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DETERIORATION MECHANISM OF SHEAR-RESISTING SYSTEM IN RC BEAM SUBJECTED TO REVERSED CYCLIC LOADING AFTER FLEXURAL YIELDING

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SUMMARY

Based on cyclic loading tests of RC beams which failed in flexural shear failure without yielding of the transverse reinforcement, the following flexural shear failure mechanism, which is associated with 'Error Catastrophe' known as a theory of aging, was observed in the hinge region.

A shear-resisting system formed in the hinge region of RC beam subjected to monotonic loading. Under reversed cyclic loading, the shear-resisting system of monotonic loading repeated temporary disappearance and rebuilding due to opening and closing of cracks, each time the loading direction was reversed. The flexural shear failure occurred due to malfunction of the rebuilding after the temporary disappearance. What inhibited the rebuilding and caused the malfunction was errors in the rebuilding. The errors accumulated each time the shear-resisting system is rebuilt, and when the errors exceeded a certain tolerance, the failure due to the malfunction of the rebuilding occurred.

INTRODUCTION

For ductility design, it is important to precisely evaluate ductility capacity of beams and columns as well as their strength. It is known that flexural failure beams subjected to reversed cyclic loading have a limit from where very large strength degradation occurs due to shear failure after flexural yielding. This failure mode is known as flexural shear failure. There have been many studies about flexural shear failure, and they have achieved useful results. However, although various models to predict the ductility capacity due to flexural shear failure have been proposed based on the results, their accuracy are not high compared with that of strength. The reason seems that very few studies have been made at the failure behavior concerning extremely damaged hinge region, and the failure mechanism under large-deformation cyclic loading is not elucidated enough.

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FAILURE DUE TO ERROR CATASTROPHE

The objective of this paper is to experimentally show the existence of a flexural shear failure mode for RC beams subjected to large-deformation cyclic loading, which is associated with 'Error Catastrophe'. Error catastrophe is a theory of aging and summarized as follows (see Fig1),

① Our cells are reproducing in our body.
② Errors in reproduction occur, causing damage to the reproduction function.
③ The errors accumulate each time cells reproduce.
④ Catastrophic failure due to malfunction of the reproduction occurs when certain tolerance of error is exceeded.

As a result of cyclic loading tests, a new flexural shear failure mode peculiar to RC beams subjected to reversed cyclic loading in large deformation rage was observed. The failure behavior is described as follows (see Fig.2),

① Under reversed cyclic loading, a certain shear-resisting system repeats temporary disappearance and rebuilding due to opening and closing of cracks (①→②→③ in Fig.2).
② Errors in the rebuilding occur, causing damage to function of the rebuilding.
③ The errors accumulate each time the shear-resisting system is rebuilt.
④ Catastrophic failure due to malfunction of the rebuilding occurs when a certain tolerance of error is exceeded (②→⑤ in Fig.2).

In order to inhibit flexural shear failure under cyclic loading, RC beam must satisfy the following two conditions. Condition 1: Shear-resisting system is rebuilt after the temporary disappearance each time the loading direction is reversed (②→③ in Fig.2). Condition 2: Applied shear force does not exceed the shear strength of the rebuilt shear-resisting system (③→④in Fig.2). While the conventional flexural shear failure occurs when the condition 2 is not satisfied (③→⑥in Fig.2), observed failure mode occurs when the condition 1 is not satisfied (②→⑤in Fig.2).

However, this paper is not to say that the conventional flexural shear failure mechanism does not exist. The purpose of this paper is to show that there is a possibility of another new

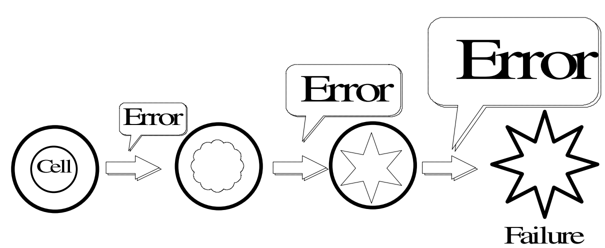


Fig.1 Error Catastrophe

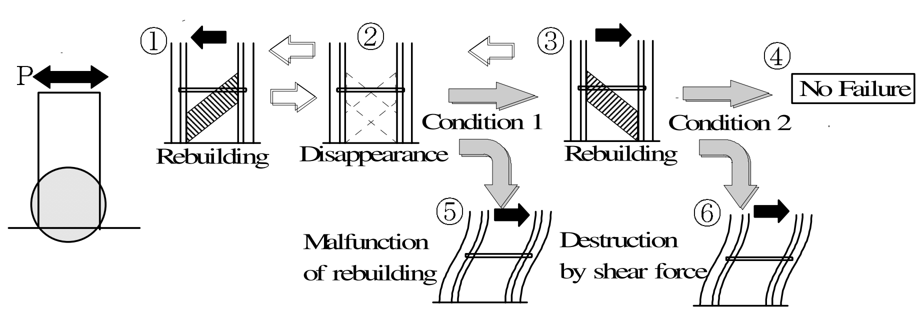
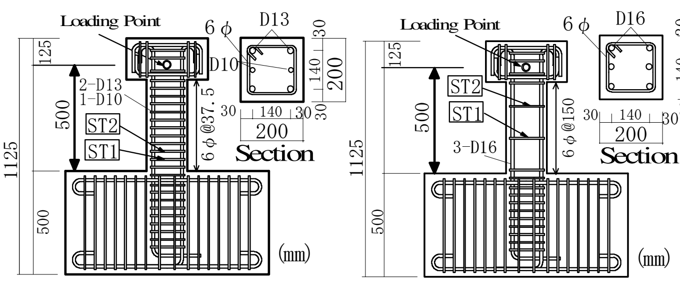


Fig.2 Flexural Shear Failure Mechanism in Hinge Region

failure mode peculiar to RC beams under large-deformation cyclic loading which fails without yielding of the transverse reinforcement.

CYCLIC LOADING TESTS OF RC BEAM

Two kinds of cantilever RC beam specimen-A and -B were made in order to investigate the cyclic deterioration behavior in large deformation range beyond flexural yielding. The details of specimen-A and specimen-B are shown in Fig.3. And the test setup is shown in Fig.4. Specimens were tested in the 90-deg rotated position with one end fixed and the other end pined. Lateral load was applied to the pined end. It was considered that the configuration and loading condition should be as simple as possible in order to investigate the complex failure mechanism of hinge region. The mechanical properties of the reinforcement are shown in table 1 and the concrete strength σ_B of each specimen is shown in Fig.7. As shown in Fig.5, the deformation behavior in the hinge region and the strains of transverse reinforcement were measured in detail.



(1)Specimen-A (2)Specimen-B

Fig.3 Geometry and Reinforcing Arrangement

Specimen-A was designed so that it would fail in flexural failure certainly. Thus, the shear strength was designed to be twice as large as the flexural strength. On the other hand, Specimen-B was designed so that it would fail in shear failure just after flexural yielding by reducing the transverse reinforcement and increasing the longitudinal reinforcement. The shear strength was slightly larger than the flexural strength.

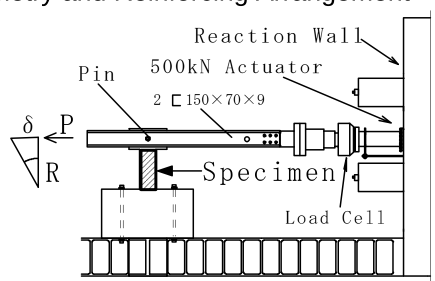


Fig.4 Test Setup

Specimen-A was tested under monotonic loading and three different loading histories as shown in Fig.6. These specimens were named Am, A1, A2 and A3 respectively. The purpose of this experiment is to investigate the flexural shear failure mechanism in specimen-A subjected to reversed cyclic loading, thus the specimen-A2 and specimen-A3. Since these two specimens had similar failure behavior, the consideration in the later chapter will be done mainly based on the failure behavior of the specimen-A2. Specimen-B was made for comparison purpose. Specimen-B was subjected to the same cyclic loading history as the specimen-A2 .

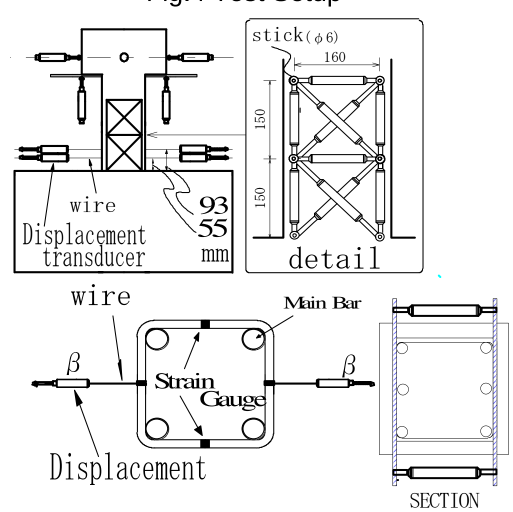


Fig.5 Measuring Apparatus

Table 1 Mechanical Properties of Reinforcement

	Yield Strength	Tense Strength	Young's Modulus
6 φ	366	463	2.04×10^5
D10	361	509	2.02×10^5
D13	352	510	2.06×10^5
D16	402	559	2.02×10^5

(N/mm^2)

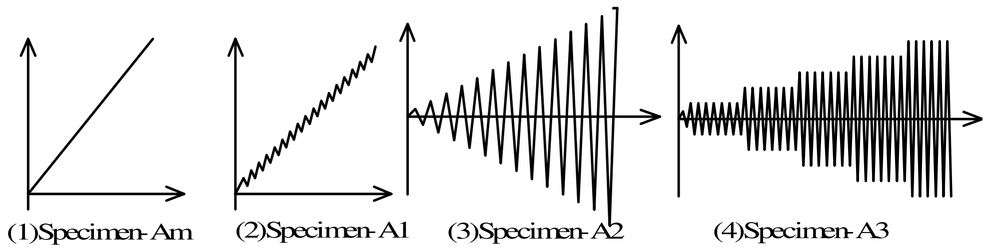


Fig.6 Loading Histories

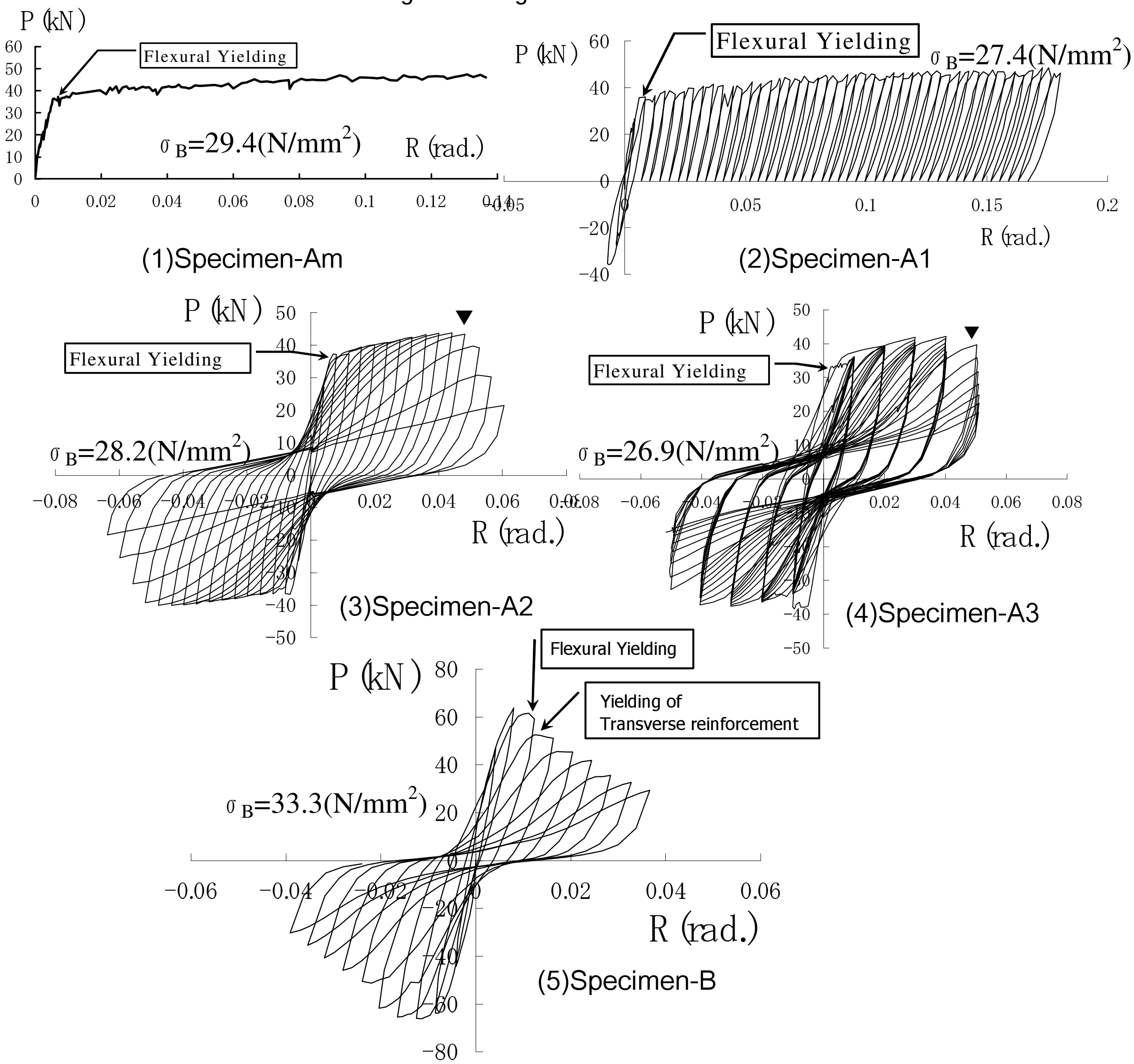


Fig.7 Load P vs. Drift ratio R Relation

The observed load P - drift ratio R relationships for specimen-A are shown in Fig.7. The load P and drift ratio R are defined in Fig.4. As seen in Fig.7(1), specimen-A has a very large deformation capacity under monotonic loading. On the other hand, specimen-A subjected to reversed cyclic loading failed in flexural shear failure at smaller drift ratio(See ▼ in Fig.7(3),(4)). Fig.8 shows a typical strain of the transverse reinforcement vs. drift ratio relation for these specimens subjected to reversed cyclic loading. The strain was observed at the transverse reinforcement ST1 which was in the severely damaged region as shown in Fig.17. Since the strain was kept small as can be seen in Fig.8, it is obvious that yielding of the transverse reinforcement did not occur despite the severe damage.

The observed load P - drift ratio R relationship for specimen-B is shown in Fig.7(5). Rapid strength degradation occurred from the 4th cycle just after flexural yielding. In the specimen-B, yielding of the transverse reinforcement was observed at the 4th cycle.

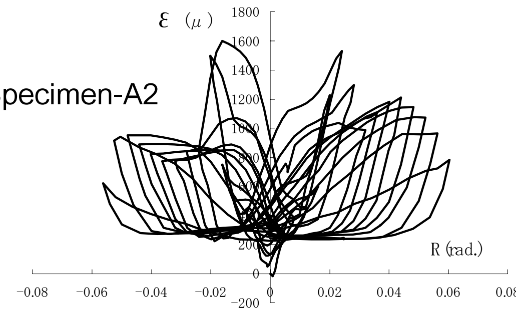


Fig.8 Strain of Transverse Reinforcement ST1 for Specimen-A subjected to Reversed Cyclic Loading

TEMPORARY DISAPPEARANCE AND REBUILDING OF SHEAR-RESISTING SYSTEM

To investigate the failure behavior in the hinge region, rotation angle θ and lateral displacement D of the point "O" shown in Fig.9 were measured. It is noted that, as shown in Fig.10, a decrease in inclination in the θ vs. D relation means an increase in shear deformation component in the hinge region. Since it is impossible to directly observe the shear-resisting system in the hinge region, the deformation behavior caused by the shear-resisting system was observed instead using the θ vs. D relation.

θ vs. D relation for specimen-A subjected to monotonic loading is shown in Fig.11. As can be seen in this figure, almost linear relationship, $\theta \fallingdotseq D/150$, was observed. This means a shear-resisting system which provides the linear relationship, $\theta \fallingdotseq D/150$, formed in the hinge region. Let us call the shear-resisting system, "shear-resisting system of monotonic loading" (SOM) hereafter. In other words, if the linear relationship, $\theta \fallingdotseq D/150$, is observed between θ and D, SOM is considered to be formed in the hinge region.

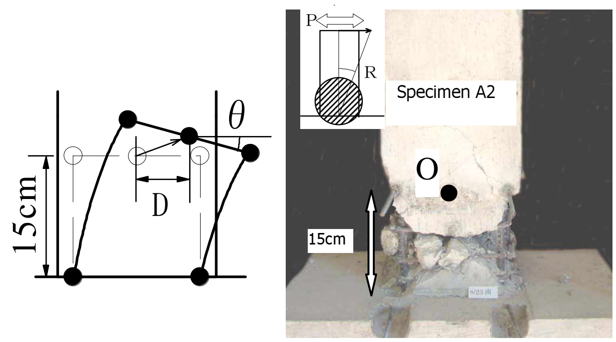


Fig.9 Rotation Angle. and Lateral Displacement D

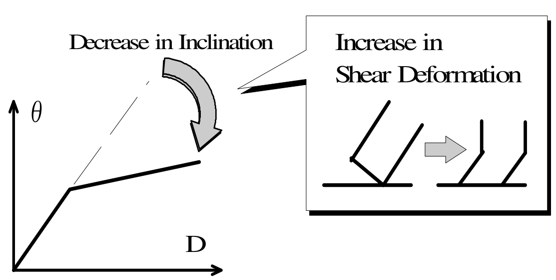


Fig.10 Decrease in Inclination caused by Shear Failure

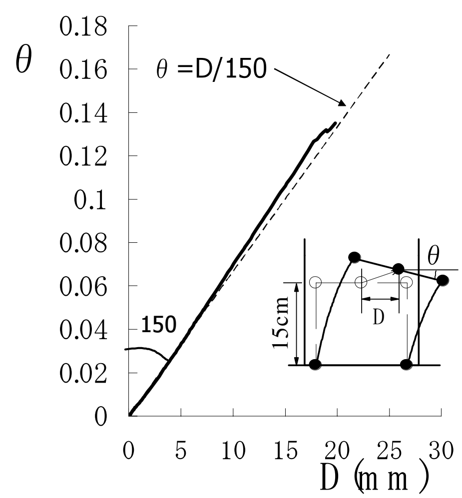
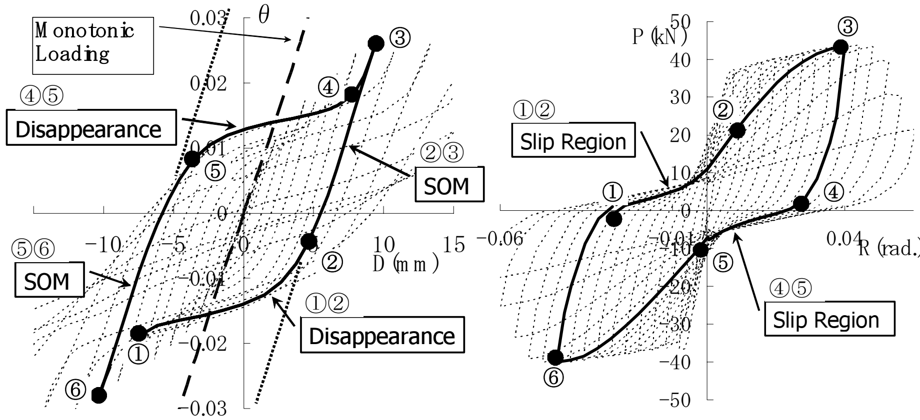


Fig.11 Deformation Behavior under Monotonic Loading



(1) θ vs. D relation (2)P vs. R relation

Fig.12 Deformation Behavior under Reversed Cyclic Loading (Specimen-A2)

Fig.12(1) shows θ vs. D relation for specimen-A2 subjected to reversed cyclic loading. A cycle before the flexural shear failure is picked out and shown in this Figure. Fig.12(2) is the corresponding load vs. drift ratio relation. A similar linear behavior, θ ≒ D/150, to that of monotonic loading can be seen in Fig.12(1) (see ②③ and ⑤⑥). In other words, the formation of SOM can be also identified under cyclic loading, indicating that deformation behavior under cyclic loading is based on that under monotonic loading.

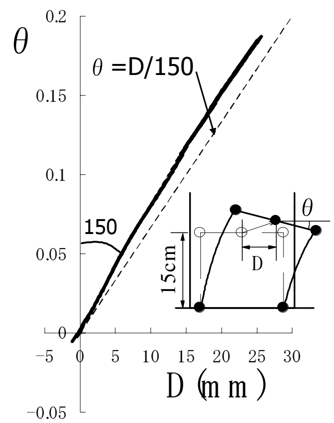


Fig.13 Deformation Behavior under Cyclic Loading without Reversed Loading (Specimen-A1)

However, it is seen that the SOM does not always exist under cyclic loading. Since the inclination decreases temporarily in the low load region just after changing loading direction (see ①② and ④⑤ in Fig.12(1)), it is considered that the SOM temporarily disappears due to reversed loading. Fig.13 shows θ vs. D relation for specimen-A subjected to cyclic loading without reversed loading, thus cyclic loading to one direction (see Fig.7(2)). Despite the plenty of cycles and the large deformation, almost the same linear behavior as monotonic loading was observed in this specimen, suggesting that the disappearance was caused by reversed loading.

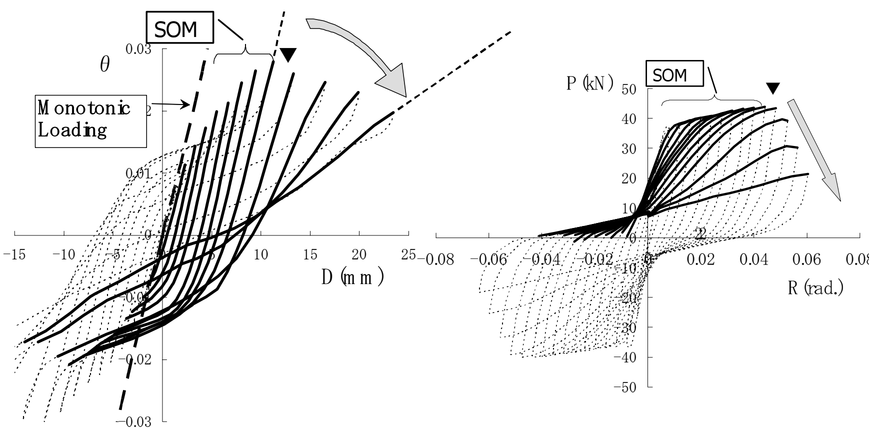
The low load region just after the onset of reversed loading (①② and ④⑤ in Fig.12(2)), where the disappearance was observed, is known as 'Slip Region', in which large shear deformation occurs due to temporary opening of cracks of both loading direction. This means SOM repeats temporary disappearance and rebuilding under reversed cyclic loading on account of opening and closing of cracks due to reversed loading, suggesting that the rebuilding of SOM is necessary to keep the shear resistance.

FAILURE CAUSED BY MALFUNCTION OF THE REBUILDING

It is not considered that the rebuilding of SOM after the disappearance always succeeds despite an increase in damage. In this chapter, the failure behavior under cyclic loading is examined in terms of SOM.

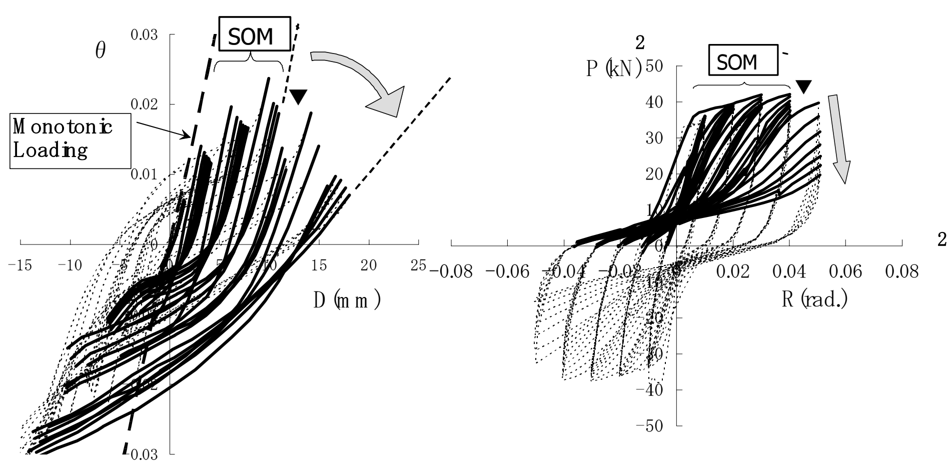
Fig.14(1) and 15(1) show the θ vs. D relation for specimen-A2 and A3 respectively, in which reversed-loading curves are picked up. Fig.14(2) and 15(2) show the corresponding load vs. drift ratio relation. As can be seen in Fig.14(1) and 15(1), before the flexural shear failure (before ▼), the inclinations of each cycle curves at peak load are almost the same as that of monotonic loading, indicating that SOM is rebuilt before the failure. However, after the occurrence of the failure(after ▼), the inclinations of the each curves at peak load gradually decreases, indicating that it becomes difficult to rebuild SOM. This suggests that the formation of SOM is necessary to keep the shear resistance and the malfunction of the rebuilding caused the strength degradation.

The question is whether the SOM was destroyed by applied shear or not at the occurrence of the failure. Conventional failure models explain that the failure behavior was caused by the destruction of the SOM



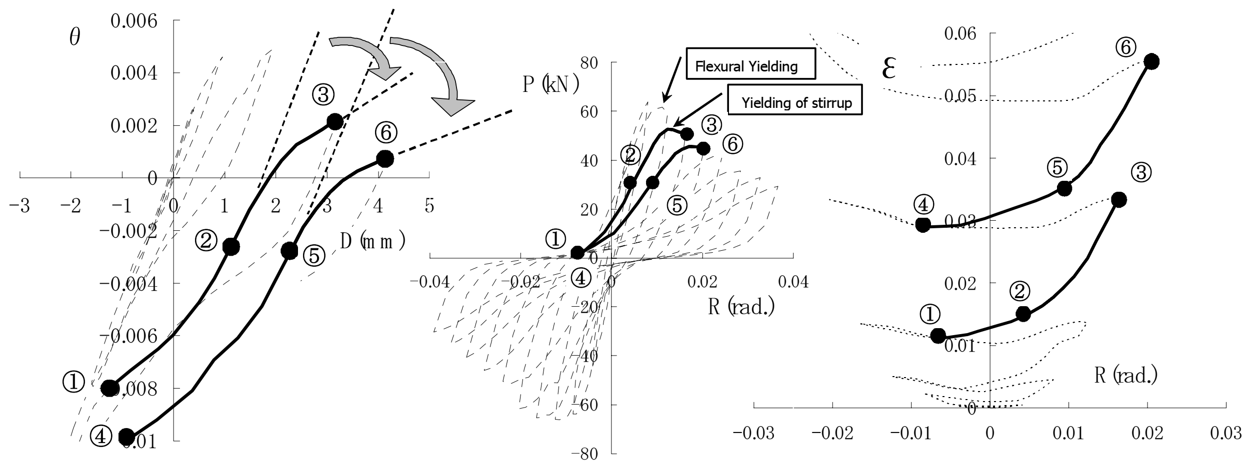
(1) θ vs. D relation (2)P vs. R relation

Fig.14 Deformation Behavior in Reversed Loading Process (Specimen-A2)



(1) θ vs. D relation (2)P vs. R relation

Fig.15 Deformation Behavior in Reversed Loading Process (Specimen-A3)



(1) θ vs. D relation (2)P vs. R relation (3) ε t vs. R relation

Fig.16 Deformation Behavior in Each Loading Process (Specimen-B)

due to a decrease in shear strength with increasing deformation. Fig.16(1) and (2) show θ vs. D relation and the corresponding load vs. drift ratio relation for specimen-B respectively. If the SOM was destroyed by applied shear force, a decrease in inclination shown in Fig.10 should be observed in the loading process, because the shear-load-carrying capacity decreases and this provides more shear deformation, decreasing a rate of increase in θ. In fact, as can be seen in Fig.16(1), a decrease in the inclination shown in Fig.10 was clearly observed in specimen-B, which failed in shear failure due to yielding of transverse reinforcement, thus destruction of the shear-resisting system by applied shear force.

In specimen-A, it is obvious from Fig.14(1) and 15(1) that the decrease in the inclination shown in Fig.10, which indicates the evidence of the destruction of SOM, can not be seen in each loading process. Particularly in Fig.15(1) for specimen-A3, the inclinations of the curves have rather a increasing tendency than a decreasing tendency (see curves after ▼), indicating that the shear deformation component is tending to decrease rather than increase in each loading process. This means SOM was not destroyed but being rebuilding in each loading process.

There is no guarantee that SOM is always rebuilt successfully after the temporary disappearance. The failure behavior, obtained by the considerations from θ vs. D relations, indicates that the flexural shear failure of specimen-A was not caused by destruction of SOM but caused by a malfunction of the rebuilding after the disappearance (see ②→⑤ in Fig.2).

ERRORS IN REBUILDING

The previous chapter has discussed about disappearance and rebuilding of SOM (Shear-Resisting System of Monotonic Loading) and a failure caused by the malfunction of the rebuilding. It is not considered that the rebuilding is always perfect. It is quite likely that some errors in the rebuilding occur, and the errors lead to the malfunction. In this chapter, the question of what caused the malfunction is examined in terms of the errors in the rebuilding.

In order to examine the failure behavior of the hinge region, transverse strain defined in Fig.17 and axial strain defined in Fig.18 were measured using the measuring apparatus shown in Fig.5. The transverse strain was measured at the transverse reinforcement ST1 and ST2 which were severely damaged region as shown in Fig.17. Since the transverse strain of ST1 was always a little larger than that of ST2 as a result of the measurement, the values of the transverse strain ST1 will be used for the considerations hereafter. Although it is important to investigate the deformation behavior of core concrete in order to understand the failure mechanism of the hinge region, it is very difficult to measure the behavior directly because of the severe damage. In this paper, the deformation behavior was indirectly measured using these strains.

Fig.19 compares the transverse strain ε_t under reversed cyclic loading with that under monotonic loading. The transverse strain consists of strain by yielding and strain by bending as shown in Fig.20. Since yielding of the transverse reinforcement was not observed in Specimen-A as shown in Fig.8, it is considered that almost all the transverse strain for specimen-A was provided by bending defined in Fig.20. As can be

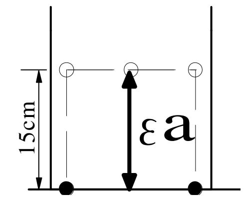


Fig.18 Axial Straine a

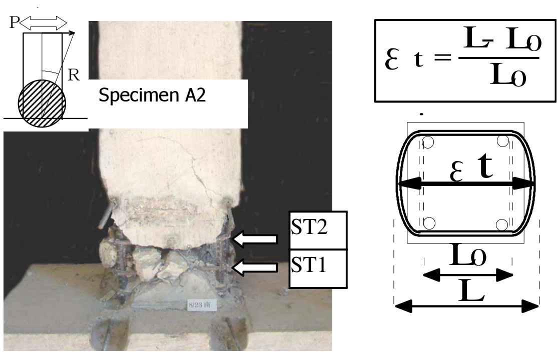


Fig.17 Transverse Strainet

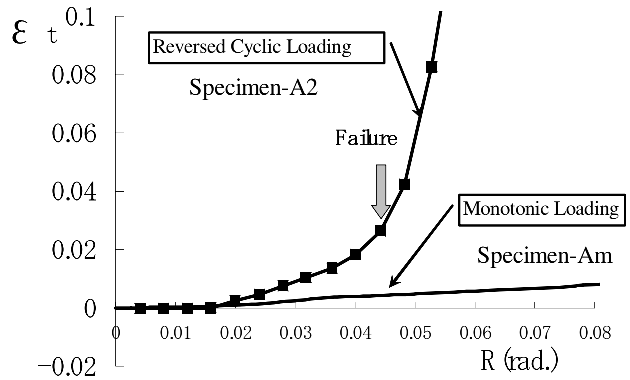


Fig.19 Increase in Transverse Strainet

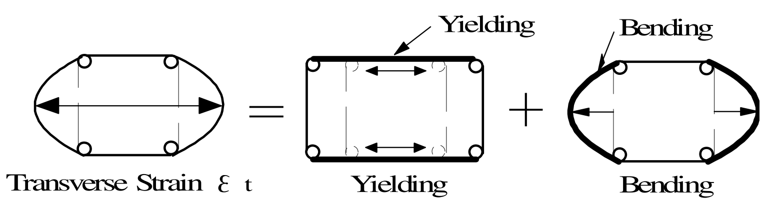
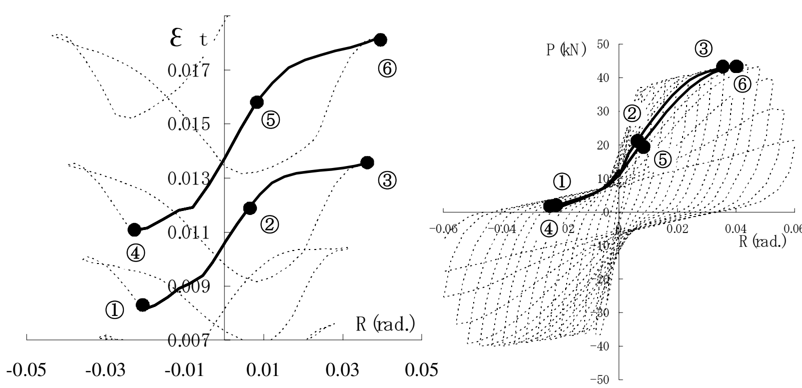


Fig.20 Transverse Strain due to Yielding and Bending



(1) ε t vs. R relation (2)P vs. R relation

Fig.21 Increase Behavior of Transverse Strainε t for Specimen-A2 seen in Fig.19, in specimen-A2 subjected to reversed cyclic loading, the transverse strain gradually accumulated with loading cycles and increased rapidly when the flexural shear failure occurred. On the other hand, in specimen-Am subjected to monotonic loading, the transverse strain was kept small, compared with that under reversed cyclic loading.

Fig.21(1) shows the increase behavior of the transverse strain for specimen-A2, and Fig.21(2) shows the corresponding load vs. drift ratio relation. It is obvious from Fig.21(1) that the transverse strain increased in the slip region (see①②,④⑤) where the SOM temporarily disappeared.

Therefore, the following considerations were obtained from Fig.19 and Fig.21.

①The transverse strain was kept small under monotonic loading.

②However, under reversed cyclic loading, the transverse strain gradually increased during the disappearance where the SOM was being rebuilt.

③The transverse strain increased rapidly when the flexural shear failure due to the malfunction of the rebuilding occurred.

These considerations suggest that the transverse strain is an error in the rebuilding and the error accumulates each time SOM is rebuilt under cyclic loading, resulting in the malfunction of the rebuilding.

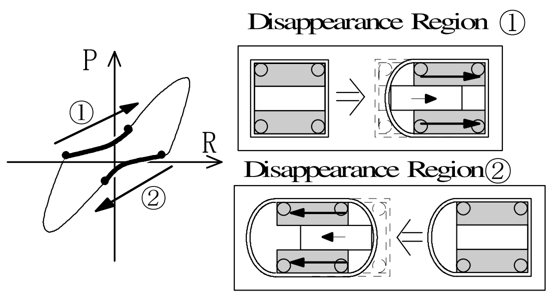


Fig.22 Transverse Strainε t caused by 3-Dimensional Deformation in Slip Region

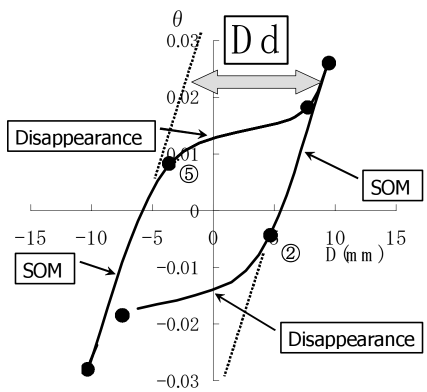


Fig.23 Intensity of Disappearance Dd

INCREASE MECHANISM OF ERRORS IN REBUILDING

In order to understand the failure mechanism that has been discussed above, it is necessary

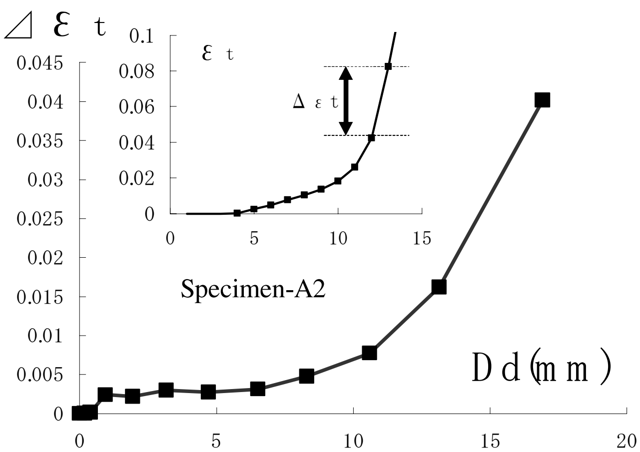


Fig.24 Increase in Transverse Strain ε t with Dd

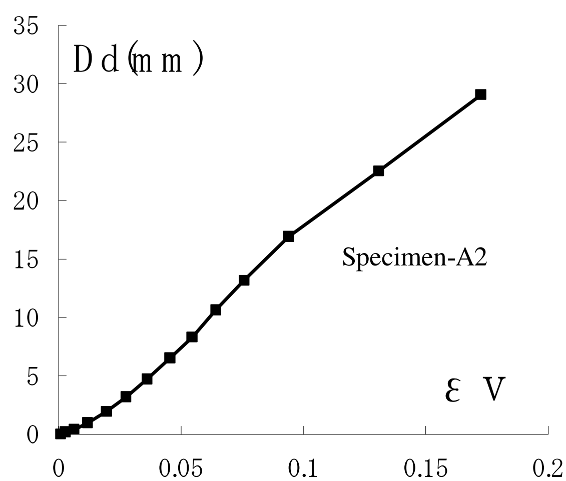


Fig.25 Increase in Dd with Volume Strain ε v

to examine how the errors are produced. In this chapter, the increase mechanism is examined.

Fig.21(1) and Fig.16(3) show the increase behavior of the transverse strain for specimen-A2 and specimen-B respectively. As can be seen in Fig.16(3), the transverse strain for specimen-B increased in the high load region (see ②③ and ⑤⑥ in Fig.16(2)(3)). Since specimen-B failed in shear failure because of yielding of stirrup, the increase in high load region is quite natural. On the other hand, as mentioned in the previous chapter, the transverse strain for specimen-A2 increased in the low load region after the onset of reversed loading, thus the slip region (see ①②,④⑤ Fig.21(1)).

As shown in Fig.20, the transverse strain consists of strain by yielding and by bending. The transverse strain in specimen-B was mainly provided by the strain due to yielding, because yielding of transverse reinforcement was observed in specimen-B. On the other hand, as mentioned already, the transverse strain in specimen-A was mainly provided by the strain due to bending, because no yielding was observed in specimen-A as shown in Fig.8.

From these two considerations, it is estimated that the increase in the transverse strain due to the bending in the slip region resulted from 3-dimentional shear deformation behavior shown in Fig.22. Since large shear deformation occurs in the slip region due to the disappearance of the shear-resisting system, it is quite likely that the shear deformation in such an extremely damaged hinge region was not 2-dimentional.

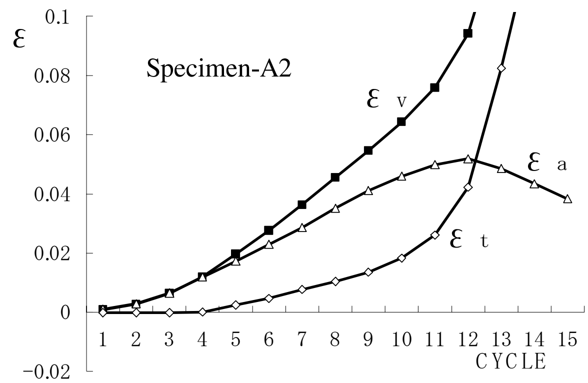


Fig.26 Volume Strain ε_v (=ε_t+ε_a)

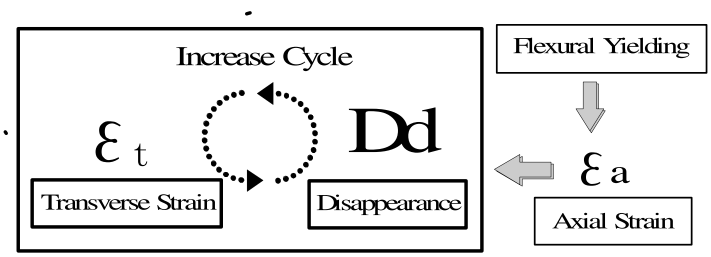


Fig.27 Increase Cycle of Errors in Rebuilding

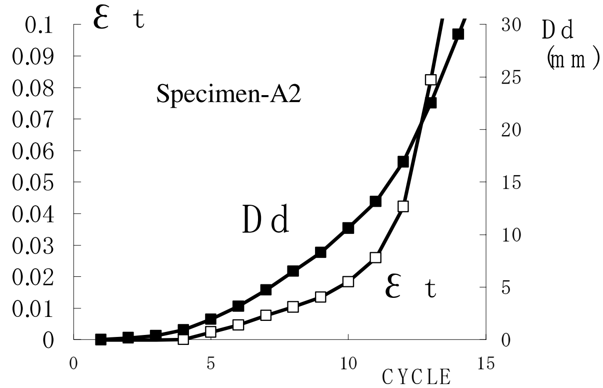


Fig.28 Increase Behavior of Dd and ε_t

Fig.23 indicates the definition of Dd which represents the magnitude of shear deformation during the temporary disappearance, thus the intensity of the disappearance. Increment of the transverse strain ε_t vs. Dd relationship for specimen-A2 is shown in Fig.24. As can be seen in this figure, the transverse strain increased with Dd. This suggests that an increase in Dd, which means stiffness degradation of the hinge region, caused the 3-dimentional shear deformation behaviour shown in Fig.22, resulting in the increase in the transverse strain.

It has been shown that the intensity of the disappearance Dd increased the transverse strain ε_t. That raises a question of what caused the Dd. Fig.25 shows Dd vs. volume strain ε_v relation for speciemen-A2. The volume strain is calculated as the sum of the transverse strain ε_t and axial strain ε_a which are defined in Fig.17 and 18 respectively. Fig.25 indicates that Dd increased in proportion to the volume strain. Since the volume strain is mainly provided by crack opening in the hinge region, it is quite likely that an increase in the volume strain inhibited the rebuilding because of the reduction of aggregate interlock, and increased the intensity of the disappearance Dd.

Fig.26 shows increase behaviour of the volume strain ε_v, the transverse strain ε_t, and the axial strain ε_a for pecimen-A2. As can be seen in Fig.26, the axial strain increased in the beginning, but in the later cycles, the transverse strain increased remarkably. Therefore, the following increase mechanism of the transverse strain shown in Fig.27 is estimated from these considerations concerning Fig.24, 25, and 26.

First the axial strain increased due to flexural deformation, causing Dd, thus the disappearance, and then, the produced Dd provided transverse strain ε_t, and the produced transverse strain provided more Dd. By repeating the increase cycle shown in Fig.27, transverse strain ε_t, thus the error in the rebuilding increased. Fig.28 compares the increase behavior of Dd and ε_t for specimen-A2. As seen in this Figure, Dd and ε_t have a similar increasing tendency, suggesting that they are produced by the increase cycle activated by axial strain. The increase cycle shown in Fig.27 indicates that the errors in the rebuilding cause the intension of the disappearance; i.e., the errors inhibit the rebuilding, and the intensified disappearance leads to more errors in the rebuilding, resulting in a chain reaction which causes catastrophic failure.

CONCLUSIONS

From large-deformation cyclic loading tests of RC beams which failed in flexural shear failure without yielding of transverse reinforcement, the following failure mechanism was observed in the hinge region.
(1)A certain shear-resisting system (SOM) forms under monotonic loading. Under cyclic loading, the SOM repeats temporary disappearance and rebuilding due to opening and closing of cracks caused by changing loading direction. Flexural shear failure can occur due to malfunction of the rebuilding (see Fig.2).
(2)What inhibits the rebuilding and causes the malfunction is errors in the rebuilding. The errors lead to expansion of the disappearance region and the expanded disappearance region provides more errors. The errors increase by repeating this increase cycle of error. (see Fig.27)
(3)When the error exceeds a threshold, a chain reaction in the increase cycle is induced explosively, increasing the errors in the rebuilding abruptly, causing catastrophic failure due to the malfunction of the rebuilding.
(4)Transverse strain due to bending (see Fig.17) is considered to be an error in the rebuilding which finally causes the malfunction. The occurrence of this failure mode is considered to be defined by certain tolerance of error, thus a value of the transverse residual strain. It is estimated that the transverse strain is provided by 3-dimensional shear deformation during the temporary disappearance (see Fig.22).
(5)Axial strain (see Fig.18) is provided by flexural yielding and produce the disappearance region in the early stage, activating the increase cycle.

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