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CORRELATION OF EXPERIMENTAL AND ANALYTICAL RESPONSES OF A 1:12 SCALE 10-STORY REINFORCED CONCRETE FRAME HAVING NONSEISMIC DETAILS

Han-Seon LEE[1] And Kyi-Yong KANG[2]

SUMMARY

The pushover analysis technique is now attracting the world-wide interest for the prediction of elastic and inelastic behavior of structures in the seismic evaluation of existing buildings. However, the reliability of this analysis technique has not been fully checked with regards to the test results in the case of structures having nonseismic details. The objective of this study is to investigate the correlation between the experimental and analytical responses of a 1:12 scale 10-story reinforced concrete frame having non-seismic details by using DRAIN-2DX[Prakash 1993] and the test results reported elsewhere[Lee 1999]. This study concludes from this comparison that the overall responses such as story shear versus inter-story drift can be predicted with quite high reliability while the local deformations or failure modes in the critical regions of the structure can be described with the only limited credibility by DRAIN-2DX.
Keywords : pushover analysis, inelastic behavior, correlation, experiment, reinforced concrete

INTRODUCTION

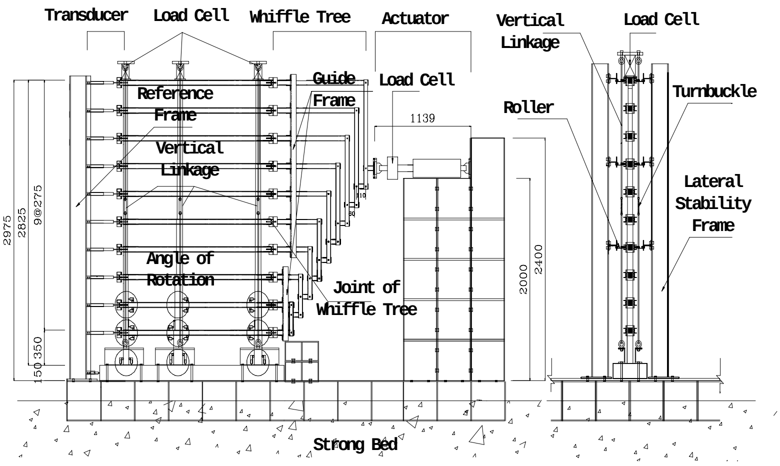
Seismic evaluations of existing building structures which have been recently developed[ATC 1996 and BSSC 1997] generally adopt the nonlinear pushover analysis technique as a simple and useful tool to check the overall strength, stiffness and ductility of the whole structure as well as the deformability demands on the local elements and joints. Nowadays, several analysis computer codes[Prakash 1993 and Kunnath 1996] are available for the prediction of these characteristics in the behaviors of structures. Before using this technique as a sound and universal tool, it seems necessary to verify the credibility of these programs by investigating the correlation between the analysis and the experiment. There have been several researches on this subject[Charney 1991 and Negro 1998]. However, very little research work on the calibration of these programs to the actual response of the structures having nonseismic details has been conducted. Thus, this study is aimed at verifying the correlation between the experimental and analytical responses of a high-rise RC frame having nonseismic details.

EXPERIMENTAL MODEL AND SETUP

A building frame designed according to the current Korean seismic code[Korea 1988] and detailed in the Korean conventional practice was selected. A 1:12 scale plane frame model was manufactured according to the similitude law (**Fig. 1**). A typical nonseismic detail in an exterior joint of the structure is shown in **Fig. 2**. The Korean reinforcement details generally have the characteristics of nonseismic details as follows : (1) The lap splices of column bars are located at the bottom of columns. (2) There is no hoop in the joint. (3) The tail of hooked anchorage for the bottom bars of the beam is oriented downward. (4) Large spacings between column hoops. The reversed lateral load test in the lower level of displacements and the monotonic push-over test up to

[1] *Department of Architectural Engineering, Korea University, Seoul, 136-701, Korea e-mail : hslee@kuccnx.korea.ac.kr*
[2] *Engineer, LG Construction Corp., Seoul, 100-722, Korea*

the maximum capacity of the used displacement transducer at the roof were performed quasi-statically under the displacement control. To simulate the earthquake effect, the lateral force distribution was maintained to be an inversed triangle by using a whiffle tree(**Fig. 1**). From the tests, lateral force, story displacements, and local rotations were measured. In particular, the angular rotations in some ends of members were measured over the length of the depth of beams or the dimension of column sections in the direction of loading. The details on the procedure and results of the experiment are given elsewhere[Lee 1999].



(a) Front view (b) Side view

Fig. 1 Experimental setup of test model (unit : mm)

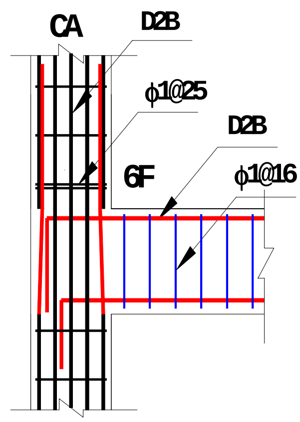


Fig. 2 Detail in exterior joint at sixth floor

ANALYTIC MODELING BY DRAIN-2DX

Analysis was made using the plastic hinge beam-column element (type 02)[Prakash 1993]. This element model is composed of one elastic beam, the plastic hinges and the rigid end zones at both ends (**Fig. 3**). The joint is assumed rigid end zone. **Fig. 4** shows the analytic model of the whole structure used for the pushover analysis. The deformation hardening ratio of each section is assumed 10% and effective moments of inertia (I_e) are assumed $0.5I_g$ for all columns and beams. **Table 1** indicates the P and M values for the P-M interaction diagrams of the columns and beams whose sectional properties and mechanical characteristics of materials are given elsewhere[Lee 1999]. The data in column A1 means the initial input obtained by using the average yield strength of sampled model materials.

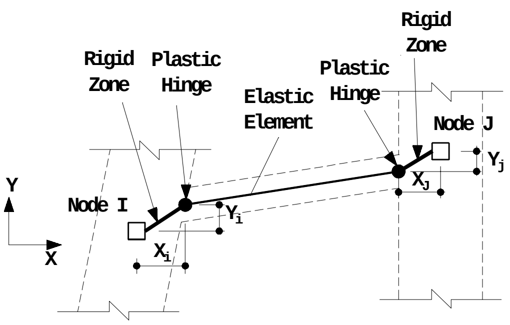


Fig. 3 Composition of Type 02 element (adapted from [Prakash 1993])

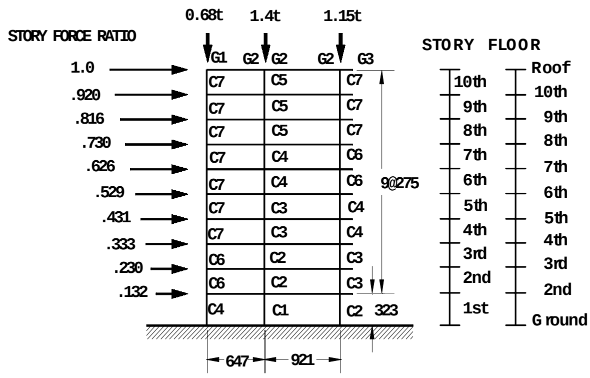


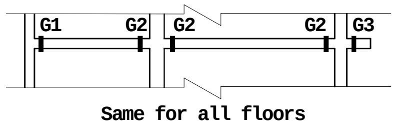
Fig. 4 Structural model and member notation (unit : mm)

CORRELATION BETWEEN ANALYSIS AND EXPERIMENT

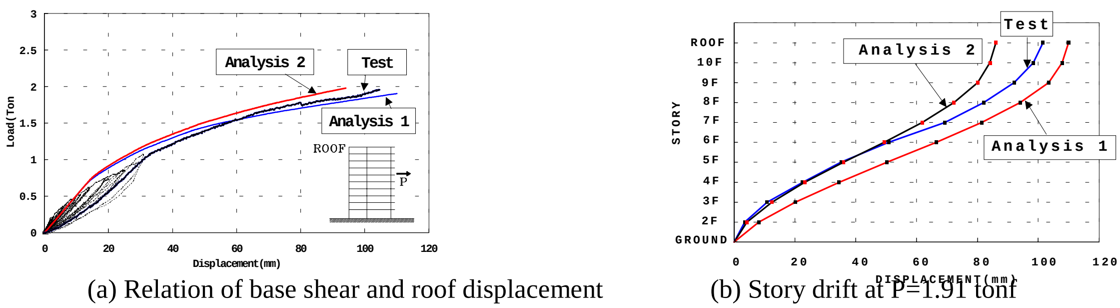
Pushover analysis using input data A1 in **Table 1** has revealed that the columns at the lower stories have yielded and undergone large plastic deformations, which contradict the test results. So, the model reinforcements at the lower stories were extracted from the relatively undamaged portion of the model after the completion of test and the tensile test was conducted again to check the validity of the initial data. The results of this retest have shown that the average of the yield strength of D2B(D22) reinforcements used for the beams is about 10% higher than that of the initially sampled model reinforcements. Furthermore, it was found that D2A(D25) reinforcements used for the columns at the first and second stories were not heat-treated at all and that the average of the yield strengths of these model reinforcements is about 2.8 times the initial input value. Therefore, these input values of axial load P and bending moment M in the P-M interaction diagram were revised to resolve this discrepancy between the results of the initial analysis and the experiment. The initial input values given in column A1 of **Table 1** have the output denoted analysis 1 whereas the revised ones given in column A2 of **Table 1** produced the output denoted analysis 2 from here on. In the following, the results of analysis 1 and analysis 2 together with those of test will be compared and the correlation of analyses and experiment will be investigated.

Table 1 P and M values of columns and beams

Section	P_{yt} (tonf)		P_{yc} (tonf)		M_y^+(tf-mm)		M_y^-(tf-mm)		M_b^+(tf-mm)		P_b^+(tonf)		M_b^-(tf-mm)		P_b^-(tonf)	
	A 1	A 2	A 1	A 2	A 1	A 2	A 1	A 2	A 1	A 2	A 1	A 2	A 1	A 2	A 1	A 2
C1*	7.3	21.1	26.0	39.8	333.2	624.2	333.2	624.2	476.5	644	9.8	0.9	476.5	644	9.8	0.9
C2*	6.3	18.1	21.9	33.7	238.4	450.2	238.4	450.2	341.3	463.4	8.0	1.1	341.3	463.4	8.0	1.1
C3*	4.4	4.8	17.2	17.6	139.5	152.1	139.5	152.1	218.7	226.6	7.2	6.9	218.7	226.6	7.2	6.9
C4*	3.6	3.9	13.6	13.9	99.3	107.4	99.3	107.4	151.9	157.9	5.6	5.4	151.9	157.9	5.6	5.4
C5*	2.5	2.7	10.1	10.3	59.9	64.6	59.9	64.6	98.0	101.4	4.0	3.9	98.0	101.4	4.0	3.9
C6*	3.3	3.6	12.1	12.4	79.5	85.8	79.5	85.8	120.8	125.3	4.9	4.7	120.8	125.3	4.9	4.7
C7*	2.2	2.4	8.8	9.0	45.6	48.9	45.6	48.9	73.4	75.8	3.5	3.4	73.4	75.8	3.5	3.4
G1†	-	-	-	-	37.9	41.3	25.7	28.4	†							
G2†	-	-	-	-	29.8	31.9	68.1	73.2								
G3†	-	-	-	-	13.6	14.7	37.8	41.1								



*See **Fig.4** for the definition.



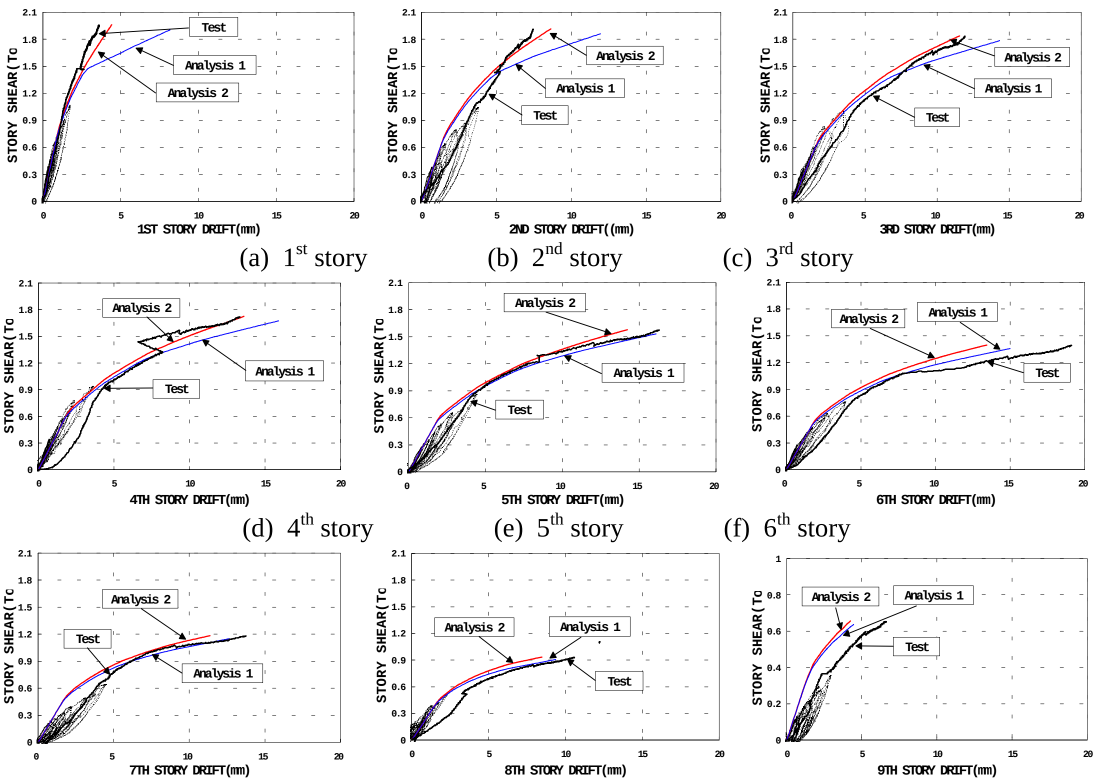
(a) Relation of base shear and roof displacement (b) Story drift at P=1.91 tonf

Fig. 5 Lateral displacements

Overall behavior : The overall behavior of the model structure can be represented by the curve of the base shear versus the roof drift and the curve of the vertical distribution in story drifts (**Fig. 5(a)** and **(b)**). Though the input values of P and M in analysis 2 is much larger in the lower stories than those of analysis 1, the ultimate strengths of the whole structures are similar in both cases (**Fig. 5(a)**). The distribution of story drifts can be predicted by analyses with fairly high reliability as well though the order of discrepancy may be higher in this case than in the case of the ultimate strength. In this paper, the test curves are always composed of dotted hysteretic curves given by the reversed lateral load test in the first phase and a solid curve obtained through the monotonic pushover test in the second phase. Therefore it should be noted that the curve given by the pushover test must be the envelope of these curves. This is the case for all the figures shown later.

Story shear versus interstory drift : Fig. 6 shows the relation between the story shear versus the story drift at each story. In general, the results of analyses are quite similar to those of the test. However, it can be found that the curves given by both analysis 1 and analysis 2 can not describe the clear yielding phenomenon at the 6th and 7th stories. The analytic curves in the upper stories generally tend to underestimate the story drifts given by the test.

Vertical distribution of response parameters at max. base shear : The results of the story shear, story drift, interstory drift ratio (I.D.R.) and the absorbed energy at the base shear of 1.96 tonf are shown in **Table 2**. The distributions of I.D.R. and absorbed energy over the height of the structure are shown as histograms in **Fig. 7**. The maximum I.D.R. occurs at the sixth story in the test whereas this occurs at the fifth story in the analysis 2. On the other hand, the sixth story has the maximum absorbed energy in the test while the fourth story has the maximum in the analysis 2. In general, the vertical distribution of I.D.R.'s and the absorbed energy at each story in the results of analysis 2 are more dispersed than in those of the test.

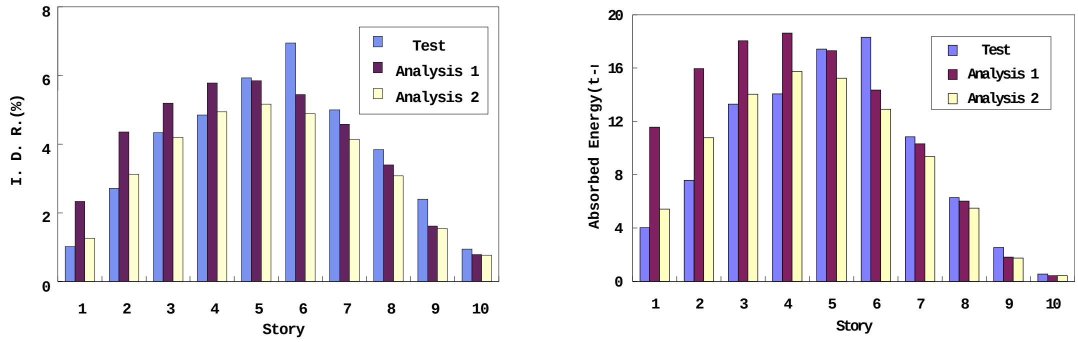


(a) 1st story (b) 2nd story (c) 3rd story

(d) 4th story (e) 5th story (f) 6th story

(g) 7th story (h) 8th story (i) 9th story

Fig. 6 Story shear versus interstory drift

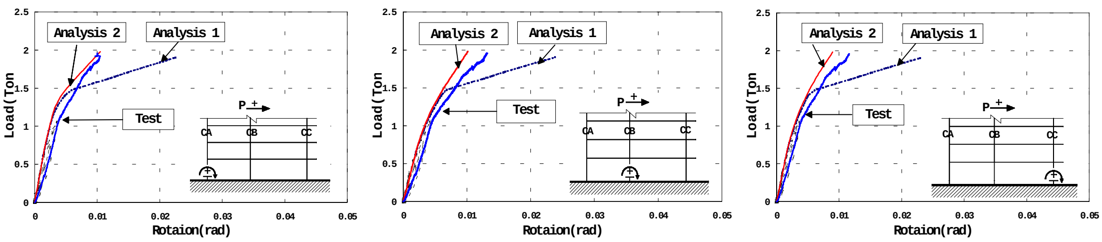


(a) Interstory drift ratio (b) Absorbed energy

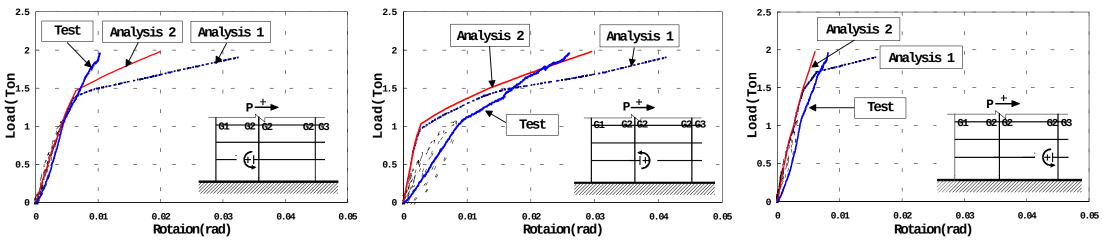
Fig. 7 Vertical distribution of interstory drift ratio and absorbed energy

Table 2 Comparison of test and analysis results at max. base shear

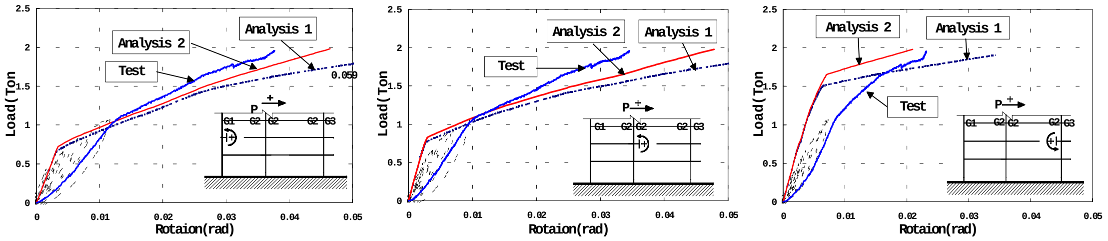
Story	Inter-Story Drift (mm)		Inter-Story Drift Ratio (%)		Absorbed Energy (tf-mm)		Story Shear (tonf)
	Test	Analysis 2	Test	Analysis 2	Test	Analysis 2	
1st	3.57	4.42	1.02	1.26	4.04	5.41	1.96
2nd	7.46	8.63	2.71	3.13	7.57	10.76	1.91
3rd	11.93	11.56	4.34	4.20	13.29	14.04	1.83
4th	13.34	13.61	4.85	4.95	14.07	15.73	1.72
5th	16.31	14.21	5.93	5.17	17.41	15.24	1.58
6th	19.1	13.44	6.95	4.89	18.32	12.90	1.39
7th	13.75	11.37	5.0	4.13	10.83	9.35	1.18
8th	10.6	8.45	3.85	3.07	6.29	5.49	0.93
9th	6.61	4.24	2.40	1.54	2.53	1.74	0.65
10th	2.6	2.11	0.94	0.77	0.55	0.42	0.34



(a) CA column (1st story) (b) CB column (1st story) (c) CC column (1st story)



(d) 2nd floor beam end I (e) 2nd floor beam end II (f) 2nd floor beam end III

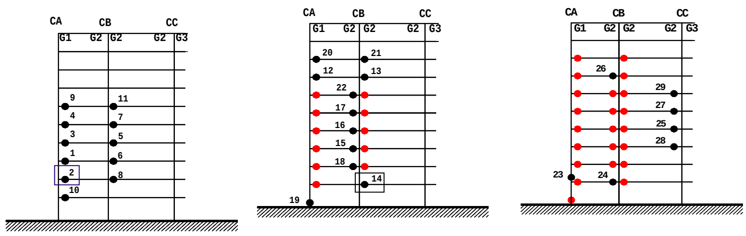


(g) 3rd floor beam end I (h) 3rd floor beam end II (i) 3rd floor beam end III

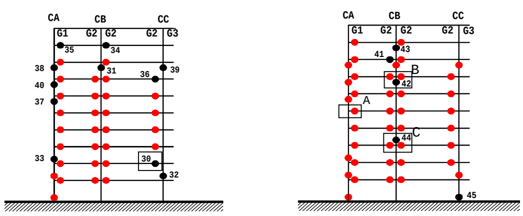
Fig. 8 Rotational angle at critical regions

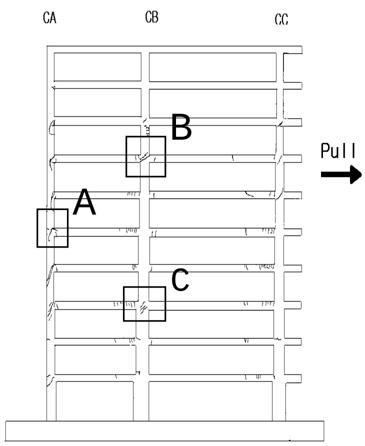
Angular rotations in ends of critical members : Since DRAIN-2DX produces the angles of plastic rotations at plastic hinges as lumped plasticity on the 1:1 basis to the history of applied loads, it is necessary to add the elastic rotations to these plastic rotations to verify the correlation of analysis and experiment. The elastic rotations which occurred over the instrumented range in the ends of members can be calculated assuming linear distribution of curvatures between the ends of members. Then, these angles are added to the corresponding plastic rotational angles to obtain the total. **Fig. 7** shows the curves of the base shear versus the rotational angles in the ends of critical members. The curves by analysis 2 are quite similar to those of the test though they overestimate the rotations in the elastic range while they underestimate those in the plastic range.

Occurrence of plastic hinges and crack patterns : The occurrence of plastic hinges throughout the structure predicted by analysis 2 is shown in **Fig. 9**. When we investigate the curves in **Fig. 8(g), (e)** and **(i)** which correspond to the plastic hinges 2, 14, and 30, respectively in **Fig. 9**, it can be noted that the sequence of the occurrence of plastic hinges predicted by analysis 2 is highly reliable. Finally, when we compare the final distribution of plastic hinges as shown in **Fig. 9(e)** with the crack patterns after the completion of the test in **Fig. 10**, the damage predicted by analysis 2 is also credible to a reasonable extent. It is interesting to find that where the exterior joint, the detail of which is shown in **Fig. 2**, has a plastic hinge only at the beam end in A of **Fig. 9(e)**, the joint has diagonal shear cracks as shown in A of **Fig. 10**. In B and C of **Fig. 9(e)** where the interior joints have plastic hinges at both beams and one of the columns, the joint has also shown diagonal shear cracks in B and C of **Fig. 10**. Here, it is important to note that the analysis 2 does not mean this type of failure by the occurrence of plastic hinges adjacent to a certain joint. This is a sort of limitation of the type 02 model in DRAIN-2DX.



(a) Roof drift = 20mm (b) Roof drift = 40mm (c) Roof drift = 60mm





(d) Roof drift = 80mm (e) Roof drift = 100mm

Fig. 9 Occurrence of plastic hinges in Analysis 2
(The number denotes the sequence of occurrence.)

Fig. 10 Crack pattern after test

CONCLUSIONS

Based on the investigation of the correlation between the analytic and experimental responses of a 1:12 scale 10-story reinforced concrete frame having nonseismic details, the following conclusions can be drawn.

(1) Though the analytic model of the plastic hinge beam-column element is simple and easy to apply, the prediction by using this model turns out to be reliable in the following aspects : (a) The ultimate strength of the whole structure and the vertical distribution of story drifts can be predicted with high reliability even if there may be some errors in the input information on the section properties. (b) The sequence of occurrence and the distribution of plastic hinges are similar to the test results.

(2) However, DRAIN-2DX seems to have some limitations in the exact prediction of local inelastic behavior or damage patterns in the following aspects : (a) The curves of rotational angles in the critical ends of members have rounded smooth curve in the test with respect to the applied load, while those given by DRAIN-2DX always show bi-linear responses. Hence, the results of DRAIN-2DX tend to overestimate the rotational angle in the elastic range and underestimate that in the inelastic range. (b) The plastic hinge beam-column model reflects the flexural behavior only. Therefore, the shear failures in the joints can not be expected to be predictable with this model. In particular, in case when the beam-column joints have the nonseismic details, it appears to be necessary to perform the experiment to clarify the characteristics of inelastic behaviors of these details and to establish the appropriate analytic model for those elements, and finally to incorporate this model to the base module in DRAIN-2DX.

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