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Characteristics of fatigue damage for reinforced concrete beams under reversed cyclic loading

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ABSTRACT: A new cyclic failure mode is proposed on the basis of shear bending cyclic tests of reinforced concrete flexural failure beam. It is observed that member subjected to cyclic loading has a limit from where pretty large deterioration occurs, even though it has more deformation capacity under monotonic loading. Under cyclic loading, strain is accumulated in hinge zone as member absorbs energy. When the accumulated strain becomes large enough (when vertical strain exceeds 4~5%), the rapid cyclic failure occurs. We define such a failure as "strain accumulation failure" on cyclic loading. This failure mode is peculiar to cyclic loading. Strain accumulation failure is simulated on the basis of an assumption that the stiffness of hinge zone decreases monotonously as accumulated strain in hinge zone increases. Characteristics of the failure process can be explained well by the simulation.

1 INTRODUCTION

In order to establish a seismic design based on ultimate strength concept for reinforced concrete (RC), it becomes necessary to clarify the cyclic behavior in large deformation range beyond flexural yielding. It is known that member subjected to cyclic loading has a limit from where pretty large deterioration occurs, even though it has more deformation capacity under monotonic loading. The purpose of this paper is to clarify the fatigue failure mechanism of RC beams under cyclic loading and propose a new failure mode which is peculiar to cyclic loading.

2 SHEAR BENDING CYCLIC TESTS OF CANTILEVER RC BEAM

2.1 Outline of Experiment

The detail of specimen is shown in Fig.1, which is about 1/3 scale beam model. The test set-up is shown in Fig.2. Five specimens were tested with different 5 cyclic loading histories(cyclic-1~5 in Fig.3). Monotonic loading test was also carried out for comparison. The measuring arrangement is shown in Fig.4. The behavior of hinge zone is observed in detail by measuring the relative displacement of embedded sticks (5ϕ) in hinge zone. Vertical and axial strain (see Fig.5) are calculated by the observation in AREA-1 and AREA-2 (Fig. 4). As a result of the observation, vertical and axial strain in AREA-1 is considered to be these of hinge zone, because obtained values of AREA-2 was negligible small compared with these of AREA-1. Material properties of reinforcement is shown in Table-1 and concrete strength σ_B is shown in Fig.6.

2.2 Test Results

Load(P)—deflection angle(R) relationship obtained by the experiment is shown in Fig.6. Deflection angle(R) is defined in Fig.6(a). Axial and vertical strain in hinge zone is calculated on the basis of the observation of AREA-1 (see Fig.5). Axial strain (ε_A) and vertical strain (ε_V)—absorbed energy(E) relationship is shown in Fig.7.

3 CYCLIC FAILURE

3.1 Failure Behavior under Cyclic Loading

Specimen subjected to monotonic loading keeps almost constant strength till deflection angle reaches 200/1000rad after flexural yielding (Fig.6(a)). That shows specimen has enough deformation capacity under monotonic loading. On the other hand, specimen subjected to cyclic loading (cyclic-2~5) has a limit from where pretty large deterioration occurs, even though it has more deformation capacity under monotonic loading (see Fig.6(c)~(f)). In case of cyclic-4 specimen, the limit is not apparent because it is subjected to cyclic loading under small deflection angle and the deterioration proceeds slowly. Characteristics of observed deterioration behavior under cyclic loading is shown in Fig.8. It is considered that the deterioration under

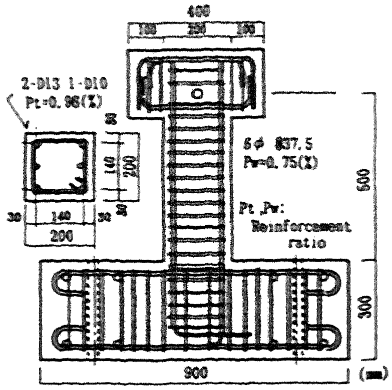

Fig. 1 Reinforcement details of specimen

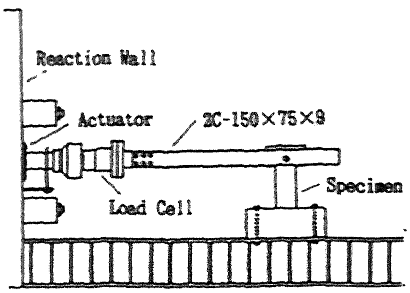

Fig. 2 Test set-up

Table-1 Material properties of reinforcement

Type	size	Yield strength (kgf/cm²)	Tensile strength (kgf/cm²)	Modulus of elasticity ($\times10^6$ kgf/cm²)
SD30	D13	4120	5800	2.13
	D10	4560	6090	2.09
SR24	6φ	4970	5200	2.09

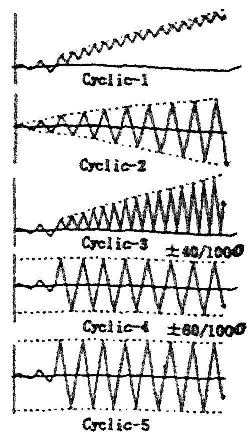

Fig. 3 Loading histories

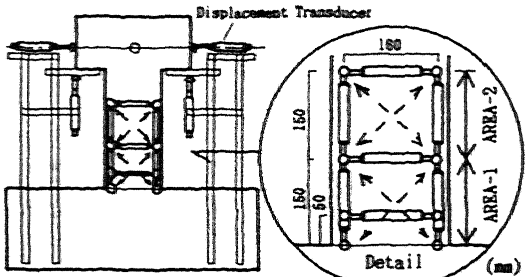

Fig. 4 Measuring arrangement

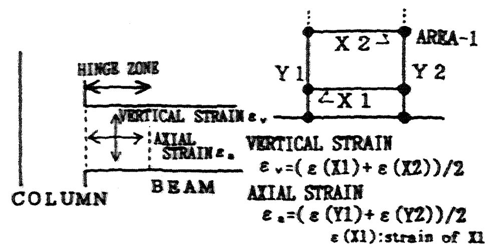

Fig. 5 Vertical and axial strain in hinge zone

cyclic loading is not caused by increasing load and deformation (A→F), but caused by cyclic loading(A→B→C→D→E). Unloading(A→B) →reversed loading(B→C)→unloading(C→D)→reloading(D→E), a series of the loading causes deterioration of strength. In case of cyclic-1 specimen, the deterioration of strength does not occur, even though it is subjected to cyclic loading(Fig. 6(b)). That shows reversed loading (B→C in Fig. 8) plays an important role in deterioration.

3.2 Strain Accumulation in Hinge Zone and Cyclic Failure

It seems difficult to estimate the beginning of the strength deterioration on the basis of maximum load and maximum deformation. Instead of these values, strain accumulation in hinge zone is investigated in order to clarify the cyclic failure mechanism. Axial and vertical strain in hinge zone is shown in Fig. 7. They are increasing as member absorbs energy. Monotonic loading and cyclic-1 (Fig. 7(a)) show a similar tendency. Vertical and axial strain increase linearly. And the rate of increase of vertical strain is very small compared with that of axial strain. Vertical strain on monotonic loading and cyclic-1 remains less than 1.5% at the deflection angle 140 and 180/1000rad respectively. On the other hand, the rate of increase on cyclic-2~5 is not constant (Fig. 7(b)~(d)). In case of vertical strain, the rate of increase gradually increases, as member absorbs energy. But in case of axial strain, the rate of increase gradually decreases contrastively.

Marks ○ and ● in Fig. 6 and 7 show the point that vertical strain exceeds 4% and 5% respectively. It is considered that marks ○ and ● agree with the beginning of strength deterioration(SEE Fig. 6(c)~(f)). The deterioration of strength occurs when vertical strain reaches 4~5%

Vertical strain on cyclic-1 remains less than 1.5% and deterioration of strength does not occur, though the axial strain reaches almost 9%. On the other hand, in case of cyclic-2~5, vertical strain is accumulated and deterioration of strength occurs when the vertical strain reaches 4~5%.

As described before, under monotonic loading the rate of increase of vertical strain is very small. According to the observed rate of increase, it is estimated that the vertical strain reaches 4~5% when the deflection angle exceeds 400~500/1000rad under monotonic loading. The deflection angle 400~500/

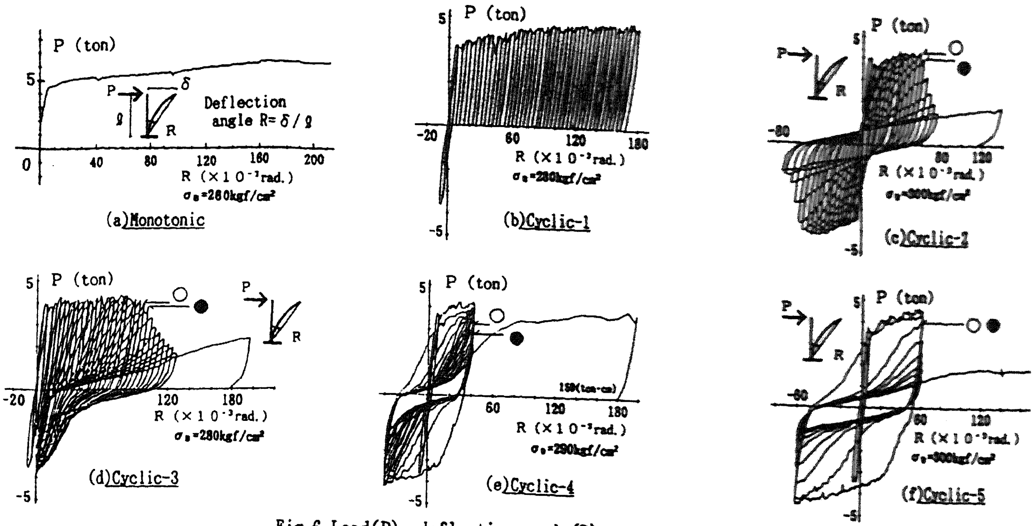

Fig.6 Load(P)- deflection angle(R) relationship

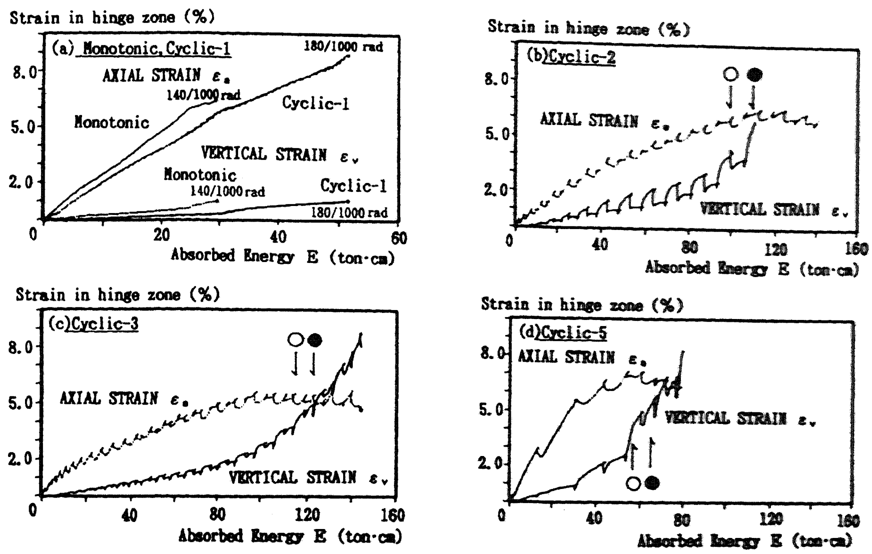

Fig.7 Vertical(ε_v) and axial strain(ε_a)- absorbed energy(E) relationship

1000rad is beyond the subject of ordinary investigation. And it is not altogether imaginable that before 400/1000~500/1000rad, strength deterioration is caused by something other factor. Based on the considerations, it can be considered that under monotonic loading, the rate of increase of vertical strain is so small that the strength deterioration is not caused by vertical strain accumulation.

3.3 Strain Accumulation Failure on Cyclic Loading

It is considered that vertical strain accumulation in hinge zone is closely connected with the cyclic failure mechanism. And it is estimated that the cyclic failure is caused by vertical strain accumulation. Vertical strain is accumulated under cyclic loading overwhelmingly. And that means this failure mode is peculiar to cyclic loading. On the basis of the considerations, a new failure mode peculiar to cyclic loading is defined as follows. Under cyclic loading, strain is accumulated in hinge zone as member absorbs energy. When the accumulated strain becomes large enough (when vertical strain exceeds 4~5%), the rapid cyclic failure occurs. We define such a failure as "strain accumulation

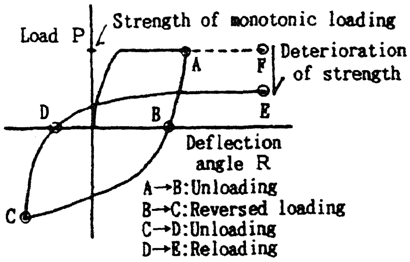

Fig.8 Characteristics of strength deterioration under cyclic loading

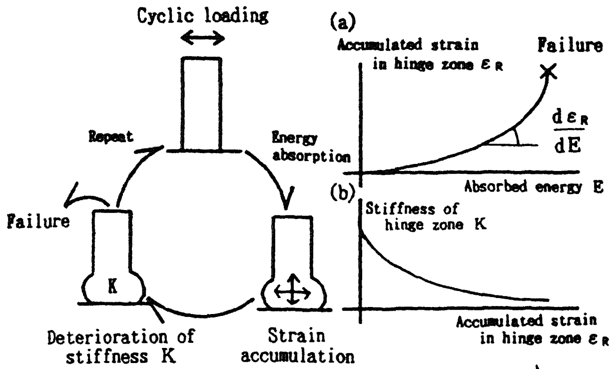

Fig.9 Strain accumulation failure on cyclic loading

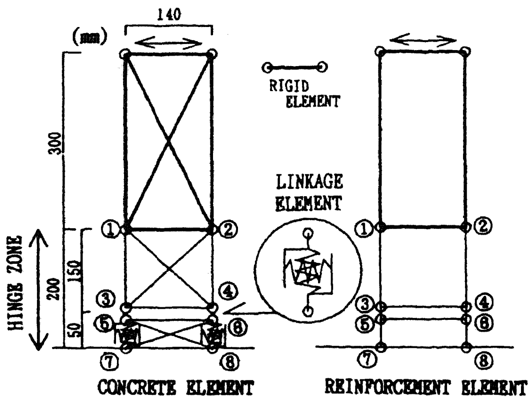

Fig.10 Analysis model

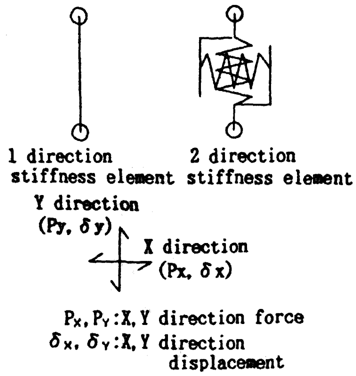

Fig.11 1 and 2 direction stiffness element

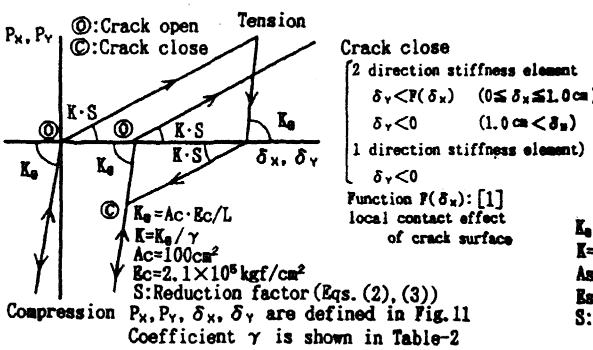

Fig.12 Restoring force characteristics for concrete and linkage element

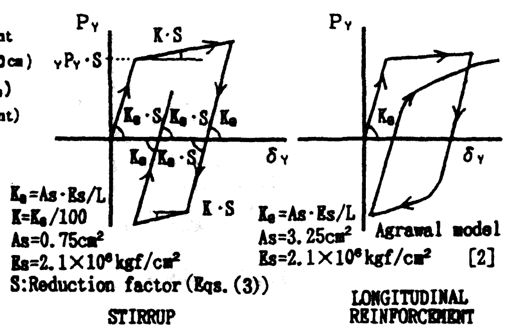

Fig.13 Restoring force characteristics for reinforcement element

Table-2 Assumed values for α, β, δ_{R1}, δ_{R2} and γ

		Y direction					X direction				
		α	β	δ_{R1}	δ_{R2}	γ	α	β	δ_{R1}	δ_{R2}	γ
Concrete	1 direction element	1.5	1.0	—	δ_Y	500	—	—	—	—	—
	2 direction element	1.5	1.0	δ_X	δ_Y	500	3.0	1.0	δ_X	δ_Y	50
Stirrup		1.5	2.0	Ⓐ	δ_Y	—	—	—	—	—	—
Linkage		1.5	1.0	δ_X	δ_Y	500	3.0	1.0	δ_X	δ_Y	50

Ⓐ : Axial displacement of hinge zone (the smaller of maximum displacement of ①⑦ section and maximum displacement of ②⑧ section)
δ_X, δ_Y are defined in Fig.11

failure" on cyclic loading. This failure mode is peculiar to cyclic loading and influenced by difference of cyclic loading histories, because vertical strain is accumulated under cyclic loading overwhelmingly and the accumulation behavior is influenced by difference of loading histories (see Fig.7).

4 SIMULATION OF STRAIN ACCUMULATION FAILURE ON CYCLIC LOADING

From the previous chapter, it is considered that strain accumulation in hinge zone causes rapid strength deterioration under cyclic loading. The purpose of this chapter is to simulate the failure process and clarify the mechanism of strain accumulation failure on cyclic loading.

4.1 Fundamental Assumption

The process of strain accumulation failure is shown in Fig.9.The failure process (cyclic loading→energy absorption of member→strain accumulation in hinge zone→deterioration of hinge zone) is repeated and the strain accumulation failure occurs. As the deterioration of hinge zone due to strain accumulation proceeds, velocity of strain accumulation ($d\varepsilon_R/dE$) gradually increases(see Fig.9(a)). Finally the velocity becomes very large, and pretty large deterioration of strength occurs. In order to simulate the failure process, it is necessary to model the deterioration behavior of hinge zone due to strain accumulation(see Fig.9(b)). For this purpose, it is assumed that element stiffness K in hinge zone decreases monotonously as displacement accumulated in the element increases. Element stiffness K is modeled to be a function of accumulated displacement δ_R and decreases exponentially as follows.

$$K=\overline{K}\cdot S \tag{1}$$

$$S=EXP(-\alpha\,\delta_R{}^{\beta}) \tag{2}$$

where K:element stiffness, $\overline{K}$:stiffness K when $\delta_R=0$, S:reduction factor due to strain accumulation, δ_R :Accumulated displacement in the element, α and β:constant values.

If accumulated displacement in a element is represented by two variables δ_{R1}, δ_{R2}, reduction factor S is described as follows

$$S=EXP\left[-\alpha\sqrt{\{(\delta_{R1}{}^{\beta})^2+(\delta_{R2}{}^{\beta})^2\}}\,\right] \tag{3}$$

4.2 Outline of Modeling

Analysis model is shown in Fig.10. Hinge zone is modeled by concrete, reinforcement and linkage element. And other portion except hinge zone is assumed to be rigid. Concrete and reinforcement is modeled by line element. Two kinds of elements are assumed, one is 1 direction and the other is 2 direction stiffness element (Fig.11). Hinge zone is divided into two portions. And upper and lower part is jointed with linkage elements. Linkage element represents the dowel action of longitudinal reinforcement between two portions. Linkage element has no physical dimension and has two direction stiffness. Restoring force characteristics assumed for concrete, linkage and reinforcement element is shown in Fig.12 and 13. Element stiffness K is multiplied by reduction factor S(Eqs.(2),(3)) except longitudinal reinforcement. Parameter α、β and accumulated displacement δ_{R1}, δ_{R2} which is used to calculate S is shown in Table-2. Parameter α、β were assumed by parametric studies.Tension strength of concrete and linkage element is assumed to be zero for simplicity of calculation except ①③ and ②④ concrete element(Fig.10), because the subject of the simulation is behavior on large deformation range.

4.3 Results of simulation

Simulation results of load(P)−deflection angle(R) relationship is shown in Fig.14. Vertical(εv) and axial strain(εa) in hinge zone-absorbed energy(E) relationship is shown in Fig.15. Vertical strain is the larger of strain of ③④ section and strain of ⑤⑥ section(Fig.10). Marks ○ and ● in Fig.14,15 show the point that vertical strain(εv) exceeds 4% and 5% respectively. Compared with the experimental results (Fig.6,7),it is considered that the characteristics of strain accumulation failure can be explained well by the simulation. Axial and vertical strain is accumulated in hinge zone as member absorbs energy. In case of cyclic-2~5,rapid deterioration of strength occurs. And marks ○ and ● corresponds to the beginning of the strength deterioration. On the other hand, monotonic loading and cyclic-1 don't deteriorate strength and vertical strain is kept very small,though axial strain reaches almost 9%.

It is simulated that accumulation of vertical strain causes deterioration of confinement in hinge zone and that induces more accumulation of vertical strain. Repeating the failure process, the rapid deterioration of strength occurs. It is considered that the behavior of strain accumulation and deterioration of confinement due to the strain accumulation play an important role for strain accumulation failure.

5 CONCLUSIONS

Shear bending cyclic tests of cantilever RC beams were carried out. And a few considerations were obtained.

1. Specimen subjected to cyclic loading has a limit from where pretty large deterioration occurs, even though it has more deformation capacity under monotonic loading.

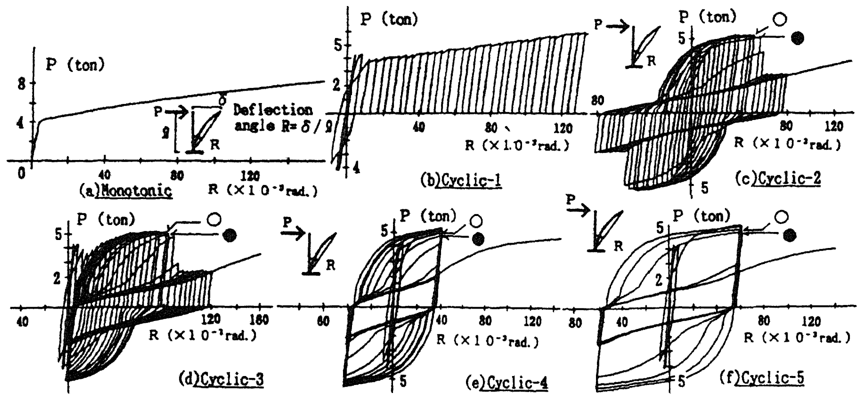

Fig.14 Simulation results of load(P)- deflection angle(R) relationship

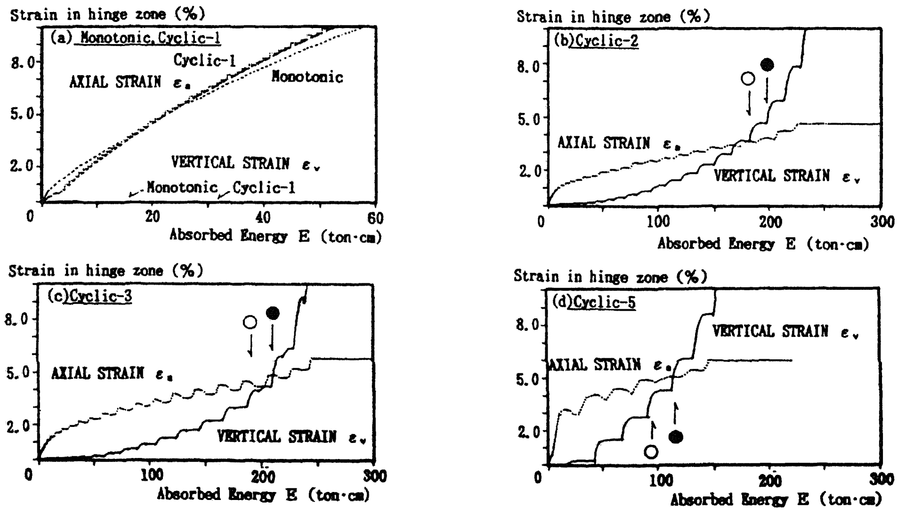

Fig.15 Simulation results of Vertical(ε_v) and axial strain(ε_a)- absorbed energy(E) relationship

2. Axial and vertical strain in hinge zone is accumulated and increase as member absorbs energy under cyclic loading. When vertical strain exceeds 4~5%, the pretty large deterioration of strength occurs.

On the basis of these considerations, a new failure mode peculiar to cyclic loading is proposed as follows. Under cyclic loading, strain is accumulated in hinge zone as member absorbs energy. When the accumulated strain becomes large enough (when vertical strain exceeds 4~5%), the rapid cyclic failure occurs. We define such a failure as "strain accumulation failure" on cyclic loading. This failure mode is peculiar to cyclic loading and influenced by difference of cyclic loading histories, because vertical strain is accumulated under cyclic loading overwhelmingly and the accumulation behavior is influenced by difference of loading histories

Strain accumulation failure is simulated on the basis of the assumption that the stiffness of hinge zone decreases monotonously as accumulated strain in hinge zone increases. It is considered that the characteristics of failure process can be explained well by the simulation. And it is confirmed that vertical strain is accumulated in hinge zone under cyclic loading and that causes rapid deterioration of strength.

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