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BIDIRECTIONAL SHAKING TABLE TESTS OF A ONE-FOURTH SCALE REINFORCED CONCRETE SPACE FRAME

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SUMMARY

Shaking table tests on the 1/4th-scale three-story reinforced concrete frames were carried out to investigate the effects of bidirectional earthquake motions on overall nonlinear response of reinforced concrete frame buildings. Two identical models were constructed and one was subjected to bidirectional horizontal earthquake motions and the other was subjected to unidirectional one. A series of earthquake input tests with step-by-step increased the intensity were conducted for both models. The two models exhibited the strong column-weak beam collapse mechanism at a same input level where the maximum interstory drift angle was about 1/40 for both models. Until this input level, the story restoring force characteristics under the bidirectional input was almost the same as the one under the unidirectional input. However, at the next input level where the maximum interstory drift angle was about 1/25 under the unidirectional motion, the story shear reductions and the increase of interstory drifts were observed in the bidirectional test compared to the unidirectional one.

INTRODUCTION

In the seismic design of reinforced concrete (RC) buildings, the evaluation of the effect of bidirectional earthquake motions on the inelastic behavior of RC buildings is indispensable to ensure the seismic safety. Therefore, many experimental studies have been conducted on the inelastic performance of RC members and subassemblies, such as columns and slab-beam-column joints, under static multidirectional load conditions. However, few experimental studies have been conducted on the dynamic nonlinear response of overall RC buildings subjected to the bidirectional ground motions [Hosoya, et al, 1995], and the nonlinear behavior is not yet clarified sufficiently, especially near the collapse stage of RC buildings.

Strong column-weak beam collapse mechanisms should be achieved even under the bidirectional severe earthquake motions to avoid the catastrophic soft-story or column side-sway collapse. However, the bidirectional bending moment interactions will decrease the flexural strength of columns under the bidirectional motions, and that might be a trigger for the soft-story collapse. Moreover, the increase of bending strength of beams in a large deformation region due to the slab reinforcement contributions, which have been acknowledged from the many experimental studies, may induce the soft-story collapse when subjected to the unexpected severe ground motions, even if the strong column-weak beam mechanism was expected under the intensity of earthquake motions considered in the seismic design.

Shaking table tests using two identical 1/4th-scale RC models were carried out to obtain a clear insight on the inelastic response of RC frame structures subjected to the bidirectional and unidirectional earthquake motions. The main objectives of the tests are as follows; 1) Investigate the bidirectional-input effects on the overall inelastic response of RC frame structures. 2) Investigate the response behavior up to the collapse region of the RC structures to examine the seismic safety margin. This paper describes main results of the shaking table tests.

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TEST METHOD

The prototype of a model, which was three-story space frame without walls, was designed based on Japanese seismic code, and two identical 1/4th-scale models of the prototype were constructed. One was subjected to bidirectional earthquake motions horizontally in X and Y direction simultaneously (Bidirectional tests), and the other was subjected to unidirectional motions only in X direction (Unidirectional tests).

Design of prototype building

The prototype was designed based on the current Japanese seismic design code. The seismic design force with base shear coefficient of 0.2, which indicates the first-story shear force equals to 0.2 times of the total weight of superstructure, was applied and allowable stress design was carried out. After reinforcing bar arrangements were determined so as to satisfy material allowable stresses and minimum requirements of reinforcing bar on the seismic design code [AIJ, 1991], the retained horizontal strength was estimated based on ultimate strength concept [AIJ, 1990] and confirmed that it satisfied a required retained horizontal strength by the seismic design code. The dimension of the prototype was scaled to 1/4 considering the shaking table's capacity and available materials for the model test structures used in the shaking table tests.

Law of similarity

The replica model of the prototype was used for the tests. Assuming material scaling identity in accordance with constant acceleration similitude, the stress scale factor equals to unity was applied for the similarity law of the model. Since the size reduction ratio of the model was 1/4, the time axis of input earthquake motions was scaled to 1/2 and lead ingots were loaded on the roof and floor slabs of the models for mass density compensation.

Model test structure

The 1/4th-scale model is shown in Fig.1. The model was a three-story, single bay by single bay space frame with span length of 1500x1500mm and each story height of 750mm. Section dimensions and reinforcing bar arrangements of the column, beam and slab are summarized in Table1, and its details are also shown in Fig.1. All stories had the same section and reinforcing bar arrangement of columns, beams, and slabs, respectively. D6 deformed bar was used for longitudinal reinforcements of the columns and beams, and D3 was used for hoops, stirrups and slab reinforcements. Mechanical properties of D6 and D3 bars obtained from the material tests are summarized in Table 2. Microconcrete, its material mix proportion was carefully decided through some trial mixings, was used for the columns, beams and slabs, and ordinal ready-mixed concrete was used for the foundation. Gravels with maximum size of 10mm were used for the coarse aggregate of the microconcrete. Two identical model test structures were constructed at the same time, and the casting of the microconcrete was implemented story-by-story in the vertical standing position. Mechanical properties of the microconcrete at the date of shaking table tests were summarized in Table 3.

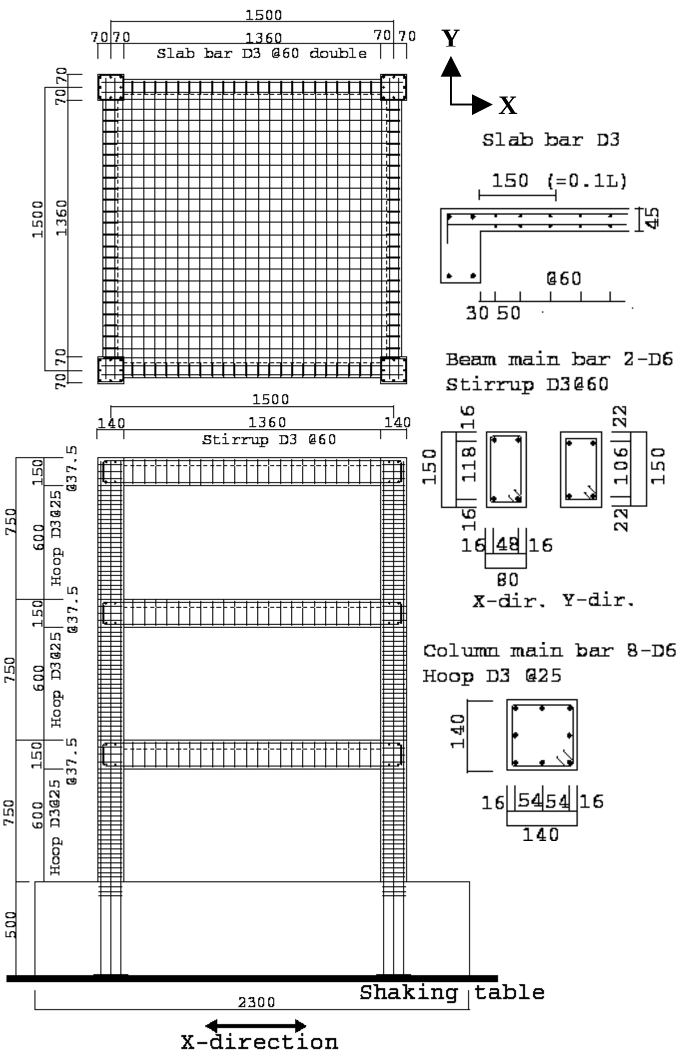


Figure 1: 1/4th-scale model test structure

Based on mass similitude requirement, lead ingots (472N per each) were used as an additional weight. Considering both the similitude requirement and the arraignment of ingots, forty pieces of ingot (22.66kN) were fixed on each slab of the model. As a result, the live load considered for the model was 1.67kN/m^2. The axial stress of the first-story columns without earthquake loads was estimated to 0.9N/mm^2. Total weight of the model including the ingots and the foundation was estimated to 134kN.

Table 1: Members of the model

Member	Column	Beam	Slab
Section	140x140mm	80x150mm	t=45mm
Reinforcement	Main 8-D6 Hoop D3 @25mm (Joint D3 @37.5mm)	Main upper 2-D6 lower 2-D6 Stirrup D3 @60mm	Upper D3 @60 mesh Lower D3 @60 mesh

Table 2: Mechanical properties of reinforcement

Type	Yield strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)	Yield strain (micro)
D6 bar	412	564	212	1946
D3 bar	363	388	236	1539

*Stress was calculated based on the section area after burnishing for a stran gage

Table 3: Mechanical properties of microconcrete

Model test structure	Story	Age	Compressive strength (MPa)	Splitting strength (MPa)	Secant modulus (GPa)
Model for Unidirectional tests	3	64	29.0	2.7	23.4
	2	77	31.9	2.2	22.4
	1	93	36.2	2.4	23.8
Model for Bidirectional tests	3	49	31.1	2.2	22.8
	2	62	33.7	1.9	21.2
	1	78	34.0	2.6	21.7
		Average	32.7	2.3	22.6

*Results of 10x20cm specimens sealed cured on site

Table 4: Calculated structural strength of the model

Slab reinforcement contribution	Floor	(ƒ Mcy) / Mby Slab in compression	(ƒ Mcy) / Mby Slab in tension	Retained horizontal strength (kN)
Case 1:	RF	1.57	1.42	26.36
Upper bars	3F	3.15	3.04	24.25
within 0.1L region	2F	3.18	3.45	46.41
Case 2:	RF	1.32	0.60	39.22
Upper & lower bars	3F	2.54	1.30	44.98
in whole slab width	2F	2.34	1.53	58.72

*ƒ Mcy is sum of the yield moment of colum top and bottom at a joint
*Mby is yield moment of beam
*L is span length of 1500mm

Estimation of the structural properties and the retained horizontal strength of the model

Bending strengths of the beams and columns of the model were calculated using simplified formulas on ultimate strength [AIJ, 1991], and the retained horizontal strength of the model was estimated. The average strength of microconcrete of both models was used for the calculation. For the bending strength of the beams when the slab is in tension, two cases of slab reinforcement contribution were considered; Case1) Slab upper reinforcements within 0.1L (=150mm; L is span length) width of the slab were considered according to standard for structural calculation of reinforced concrete structures, and Case2) Slab upper and lower reinforcements within a half width of the slab were considered, that means the whole slab contribution for the model. In Table 4, the ratio of the sum of the bending strength of column top and bottom to the bending strength of beam is summarized along with the retained horizontal strength of the model in X direction. Because of all the beam-column joint of the model was an exterior joint, those strength ratios were relatively high compared to strength ratios at interior joints. For case1, an ideal overall collapse mechanism with yielding at all beam ends and the first-floor column bottoms was estimated. The retained strength as the base shear coefficient was estimated to 0.66 for case1. For case2, yielding at the column top of the third and second-story was also estimated when the slab was in tension but soft-story collapse mechanisms did not form. The retained strength as a base shear coefficient was 0.83 for case2.

Input earthquake motions and measurements

A series of earthquake input tests with step-by-step increased the intensity were carried out. One model was subjected to unidirectional (X) inputs, while the other was subjected to bidirectional (X and Y) inputs. El Centro (1940) and JMA Kobe of Hyogo-ken Nanbu Earthquake (1995) records were used with the time axis scaled to 1/2. For the unidirectional tests, only NS component of the records was used. The maximum acceleration of El Centro NS was adjusted to 50, 242, 483, 725cm/s^2, and the recorded maximum acceleration 821cm/s^2 of Kobe NS was also used. Note that the last three adjusted maximum accelerations of El Centro NS correspond to its maximum velocity of 25, 50 and 75cm/s in the prototype scale, respectively. Earthquake motions with its maximum velocity is normalized to 25 and 50cm/s are often used for the earthquake response analyses of RC buildings to confirm the seismic safety in Japan. For the bidirectional tests, NS and EW component were used simultaneously. The maximum acceleration and the input direction of the NS component for the bidirectional tests were the same as the one for the unidirectional tests, and the ratio of NS and EW maximum acceleration was the same as the records. One of the acceleration waveforms of El Centro and Kobe measured on the shaking table during the bidirectional tests is shown in Fig.2. Free vibration tests were also conducted before and after the earthquake shaking to identify the vibration characteristics of the models. All the test sequence is shown in Table 5. 6-DOF shaking table at Kajima technical research institute was used for the tests. The shaking table is 5m x 5m and its rated load capacity is 294kN.

Measurements were carried out on accelerations at floor levels of the model and the shaking table, interstory displacements, strains of the reinforcing bars and rotation angles at the member ends. Servo-type accelerometers and laser-type displacement sensors were used, and they were arranged so that both horizontal and torsional responses could be measured. Strains of the main bar at all critical sections of the columns and beams, and strains of the slab upper reinforcements at the second-floor were measured. A pair of LVDT (linear valuable displacement transducer) were installed at the first-story column bottom and the second-floor beam end to measure relative rotational angles at a distance D (=depth of the beam or column cross-section) from the critical section. During the free vibration tests, velocity sensors were also used to measure free vibration responses. The measurement system of the shaking table was used and analog outputs from the instrumentation were recorded digitally at a frequency of 1000Hz during the earthquake inputs.

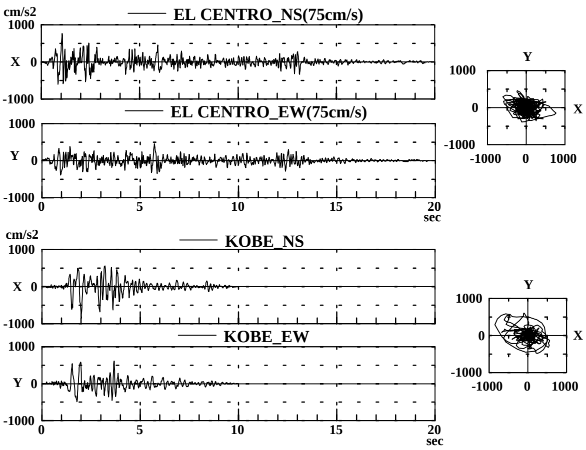


Figure 2: Measured earthquake motions on the shaking table (El Centro at 75cm/s input level and Kobe of the bidirectional test)

Table 5: Test sequence

No.	Unidirectional tests	Bidirectional tests
1	Free vibration tests (Before additional weight setting)	Free vibration tests (Before additional weight setting)
2	Free vibration tests (After additional weight setting)	Free vibration tests (After additional weight setting)
3	EL CENTRO (PGA x=50) X-EL05	EL CENTRO (PGA x=50,y=31) XY-EL05
4	Free vibration tests	Free vibration tests
5	EL CENTRO (PGA x=242) X-EL25v	EL CENTRO (PGA x=242,y=149) XY-EL25v
6	Free vibration tests	Free vibration tests
7	EL CENTRO (PGA x=483) X-EL50v	EL CENTRO (PGA x=483,y=297) XY-EL50v
8	Free vibration tests	Free vibration tests
9	EL CENTRO (PGA x=725) X-EL75v	EL CENTRO (PGA x=725,y=446) XY-EL75v
10	Free vibration tests	Free vibration tests
11	KOBE (PGA x=821) X-KOBE	KOBE (PGA x=821,y=619) XY-KOBE
12	Free vibration tests	Free vibration tests

*Maximum input velocities for X-EL25v, X-EL50v, X-EL75v and X-KOBE are correspond to 25, 50, 75, and 91 cm/s in prototype scale, respectively.
*PGA : Peak Ground Acceleration (cm/s2)

TEST RESULTS

Maximum responses and damage observations

The maximum interstory drift angles and the story shear forces of the models, and the maximum accelerations of the shaking table are summarized in Table 6. In Fig.3, the relative displacement distributions at the time when the roof floor exhibit the maximum displacement, the maximum interstory drifts and the maximum story shear distributions for each input intensity are shown. Note that the story shear force is an inertia force calculated by the story mass and the response accelerations. The maximum acceleration of the shaking table for X direction was almost the same between the unidirectional tests and the bidirectional tests at each input level, therefore, the response of both models for X direction was comparable under the same

Table 6: Maximum responses

Input E.Q.		Unidirectional tests		Bidirectional tests			
		X direction		X direction		Y direction	
	Story	Interstory drift (rad)	Story shear (kN)	Interstory drift (rad)	Story shear (kN)	Interstory drift (rad)	Story shear (kN)
EL25v	3	1/507	16.9	1/547	17.1	1/1000	10.1
	2	1/329	25.8	1/335	25.5	1/573	17.8
	1	1/503	30.4	1/493	31.2	1/682	22.2
	Shaking table	284cm/s2		284cm/s2		143cm/s2	
EL50v	3	1/122	26.8	1/109	*	1/205	*
	2	1/85	43.8	1/73	*	1/122	*
	1	1/131	56.1	1/117	*	*	*
	Shaking table	535cm/s2		532cm/s2		287cm/s2	
EL75v	3	1/64	42.4	1/54	35.7	1/97	25.1
	2	1/41	63.6	1/38	51.4	1/61	40.5
	1	1/56	70.9	1/53	60.2	1/77	48.8
	Shaking table	782cm/s2		768cm/s2		454cm/s2	
KOBE	3	1/30	35.0	1/27	28.1	1/42	26.6
	2	1/24	58.2	1/21	45.7	1/30	40.9
	1	1/31	73.1	1/27	52.0	1/37	50.9
	Shaking table	853cm/s2		852cm/s2		625cm/s2	

* : Data was not obtained

earthquake intensity. The torsional responses were scarcely observed for the both models at any input levels. The relative displacement distributions and the maximum interstory drift in X direction of the bidirectional tests were almost the same as the one of the unidirectional tests up to EL75v input level. The maximum interstory drift angle of the both models at EL75v was about 1/40. At Kobe input, however, the maximum interstory drift angle was 1/24 under the unidirectional input, while 1/21 under the bidirectional. The maximum story shear force at Kobe input of the bidirectional test was smaller than that of the unidirectional test.

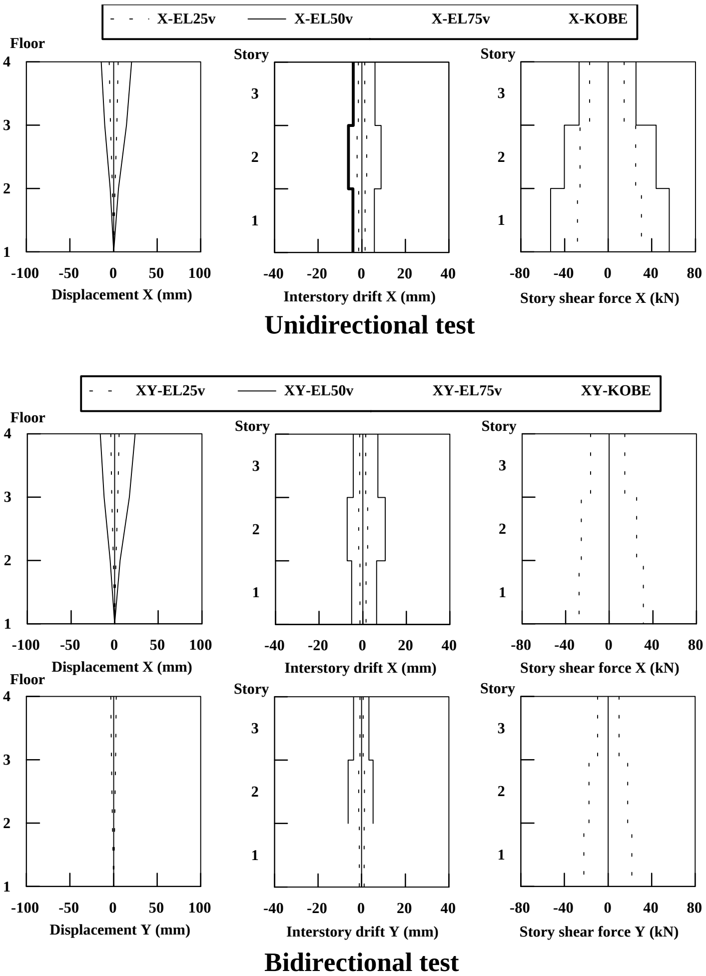
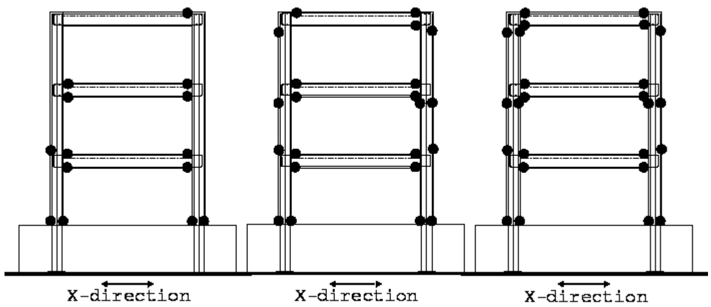


Figure 3: Maximum response distributions

The outlines of observed damage for the models after each shaking were as follows; a) After EL25v, a hairline crack appeared at the critical sections of the second and third-floor beam ends for both models. But no visible cracks were observed on the columns. b) After EL50v, minor bending cracks were observed at all beam ends, and hairline cracks were observed at the critical sections of the first-story column bottoms and the second-story column top and bottoms for both models. c) After EL75v, the cracks progressed in width and in numbers at all beam ends and the first-story column bottoms for both models. In addition, some slight spallings of concrete were occurred at the second and third-floor beam ends and at the first-story column bottoms in case of the bidirectional test. A tendency was observed that the cracks concentrate at the critical section of beams for both models. d) After Kobe, cracks widened and expanded at all beam ends, the first-story column bottoms, and at the second and third-story column top and bottoms of both models. The maximum crack width at the second-floor beam end was about 1mm for the unidirectional test and about 5mm for the bidirectional test. In addition, in case of the bidirectional test, the main bars at some of the second-floor beam ends and at the first-story column base corners appeared by the heavy concrete spalling. And also, spalling of concrete were occurred at some of the second-story column top and bottom corners in a diagonal direction, which correspond to the major response direction under the bidirectional Kobe earthquake.



XY-EL50V XY-EL75V XY-KOBE

Figure 4: Locations of yielded main bars in X direction (Bidirectional tests)

Main bar yielding and collapse mechanism

The locations of yielded main bars at the critical sections in X direction of the bidirectional test model are illustrated in Fig.4. The yield strain of the material test was used to judge yielding of main bars. Almost the same locations of yield were observed for the unidirectional and the bidirectional test model in Y direction. The progress of the location and the collapse mechanism of the model were as follows; 1) During EL25v, every main bars did not yield. 2) During EL50v, the main bars at the second and third-floor beam ends and at the first-story column bottoms yielded. 3) During EL75v, almost all the main bars at all beam ends yielded and a desirable overall collapse mechanism was made. However, some of the main bars at the top and bottoms of the second-story columns, and at the top of the third-story columns were also slightly exceeded the yield strain. 4) During Kobe, yielded main bars at the critical sections of columns were increased in number. However, a soft-story collapse mechanism might not yet be made at the second story.

Story restoring force characteristics and response waveforms

In Fig.5, story shear-interstory displacement relations in X direction at EL75v and Kobe are compared between the unidirectional and the bidirectional tests. At EL75v, although some partial differences were found in the story shear force, the maximum interstory displacement and the loop characteristic was almost the same between the unidirectional tests and the bidirectional tests. At Kobe input, however, the maximum story shear force at the first and second-story of the bidirectional test was about 20% lower than that of the unidirectional, and the maximum interstory displacement of the bidirectional test was larger than that of the unidirectional, especially at the second-story. One of the reasons of this difference between the bidirectional test and the unidirectional test at Kobe input was that the failure of the column corners in a diagonal direction was severe, where the diagonal direction corresponds to the major response direction for the bidrectional input of Kobe. (See the X-Y orbit in Fig.6)

The estimated retained horizontal strength of the model is also indicated in Fig.5. In the calculation of the beam bending strength when the slab was in tension, slab reinforcement contribution was considered in two cases; Case1) Slab upper reinforcements within 0.1L region, and Case2) Both upper and lower reinforcements within the whole slab width, as mentioned in section 2.4. At EL75v input of both unidirectional and bidirectional test, the maximum story shear at the first and second-story was almost the same as the calculation considering the whole slab contribution. At Kobe input of the unidirectional test, the maximum story shear at the first-story exceeded the

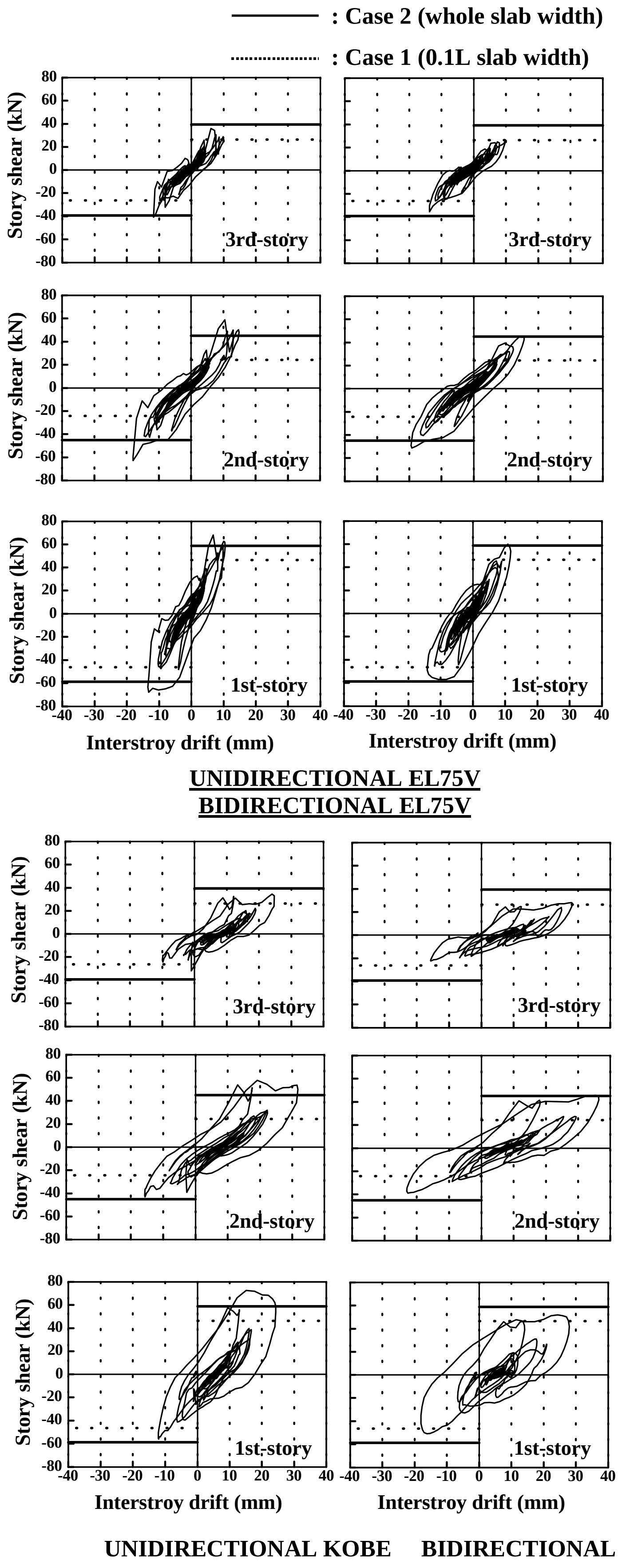


Figure 5: Story shear-interstory displacement relations (Unidirectional tests vs. Bidirectional tests)

calculation considering the whole slab contribution, while for the bidirectional test, the story shear force decreased especially at the first story.

In Fig.6, the interstory displacement waveforms at the second-story of the bidirectional tests are superimposed on that of the unidirectional tests. The interstory displacement orbits of the bidirectional tests are also shown. From the comparison of the interstory displacement waveforms of the bidirectional tests with the unidirectional one, it was found that there was no difference at EL25v input. At EL50v and EL75v, there were slight differences in some part of the waveforms, but the maximum interstory displacement was almost the same between the bidirectional test and the unidirectional one. At Kobe, however, the maximum interstory displacement of the bidirectional test was about 15% larger than that of the unidirectional test. From the interstory displacement orbit for the bidirectional tests, the major response direction was observed diagonally at Kobe input.

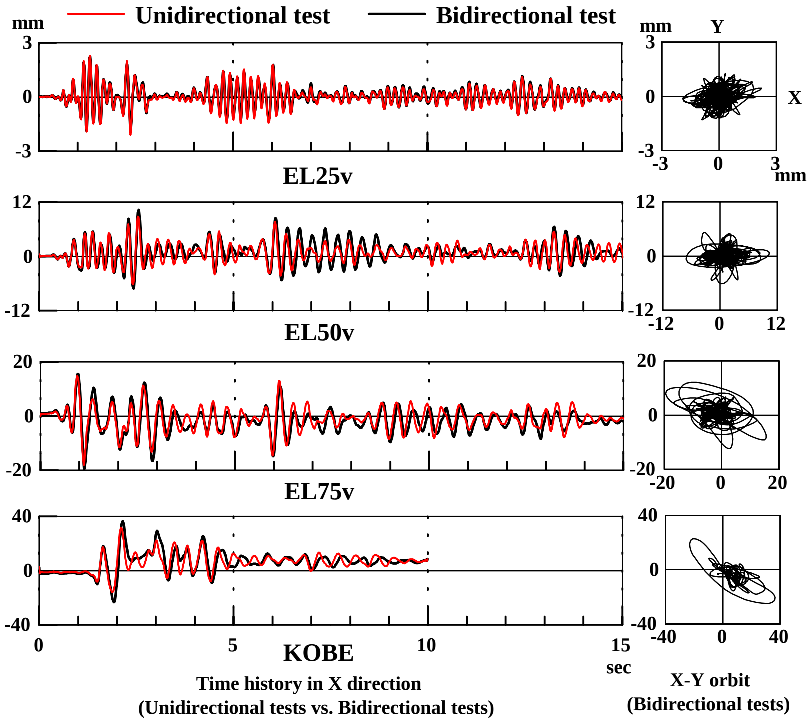


Figure 6: Interstory displacement at 2nd-story

Maximum strain distribution of slab reinforcement

The maximum strain distributions of the slab upper reinforcements at the second-floor for each input level of the unidirectional tests are shown in Fig.7. Maximum rotational angles at the second-floor beam end when the slab was in tension for each input level are also indicated in the notation. The locations of the slab bars where strain was measured were 0.02L, 0.09L, 0.21L and 0.33L from the beam edge, where L indicate the model span length

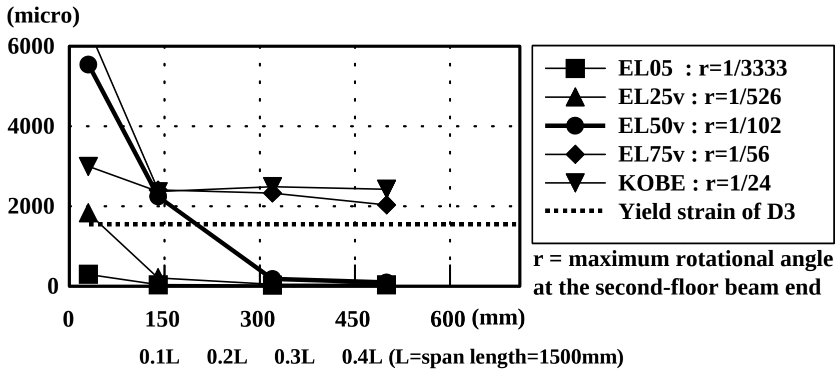


Figure 7: Maximum strain distributions of slab upper reinforcements at 2nd-floor (Unidirectional tests)

of 1500mm. Slab upper reinforcements within 0.1L region are often taken into account to estimate the bending strength of beams in the seismic design of RC frame structures. At EL50v input, the slab upper reinforcements within 0.09L region exceeded the yield strain obtained from the material tests of D3 bars, and the maximum rotational angle at the beam end was 1/102. However, at EL75v and Kobe inputs, all the slab upper reinforcements where strain was measured were exceeded the yield strain level, and the maximum rotational angles at the beam end were 1/56 and 1/24, respectively.

CONCLUDING REMARKS

From the shaking table tests of the two 1/4th-scale three-story RC frame models subjected to the bidirectional and the unidirectional earthquake motions, following main results were obtained;

1) The models exhibited the strong column-weak beam collapse mechanism under the intense ground motion of both unidirectional and bidirectional inputs, where the maximum intersroty drift angle was about 1/40 for both models. However, some of the column main bars at the second and third-story were also slightly exceeded the yield strain.
2) Bidirectional-input effects on the story shear-interstory displacement relations were not recognized until the strong column-weak beam collapse mechanism was made with the maximum interstroy drift angle of about 1/40. However, at the subsequent bidirectioal input of Kobe, the story shear reductions and the increase of interstory displacements were observed compared to the unidirectional test, where the maximum interstory drift angle was about 1/25 under the unidirectional input. One of the reasons of this difference was that the failure of the column corners in a diagonal direction was severe, where the diagonal direction corresponds to the major response direction for the bidrectional input of Kobe.
3) Under the unidirectional earthquake motions, the second-floor slab reinforcements within 0.1L (L=span length) region from the beam edge exceeded the yield strain when the maximum rotational angle at the beam end was about 1/100. Therefore, considering slab reinforcements within 0.1L region on the beam strength as a slab effect is thought to be appropriate in the seismic design of RC frames with a allowable maximum story drift angle is about 1/100. However, the slab reinforcement within at least 0.33L region yielded when the maximum rotation angle at the beam end was larger than 1/50.
4) The simple calculation of the retained horizontal strength considering the whole slab reinforcement contribution on the bending strength of beams could estimate the maximum story shear force at the first and second-story when the maximum interstory drift angle was more than 1/40.

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