Fracture Mechanics of Concrete Structures
Proceedings FRAMCOS-3
AEDIFICATIO Publishers, D-79104 Freiburg, Germany

SHEAR STRENGTH OF RC MEMBERS UNDER LOAD REVERSALS

H. Watanabe and H. Kawano
Concrete Division, Public Works Research Institute, Ministry of Construction, Japan
S. Eguchi
Oriental Construction Co., Ltd., Japan

Abstract
The prevention of shear failure is the primary requirement when designing RC structures to withstand severe earthquake loads. However little is known about the shear resistance mechanism of RC structures under cyclic shear force, which is very different from that under monotonic load. We carried out load reversal tests of 12 RC column specimens and observed shear deformations and transverse strains. From the test results we discuss the shear strength decay of concrete and change of shear resistance mechanism under cyclic loads.
Key words: shear strength, Reinforced concrete, cyclic loading, hoop

1 Introduction

Shear strength of RC members is usually evaluated as Vc+Vs where Vc is shear strength sustained by concrete and Vs is the contribution of shear reinforcement in most design specifications. Vc is determined on the basis of loading test data with RC beam specimens without any web reinforcement. Vs is estimated according to truss analogy. However the meanings of Vc used for the shear design of RC members with web reinforcement is different from the shear strength of those without web reinforcement. After diagonal shear crack occurrs, shear contribution of concrete is mainly brought about by shear transfer of concrete in the compressive zone, shear transfer of the diagonal crack interface, and dowel action of longitudinal reinforcing bar. In comparison, the shear contribution of concrete observed in RC members without web reinforcement mainly consists of the tensile strength of concrete. Therefore, in order to estimate the shear strength of RC members under load reversals, we must clarify the nature or basic mechanism of the shear contribution of concrete.

The shear strength of RC members under load reversals is usually smaller than that under monotonic load. Many previous researchers pointed out that the smaller shear strength is caused by the reduction of shear transfer of concrete in the compression zone. Load reversals in the plastic range cause residual tensile strain in the compression zone of concrete, and this residual strain prevents shear transfer of concrete. For example, Wight et al.(1975) performed load reversal tests of RC members in which the axial compressive load was varied, and found that the lower axial load specimen showed even more severe loss of strength. From the test results they concluded that all of the shear shoud be carried by shear reinforcement under load reversals in the design.

On the other hand, Priestry et al. (1994) derived a shear reduction factor which is defined as the function of displacement ductility factor for the seismic design of RC columns. They pointed out that ignoring the whole of the shear contribution of concrete is too conservative and the minimum value of reduction factor is approximately 1/3 of shear strength under monotonic load. Though the reduction factor is derived from the load reversal test results, it is difficult to determine the shear strength of RC members under load reversals because the shear strength is governed by the yield strength by the bending or yield point and the amount of longitudinal reinforcement.

This study evaluates the strength decay of RC members under load reversals on the basis of the shear contribution mechanism of concrete.

2 Loading test procedure

Load reversal tests of 12 RC column-footing specimens were performed for varing amount of hoops and loading patterns. Shear span depth ratio and the amount of longitudinal reinforcing bar of the specimens were fixed. Figure 1 shows the dimensions of the test specimens. Figure 2 shows the cross section of specimens. The diameter of the longitudinal bar was 25mm. Specimens No.701 and No.702 had cross ties as shown in

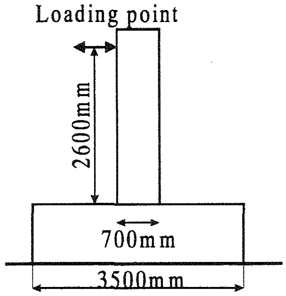


Fig.1 Dimensions of specimen

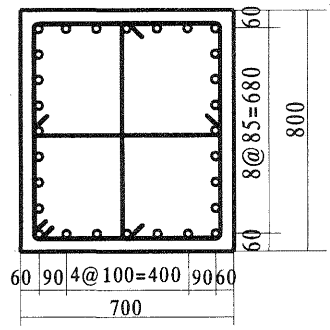


Fig. 2 Cross section of column (unit:mm)

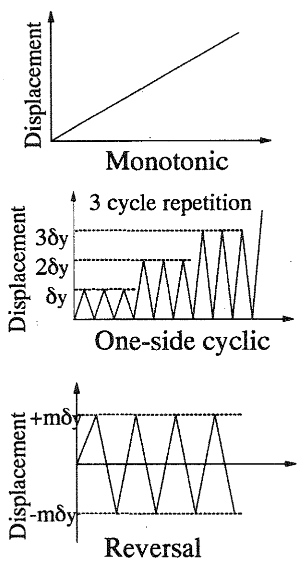


Fig.3 Loading pattern

Table 1 Test condition of each specimens

No. of spec.	Hoop		Loading	
	Diameter (mm)	Spacing (mm)	Pattern	Disp. amplitude
1	–	–	monotonic	-
301	6	80	one-side cyclic	–
302	6	80	monotonic	–
303	6	80	reversal	±3δy
304	6	80	reversal	±2δy
305	6	80	reversal	±5δy
306	6	80	reversal	±4δy
501	10	120	reversal	±3δy
502	10	120	reversal	±2δy
503	10	120	reversal	±4δy
701	10*	80	reversal	±3δy
702	10*	80	reversal	±4δy

*:Cross ties were arranged with only No.701 and No.702

Figure 2. The conditions of the test specimens are shown in Table 1.

Loading programs in the tests can be classified into three patterns : 1) monotonic loading, 2) one-side cyclic loading, and 3) reversed cyclic loading with fixed displacement amplitude as shown in Figure 3. Only horizontal shear force was applied by a displacement controlled actuator whose capacity was 750 kN. The yield displacement of specimens (δy) was determined from the yield strain of longitudinal reinforcing bar measured by strain gauges attached at the bottom cross section of the column.

Concrete used for the specimens was ready-mixed concrete whose

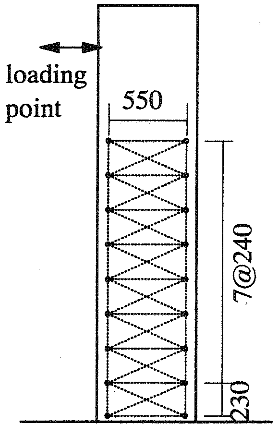


Fig. 4 Location of relative displacement measurement (unit: mm)

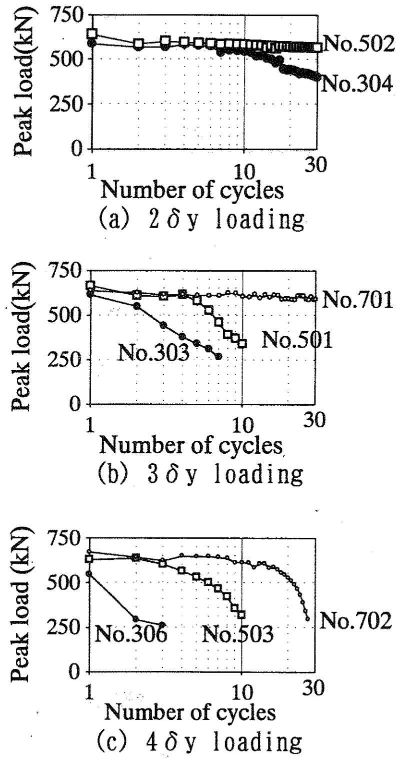


Fig. 5 Strength degradation of each pecimen

nominal strength was 30 MPa. Maximum size of coarse aggregate was 20mm.

Applied load, the displacement at the loading point, and pull out of longitudinal bar from the footing were measured. Relative displacement between the reference points settled in concrete of columns was also measured. The position of the section where relative displacement was measured is shown in Figure 4.

3 Test results

3.1 Overview of test results

Specimen No.1, which contains no hoops, failed in shear before the longitudinal bar yielded. Specimens No.301 and No.302 showed shear compression failure of concrete after the longitudinal bar yielded.

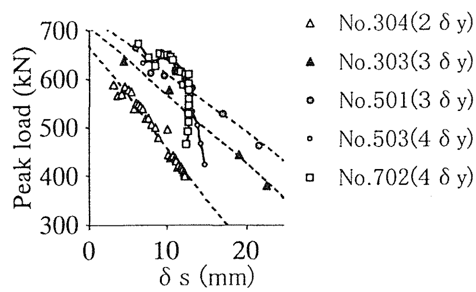


Fig.6 Relationship between δ_s and strength degradation

Table 2 Failure pattern of specimens

Hoop ratio (%)	Displacement amplitude		
	2δy	3δy	4δy
0.1	No.304: gradually failed in shear	No.303: failed in shear	No.306 failed in shear in a few cycles
0.15	No.502: did not fail in 30 cycles	No.501: failed in shear	No.503: failure pattern was not clear
0.33	–	No.701: did not fail in 30 cycles	No.702 gradually failed in bending

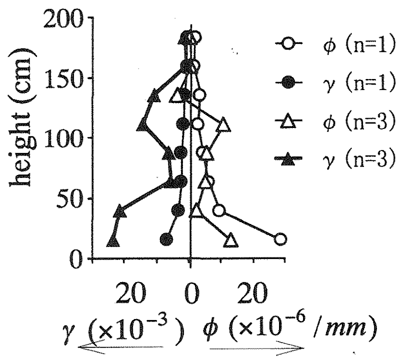
Specimens under load reversals showed X-shaped shear cracks and gradually lost strength after yielding. Figure 5 shows strength degradation of specimens with increasing load cycles.

3.2 Separation of displacement components of columns

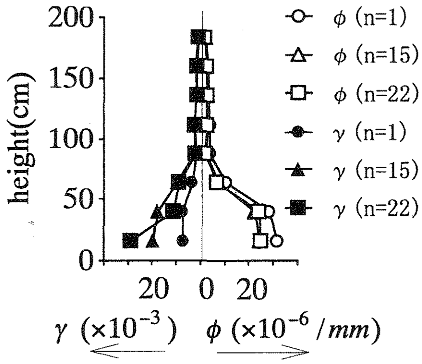
Displacement of RC members seems to consist of three components: 1) bending deformation (δ_b), 2) rotational deformation at the bottom of columns by pull-out of longitudinal bar from the footing (δ_r), and 3) shear displacement (δ_s).

Figure 6 shows the relationship between δ_s and peak horizontal load acting on specimens. Specimens No.303, No.304, and No.501 lost their strength with increasing δ_s, which means that these specimens failed in shear. On the other hand, specimen No.702 lost its strength without increasing shear deformation, which shows that this specimen failed due to bending or buckling of longitudinal reinforcing bar in compression. .

Table 2 summerizes the type of failure of specimens under load reversals.



(a) No.303



(b) No.702

Fig.7 Curvature and shear strain distribution
(n: number of load cycle)

Figure 7 shows examples of curvature and nominal shear strain distribution along the column axis. The distribution of curvature and nominal shear strain varied greatly with the failure pattern of the specimens. In case of No.303, which failed in shear, a second peak of nominal shear strain and curvature was observed, but in case of No.702, which failed in bending, nominal shear strain and curvature were concentrated at only the plastic hinge zone, i.e., at the bottom of the column.

3.3 Evaluation of shear strength decay of columns failed in shear

3.3.1 Procedure to obtain shear contribution of concrete

Shear strength decay of RC columns under load reversals is caused by the reduction of Vc which can not be directly evaluated. In this study, Vc was evaluated by subtracting Vs from shear load acting on the column specimens. To evaluate Vs accurately, the total cross sectional area of hoops which cross diagonal shear crack must be properly determined. Figure 8 shows the angle of diagonal shear crack observed in the loading tests. In Figure 8, the angle of diagonal cracks obtained by nonlinear FEM analysis with rotational crack model, has also been plotted. Figure 9 shows an example of crack pattern by FEM analysis. As the rotational crack model was used, crack angle changs according to load, but the change of angle becomes small after longitudinal bar has yielded. The angle of diadonal observed in the experiment agreed closely with that derived by analysis.

The observed shear crack angle is used to calculate Vs in this study. Shear carried by concrete is given by

$$V_c = V - V_s = V - nA_w \overline{\sigma}_{sw} \qquad (1)$$

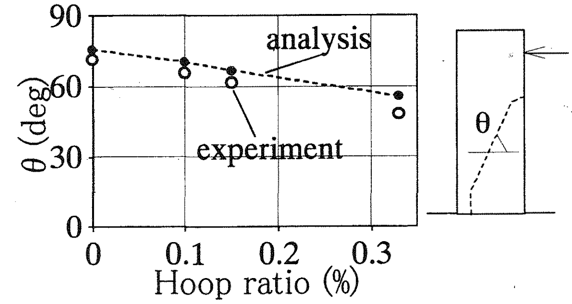


Fig.8 Angle of shear crack

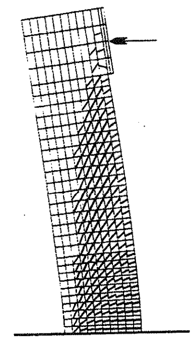


Fig.9 Crack pattern by FEM analysis

where,

n : number of hoops which cross the diagonal shear crack

A_w: cross sectional area of hoop

$\overline{\sigma}_{sw}$: average tensile hoop stress which cross the diagonal shear crack

and

$$n = \frac{d \cdot \tan\theta}{s} \qquad (2)$$

where

d : effective depth of cross section of column

s : spacing of hoops

θ: angle of shear crack

3.3.2 Reduction of shear carried by concrete in compressive zone

Vc consists of shear transfer of concrete in the compressive zone (V_{cc}), the dowel effect of longitudinal reinforcing bar (V_d) , and tensile stress acting on the diagonal shear crack (V_{dt}).

As Gosain et al. (1977) pointed out, residual tensile strain in reinforcement after load reversal prevents closing of bending cracks in concrete which reduces shear transfer by concrete in the compression zone. Figure 10 shows the relationship between the reduction coefficient of Vc and the nominal concrete strain at the bottom of the column derived from the measurement of relative displacement of concrete in the first loading cycle after load reversed. A positive value of x-axis means tensile strain. The reduction coefficient is defined as the ratio of shear carried by concrete to shear strength obtained from specimen No.1 which has no web reinforcement.

The reduction coefficient becomes smaller as the tensile strain of concrete becomes larger. But the reduction coefficient has a lower bound, which means that Vc does not become zero only by the loss of shear

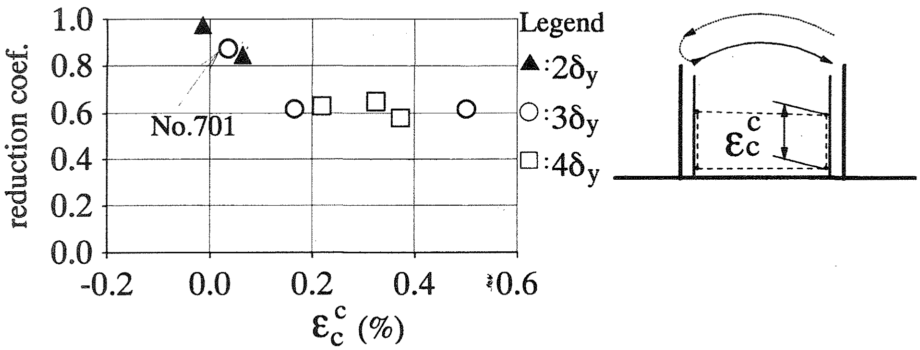


Fig.10 Reduction of shear transfer of concrete in compression zone

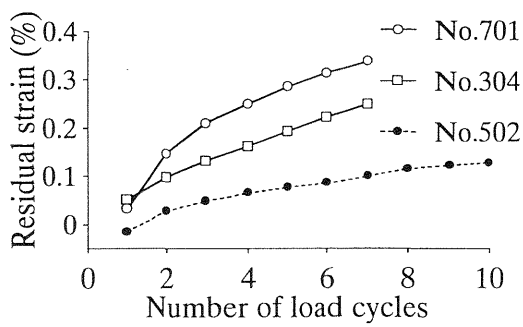


Fig.11 Residual strain history

transfer of concrete in the compressive zone and other shear resisting components of concrete still exist. When the displacement amplitude at the loading point is $2\delta_y$, residual tensile strain is small, and shear transfer of concrete in compression zone is effective in the first loading cycle. But as shown in Figure 11, with increasing number of load cycles, residual tensile strain becomes larger, which means that most of shear transfer of concrete in compression zone is finally lost.

3.3.3 Shear strength reduction after the second load cycle

When a repeated load was applied, tensile hoop stress gradually increased with number of load cycles. Residual hoop stress after unloading is also a typical feature under repeat loading as Ruhnau (1974) pointed out. Proper interpretation of the effect of residual hoop stress is important for the

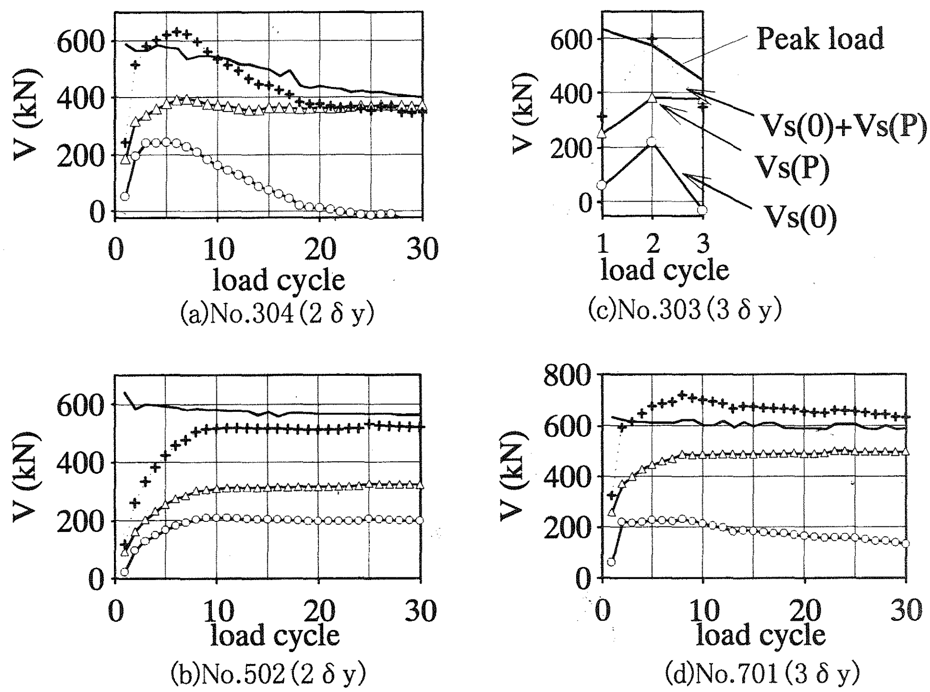


Fig.12 Variation of Vs

estimation of shear strength decay under load reversals.

Figure 12 shows the history of the shear contribution of hoops of column specimens. Vs(P) means Vs at the peak load in each load cycle. Vs(0) means Vs at the unloaded point in each load cycle. As the residual hoop stress, Vs(0) was not zero even when unloaded. The solid line without marks is the peak shear force acting on column specimens.

According to Figure 12, Vs(0) increased in the early cycles of load reversals, but decreased in case of column No.303 and No.304 which failed in shear. In Figure 12, Vs(0)+Vs(P) are also plotted as '+' . Roughly speaking, Vs(0)+Vs(P) coinsides with shear load except in early load cycles, which means that Vs(0) can be accounted for by the shear resisting component.

Vs(0) is due to residual tensile stress of hoops and acts as a confining force on core concrete which has a beneficial effect for resisting shear. In other words, the shear strength of concrete is maintained by the confinement by hoops in the form of residual tensile stress of hoops.

Therefore part of the reduction of shear carried by concrete depends on the amount of shear reinforcement. In this experiment, loss of some of the shear carried by concrete is thought to be unavoidable under load reversals because of the reduction of shear transfer by concrete in the compression zone, still about 40% of Vc remained provided that there were enough hoops arranged and confinement remained.

4 Conclusions

Based on the load reversal tests the following conclusions were drawn;

1) The change of displacement component as well as the the curvature and nominal shear strain distribution varied greatly, depend on the failure pattern of columns.

2) The shear strength decay carried by concrete was estimated. Under load reversals shear transfer by concrete in compression zone reduces and can not be avoided. However, some amount of (in this experiment about 40%) shear resistance remains due to the hoop confinement.

3) Shear resistance by hoop confinement depends on the amount of hoops. This means that in order to estimate the shear strength reduction carried by concrete, the amount of shear reinforcement has to be taken into consideration.

5 References

Gosain, N. K., Brown, R. H., Jirsa, J. O. (1977) Shear Requirements for Load Reversals on RC Members, **Journal of Structural Division ST7**, pp.1053-1065.

Priestley, M. J. N.,Verma, R., Xiao, Y. (1994) Seismic Shear Strength of Reinforced Concrete Columns, **Journal of Structural Division ST8**, pp.2310-2329.

Ruhnau, J. (1974) Influence of Repeated Loading on the Stirrup Stress of Reinforced Concrete Beams, **ACI SP-42**, Vol.1 , pp.169-181.

Wight J. K., Sozen A. (1975) Strength Decay of RC Columns under Shear Reversals, **Journal of Structural Division ST5**, pp.1461 - 1476.