INELASTIC SEISMIC PERFORMANCE OF RC TALL PIERS WITH HOLLOW SECTION

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SUMMARY

The flexural and shear behaviors of rectangular hollow reinforced concrete columns under earthquakes were investigated. Since it is difficult to confine the web parts of hollow sections effectively and the thinner web causes the deterioration of concrete shear resistance, the behavior in the ultimate state becomes complicated. In this study, seven hollow columns were subjected to constant axial load and cyclic horizontal displacements. In these tests, it was observed that even in the specimen of flexural failure the flexural cracks in the flange part changed into shear diagonal cracks once they progressed in the web part. This result shows that the influence of shear deformation cannot be neglected in hollow reinforced concrete piers. Then to assess the seismic performance, the pseudo dynamic test was carried out. Although the hysteresis response was stable and the pier can dissipate energy under the earthquake, the behavior might become complicated by random loading process. Therefore it is necessary to establish the rational design method taking into account the deterioration of flexural and shear resistance due to the loading process of earthquakes.

INTRODUCTION

When designing a reinforced concrete tall pier, a hollow section is often adopted to reduce the weight and hence to reduce the seismic force which acts on the pier. Since the confinement of hollow sections is difficult, some researchers investigated behavior of hollow reinforced concrete piers.

Mander [Mander 1984] has investigated the flexural strength and ductility available from rectangular and circular hollow RC columns. Such columns, when properly detailed, were shown to perform in a ductile manner during cyclic lateral loading in the inelastic range. Of course, the important detail of RC hollow piers is the confinement of web parts. Yukawa et al. [Yukawa 1999] investigated the arrangement of special reinforcement tied though the wall thickness. And they also confirmed the stable inelastic behavior with proper arrangement under cyclic loading. These researches investigated the flexural behavior of RC hollow piers, but Inoue et al. [Inoue 1996] focused on the deterioration of concrete shear resistance of hollow beams. They concluded that the reduction in concrete shear resistance should be considered in the design of RC members subjected to earthquake loads, especially in the case of hollow section members.

A great deal of effort has been made on the research of hollow RC piers. What seems to be lacking, however, is the behavior under earthquakes. That is, almost all test methods were static cyclic loading test. Certainly this test method seems to simulate the damage process due to earthquakes. But the real earthquake produces more complicated loading history. Therefore in this paper, we carried out two kinds of tests. One is the static cyclic loading test, in which the damaging process and the deterioration of resistance were focused. The other is the pseudo dynamic test. From the results of these tests, the seismic performance of hollow reinforced concrete piers was investigated.

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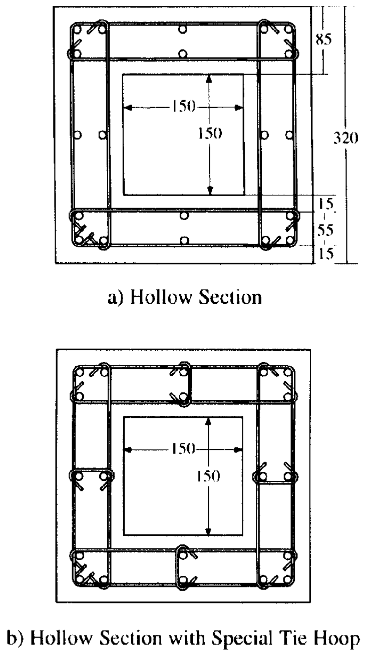

Fig. 1: Sections of Specimen

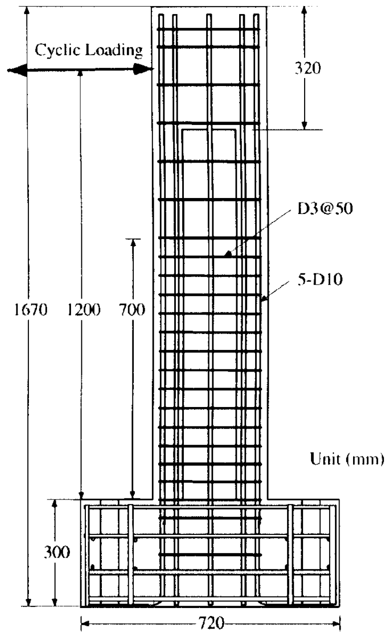

Fig. 2: RC Hollow Pier Specimen

Table 1: Parameter of Specimens

Column Unit	l/d	Axial Load (MPa)	Stirrup Ratio ρ	Special Tie
H4-1	4.0	0.0	0.34	w/o
H4-2	4.0	3.7	0.17	w/o
H4-3	4.0	3.7	0.17	w
H4-4	4.0	3.7	0.34	w/o
H4-5	4.0	3.7	0.34	w
H2-1	2.0	3.7	0.17	w/o
H2-2	2.0	3.7	0.34	w

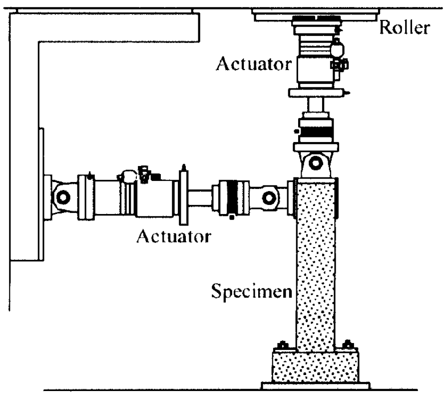

Fig. 3: Loading System

STATIC CYCLIC LOADING TESTS

Column Units

All columns had the same section dimensions, 320 mm square cross section with 85 mm thick walls (Fig. 1). Seven rectangular hollow reinforced concrete columns were constructed and tested under axial compression and cyclic flexure. The parameters varied were (a) the shear span ratio *l/d*; (b) the axial load; (c) the stirrup ratio ρ; and (d) the usage of special tie (Table 1).

Fig. 2 shows the principal dimensions and loading arrangements of the column units. This specimen had a height of 1200 mm (*l/d* = 4.0) and a spacing of 50mm as web reinforcement. And in order to assess the influence of the hollow section on the shear resistant behavior clearly, specimens with *l/d* = 2.0 were constructed too.

The longitudinal reinforcement consisted of sixteen 10 mm diameter deformed bars (SD295). The transverse hoop steel was 3 mm diameter deformed bars (SD345). Design compressive strength of concrete was 34 MPa.

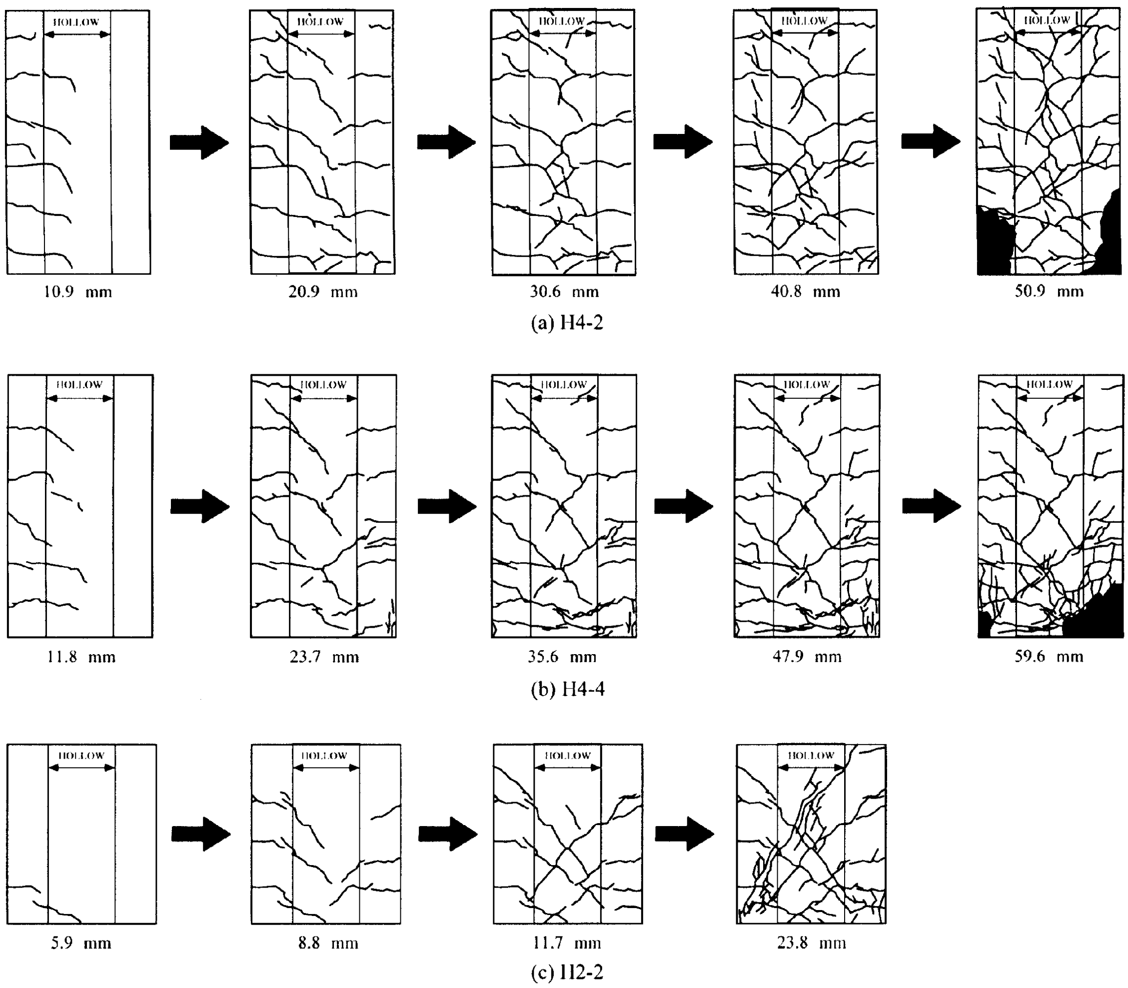

Fig. 4: Cracking Process

2.2 Instrumentation and Test Procedure

The test set up is illustrated in Fig. 3. Two digitally controlled actuators were used, the vertical one applied the axial load and the other one imposed the horizontal displacements. At the bottom, a set of two potentiometers was used to measure the curvature, and three potentiometers were used to measure the deflection of columns.

The horizontal load was applied at a quasi-static rate in displacement-controlled cycles to the rotation angle R = ±0.01, ±0.02, etc., until failure of the column occurred, where R = l/Δ; l = shear span; and Δ = actuator's displacement.

Crack Pattern and Failure Mode

Fig. 4 shows the damage process of each specimen in the loadings. Unit H4-2 and H4-4 finally failed in flexure at the bottom. After the maximum state, the buckling of reinforcement and spalling the concrete were observed, and the restoring force decreased rapidly. Focusing on the crack patterns, the flexural cracks were dominant, but the diagonal cracks were observed in the web part even in the well transverse-reinforced H4-4. In case of Unit H2-2, the diagonal cracks were observed in the web part at an early stage of loading. Finally these columns failed in shear by about 60-degree diagonal cracks.

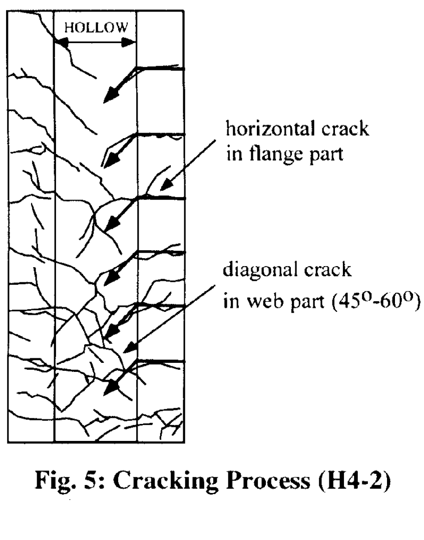

Fig. 5: Cracking Process (H4-2)

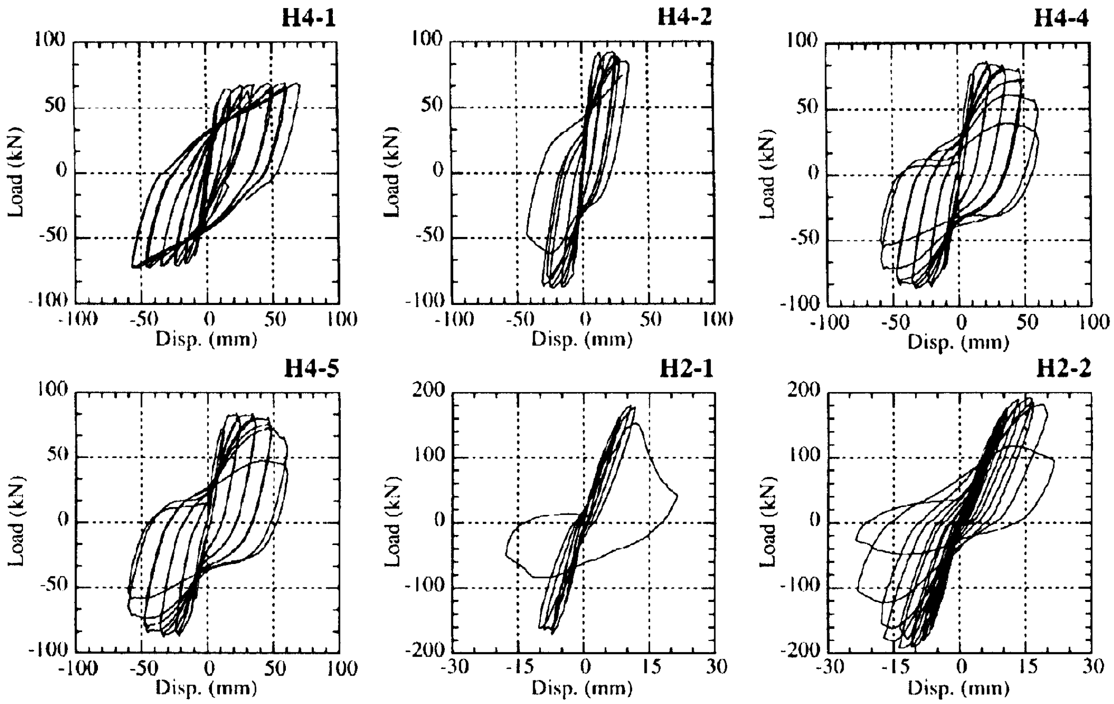

Fig. 6: Load-Displacement Hysteresis Loops

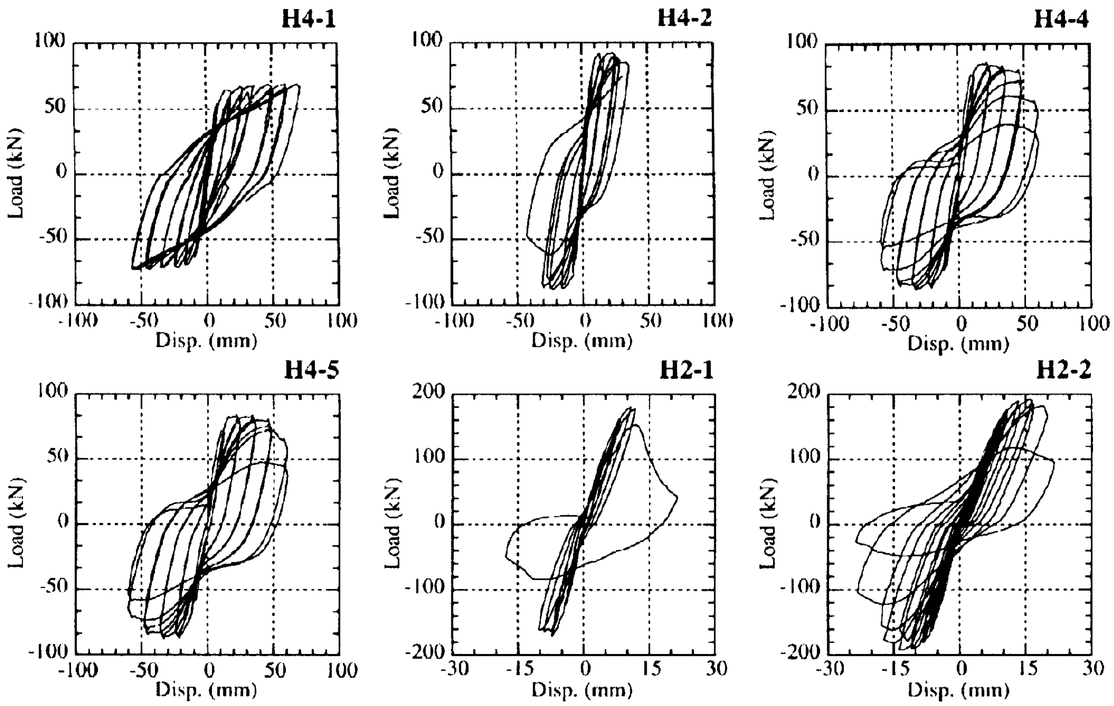

Fig. 6: Load-Displacement Hysteresis Loops

The characteristics of the hollow reinforced concrete columns are shown in crack pattern well. That is, the flexural cracks in the flange part changed into the diagonal cracks drastically when they progressed into the web part (Fig. 5). These diagonal cracks intersected under the cyclic loading, and the cracks of vertical direction generated in the center of the sections. This phenomenon was observed even in case of specimens of flexural failure type. These facts indicate that the influence of shear cannot be neglected in hollow piers and it is necessary to examine sufficiently about the shear behavior under cyclic loadings.

Load – Displacement Hysteresis Loops and Ductility

Fig. 6 shows the hysteresis loops for horizontal load versus horizontal displacement at the loading point. In this study, the ultimate displacement is defined as the displacement at the 80 percent of the maximum restoring force.

Unit H4-1, under no axial load, showed very large ductility compared with the others. Generally, it is well known that deformation performance around the ultimate state is deteriorated when the axial load applies. Since the concrete area to bear the axial load is small in the hollow section, the pier loses the restoring force rapidly once the concrete begins spalling. From this result, it is found that the level of axial load is one of the important design parameters for hollow reinforced concrete piers. While Unit H4-2 had a small ductility, Unit H4-4, 5, which spacing of stirrup was short, exhibited a large ductility. Also, as for H4-5 with special ties, the restoring force after the maximum state decreases more gradually than that of H4-4. The reason is that special ties improved the confinement of concrete. On the other hand, H4-2, 3 also had almost the same performance of H4-4, but when the decrease of the restoring force began, the loading capacity was lost. And in this case, the effect of the special ties wasn't observed, because the main failure mode was the buckling of reinforcements.

In the case of H2 series, in spite of the amount of transverse reinforcement, soon after the yielding of reinforcements, the rapid decrease of restoring force occurred.

As the overall tendency, restoring force is rapidly decreased after the maximum state. The main reasons are the spalling of concrete occurred not only outside but also into the void and the buckling of reinforcements.

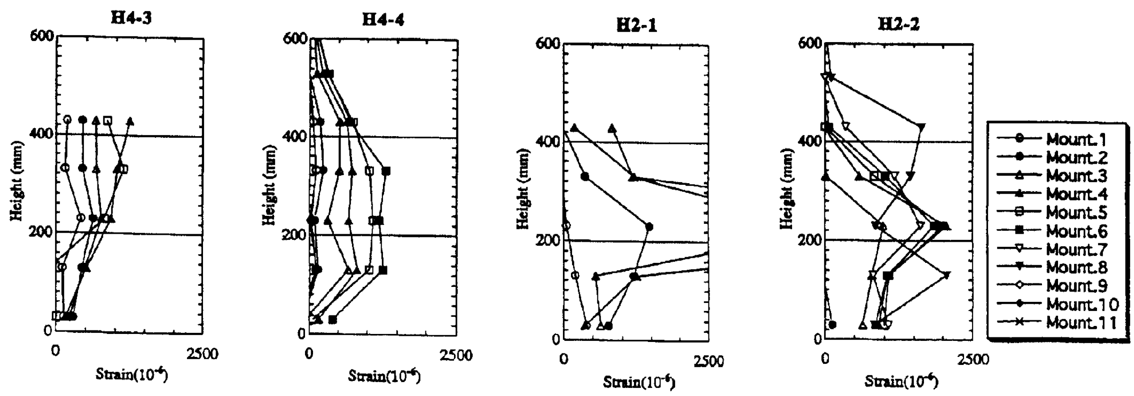

Fig. 7: Strain of Stirrups

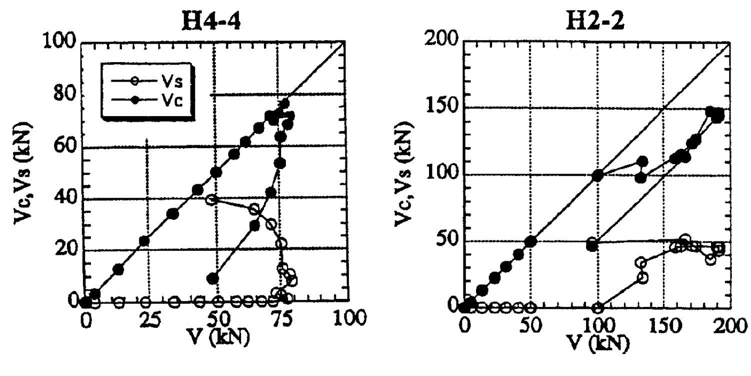

Fig. 8: Shear Force of Concrete and Stirrup

Strain of Stirrup

The strains of stirrups at each peak of input waves are shown in Fig. 7. Whereas the strains of H4 series gradually increased, in H2 series the strains became quite large from the early stage of the loading. This result also shows that the shear deformation was large in the H2 series. Also, the peak of strain about height 25 cm is recognized. This height was just the same of the intersection of the diagonal cracks, and the width of cracks became large during the cyclic loading. It is possible to assume that this fact shows deformation performance degradation by cyclic loading from the viewpoint of the stirrup strain, too.

Although H4-3 failed in flexure, the buckling of longitudinal bars between the stirrups was observed. Therefore in this case, the stirrups couldn't exhibit the performance effectively.

Shear Capacity of RC Hollow Piers

In the present JSCE Standard Specification for Design and Construction of Concrete Structures (JSCE Code) [JSCE 1996], the design shear capacity of RC members (Vyd) is defined as the summation of the design shear capacity of concrete without shear reinforcement (Vcd) and the design shear capacity carried by transverse reinforcement (Vsd). Also, after the crack occurrence, Vcd is constant and the increment of shear force is resisted by the transverse reinforcements. Fig. 8 shows the sharing ratio of the concrete contribution (Vc) and the stirrup contribution (Vs) to the applied shear force (V), in which the measured Vc is simply calculated by subtracting Vs estimated based on the stirrup strain from the applied shear force. The design shear capacity of these piers is 102 kN (Vc = 56.1 kN, Vs = 45.9 kN).

As for H4-4, the shear force of experiment was less than the shear capacity, but this is because this specimen failed in flexure. On the other hand, the shear force of H2-2 is larger than the design capacity. But around the ultimate state, the resistant load decreased rapidly and finally became smaller than the design load. This phenomenon is remarkable in case of cyclic loading state. Therefore it is necessary to establish the rational shear design method considering the deterioration of concrete shear resistance due to cyclic loading, especially earthquake loading.

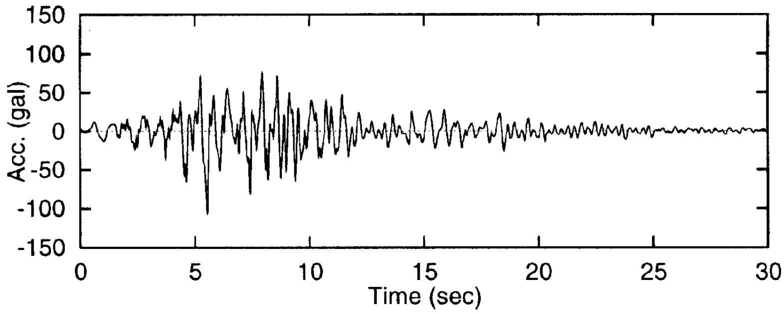

Fig. 9: Input Earthquake Motion for Hybrid Experiment

HYBRID EARTHQUAKE LOADING TESTS

Outline

The reversed cyclic loading tests are said to simulate a loading history due to earthquakes. However as mentioned in the previous section, the behavior of hollow reinforced concrete piers is complicated because of the interaction between flexure and shear, and the reversed cyclic loads. Therefore to investigate the real seismic behavior of hollow reinforced concrete piers, it is necessary to carry out the hybrid earthquake loading test.

The hybrid earthquake loading test is the computer controlled experimental technique in which the direct step-by-step time integration is used to solve the equation of motion.

In this test, the specimen which span length of 1200 mm (*l/d* = 4.0) and the spacing of stirrup of 50 mm was used. This specimen was designed as the tall pier which natural period is 2.0 sec. The experimental parameters were decided using the static experiment result. The damping coefficient of the numerical analysis part was set for 0.01.

Input Earthquake Motion

As the input earthquake motion, the Kobe JMA record (NS direction) was selected. Since this record has the peak power in the high frequency range, the tall pier that has the long natural period wouldn't response large. But in this study we assume the situation under inland direct strike earthquakes, this record which is Type II earthquake is adopted.

To evaluate the seismic performance well, the input motion was adjusted to 13 % amplitude of the original wave by which the specimen would respond up to the ultimate state (Fig. 9).

Experimental and Numerical Results

In Fig. 10, the load - displacement hysteresis responses, the acceleration and displacement time histories are shown. And results of nonlinear dynamic analysis of 1 d.o.f model with Takeda model are also shown in Fig. 10.

From the experiment, this pier exhibited the stable response although it had experienced the ultimate state. And also it is found that the analytical results agree with the experiment in the amplitude and the vibration period until the maximum state. But after that, they show a rather different tendency. It is important to investigate the reason why the difference occurs. Let us consider the reason from the hysteresis response's point of view. In the hysteresis loop of the experiment, the restoring force in the negative displacement side was smaller than that in the positive side. On the other hand, analytical hysteresis model is symmetric. This unbalance restoring force was induced by the proper loading history of the input earthquake. In the early stage of the response, the specimen responded large up to the ultimate state, and the damage concentrated to the one side. Therefore when the deflection reversal occurred, the performance deteriorated rapidly. This is the reason why the hysteresis loop was unbalance and the numerical results doesn't agree with the experimental results. Takemura et al. [Takemura 1997] suggests that the loading history has the influence of the deformation performance of RC structures. This

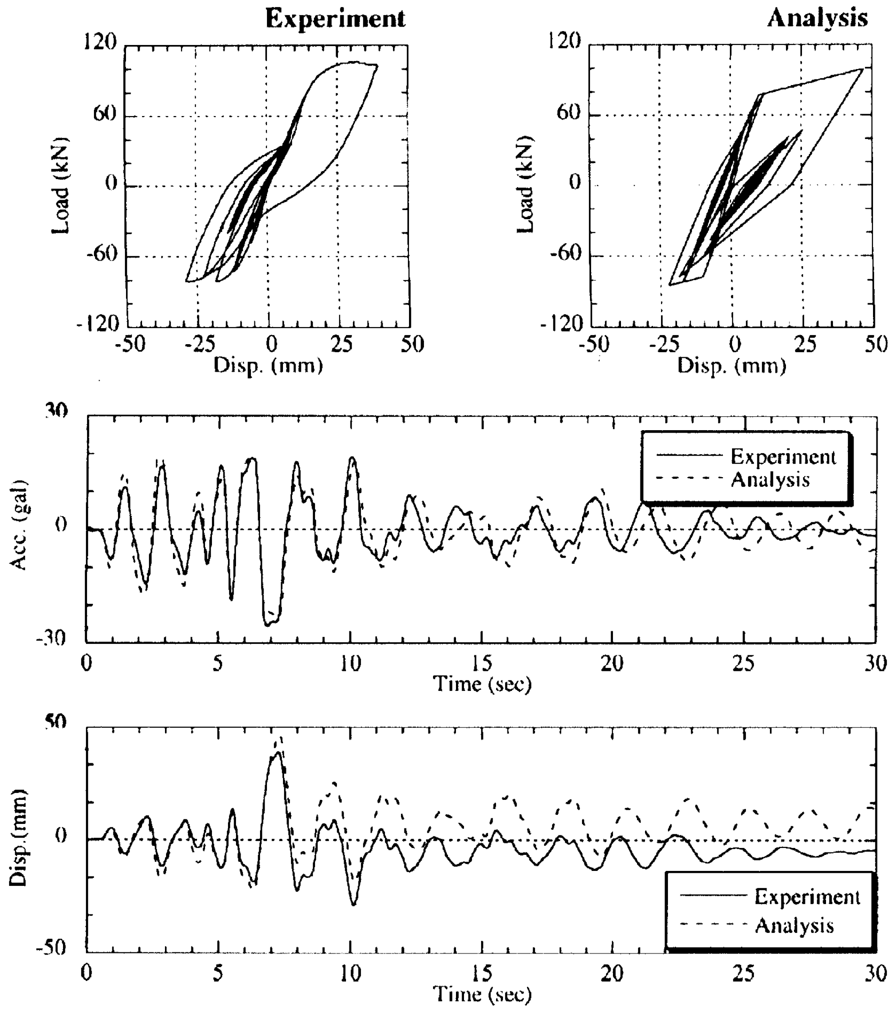

Fig. 10: Results of Hybrid Earthquake Loading Test

result also supports the fact. However, in this case, this specimen exhibited the stable response although it had responded up to the ultimate state.

Crack pattern after the experiment is shown in Fig. 11. In this figure, it is found that the flexural crack didn't turn into the shear cracks even when they progressed into the web part, likely cyclic loading test results. This phenomenon is also related closely to the loading history. That is, in cyclic loading tests, the damage is accumulating gradually in the web part, and because of the deterioration of stiffness the influence of shear becomes larger. On the other hand, when large deformation would occur in the early stage of responses, the cracks are developing as the usual flexural cracks because the web part is still undamaged.

Comparing the results of the cyclic loading and hybrid loading tests, not only the hysteresis skeleton curve but also the crack pattern of the cyclic loading tests are different to that of the hybrid loading test. From this result, in order to assess the seismic performance of RC structures, especially with hollow section, it is necessary to examine them in case that the large power is inputted in the early states, like Type II earthquakes.

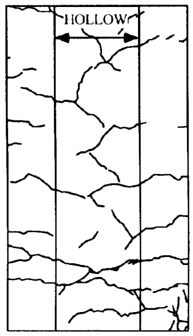

Fig. 11: Crack Pattern

CONCLUSIONS

In order to clarify the behavior of RC hollow piers under the combination of loads and earthquake loads, the static loading tests and hybrid loading tests were carried out. From this study the following results are listed:

(a) Even in case of flexural failure, in the web part, shear cracks appeared under small loads. And flexural cracks in the flange part changed into diagonal cracks when they progressed into the web part. Furthermore, because of spalling concrete into the hollow side, the restoring capability after the maximum state deteriorated rapidly. Therefore it is necessary to confine concrete by the appropriate transverse arrangement.

(b) From the static cyclic loading tests, in almost case, the JSCE code shows reasonable shear capacity. But the reduction in concrete shear resistance should be considered under the cyclic loading. Therefore it is essential to establish a rational shear design method which takes into account the shear resistant mechanism under the reversed cyclic loads.

(c) From the hybrid earthquake loading tests, it was observed that the hysteresis response was stable and it can dissipate input energy by the hysteretic action. The RC hollow piers were found to have a good performance under earthquake motions.

(d) When inputting the Kobe JMA record, the pier responded up to the ultimate state in the early stages of loading. As the result, the restoring forces in the positive and negative displacement side were different. Furthermore not only the resistant forces but also the crack pattern of hybrid loading tests were different to that of cyclic loading tests. These results suggest that the loading history has a great influence of the failure process of RC structures, and the new experimental method have to be developed to assess the effect of the loading history due to earthquakes.

(e) In this study, we found that the shear behavior of RC hollow piers is not neglected. Therefore the analysis which takes only account for the flexural deformation has the limitation for investigating the behavior. It is important to develop the analytical method which take into account the interaction between flexure and shear, and the cyclic loading.

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