Shaking Table Tests on Three Story Precast Prestressed Concrete Frame

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SUMMARY:
This paper describes results of shaking table tests on precast prestressed concrete frames. Frames with a bonded and unbonded beam specimen were tested to observe and investigate their structural capacities including their ultimate state. Input waves were artificial one under 75Kine and actual measurement on Kobe earthquake at JR Takatori in final. The results of tests indicated that precast prestressed concrete frames had high ductility and returnable capacities. The bonded beam specimen was stronger than the unbonded one. The lateral displacement of all frames mainly occurred at the joints between members. The damage was concentrated its portions. In addition to the shaking table test, the numerical investigation was carried out. Pushover and dynamic analyses using a beam model were conducted to simulate the test results.

Keywords: Precast Prestressed Concrete, Shaking Table Test, 3 Story, Bonded and Unbonded Specimens

1. INTRODUCTION

Precast prestressed concrete (PCaPC; hereafter) structure is easy to construct and set up because many precast concrete members can be combined as PC bars or PC strands. PCaPC members have been tested and reported by many researchers and many PCaPC buildings are present in Japan. However, the buildings are likely to equip base-isolate systems or multi-story shear walls. This is probably because the load-displacement relationship is likely linear and therefore, energy consumption ability becomes small during earthquakes. This is a drawback of the PCaPC building. On the other hand, the advantage of the PCaPC building is returnable behavior after large earthquake. Some PC hysteresis models are proposed based on the many static tests to the exclusion of dynamic tests for PC members. Design of the real PC frame is mainly based on the static analysis in Japan. When high-rise or large scale buildings with PCaPC are required in near future, dynamic investigation and detailed hysteresis models will be needed associated with a dynamic test. Prior to the new modeling, a dynamic test of PCaPC model structures using the shaking table is presented in this paper. Two specimens were of 1/4 scaled three-story frame with a parameter of with or without bonding between PC bar and the sheath in a beam. Normal PCaPC buildings have bonded beams that are unified with grout between PC bar and the void. Comparing with the normal bonded bean specimen, the unbonded beam specimen without grout was subjected to the dynamic test to grasp their basic capabilities as a PCPCa frame.
Outline of the test, response characteristics (maximum shear force, maximum drift angle, residual drift angle and strain of PC bar) and equivalent damping factor are reported.
In addition to the shaking table test, numerical simulation of the test was performed. Pushover (load incremental) analysis and dynamic analysis were carried out to simulate the test results.

2. SPECIMEN

The specimen was 1/4 scaled, three-story frame with a bi-directional single span of 2400mm. Each story height was 1000mm and the size of the beam and column was the same. Two specimens with the bonded beam (bonded specimen, hereafter) and the unbonded beam (unbonded specimen, hereafter), were subjected to the shaking table test. The outline of specimen is shown in Fig.1.

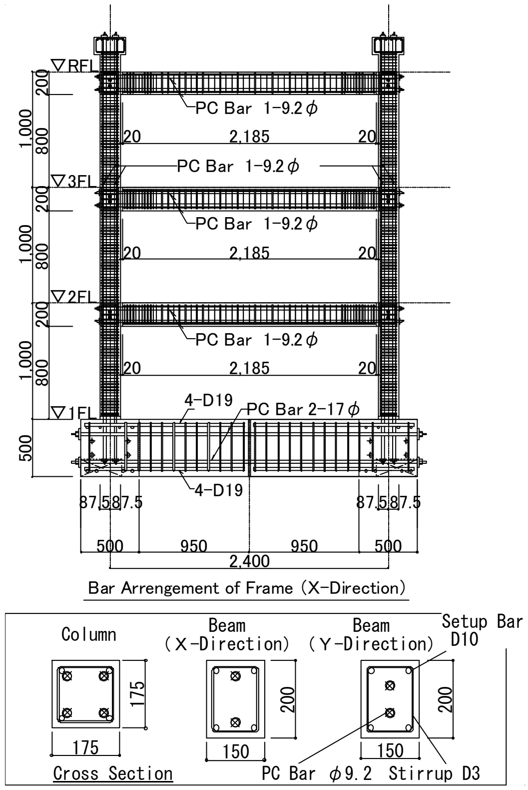


Figure 1. Outline of specimen

Photo 1. Test setup

Table 1. Similarity ratio（λ=4）

Item	Model／Real	Item	Model／Real
Time (Period)	$1/\sqrt{\lambda}$	Force(Gravity)	$1/\lambda^2$
Acceleration	1	Stiffness	$1/\lambda$
Velocity	$1/\sqrt{\lambda}$	Stress	1
Disp.(Length)	$1/\lambda$	Strain	1

Table 2. Weight of each story

	Bonded	Unbonded
RL	6.035ton	6.014ton
3F	6.033ton	6.045ton
2F	6.087ton	6.069ton

Table 3. Material properties

Diameter	Class	Yeild Stren. σ_y(N/mm^2)	Yeild Strain (μ)	Tensile Stren. σ_u(N/mm^2)	Elongation ε_u(%)	Using
D3	−	256	1381	301	−	Transverse Rebar Slab Bar
D10	SD345	388	−	533	27.1	Setup Bar (Column, Beam)
PCBar9.2φ	C−1	1238	6785	1269	−	Main Bar (Column, Beam)

Specimen	Portion	Testing Day's Value			
		Compressive Strength σ_B(N/mm^2)	Tensile Strength σ_t(N/mm^2)	Young's Modulaus Ec (×10^{4}N/mm^2)	Poiasson's Ratio ν
Bonded	Column/Beam	66.5	3.6	3.86	0.24
	Joint Mortar (Column)	101	2.9	2.68	0.21
	Joint Mortar (Beam)	101	4.1	2.45	0.20
	Grout	54.4	2.7	1.36	0.24
Unbonded	Column/Beam	65.7	3.1	3.75	0.23
	Joint Mortar (Column)	83.8	3.3	2.49	0.17
	Joint Mortar (Beam)	96.2	3.2	2.88	0.19
	Grout	71.2	2.1	1.89	0.20

The PC bars of the beam of X-direction were set at the external position, and those of Y-direction were set at the internal position because X-direction is the main direction of this shaking table test. The similarity ratio of stress controlled by the mass was closed to 1 according to the concept of the model's rule (Table 1). All the beams and columns of the specimens were cast in a factory. Those members were assembled with tensioning PC bars in the testing laboratory. The tensile stress introduced to the PC bars was 85% of the yield strength according to the AIJ Standard (AIJ 1989).

The composite slab of 30mm-thick concrete and steel plate were attached to the edge of the beam so as not to influence the frame's structural behavior. Bonded specimen had a grout between the sheath and PC bar at the beam. Unbonded specimen had the void between the sheath and the PC bar without grout. The weights applied to each story are shown in Table 2. Material characteristics of the specimen are shown in Table 3. Targeted strength of concrete and joint mortar was 60N/mm^2 or more. PC bars at the beams and columns were 9.2φ and the yield strength of 1238N/mm^2. Design natural frequencies of X and Y directions were 6.25Hz and 6.67Hz, respectively.

Base shear coefficient of the X-Direction was CB=0.74 taking account of the hinge at the both ends of the beam and the columns.

Table 4. List of input waves and its level

Input Wave	Input Level		Direction
NewRC -random Mortion (Artificial)	Elastic	50gal	X-
	Level 0.5	12.5kine	X-
	Level 1	25kine	X-
	Level 1.5	37.5kine	X-
	Level 2	50kine	X-
	Level 2	50kine	X-, Y-
	Level 3	75kine	X-
JRTakatori	Real Record (642-NS,666gal-EW)		X-, Y-

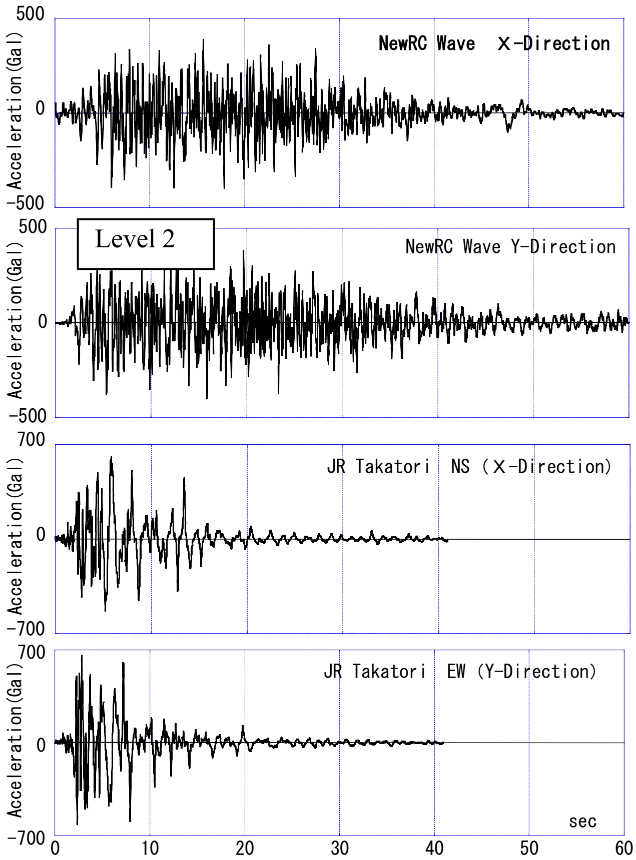


Figure 2. Input waves

3. METHOD OF EXCITATION AND MEASUREMENT

3.1 Input Waves

The input waves are shown in Table 4. The time-history of input acceleration is shown in Fig.2. The input velocity levels in Table 4 are shown as those of full scale while those of the actual input was determined according to the similarity law as noted in brackets.
A 50gal was first introduced to assess the elastic behavior and the natural period of the specimen.

Main input wave for X-direction was an artificial motion “New RC random wave”. After the Level 2 shaking, another New RC random wave was used for the simultaneous bi-directional input wave as shown in Fig.2. Each level except JR Takatori wave, was varied to the magnitude of Level 2 motion. Each level of New RC wave was adjusted its amplitude without changing its phase. The Takatori wave, observed in bi-directional at the JR Takatori at the Hyougoken Nanbu Earthquake (1995), was used for the final shaking. After each excitation, small shaking was subjected to a specimen to know its natural period and damping coefficient.

3.2 Measurement

Floor acceleration, story drift angle between floors, the rotation angle of the lowest position of columns and the both ends of beams and the strain of PC bar and steel bar, were measured. The positions of the transducers and the strain gauges are shown in Fig.3. Particulary, at all the beam ends of the PC bars including the upper and the lower positions, strain gages were attached. The sampling frequency was 200Hz.

4. TEST RESULT

4.1 Damage

No particular difference in damage and failure mode was observed between bonded and unbonded specimens after the final shaking. The both specimens showed concentrated damages of cracks and crushing of concrete at the bottom of the column and the both ends of each beam as expected. The damaged positions are shown in Photo 2. The other positions showed no damage. The joint mortar at the beam ends showed cracked at level 2 excitation, and the crushing at the bottom of the column became severe after the Level 3 excitation. The fall of joint mortar and the crushing of the column were observed after the final shaking as shown in Photo 2. Only displacement was observed by the rotational displacement between the connected positions. The summation of those displacements configured the lateral story drift displacement. The other positions behaved likely elastic.

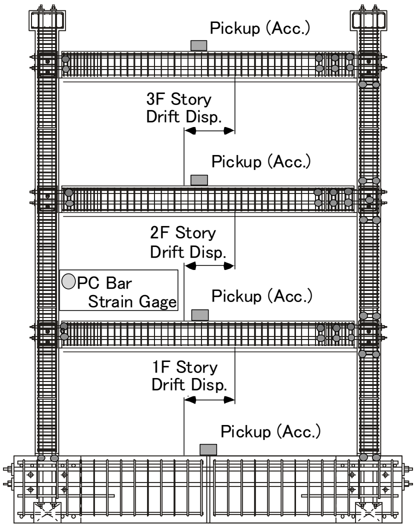


Figure 3. Outline of measurement

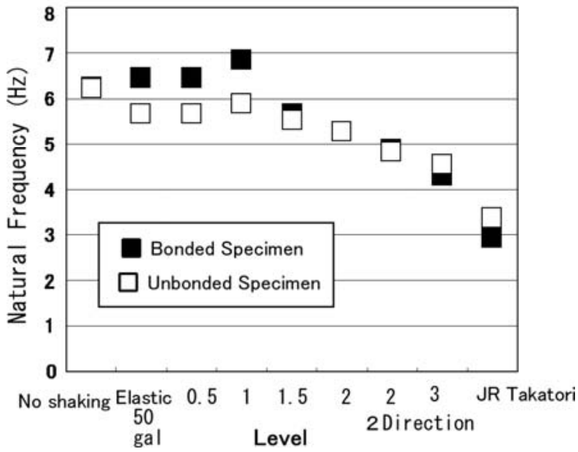


Figure 4. Changes of natural freq. (X-Dir.)

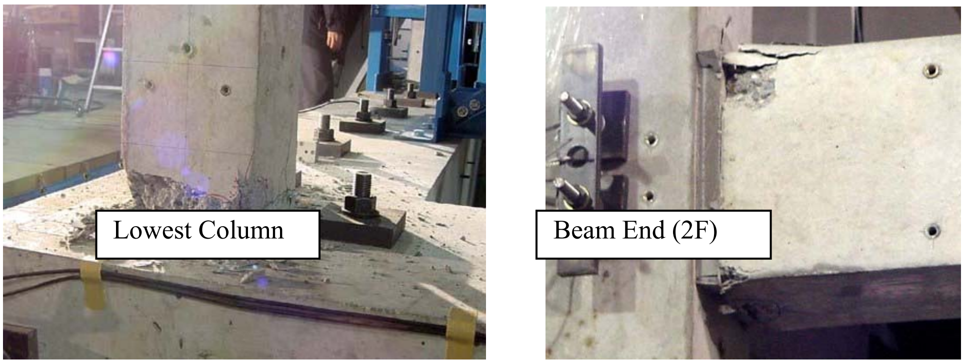


Photo 2. Failure State after JR Takatori excitation (Unbonded Specimen)

Table 5. List of test results

(Bonded Specimen)

Input Wave	Input Accelaration (Gal)	Input Velocity (Kine)	Max. Resp. Accelaration (Gal)	Max. Resp. Drift Angle(%rad.)	Residual Drift Angle%rad.)	Max. Resp. Shear Force (kN)	Base Shear Coefficient	Natural Period (Hz) X	Natural Period (Hz) Y
								6.3	6.6
Elastic 50gal	54	3.7	215	0.06	0.00	27	0.15	6.4	−
Level 0.5	94	6.0	347	0.10	0.02	44	0.25	6.4	−
Level 1	208	12.6	737	0.30	0.02	85	0.48	6.8	−
Level 1.5	324	19.1	950	0.49	0.03	110	0.62	5.7	6.4
Level 2	417	25.4	1278	1.08	0.03	144	0.81	5.3	5.7
Level 2 XY	408 (386)	25.2 (27.2)	1289 (1009)	1.10 (0.77)	0.03 (0.02)	133 (137)	0.75 (0.77)	4.9	5.3
Level 3	630	37.9	1501	2.50	0.02	178	1.00	4.3	5.5
JRTakatori XY	712 (675)	65.3 (64.8)	1532 (1347)	4.76 (1.37)	0.08 (0.03)	171 (119)	0.96 (0.67)	2.9	5.3

(Unbonded Specimen)

Input Wave	Input Accelaration (Gal)	Input Velocity (Kine)	Max. Resp. Accelaration (Gal)	Max. Resp. Drift Angle(%rad.)	Residual Drift Angle%rad.)	Max. Resp. Shear Force (kN)	Base Shear Coefficient	Natural Period (Hz) X	Natural Period (Hz) Y
								6.2	6.0
Elastic 50gal	54	3.9	273	0.086	0.01	32	0.18	5.7	−
Level 0.5	87	6.1	381	0.13	0.01	48	0.27	5.7	−
Level 1	198	12.9	663	0.32	0.03	80	0.45	5.9	−
Level 1.5	290	19.7	984	0.93	0.03	126	0.71	5.5	−
Level 2	381	25.1	1407	2.00	0.03	146	0.82	5.3	5.8
Level 2 XY	376 (374)	25.4 (23.9)	1222 (1103)	1.75 (1.41)	0.03 (0.02)	100 (136)	0.70 (0.77)	4.8	4.6
Level 3	580	37.8	1382	2.63	0.03	142	0.80	4.5	5.0
JRTakatri XY	727 (765)	65.3 (65.6)	1298 (940)	5.88 (1.89)	0.05 (0.02)	149 (140)	0.84 (0.79)	3.4	4.2

Note: ( ) Y-Direction −No Measurement

4.2 Response

The summary of the test results is shown in Table 5 where the maximum response acceleration was the value at RFL (3F), the maximum response drift angle was the value at 2F and the maximum response shear force is the value at 1F. Changes in 1st natural frequency of X-direction are shown in Fig.4. The frequency of bond specimen increased until the level 1 excitation probably due to the variability of 25gal random excitation introduced after the main excitation.

The frequency of each specimen became gradually decreased after the level 1.5 excitation. The

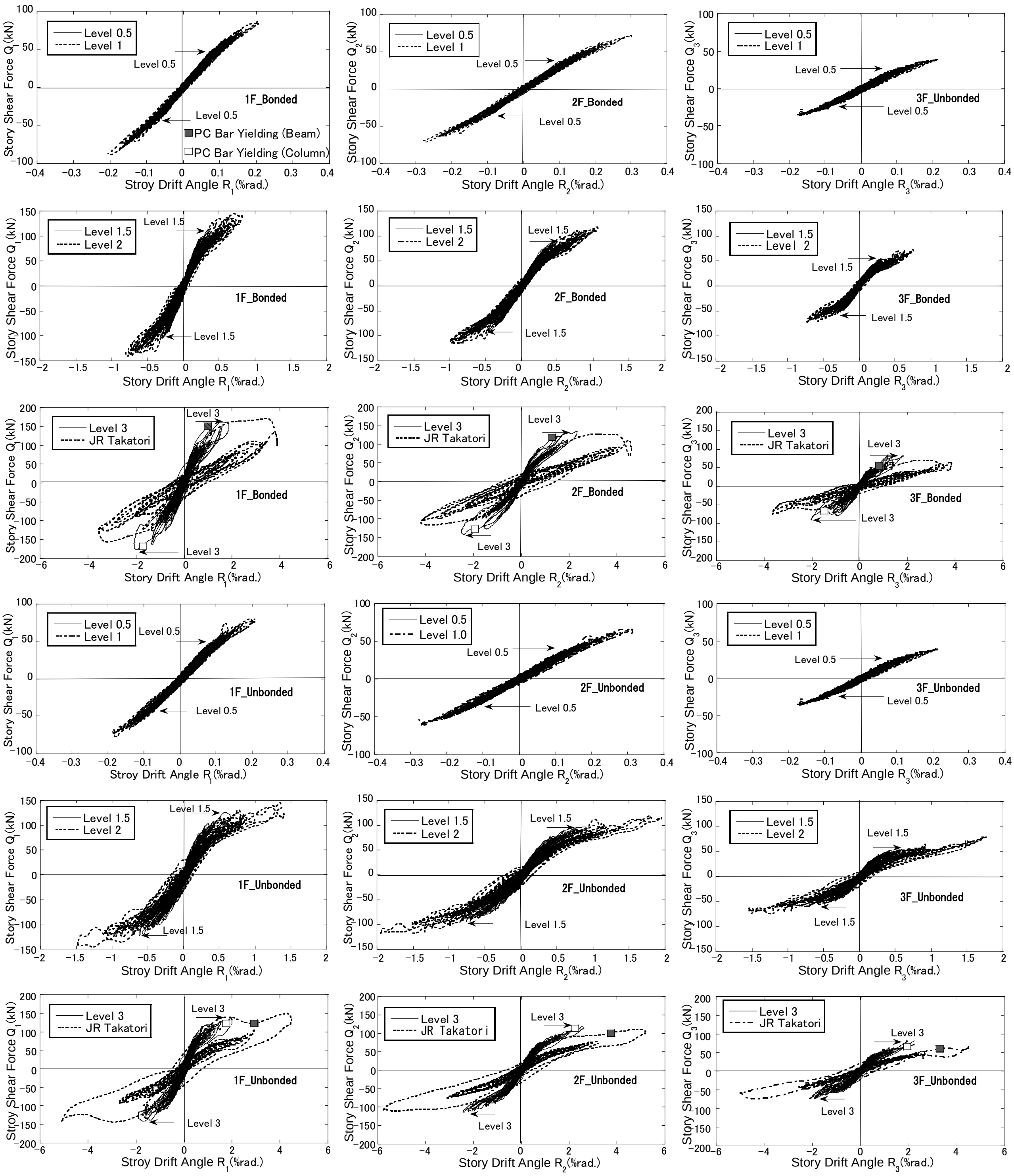
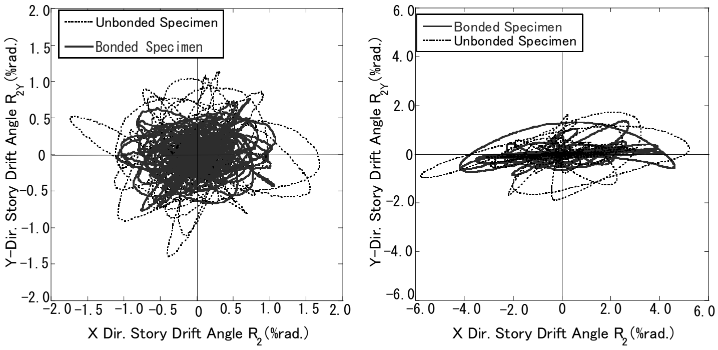


Figure 5. Story shear force – story drift angle relationship



Level 2 JR Takatori

Figure 6. Correlation of bi-directional story drift angle

frequency of 6Hz in each specimen at the first stage decreased down to 3Hz at the final stage. The trend of the degradation of natural frequency was almost the same between specimens after level 1 excitation. The base shear coefficient observed in the test was CB=1.0 unlike that of the preliminarily numerical analysis of CB=0.74.

4.3 Story shear force – story drift angle relationship

Story shear force – story drift angle relationship of bonded and unbonded specimens are shown in Fig.5. Two excitations are shown in one figure by story and by specimen.

Until level 1 excitation, almost linear behavior was observed for both specimens. S-shape hysteresis loops were observed after the level 1.5 excitation. Response rotation angle of the unbonded specimen without bond in PC bar was larger than that of the bonded specimen due to opening of the both beam ends after subjected to the level 1.5 excitation.

The stiffness degradation of all the specimen increased in accordance with the excitation level. The maximum response story drift angle of 2nd story at level 2 excitation was 1.08% rad. in bonded specimen and 2% rad. in unbonded specimen and, when the JR takarori excitation was introduced, 4.76% rad. in bonded specimen and 5.88%rad. in unbonded specimen. However, the residual drift angle was as small as 0.08% for all the specimens. This can be attributed to many small input waves introduced after the JR takatori's main shaking which allowed the deformation converged in the original point, and to the limitation in failure position of concrete and the yielding area.

Bi-directional shaking was carried out both in the level 2 and the JR Takatori excitations. The drift angle orbit of two excitations was plotted in Fig.6. The input acceleration of X-direction and Y-direction in the Level 2 excitation was almost the same amplitude as that of X- and Y- New RC wave. Also the plasticity of

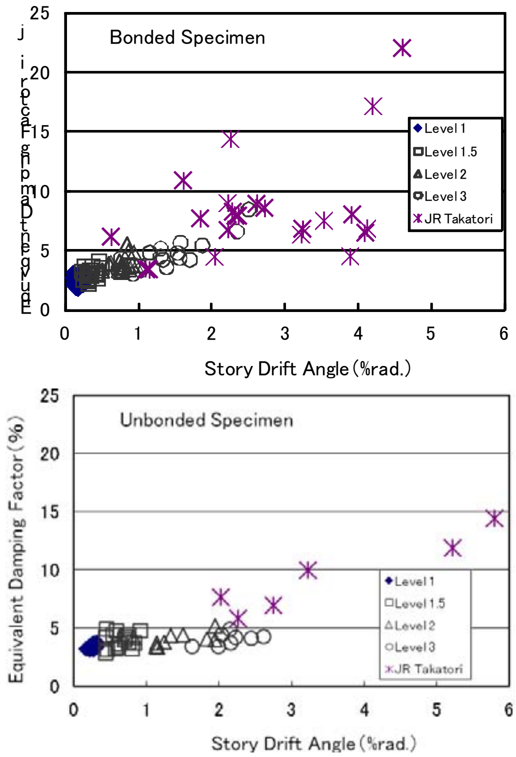


Figure 7. Changes of equivalent damping factor(2F)

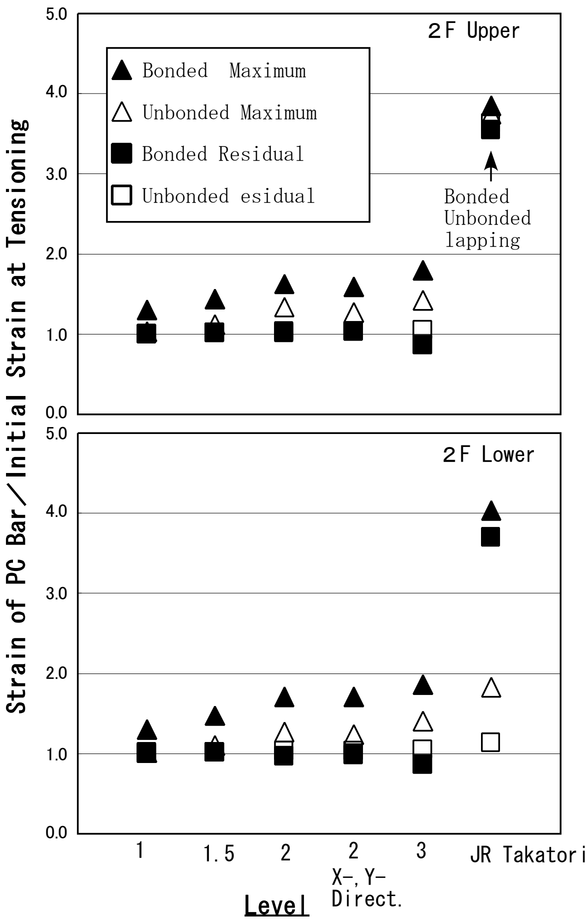


Figure 8. Changes of strain of PC bar

X-direction showed no progress until the level 1.5 excitation. Hence, there was no difference between X-direction and Y-direction. As the main motion of the JR takatori wave was X-direction, the drift angle of Y-direction was smaller than that of X-direction. The drift angle of the unbonnded specimen was larger than that of the bonded specimen at the both excitations and directions.

4.4 Equivalent damping factor (*heq*)

Chnages in the equivalent damping ratio calculated from the hysteresis loops of the 2nd story are shown in Fig.7. Equivalent damping ratio (*heq*) is normally calculated as a loop area divided by the product of equivalent potential energy and 4π, but half cycle of the hysteresis loop and 2π are used to calculate *heq* because of the asymmetry loop observed from shaking table test. Its figure included not only the steady-state loop but also the transient loop. The *heq* between 2-4% of the bonded specimen and 3-5% of the unbonded specimen showed no significant difference until the level 1.5 excitation. The yielding of PC bar was observed in the bonded specimen at the level 3 excitation and in the unbonded specimen at the JR Takatori excitation.
Equivalent damping factor suddenly increased after the yielding of PC bar. At the JR Takatori excitation, *heq* of the bonded specimen ranged from 4.5 to 22% and *heq* of the unbonded specimen ranged from 5.5 to 14%. However, the *heq* calculated on the basis of the steady-state loop that exceeded the transient one was almost less than 10%.

4.5 Strain transition of PC bar

The strains of the upper and the lower PC bar of the 2nd floor beam increased according to the excitation as shown in Fig.8 where the observed strains divided by the initial strain at prestressing are plotted. The maximum response strain of the bonded specimen was 1.5 to1.8 times larger than the initial strain at excitations larger than the level 2 excitation. However, the residual strain turned approximately to the initial strain levels. Because the strain of PC bar in the ubnbonded specimen was averaged over the length of the bar, the maximum response strain of the unbonded specimen was less than that of the bonded one. At the JR Takatori excitation, the PC bars of the bonded specimen yielded and the residual strain remained closely to the maximum strain. The PC bar's strain of the unbonded specimen didn't reach its yielding strain after the final shaking. The difference in PC bar's strain between bonded and unbonded specimens resulted in the different values of residual drift angle in Table 5.

5. NUMERICAL INVESTIGATION

Numerical investigation was carried out to confirm the accuracy of ongoing design method for PC bonded structure. Hence, the investigation for the bonded specimen was carried out prior to the unbonded specimen. The analysis of the unbonded structure is a remaining task to propose a new skeleton curve and a hysteresis model and so on. Pushover analysis and dynamic response analysis were carried out. Pushover analysis gives static push to the frame model as a incremental load. Usually, its

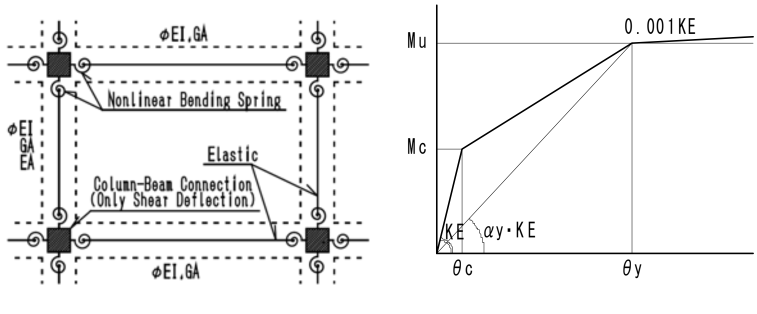


Figure 9. Analytical model

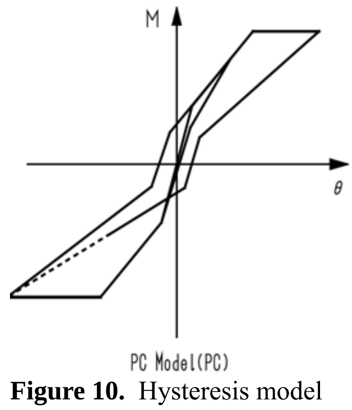


Figure 10. Hysteresis model (Hayashi)

pushover analysis is used for the structural design. Dynamic analysis is required for a high-rise building taller than 60m in Japan.

Pushover analysis (incremental load analysis) of PCaPC model shown in Fig.9 and Fig.10 was carried out expressing each column and beam as a beam element with nonlinear restoring force characteristics. Each member in the frame was represented as a lineal element at the centroid of the section. Nonlinear rotational springs were inserted at the end of a member to represent the inelastic deformation within the member. Stiffness of a member was varied at two loading levels corresponding to flexural cracking of concrete and yielding of tensile reinforcements and PC tendons. The stiffness after yielding was 1/1000 of the initial stiffness (Hayashi *et al.* 2000) .

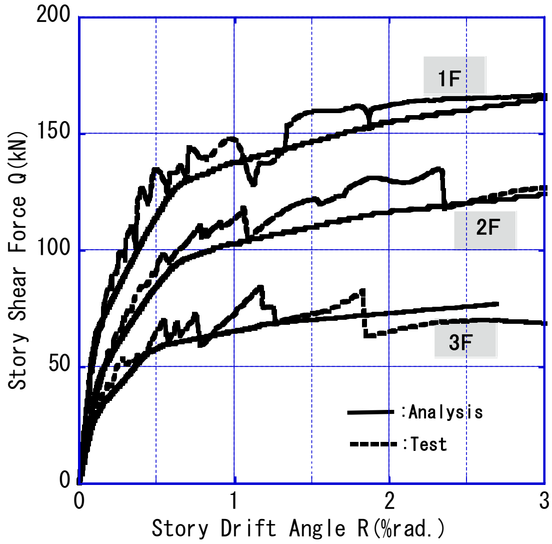


Figure 11. Comparison between test and pushover analysis

Three kind dynamic hysteresis models were prepared. 1) Hayashi model (Hayashi *et al.* 1995; Fig.10) is developed for a PC structure. The unique pinching behavior of PC members can be represented. Its model is used for a seismic design many a time. 2) Takeda model (Takeda *et al.* 1970) is popular for seismic design in reinforced concrete structures in Japan. 3) Nonlinear elastic model is the bi-linear model without energy consuming loop, and returned to original position. Pushover analysis for bonded specimen is shown in Fig.11. Its figure is included in the one side's envelope curve of the test. Lateral load distribution factor was used as Ai mode (Building Standard Enforcement Regulation by Ministry of Land, Infrastructure, Transport and Tourism, Japan) to the 3-dimentional beam model. The initial stiffness and the stiffness after cracking were corresponded between the test and the analysis. The behavior over 1% rad. was roughly assented.

The dynamic analyses comparing with test result is shown in Fig.12. The figure shows the representative 2nd story response between story shear force and story drift angle. The Level 2 input wave was used for a dynamic analysis. As the level 2 input motion is usually used for the real design, a 50kine was adopted. All the numerical results were smaller than those of the test results. Especially, results of the Takeda model showed a small value because the RC model consumes energy at early loading. Nonlinear elastic model showed better agreement with the test result when compared with the other numerical results. However, dynamic analyses cannot be estimated safely against the test result. Therefore, dynamic model has to be improved for a better accuracy in the future.

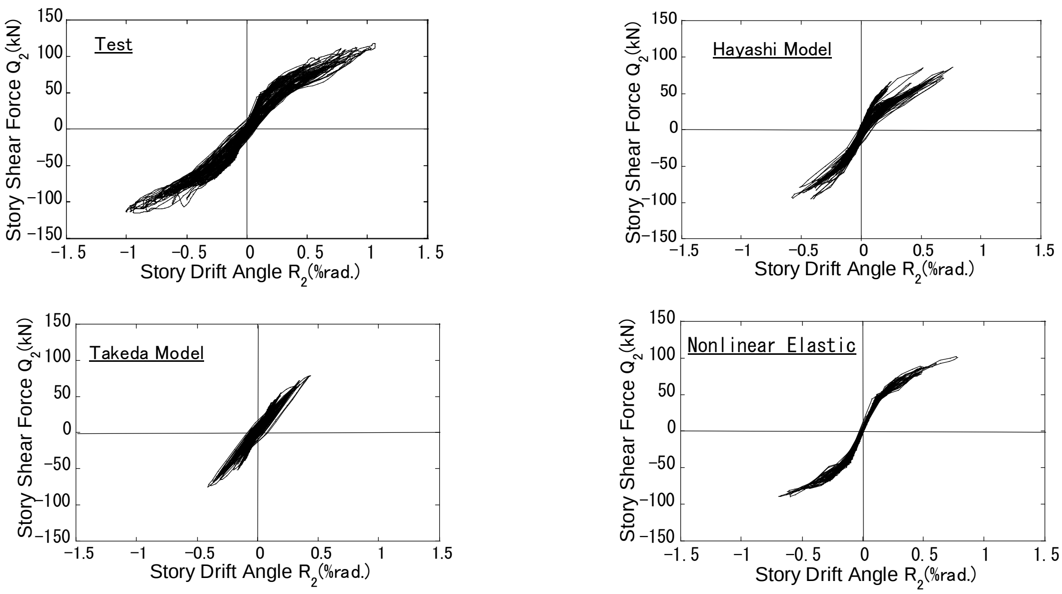


Figure 12. Comparison between test and dynamic analysis (2F)

6. CONCLUDING REMARKS

Shaking Table test of PCaPC three story specimens with bonded or unbonded beams was carried out to confirm the structural performance. Several simulation analyses for the bonded specimen were also carried out. The following findings were obtained.

1) The PCaPC specimens showed high ductility and returnable capacities after the final shaking. Especially, specimens were returned near its initial position when JR takatori excitation was introduced.
2) The damage and failure mode after the final shaking were almost the same for the bonded and the unbonded specimen. Each specimen showed the concentrated damage of cracks and crushing concrete at the bottom of the column and at the both ends of the beam.
3) The different response behavior between two specimens was observed after the level 1 excitation. Before the level 1 excitation, the both specimens showed almost linear response of shear force and drift angle relationship. The response maximum drift angle of the unbonded specimen was larger than that of the bonded specimen. PC bars in the beams of the bonded specimen yielded at the level 3 excitation. On the other hand, one of the unbonded specimen yielded at the JR Takatori excitation in delay to the bonded specimen. The different strain behavior of the PC bars between bonded and unbonded specimens resulted in the different response.
4) The both specimens showed plastic behavior at the JR Takatori excitation. The maximum drift angle were 5% rad. (R=1/20) for the bonded specimen and 6.25 % rad. (R=1/16) of the unbonded specimen. However, the damages of the both specimens including residual deformation were small after the final shaking.
5) Equivalent damping factor (*heq*) ranged from 2 to 5% before yielding of PC bars, and was more than 10% after yielding at the transient loop.
6) Pushover analysis could approximately simulate the skeleton curves obtained by the test.
7) The hysteresis of nonlinear elastic models showed good agreement with the test results when compared with the other numerical results. However, dynamic analyses cannot be estimated safely against the test result. Therefore, dynamic model has to be improved for a better accuracy in the future**.**
8) The analysis of the unbonded structure is a remaining task to propose a new skeleton curve and a hysteresis model and so on in the future.

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