test on specimen No.1 without any hoops. As shown in Fig.20, the residual tensile strain becomes greater as Vc becomes smaller. Little reduction of Vc was observed in the first loading cycle when the loading displacement amplitude was $2\delta_y$ because a much smaller residual tensile strain arose. But when the displacement amplitude was $3\delta_y$ or more, the curvature at the fixed end of column was large enough to develop considerable tensile strain in the longitudinal rebars, and the reduction of Vc became more significant. However, a lower bound for V_c exists. V_c converged to a constant value in the region where residual tensile strain exceeded 0.2%.

b) Shear strength reduction caused by repetitive reversed loading

We discuss the shear strength reduction resulting from repetitive reversed loading. As mentioned above, the tensile stress of hoops induced by one-sided cyclic loading was not released even when the load was completely removed, and this had the advantageous effect of preventing shear strength decay as a result of the confining effect of hoops. Also, in the case of reversed cyclic loading, some confinement force may be produced. Figure 21 shows the relationship between shear displacement and V or Vs for specimen No.304 in positive loading. As the number of loading cycles increases, V_s at the point when the load is removed falls and the increment in V_s between the zero point of applied load and its peak becomes larger. This means that reversed cyclic loading in the inelastic range causes a deterioration of the confining effect and the shear load is resisted by increased tensile force of the hoops. Figure 22 shows the history of the shear contribution of hoops for each column specimen. Vs(P) represents the value of Vs at peak load (V(P)) in each loading cycle. Vs(0) is the value of Vs at the completely unloaded point in each loading cycle. The solid line with no marks represents Vs(0)+Vs(P).

Both specimens No.502 and No.702, whose peak load hardly decreased in 30 cycles of loading, showed little

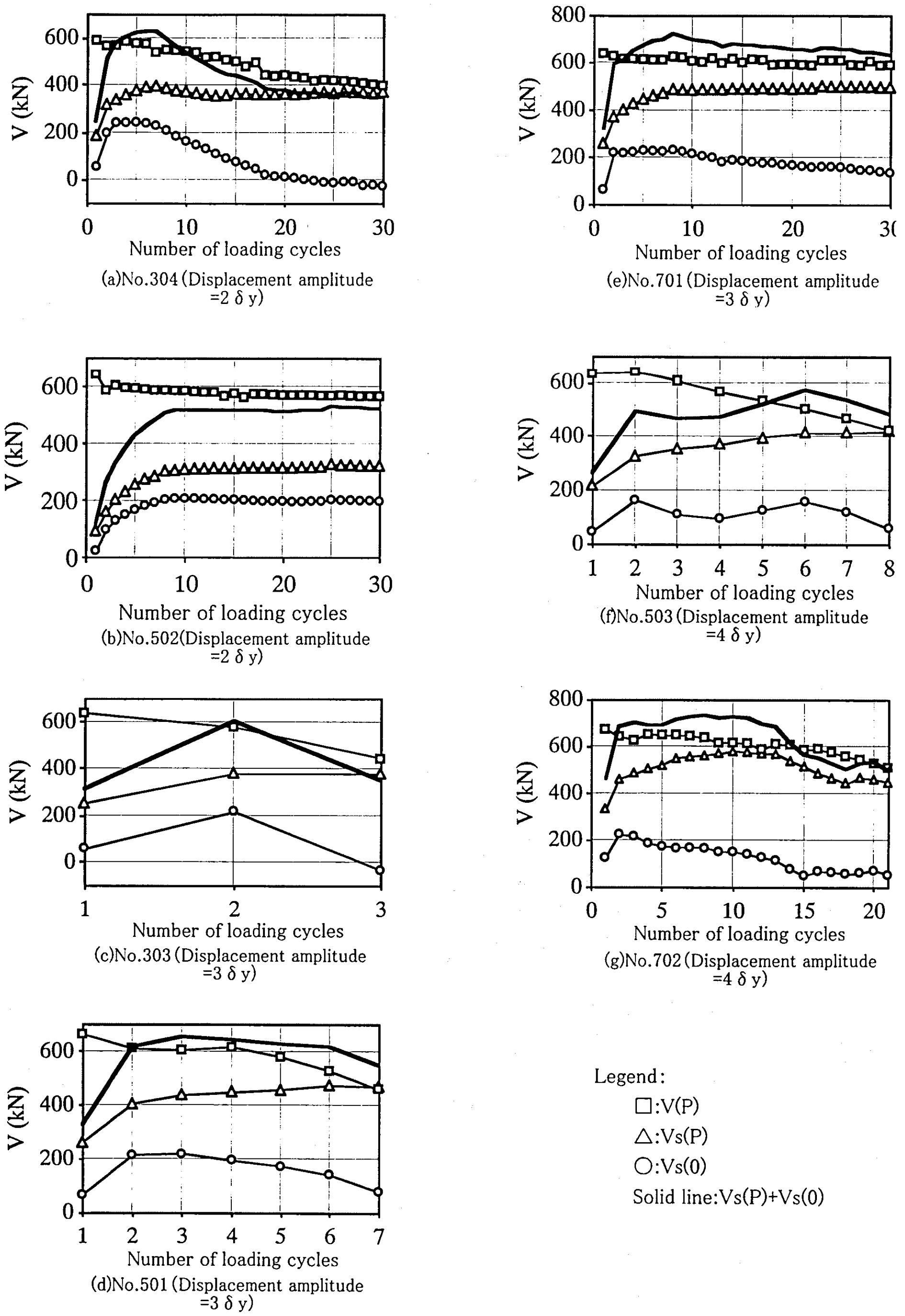


Figure 22 Variation of Vs with Number of Loading Cycles

change in Vs(0). On the other hand, the peak load of specimens No.304, No.303, No.501, all of which failed in shear, gradually decreased as Vs(0) fell, and the value of Vs(0)+Vs(P) is nearly the same as V(P) except during the early cycles.

These results indicate that confinement of the core concrete by hoops is one effective shear resistance mechanisms

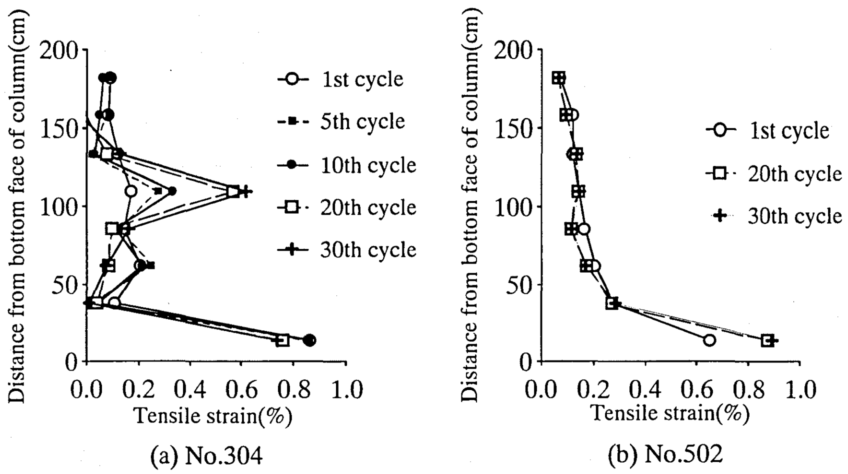


Figure 23 Distribution of Axial Strain

even under inelastic load reversals. The possibility of shear failure under inelastic load reversals depends also on the efficiency of hoop confinement.

Thus the reduction of Vc of RC members under inelastic load reversals occurs through several processes. Initially, the shear transfer of concrete in the compressive zone reduced by the residual tensile strain in the compressive zone remaining after the preceding positive loading cycle. Then further continuing cyclic loading, shear transfer of concrete across the crack surface supported by the confinement of hoops gradually reduced.

We now discuss the distribution of axial tensile strain so as to insure against loss of concrete shear transfer across the crack surface. Figure 23 shows the results for specimens No.304 and No.502. The measured tensile strain of No.304 at the point 100cm from the fixed end increased considerably between the 10th cycle of loading and the 20th cycle loading. As shown in Fig.22(a), Vs(0) also decreased during these cycles of loading. The presence of a local maximum of tensile strain means that moment shift has occurred and the bond stress between concrete and longitudinal rebars has decreased. A truss mechanism cannot be effectively formed as a result of the reduction in bond stress in the plastic hinge zone of the column.

Thus, it is important to prevent Vs(0) from decreasing so as to prevent shear failure of RC members. In order to prevent a decrease in Vc(0), the development of inelastic tensile strain in hoops should be avoided. We examine the allowable tensile stress of hoops such that a reduction of Vs(0) is prevented.

Table 5 shows the value of tensile stress of hoops at the loading cycle when Vs(0) reaches a maximum. The tensile stress of hoops shown in Tab.5 is normalized by the yield stress. Figures shown bold in Tab.5 represent the specimens that suffered shear failure. Specimens whose hoop stress exceeded 90% of the yield stress, No.303 and No.501, failed in shear. Where hoop stress was about 80% of the yield stress, one specimen underwent shear failure, and the other did not fail in shear. When the hoop stress was about 70% of the yield stress, the specimen did not fail in shear. Thus the boundary of hoop stress at which the possibility of shear failure arises is at about 80% of the yield stress. This indicates that hoop stress should be made less than the yield stress, including a safety factors, so as to avoid shear failure of RC members under load reversals. The hoop stress should be less than 80% of the yield stress from the results of this study.

The value of Vc observed immediately before shear failure was at least 40% of Vc obtained from the monotonic loading test. We can conclude from these test results that the shear strength of RC columns should satisfy the following equation so as to avoid shear failure under load reversals.

$$V(P) < 0.8V_{sy} + 0.4V_{cu}$$

here, V(P) denotes the applied shear load at the peak of each loading cycles, Vsy denotes the shear resistance of hoops at the yield point, and Vcu denotes the shear strength of a column without hoops.

6. CONCLUSIONS

Load reversal tests were carried out on RC columns to clarify the mechanism of shear strength decay of RC columns under load reversals. The conclusions reached in this study are as follows:

Table 5 Average Tensile Stress of Hoop at Peak

Specimen	Displacement amplitude	Tensile stress (MPa)	Normalized stress by yield point
No.304	2δy	**269**	**0.81**
No.502		261	0.73
No.303	3δy	**316**	**0.95**
No.501		**335**	**0.92**
No.701		302	0.82

1) The mechanism of shear strength reduction of RC columns depends on the loading procedure. In the case of monotonic loading, the cause of concrete shear strength reduction is the loss of concrete shear transfer due to shear compression failure of the concrete. On the other hand, in the case of reversed loading, the causes are the loss of concrete shear transfer of concrete due to the change in loading direction and the reduction of confinement by hoops.
2) The failure mode of RC columns can be identified by separating the displacement component. The section in which large shear deformation is observed is not limited to the fixed end of RC columns which failed in shear.
3) A loss of concrete shear transfer is inevitable in the case of reversed loading. The amount of the reduction depends on the residual tensile strain in compressive side left after the preceding loading cycle in the opposite direction. However, the shear contribution of concrete is not lost only for this reason.
4) In the case of cyclic loading, hoop tensile stress is preserved even after removal of the shear load. Such tensile stress confines the concrete and contributes to maintaining the shear resistance of the concrete. To prevent shear failure, maintaining effective confinement in this way is important.
5) The confinement effect depends on the average tensile stress of the hoops.
6) The tensile stress of hoops at the peak of each loading cycle should be limited to 80% of the yield stress to maintain the shear contribution of the concrete through the confinement effect.
As the tensile reinforcement ratio and the displacement amplitude of each reversed loading cycle were constant in these experiments, the conclusions derived from the loading tests are very limited. Further research is necessary to comprehensively estimate the shear strength of RC members.

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