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Deterioration Mechanism of Shear-Resisting System in RC Beam Subjected to Reversed Cyclic Loading after Flexural Yielding

by H. Kinugasa and S. Nomura

Synopsis: Based on cyclic tests of RC beams that failed in flexural-shear without yielding of the transverse reinforcement, a mechanism controlling flexural shear failure is proposed. This mechanism, which is associated with 'Error Catastrophe' known as a theory of aging, was observed in the hinge region of the beams.
The results of experimental testing indicate that a shear-resisting system forms in the flexural hinge region of a RC beam subjected to monotonic loading. Under reversed cyclic loading, the shear-resisting system temporarily disappears as cracks open and then is rebuilt as cracks close. A flexural shear failure occurs when the shear resisting mechanism is not rebuilt upon load reversal. What inhibits the rebuilding process and, ultimately, results in a failure to rebuild, is "errors" in the rebuilding process. These errors accumulate each time the shear-resisting system is rebuilt, and when the errors exceeded a certain tolerance, failure due to the malfunction of the rebuilding occurs.

Keywords: ductility; error catastrophe; failure mechanism; flexural shear failure; RC beam; reversed cyclic loading; shear-resisting system

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INTRODUCTION

For seismic design, it is important to precisely evaluate ductility capacity of beams and columns as well as their strength. It is known that beams subjected to reversed cyclic flexure-shear loading may exhibit significant strength degradation due to shear failure following flexural yielding. This failure mode is known as flexural shear failure. There have been many studies about flexural shear failure, and they have provided useful results. However, although various models have been proposed to predict the ductility capacity at which flexural shear failure develops, the accuracy of these models is not high and is much lower than models used to predict maximum strength. Currently, no method for predicting ductility capacity has been validated. The reason that no validated model exists is that very few studies have been made at the failure behavior of extremely damaged hinge regions and the failure mechanism that develops under large-deformation cyclic loading is not fully understood.

FAILURE DUE TO ERROR CATASTROPHE

The objective of this paper is to show experimentally 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 These 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 range was observed. The failure behavior is described as follows (see Fig.2),

①Under 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 These errors accumulate each time the shear-resisting system is rebuilt.
④Catastrophic 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 beams must satisfy the following two conditions. Condition 1: The shear-resisting system is rebuilt after the temporary disappearance that occurs each time the loading direction is reversed (②→③ in Fig.2). Condition 2: The applied shear force does not exceed the shear strength of the rebuilt shear-resisting system (③→④in Fig.2). The conventional flexural shear failure occurs when condition 2 is not satisfied (③→⑥in Fig.2); however, here the observed failure mode occurred when condition 1 was 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 failure mode that develops in RC beams under large-deformation cyclic loading.

CYCLIC LOADING TESTS OF RC BEAM

Two kinds of cantilever RC beam specimens, denoted A and B, were constructed in order to investigate cyclic strength deterioration under large deformation demands 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 rotated 90-degrees for testing. One end of the member was fixed against rotation and displacement while the other end was pined. Lateral load was applied to the pined end. 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.

Specimen-A was designed so that it would exhibit a flexural failure. To ensure a flexural failure, the shear strength of Specimen-A was designed to be twice as large as the demand associated with flexural yielding. Specimen-B was designed so that it would fail in shear following flexural yielding. This was accomplished by reducing the volume of transverse reinforcement and increasing the longitudinal reinforcement, in comparison to Specimen-A. The shear strength of Specimen-B was designed to be slightly larger than the shear demand associated with flexural yielding.

Specimen-A was tested under monotonic loading and two different cyclic loading histories as shown in Fig.6. These specimens were named Am, A1 and A2 respectively. The purpose of the Specimen-A tests was to investigate the flexural shear failure mechanism. Since Specimen-A1 and A2 exhibited similar failure behavior, further analysis is done considering the observed response of Specimen-A1. Specimen-B was intended for comparison. Specimen-B was subjected to the same cyclic loading history as the Specimen-A1.

The observed load (P) versus drift ratio (R) relationships for the specimens 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 had a very large deformation capacity under monotonic loading. On the other hand, specimen-A, when subjected to reversed cyclic loading, failed in flexural shear at smaller drift ratios (See ▼ in Fig.7(2),(3)). Fig.8 shows a typical transverse steel strain versus drift ratio relationship for Specimen-A 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.16. Since the strain was kept small (Fig.8), it is obvious that yielding of the transverse reinforcement did not occur despite the severe damage.

The observed load (P) versus drift ratio (R) relationship for Specimen-B is shown in Fig.7(4). 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.

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 slope in the θ vs. D relationship represents an increase in the 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 relationship.

The θ vs. D relationship for Specimen-A subjected to monotonic loading is shown in Fig.11. As can be seen in this figure, an almost linear relationship, $\theta \fallingdotseq D/150$, was observed. This implies a shear-resisting system that provides a linear relationship, $\theta \fallingdotseq D/150$, formed in the hinge region. This shear-resisting system will be referred to as shear-resisting system of monotonic loading (SOM) hereafter. 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.12(1) shows θ vs. D relationship for Specimen-A1 subjected to reversed cyclic loading. Fig.12(2) is the corresponding load vs. drift ratio relationship for the specimen. In Figure 12(1) and Fig. 12(2), the solid line shows response for one cycle before flexural shear failure occurs. For a portion of the cycle, a similar linear behavior to that of monotonic loading, $\theta \fallingdotseq D/150$, can be seen in Fig.12(1) (see ②③ and ⑤⑥ in Fig.

12 (1)). In other words, the formation of SOM occurs under cyclic loading, indicating that deformation behavior under cyclic loading is based on that under monotonic loading.

However, it is seen that the SOM does not always exist under cyclic loading (Fig. 12(1)). The slope of the θ vs. D relationship decreases temporarily in the low load region just after there is a change in the direction of loading (see ①② and ④⑤ in Fig.12(1)). It is considered that the SOM temporarily disappears due to reversed loading. The low load region just after load reversal (①② and ④⑤ in Fig.12(2)), where the disappearance of SOM is observed, is defined as the 'Slip Region', in which large shear deformation occurs due to temporary opening of cracks of both loading direction. These data indicate that SOM exhibits repeated temporary disappearance and rebuilding under reversed cyclic loading as a result of crack opening and closing. Thus, the rebuilding of SOM is necessary to maintain shear resistance.

FAILURE CAUSED BY MALFUNCTION OF THE REBUILDING

It is possible that the rebuilding of SOM does not always succeed due to an increase in damage in the hinge region. In this section, failure behavior under cyclic loading is examined in terms of SOM.

Fig.13(1) and 14(1) show the θ vs. D relationship for Specimen-A1 and A2 respectively. Fig.13(2) and 14(2) show the corresponding load vs. drift ratio relationship for the specimens. As can be seen in Fig.13(1) and 14(1), before the flexural shear failure (before ▼), for each loading process, the slope of the θ vs. D curve is approximately the same as peak displacement demand is approached. This suggests that SOM is rebuilt. However, once significant strength loss is observed (after ▼), the slope of the θ vs. D curve at peak displacement demand gradually decreases. This indicates that it becomes difficult to rebuild SOM. This suggests that the formation of SOM is necessary to maintain shear strength and that the malfunction of the rebuilding process causes strength degradation.

One question that must be answered is whether the SOM is destroyed by applied shear at the point where strength deterioration initiates. Conventional failure models explain that failure is caused by the destruction of the SOM due to a decrease in shear strength with increasing deformation. Fig.15(1) and (2) show the θ vs. D relationship and the corresponding load vs. drift ratio relationship for Specimen-B, respectively. If the SOM was destroyed by applied shear force, then a decrease in the slope of the θ vs. D relationship, such as that shown in Fig.10, should be observed during the loading process. This decrease in slope during loading results because shear strength decreases and shear deformation increases. The data in Fig.15(1) show a decrease in the slope ; thus destruction of the shear-resisting system occurs as a result of applied shear force for Specimen-B.

On the other hand, the data in Fig.13(1) and 14(1) do not show the decrease in the slope of the θ vs. D history under loading that is shown in Fig.10 and Fig.15(1). Thus, for Specimen-A, the destruction of SOM does not occur during the loading process. Particularly in Fig.14(1) for Specimen-A2, the slope of the curves tend to increase rather than decrease (see curves after ▼), indicating that shear deformation tends to decrease rather than increase during loading. Again, this implies that SOM is going to be rebuilt, rather than destroyed, during loading.

There is no guarantee that SOM is always rebuilt successfully after the temporary disappearance. Evaluation of the θ vs. D relationship for Specimen-A indicates that the flexural shear failure of Specimen-A was not caused by destruction of SOM but by a malfunction of the rebuilding of SOM after its disappearance (see ②→⑤ in Fig.2).

ERRORS IN REBUILDING

The previous section discusses the disappearance and rebuilding of SOM (Shear-Resisting System of Monotonic Loading) and failure caused by malfunction of the rebuilding process. Rebuilding is not always perfect, and it is likely that some errors in the rebuilding process occur. These errors likely lead to malfunction of the rebuilding process and failure. In this section, the question of what causes malfunction of the rebuilding process is addressed.

In order to examine the failure behavior of the hinge region, the transverse strain in the hinge region (Fig.16) was measured using the measuring apparatus shown in Fig.5. The transverse strain was measured at the location of transverse reinforcement ST1 and ST2, which were located within the severely damaged region of the specimens (Fig.16). Since the transverse strain of ST1 was always a little larger than that of ST2, the strain values for ST1 are used. Although it is important to investigate the deformation of the core concrete in order to understand the failure mechanism of the hinge region, it is very difficult to measure concrete strain directly. Here, concrete behavior was observed indirectly from steel strains.

Fig.17 shows the transverse strain vs. drift ratio relationships for Specimen-A subjected to reversed cyclic loading and monotonic loading. The transverse strain consists of strain due to “yielding” and “bending”(Fig.18). Since yielding of the transverse reinforcement was not observed in Specimen-A, it is considered that almost all the transverse strain for specimen-A was provided by “bending” (Fig.18). As can be seen in Fig.17, in specimen-A1 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.19(1) shows the transverse strain history and Fig. 19(2) shows the load versus drift ratio history for specimen-A1. It is obvious from Fig.19(1) that the transverse strain increased in the slip region (see①②,④⑤) where the SOM temporarily disappeared. It is estimated that the increase in the transverse strain due to "bending" resulted from 3-dimensional shear deformation behavior shown in Fig.20. 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 is not 2-dimensional.

Consideration of the data in Fig.17 and Fig.19 results in the following observations:
①Transverse strain remained small under monotonic loading.
②Under reversed-cyclic loading, transverse strain accumulated during the period in which the SOM disappeared.
③Transverse strain increased rapidly when flexural shear failure, resulting from malfunction of the SOM rebuilding process, occurred.
These observations suggest that transverse strain is an error in the rebuilding process, the error accumulates each time SOM is rebuilt under cyclic loading, and accumulated error results in malfunction of the SOM rebuilding process.

CONCLUSIONS

The results of large-deformation cyclic tests of RC beams that exhibit flexural shear failure without yielding of transverse reinforcement provide a basis for the following characterization of the failure mechanism 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. Flexural shear failure can occur due to malfunction of the rebuilding process (see Fig.2).
(2) What inhibits the rebuilding process and causes the malfunction is errors in the rebuilding. The errors accumulate each time the shear-resisting system is rebuilt, and when the errors exceed a certain tolerance, failure due to the malfunction of the rebuilding occurs.
(3) Transverse strain (see Fig.16) is considered to be the error in the rebuilding process that finally causes the malfunction. It is estimated that the transverse strain is due to 3-dimensional shear deformation that occurs during the temporary disappearance of the SOM (see Fig.20). The occurrence of this failure mode is considered to be defined by certain tolerance of error, thus a value of the transverse strain.

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Table 1 -- Mechanical Properties of Reinforcement

	Yield Strength	Tensile 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)

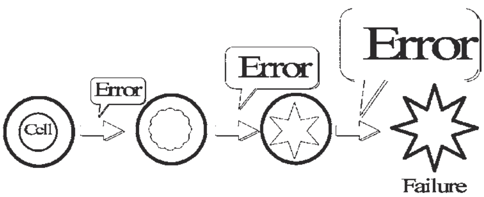

Figure 1 -- Error Catastrophe

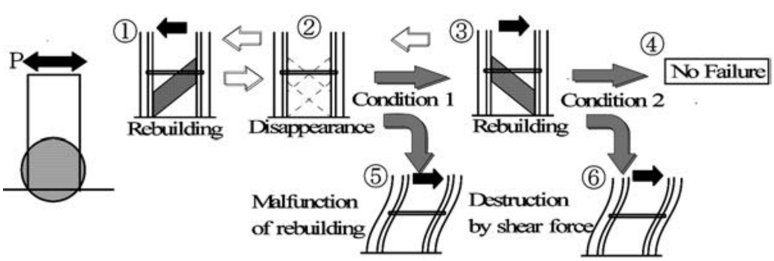

Figure 2 -- Flexural Shear Failure Mechanism in Hinge Region

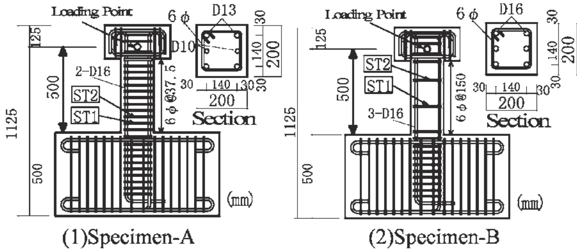

Figure 3 -- Geometry and Reinforcing Arrangement

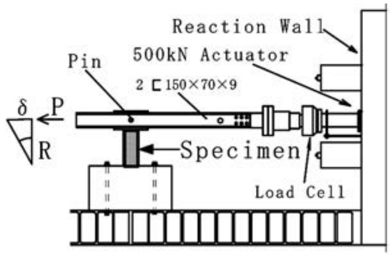

Figure 4 -- Test Setup

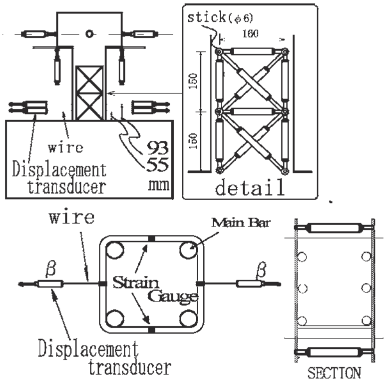

Figure 5 -- Measuring Apparatus

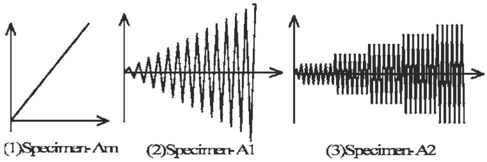

Figure 6 -- Loading Histories

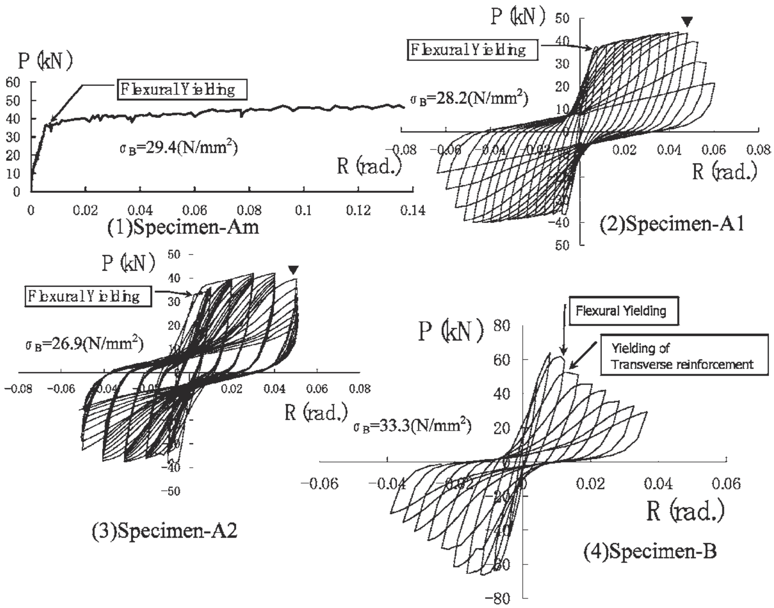

Figure 7 -- Load (P) vs. Drift ratio (R) Relation

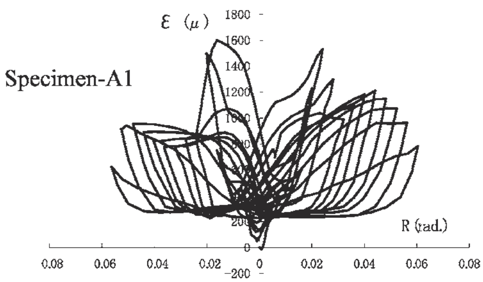

Figure 8 -- Strain of Transverse Reinforcement ST1 for Specimen-A subjected to Reversed Cyclic Loading