EARTHQUAKE RESPONSE OF AN ELEVEN-STORY PRECAST PRESTRESSED CONCRETE BUILDING BY SUBSTRUCTURE PSEUDO DYNAMIC TEST

Hiroto KATO[1], Yuuhiko ICHISAWA[2], Kei TAKAMATSU[3] And Naoto OKAMOTO[4]

SUMMARY

This paper presents the results and discussions of experimental study on precast prestressed concrete (PC) frame specimen. The specimen is a scaled model and lower three stories of a prototype PC building, which is eleven-story and 45m height moment resisting frame structure and composed of all precast structural members. A series of loading tests has been executed, which are static loading tests and substructure pseudo dynamic (PSD) tests to the specimen. Though the actual loading part is lower three story of the building, every loading test has been carried out as the eleven-story building taking account of effects of upper computed stories. In Japan, many middle and low-rise PC buildings have been constructing and shows generally good seismic performance to sever earthquake motions from former damaged earthquake surveys. On the other hand, some subjects awaiting solution have been remained for realizing high-rise PC building construction. The objectives of the study are to grasp the earthquake response behavior of the specimen and evaluate the basic structural performance of it.

The specimen shows good load carrying capacity even in large deformation region and high restoring characteristics, which is particular one of PC structure. The maximum base shear coefficient is approximately 0.4, it satisfies the assumed tentative design criteria what is more than 0.33 at 1/50 of story drift angle. The dynamic responses obtained from substructure PSD tests are dominated with the elastic first mode of the specimen. And the post dynamic analyses show good coincidence with the experimental results, the employed restoring characteristics model can adequately reproduce the dynamic behavior of specimen.

In the result, it is evident that the specimen has enough seismic performance and the adopted design procedure is reasonable. And the substructure PSD test method is useful and valid for investigating seismic behavior of building structure.

INTRODUCTION

The prestressed concrete (PC) structure has been used for middle and low-rise building whose height is less than 31m in Japan, which the regulation is prescribed by the current Building Standard Law Enforcement Regulation. It is generally evident from former damaged earthquake surveys that PC buildings have good earthquake proof property. On the other hand, few investigations on seismic performance and design procedures of high-rise PC building of which height is over 31m has been reported. This paper presents the results of experimental study, that are static loading test and the substructure pseudo dynamic (PSD) test, on seismic performance of an eleven-story precast PC building. The major objectives of the study are to observe the seismic response of the specimen in sever earthquake motion, grasp the restoring characteristics of it and look at the failure mode in several deformation regions.

[1] *Building Research Institute, Ministry of Construction, Tsukuba, JAPAN, Email: pckato@kenken.go.jp*
[2] *P.S. Corporation, Tokyo, JAPAN, Email: ichisawa@psgate.psc.co.jp*
[3] *Itho-Gumi Construction Co., Ltd., Sapporo, JAPAN, Fax: +81-11-241-7515*
[4] *Ohmoto-Gumi Co., Ltd., Tokyo, JAPAN, Fax: +81-3-3593-1543*

PROTOTYPE BUILDING AND SPECIMEN

Design Of Prototype Building

An eleven-story PC office building of which height was 45m had been designed for a prototype of specimen. The building was moment resisting frame structure with two continuous 15m span bays in X-direction and several 7.5m span bays in Y-direction as shown in Fig.1. Height is 5.0m in 1st story and 4.0m in other story. The size of 1st story column is 1000 x 1000mm and the beam is 400 x 1200mm in mid-span. The building was composed of all precast structural members; in short precast PC beams were fastened to precast PC columns with PC tendons. The seismic design had been carried out tentatively conforming to the PRESSS design guideline [Nakata, 1994]. The main feature of that design procedure is to verify the assumed design criteria by non-linear frame analyses. The employed tentative design criteria are listed in Table 1. Assumed possible yield hinge positions were the bottom of 1st story column and the beam-ends at each story. In non-linear frame analysis, the building was substituted in a planer frame composed of linear members with elasto-plastic spring at the end of it and the seismic design load distribution were determined by the current seismic design regulation, called *Ai*-distribution.

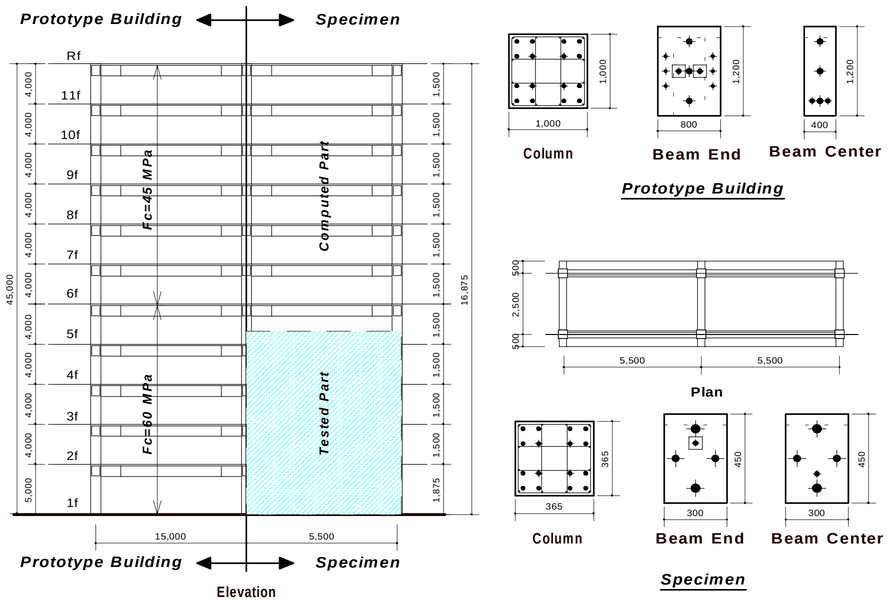
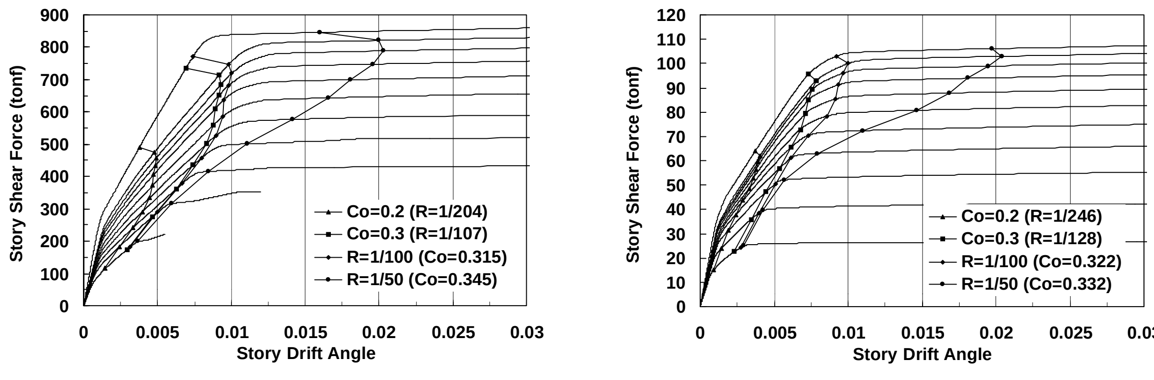


Fig.1 Prototype Building and Specimen

The results of analysis are shown in Fig. 2(a) and Table 1. The maximum story drift angle R_{max} was 1/204 at *Co*=0.2, and R_{max} =1/107 at *Co*=0.3 and no yield hinge occurred in beams and columns. Here, *Co* is the standard base shear coefficient. On the other hand the *Co* was 0.345 at R_{max} =1/50, it means satisfying the assumed design criteria. At the moment yield hinges occurred at beam-ends from 1st to 9th story and bottom of 1st story column, that hinge mechanism was in accord with the assumed one. The fundamental natural period of the prototype building was 1.09sec.



(a) Prototype Building (One frame) **(b) Specimen (One frame)**

Fig.2 Results of Non-linear Frame Analyses

<table>
<tr><th colspan="3">Tentative Design Criteria</th><th colspan="5">Results of Non-linear Frame Analyses</th></tr>
<tr><th rowspan="2">Standard Base Shear Coefficient, Co</th><th rowspan="2">Max. Story Drift Angle, R_{max}</th><th rowspan="2">Ductility Factor of Member, μ</th><th rowspan="2"></th><th rowspan="2">Co</th><th rowspan="2">R_{max}</th><th colspan="2">Ductility Factor μ</th></tr>
<tr><th>Beam</th><th>Column</th></tr>
<tr><td rowspan="2">when 0.2</td><td rowspan="2">less than 1/200</td><td rowspan="4">less than 1.0</td><td>Prototype</td><td rowspan="4"></td><td>1/204</td><td colspan="2" rowspan="3">less than 1.0</td></tr>
<tr><td>Specimen</td><td>1/246</td></tr>
<tr><td rowspan="2">when 0.3</td><td rowspan="2">less than 1/100</td><td>Prototype</td><td>1/107</td></tr>
<tr><td>Specimen</td><td>1/128</td><td>1.1</td><td></td></tr>
<tr><td rowspan="2">More than 0.33</td><td rowspan="2">When 1/50</td><td rowspan="2">less than 2.0</td><td>Prototype</td><td>0.345</td><td rowspan="2">when 1/50</td><td>2.4</td><td>2.3</td></tr>
<tr><td>Specimen</td><td>0.332</td><td>3.1</td><td>2.8</td></tr>
</table>

Design Of Specimen

The specimen is a 1/2.74-scaled model of the prototype building and lower three stories of it had been constructed. The specimen has two frames with continuous 5.5m span bays in X-direction and two transverse frames with 2.5m span bay and 0.5m cantilever beam in Y-direction. Area of each story is about 40m^2. Total height of the specimen is 5.4m and height of 1st story is 1.875m and 1.5m in 2nd and 3rd story. The column of 3rd story were extended until mid height of 4th story in order to receive large lateral shear force, which comes from computed part from 4th to 11th stories. All of loading tests had been executed as the eleven-story building. The outline of PC tendon arrangement of the specimen is illustrated in Fig. 3. All structural members which were fabricated in factory had been framed and connected with PC tendons interposing 20mm thick mortal joint in the laboratory, then slab concrete were cast on each floor. The design compressive strength of precast concrete members was 60N/mm^2 and one of slab concrete was 30 N/mm^2.

The results of non-linear frame analysis of the specimen are shown in Fig. 2(b) and Table 1 comparing with ones of the prototype. Those two analyses show good coincidence, it means that the specimen was designed adequately. The fundamental natural period of the specimen was 0.64 sec.

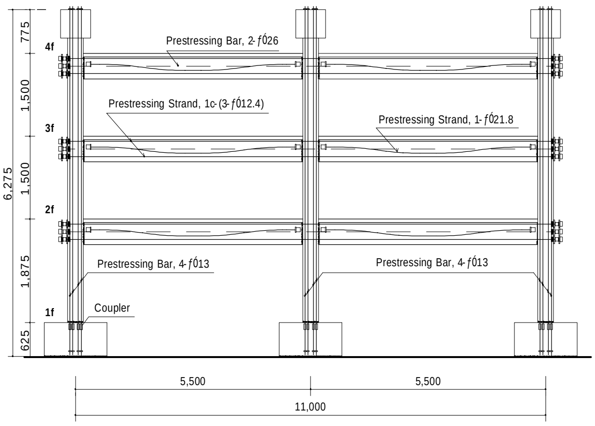


Fig. 3 PC Tendon Arrengement of The Specimen

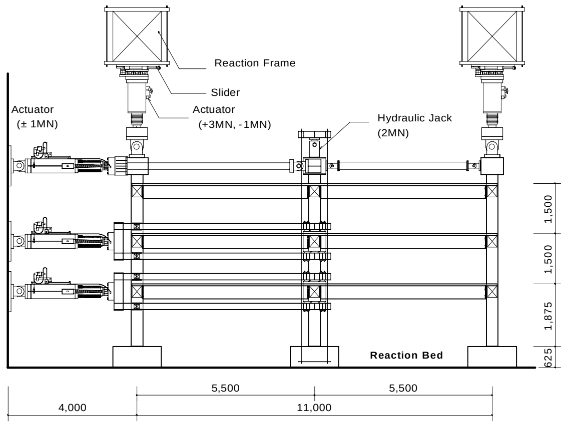


Fig. 4 Overview of Test Set-up

TEST SETUP

The four horizontal actuators were installed at 2nd and 3rd floor and top of columns in roof floor, respectively. The other four actuators on head of outer columns applied varied vertical load and two hydraulic jacks on head of inner columns applied constant vertical load. In addition, some weights on PC beams reproduced the design live load. The overview of test set-up is shown in Fig. 4. At the beginning of a series of the test, static cyclic loading test (*Static-1*) were carried out until the base shear force reached the value equivalent to *Co*=0.3, in order to grasp the basic structural property of the specimen that are stiffness, restoring force and crack pattern, etc. The horizontal load distribution pattern was determined with SRSS method using the eigenvalue of specimen.

The shear force at 4th story and horizontal load at 3rd story were loaded on the top of the column at roof floor. Constant vertical load on inner column was 150tonf. On outer column, constant load was 86tonf and furthermore varied axial load applied, which was controlled to reproduce the relationship of axial load and moment of 1st story column in the pre-analysis.

After that a series of substructure PSD test were executed. The basic concept of substructure PSD test is illustrated in Fig. 5. The substructure PSD test is one of earthquake response test combining actual loading test on a portion of specimen and computer simulation on the remaining part, and its efficiency have been reported by Dr. Nakashima, et al [Nakashima, 1990], [Tsutsumi, 1990]. The applied restoring characteristics model for computed part from 4th to 11th story were the "*PC-model*" proposed by Dr. Okamoto, et. al [Okamoto, 1992], which can express the particular behavior of PC structures. The integration method of PSD test was *Operator-Splitting* method, and time interval was 0.006sec in accordance with scale effect. The stiffness proportional damping with 3% to fundamental natural period was used. The input accelerations were *Hachinohe EW*(1968) with 25(*Level-1*), 50(*Level-2*) and 75cm/sec (*Level-3*) as normalized maximum velocity and *JMA-Kobe* which were recorded in Japan Meteorological Agency Kobe Observatory at Hyogoken-nanbu earthquake(1995), which maximum acceleration was 820cm/sec^2. In substructure PSD test, above four accelerations were intermittently given such as continuous one wave in order to reflect the suffered damage of specimen in previous loading to next test. At the end, static cyclic loading test was executed again in large deformation region.

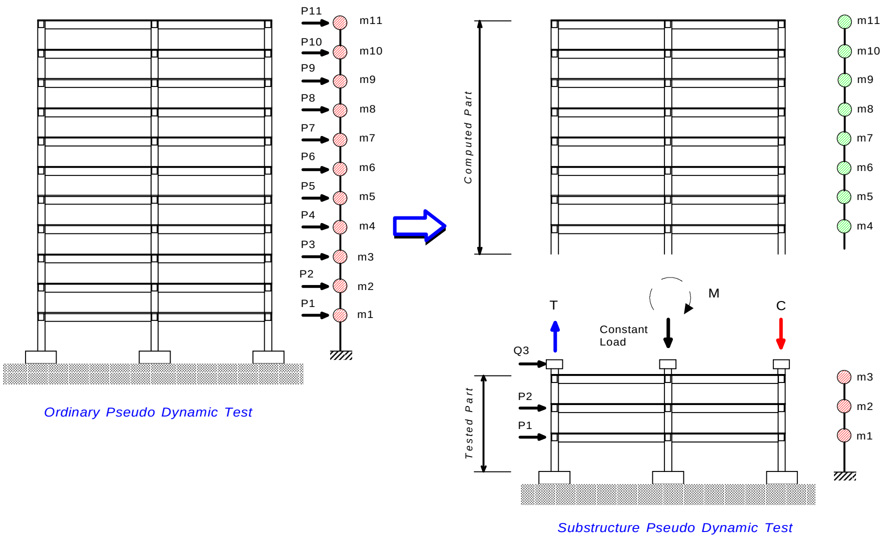


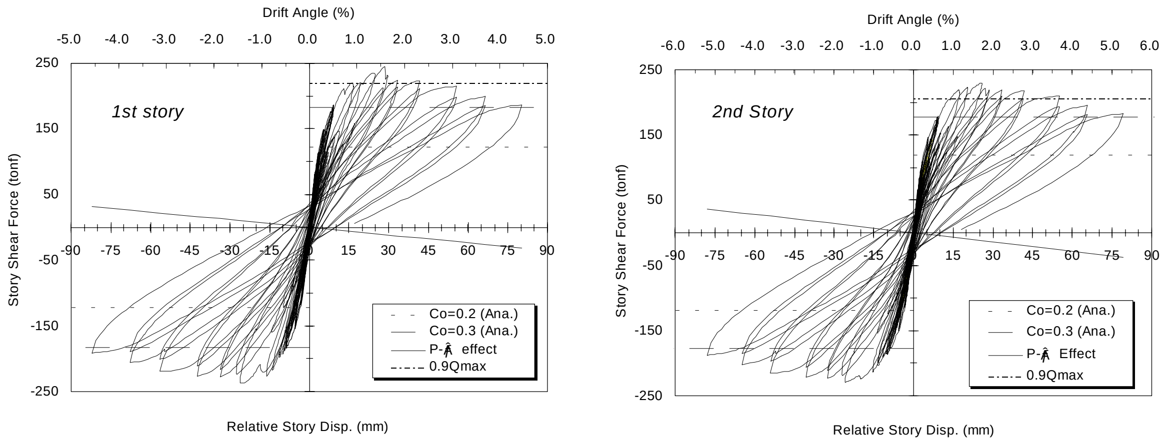
Fig. 5 Basic Concept of Substructure PSD Test

TEST RESULTS

Relationship Of Shear Force And Story Drift Angle

The story shear force and relative story displacement relationships of 1st and 2nd story are shown in Fig. 6. The maximum story drift angle (R_{max}) at 121.4tonf (*Co*=0.2) in *Static-1* test was 1/404 at 2nd story and was 1/166 at 182.8tonf (*Co*=0.3). Those story drift angles were a little smaller than that obtained from the pre-analysis. The restoring characteristics of specimen were the particular one of PC structure, which is small residual displacement and less hysteresis loop area. The maximum story drift angles were -1/151 in *Level-1* test and 1/86 in *Level-2* test and the base shear force (Q_1) at the moment were 187.8 and 220.3tonf, respectively. In *Level-3* test, obtained maximum response was R_{max} =1/73 and Q_1=220.9tonf and the restoring force tended still to increase. The hysteresis loop became gradually large with increasing of displacement response, but the residual displacement were still small, high restoring characteristics were observed. The maximum response in *JMA-Kobe* test were R_{max}=1/52 and Q_1=244.7tonf, which approximately coincided with *Co*=0.4. Those values were maximum response of specimen. From the outcomes of those tests, it understands that the pre-analysis could predict the structural performance of specimen with adequate accuracy.

In *Static-2* test, the envelope curve of story shear force and story drift relationship was stable in over 1/25 of drift angle with no deterioration of load carrying capacity. The shape of hysteresis loop grew and the residual displacement became also large after 1/50 in drift angle, but the residual displacement at R_{max} =1/25 was still 1/7 of maximum response displacement. Though the deterioration of restoring force of second loop to first loop in *Static-1* test hadn't been observed, its phenomena appeared in *Static-2* test and that value was less than 10%. The decreasing of restoring force with displacement increasing was less than 10% in 1/25 drift angle.

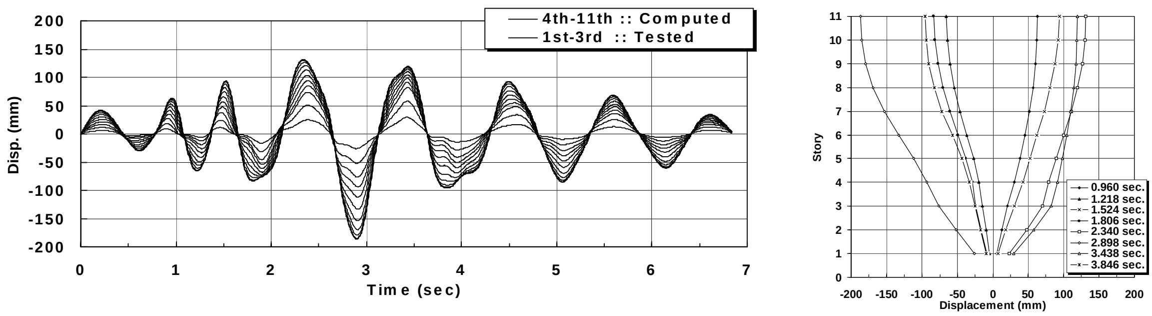


(a) First Story **(b) Second Story**

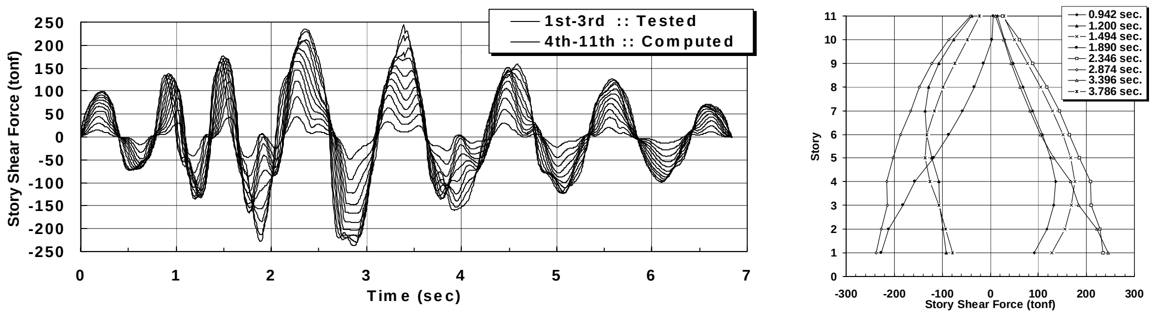
Fig. 6 Story Shear Force and Relative Story Displacement Relationship

Dynamic Response Behavior

The displacement and story shear force responses obtained from the substructure PSD test are shown in Fig. 7 with response mode. Here, the responses from 4th to 11th story were acquired from computed part of the specimen.



(a) Displacement Rresponses and Mode



(b) Shear Force Rresponses and Mode

Fig. 7 Dynamic Responses of Specimen in *JMA-Kobe* Test

The maximum displacement responses of *Level-2* test were 50.8mm at 3rd story and 109.8mm at 11th story. The maximum ones of *JMA-Kobe* test were 82.53mm at 3rd story and -185.56mm at 11th story, and 244.7tonf in base shear force. The shapes of displacement response mode showed good agreement with that of elastic first mode but the ones of shear force were disturbed with higher mode response.

The comparison of maximum story displacement, story drift angle and shear force response of each tests are illustrated in Fig. 8. The maximum story drift response appeared at 2nd story in every test. In *JMA-Kobe* test, the story drift angles from 1st to 8th story were bigger than 1/100, the value of 2nd story reached 1/52. The story drift from 1st to 3rd story were relatively large, one of 4th story was inversely small. The 4th story was boundary between tested part and computed part, it might affect the test results.

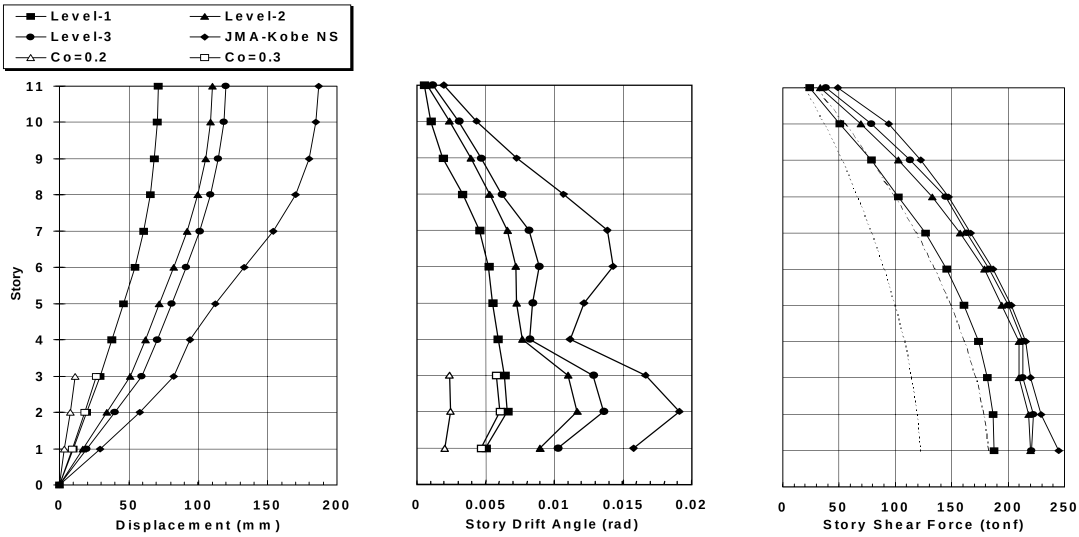


Fig. 8 Comparison of Maximum Responses of Each Tests

Crack Pattern Of The Specimen

Figure 9 shows final damage of the specimen after *Static-2* test, of which R_{max} was 1/21. The first crack occurred in mortal joint of 1st story column at about R_{max} =-1/753 and several bending cracks distributed on beam and 1st story column. In substructure PSD test (*Level-1* to *3* and *JMA-Kobe*), new crack was hardly looked at but development of existing cracks and increasing of crack width were observed. After *Level-2* test, the specimen showed a tendency that cracks gathered to around mortal joint and existing cracks far from joint remained close even in large deformation. In *JMA-Kobe* test, the maximum crack width of beam-end was roughly 8.0 mm.

The cover concrete of 1st story column bottom gradually crashed and fell off after around 1/160 in story drift angle, the area of it expanded 1D (D: width of column) from the foundation after *JMA-Kobe* test. However, no crushing of core concrete which was confined with spiral hoops and no buckling of axial reinforcing bars had been observed. The specimen had wire netting in mortal joint, it seemed effective to prevent mortal felling off and keep the load carrying capacity of the specimen even in large deformation region.

DISCUSSION

Equivalent Damping Factor

The relationship between equivalent damping factor (*heq*) and story drift angle is shown in Fig. 10, which have been obtained from *Static-1* and *Static-2* tests. White marks show the *heq* obtained from 2nd hysteresis loop, those are smaller than the value of black mark, which were obtained from 1st hysteresis loop. The broken line in the figure is drawn going through mean values of white marks. The *heq* value was about 0.05 before R_{max} =1/100, even in over R_{max} =1/33 the value is still 0.06 – 0.08. The specimen is one kind of structure that energy dissipation by hysteresis loop was hardly expected, such as all precast structural members was connected with PC tendons.

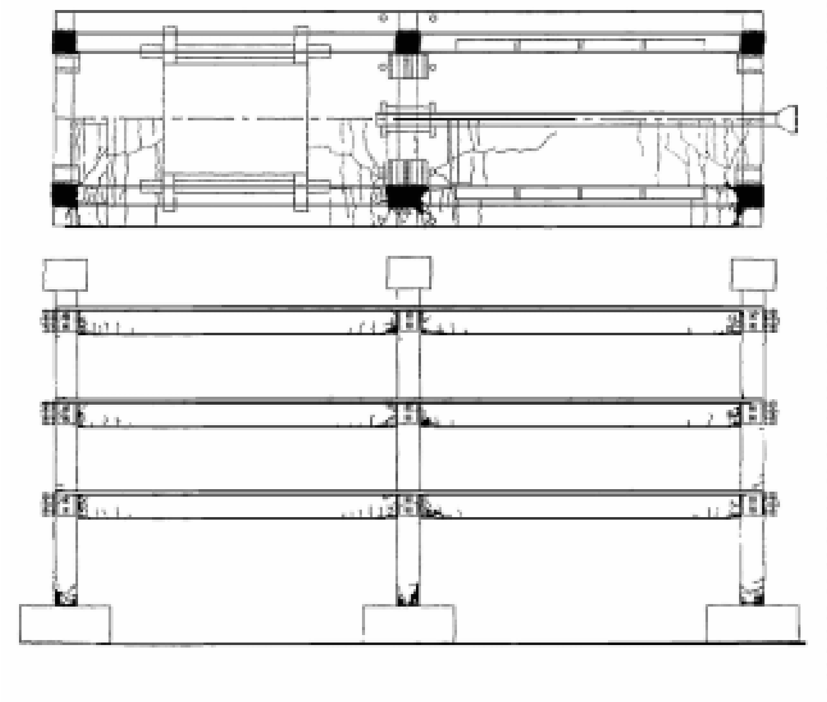


Fig. 9 Final Crack Pattern of Specimen

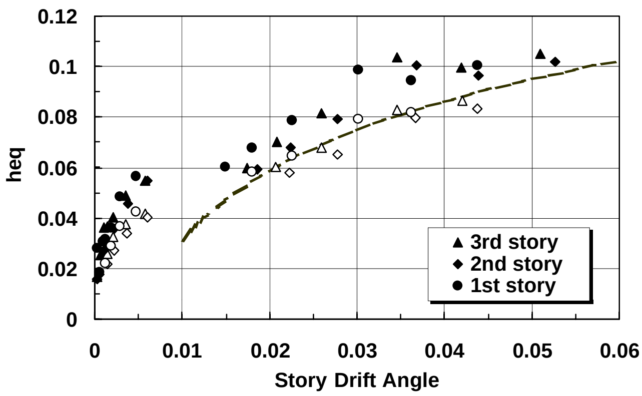
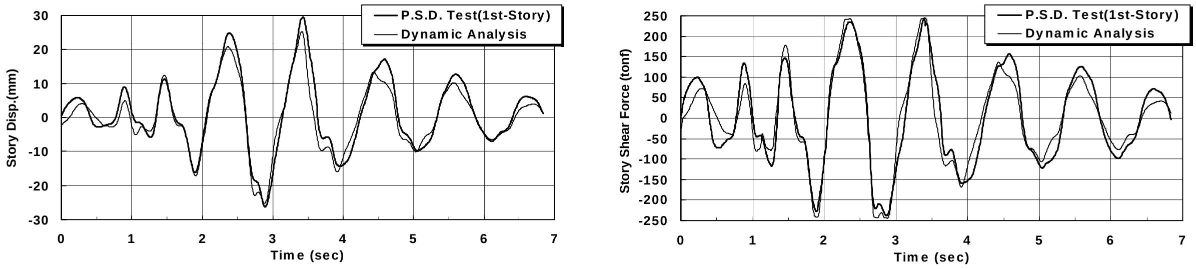


Fig. 10 *heq* and Story Drift Angle Relationship

Comparison Of Substructure Psd Responses And Dynamic Analyses

The results of post-analyses are compared with the outcomes of test in Fig. 11. In the analyses, the specimen had been substituted for equivalent lumped mass system with eleven-degree-of-freedom, the numerical hysteresis model was "*PC-model*" and other analytical conditions were same as that of substructure PSD test including input accelerations.

The period and story shear force responses obtained from the analyses corresponded well to ones of the test. Though the displacement responses of the analyses are 15-20% smaller than the results of *JMA-Kobe* tests and showed a little different from them, it understands that the analyses could approximately reproduce the dynamic behavior of the specimen.



(a) Displacement of First Story **(b) Shear Force of First Story**

Fig. 11 Comparison of Analyses and Experimental Results of *JMA-Kobe* Test

CONCLUSIONS

The major findings obtained from the static loading tests and substructure PSD tests are summarized as follows:

1) The precast PC specimen had sufficient seismic property to sever earthquake excitation and showed good performance in large deformation region.
2) The cracks due to loading tests on the specimen concentrated near the joint between precast structural members.
3) The equivalent damping factor (*heq*) was small, the value was about 0.08 even in large deformation such as 1/25 of story drift angle.
4) The dynamic response analyses using "*PC-model*" could adequately reproduce the elasto-plastic behavior of specimen.
5) The applied seismic design procedure was efficient for seismic design of high-rise PC buildings.

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