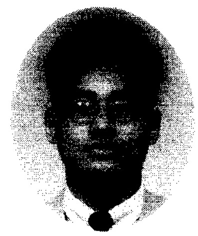
비내진 상세를 가진 1:12축소 10층 R.C.골조의 비선형 거동에 대한 실험과 해석의 상관성

Correlation of Experimental and Analytical Inelastic Responses of A 1:12 Scale 10-Story Reinforced Concrete Frame with Non-seismic Details

이한선*
Lee, Han-Seon

강귀용**
Kang, Kyi-Yong

ABSTRACT

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 by the test results in the case of structures with nonseismic details. The objective of this study is to verify the correlation between the experimental and analytical responses of a 1:12 scale 10-story reinforced concrete frame with non-seismic details by using DRAIN-2DX[9] program and the test results[1] performed previously.

It is concluded from this comparison that the overall responses such as the relations between story shear versus interstory drift and the local deformations such as plastic rotations can be predicted with quite high reliability.

Keywords ; Pushover analysis, Inelastic behavior, Correlation of analysis and experiment, Story shear, Interstory drift, Response modification factor, Plastic hinge

* 정회원, 고려대학교 건축공학과 부교수

** 정회원, 고려대학교 건축공학과 석사과정

• 본 논문에 대한 토의를 1999년 6월 30일까지 학회로 보내 주시면 1999년 8월호에 토의회답을 게재하겠습니다.

1. Introduction

Seismic evaluations of existing building structures and performance-based design methodology which have been recently developed[3],[4] generally adopt the nonlinear pushover analysis technique as a simple and useful tool to check the overall strength of the whole structure as well as the deformability demands in the local elements and joints. Also, in the current seismic codes such as UBC 97[5] and Korean seismic code[6], the overstrength and the ductility or energy dissipation capacity by inelastic deformation of the whole structures are considered indirectly by using response modification factor R in the equation of design base shear. However, the reasoning behind the determination of these response modification factors is not clear even to the specialists in the field of earthquake engineering. Therefore, some researchers[7],[8] tried to reach more reasonable values of response modification factors by analysing the structural inelastic characteristics.

Nowadays, several analysis computer programs[9],[10] are available for the prediction of non-linear behaviors of structures. But it is necessary to verify the credibility of these programs by comparing the analytic results with the test results. Particularly, most of the reinforced concrete structures, generally designed and constructed in Korea, have non-seismic details. However, very few research work on the calibration of these programs to the actual response of the structures with nonseismic details has been conducted in the world.

In the experimental research stated in the reference (2), a structure actually built in Korea was selected and manufactured at the scale of 1:12. And lateral load tests (reversed lateral load test, monotonic pushover test) were performed. In this paper, these test results are compared with analytic ones using DRAIN-2DX V1.10[9] to verify its reliability and limitations in the applications.

2. Analysis Model using DRAIN-2DX

2.1 Material Models

Compressive strength(f_c') of model concrete, and the tensile and yield forces of model reinforcements are obtained from the test and shown in **Table 1** and **2**, respectively. For other informations not available, assumed values are used.

The strain of the model concrete at the maximum strength is assumed to be 0.0025[13]. The moduli of elasticity of model concrete and model reinforcement are taken to be 213,000 $\mathrm{kgf/cm^2}$ and 2.1×10^6 $\mathrm{kgf/cm^2}$, respectively.

Table 1 Test result of model concrete (f_c': $\mathrm{kgf/cm^2}$)

Moist Curing (28days)	Field Curing (51days)
245.1	315

*Mean value of compressive strength(f_c') based on ϕ 5cm×10cm cylinder

Table 2 Test result of model reinforcement

Model Reinforcement Yield and Tensile Force (kgf)						
	D2A (D25)*		D2B (D22)		ϕ 1.0 (D10)	
	Yield Force	Tensile Force	Yield Force	Tensile Force	Yield Force	Tensile Force
Initial	174	199	138	179	35	50
Revised	502	536	150	173		

* D25 in the parenthesis denotes the corresponding prototype reinforcement.

2.2 Structural Model

The joint of the analytic model was assumed rigid end zone as shown in **Fig. 1** and the length of the rigid end zone is taken to the effective depth of the beam or the dimension of columns sections in the direction of the loading[3]. The weight of the model was concentrated on each node. Considering the use vertical linkages[1] in the test, concentrated loads of 0.68 tonf, 1.4 tonf and 1.15 tonf are applied to the columns as shown in **Fig. 2** at the roof. Analysis was made using the plastic hinge beam-column element (type 02)[9]. As shown in **Fig. 1**, this element is composed of one elastic beam, the plastic hinges and the rigid end zones at both ends.

Fig. 2 shows the analytic model of the structure used for the pushover analysis. **Fig. 3** shows the sections of column and beam elements. The strain hardening ratio of reinforcements is assumed 10% and effective moments of inertia(I_e) are assumed $0.5I_g$ for all columns and beams.[11] **Table 3** shows the P and M values for the P-M interaction diagrams of the columns and beams.

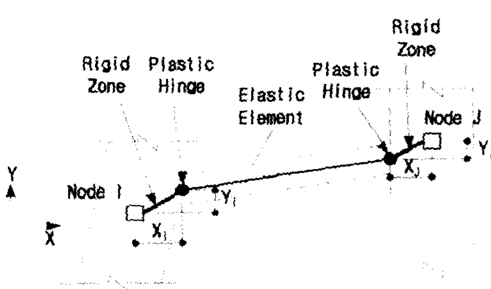


Fig. 1 Composition of Type 02 element (adapted from Ref. (9))

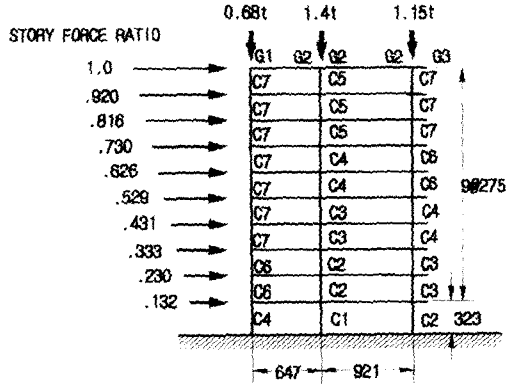
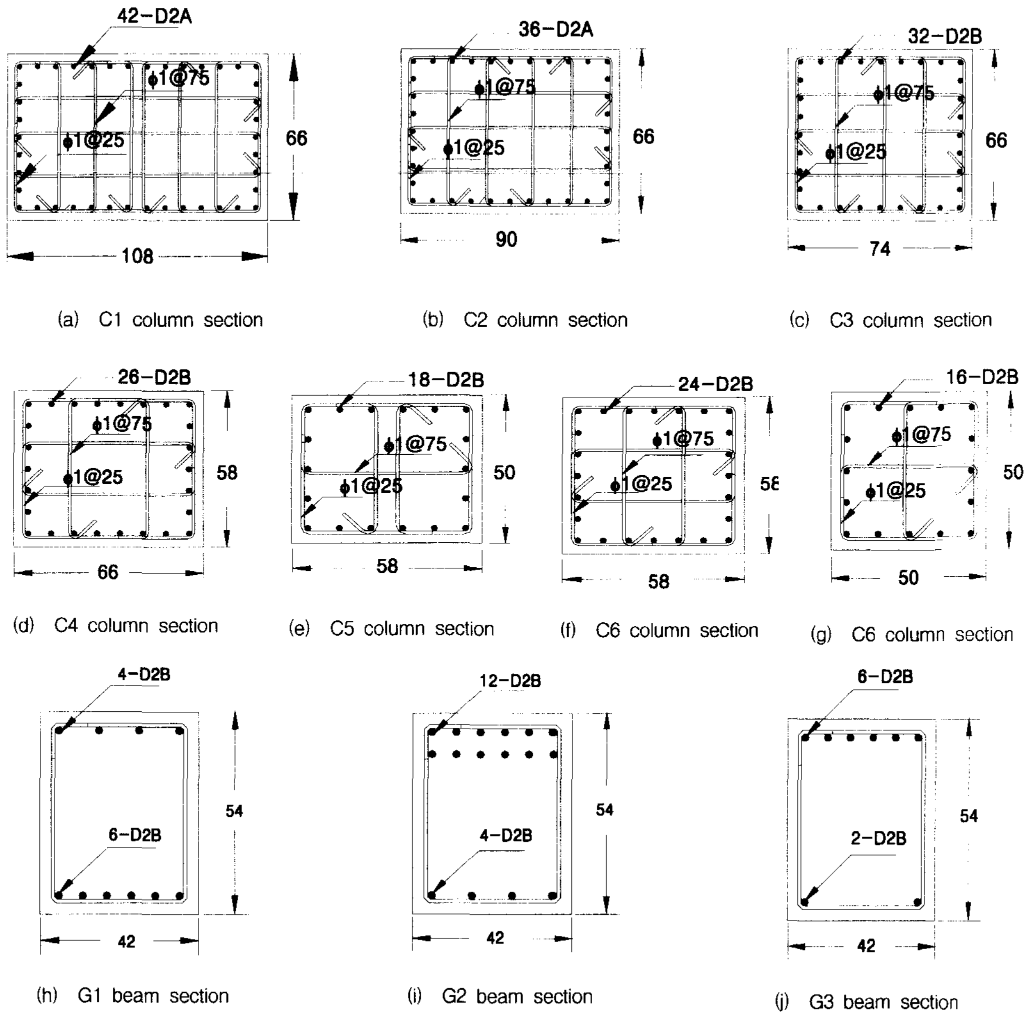


Fig. 2 Analysis model of the structure and member notation (unit : mm)

3. Correlation between analysis and experiment.

Pushover analysis using input data as shown in **Table 4** has revealed that the columns at the lower stories have much lower yield strengths in analysis than in test. So, the model reinforcements at the lower stories were extracted from the model after the completion of test and the tension test was conducted again. The results of this retest have shown that the average of the yield strength of D2B(D22) is about 10% higher than that of the initially sampled model reinforcements. Unfortunately, it was also found that D2A(D25) reinforcements in the columns at the first and second stories were not heat-treated at all and that the yield strength of this un-treated model reinforcement is about 2.8 times the initial input value. Therefore, the input values of axial load P and bending moment M were revised to perform the new pushover analysis. The initial input values as given in **Table 3** have the output denoted analysis 1 whereas the revised



(a) C1 column section (b) C2 column section (c) C3 column section

(d) C4 column section (e) C5 column section (f) C6 column section (g) C6 column section

(h) G1 beam section (i) G2 beam section (j) G3 beam section

Fig. 3 Sections of column and beam elements (unit : mm)

Table 3 P, M values of columns and beams (Analysis 1)

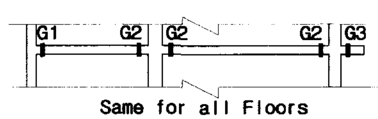
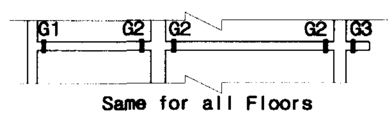
Section	P_{yt} (tonf)	P_{yc} (tonf)	M_y^+(tf-mm)	M_y^-(tf-mm)	M_b^+(tf-mm)	P_b^+ (tonf)	M_b^-(tf-mm)	P_b^- (tonf)
C1	7.3	26.0	333.2	333.2	476.5	9.8	476.5	9.8
C2	6.3	21.9	238.4	238.4	341.3	8.0	341.3	8.0
C3	4.4	17.2	139.5	139.5	218.7	7.2	218.7	7.2
C4	3.6	13.6	99.3	99.3	151.9	5.6	151.9	5.6
C5	2.5	10.1	59.9	59.9	98.0	4.0	98.0	4.0
C6	3.3	12.1	79.5	79.5	120.8	4.9	120.8	4.9
C7	2.2	8.8	45.6	45.6	73.4	3.5	73.4	3.5
G1	-	-	37.9	25.7				
G2	-	-	29.8	68.1				
G3	-	-	13.6	37.8				

Table 4 Revised P, M values of columns and beams (Analysis 2)

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)
C1	21.1	39.8	624.2	624.2	644	0.9	644	0.9
C2	18.1	33.7	450.2	450.2	463.4	1.1	463.4	1.1
C3	4.8	17.6	152.1	152.1	226.6	6.9	226.6	6.9
C4	3.9	13.9	107.4	107.4	157.9	5.4	157.9	5.4
C5	2.7	10.3	64.6	64.6	101.4	3.9	101.4	3.9
C6	3.6	12.4	85.8	85.8	125.3	4.7	125.3	4.7
C7	2.4	9.0	48.9	48.9	75.8	3.4	75.8	3.4
G1	-	-	41.3	28.4				
G2	-	-	31.9	73.2				
G3	-	-	14.7	41.1				



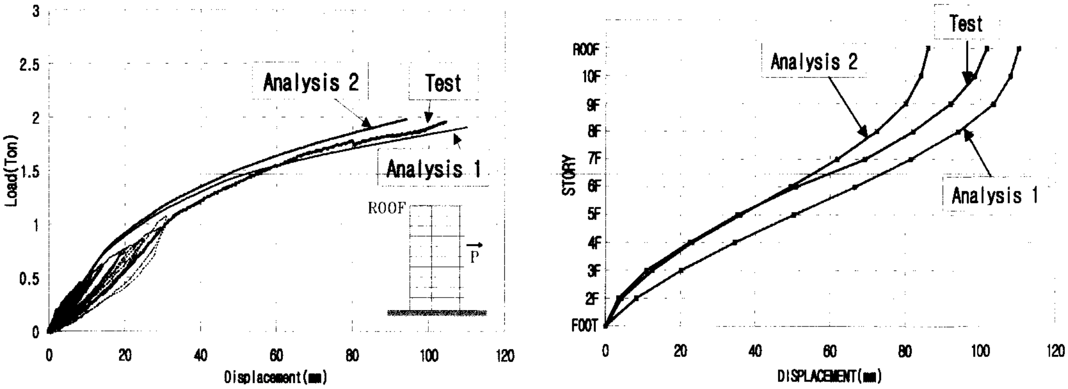
ones as shown in **Table 4** produced the output denoted analysis 2 from here on. In the following, the results of analysis 1 and analysis 2 together with those of test will be compared and the correlations of analyses and experiment will be investigated.

3.1 Story shear versus story drift

The overall behavior of the model structure can be represented by the curve of the base shear versus roof drift and the curve of the vertical distribution in story drift as shown in **Fig. 4(a)** and **(b)**. Though the input values of P and M in analysis 2 is larger than those of analysis 1, the ultimate strengths of the whole structure are similar in both cases as shown in **Fig. 4(a)**. It also shows that the result of test can be well predicted by these analyses even though they may have some errors in the information on sections. The distribution of story drifts can be predicted by analyses with reasonable reliability as well though the order of error may be higher in this case than in the case of the ultimate strength.

Fig. 5 shows the relation between the story shear versus 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.

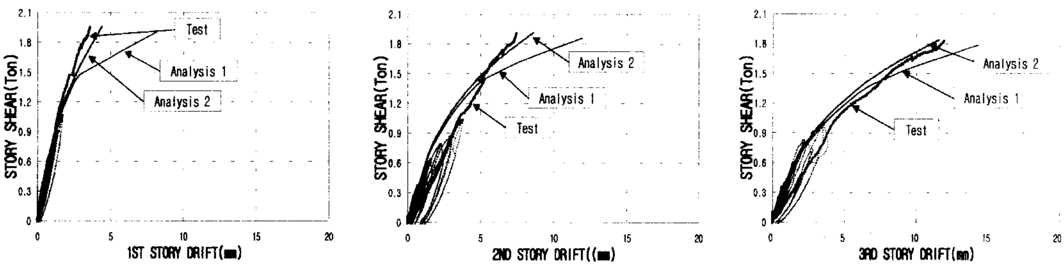
The story shear, story drift, interstory drift ratio(I.D.R.) and the absorbed energy at the base shear of 1.96 ton are shown in **Table 5**. The distributions of I.D.R. and absorbed energy are shown as histograms in **Fig. 6**. The maximum I.D.R. ratio occurs at the sixth story in the test whereas this 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 and absorbed energy in the results of analysis 2 are more dispersed than in those of the test.



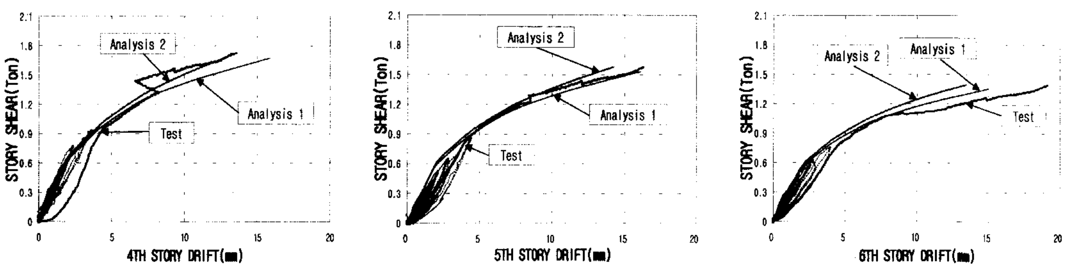
(a) Relation of force and displacement at roof

(b) Comparison of story drift at P=1.91 tonf

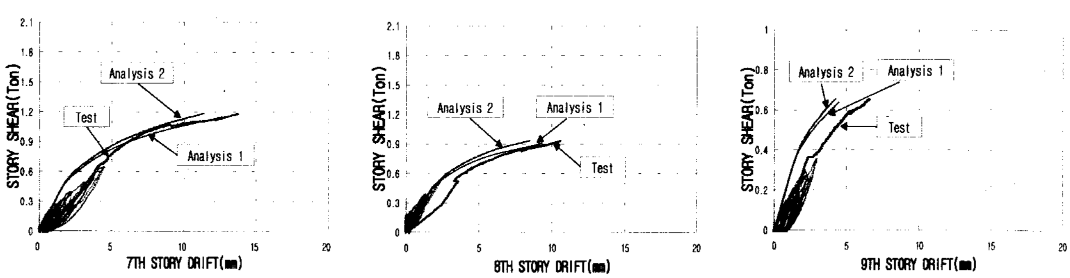
Fig. 4 Comparison of story drift



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



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

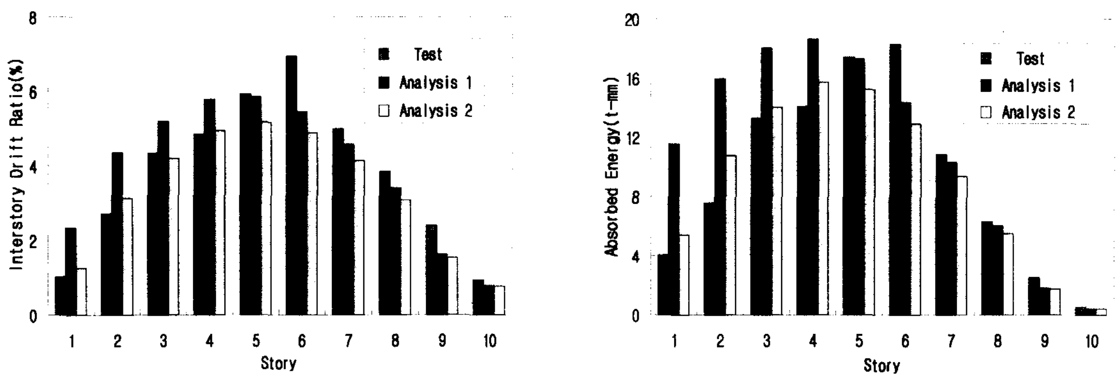


(g) 7th story (h) 8th story (i) 9th story

Fig. 5 Comparison of story shear versus interstory drift

Table 5 Comparison of test and analysis results

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



(a) Interstory drift ratio

(b) Absorbed energy

Fig. 6 Comparison of interstory drift ratio and absorbed energy

3.2 Angular rotations in ends of critical members

Since DRAIN-2DX produces the angles of plastic rotations at plastic hinges as output 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 in the critical ends of members can be calculated assuming linear distribution of curvatures between the ends of members as shown in **Fig. 7**. From this figure, the elastic rotation angle in the critical regions can be obtained by **Eq. (2)**.

$$\theta_A = \theta_{AA'} = \int_A^{A'} \frac{M}{EI} dx \qquad (2)$$

Knowing the x and l from the geometry of the structure and M_A and M_B given by DRAIN-2DX, θ_A and θ_B can be calculated by **Eq. (3)**.

$$\theta_A = \frac{x}{2EI}[(2-\frac{x}{l})M_A - \frac{x}{l}M_B] \quad (3.a)$$

$$\theta_B = \frac{x}{2EI}[(2-\frac{x}{l})M_B - \frac{x}{l}M_A] \quad (3.b)$$

where l = Clear length of member

x = the length of the plastic hinge of member

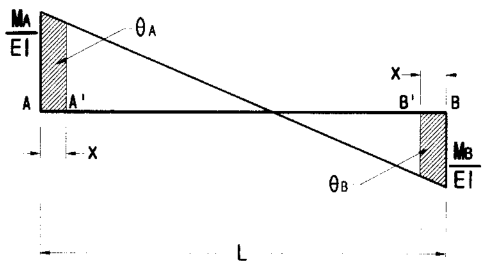


Fig. 7 Distribution of elastic curvature

EI_{eff} = effective flexural rigidity

Then these angles are added to the corresponding plastic rotational angles to represent the total. The example showing this procedure is illustrated in **Fig. 8** for the CA column at the first story.

Fig. 9 shows the curves of the base shear versus the rotational angle in the end of critical members. The curves by analysis 2 are quite similar to those of the test though they underestimate the rotations in the elastic range while overestimate in the plastic range.

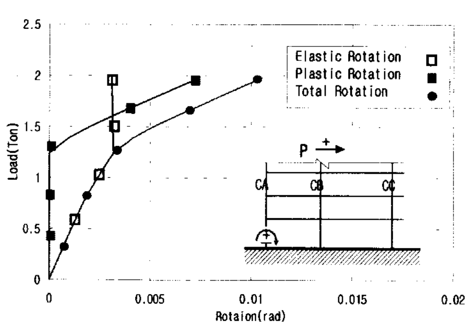
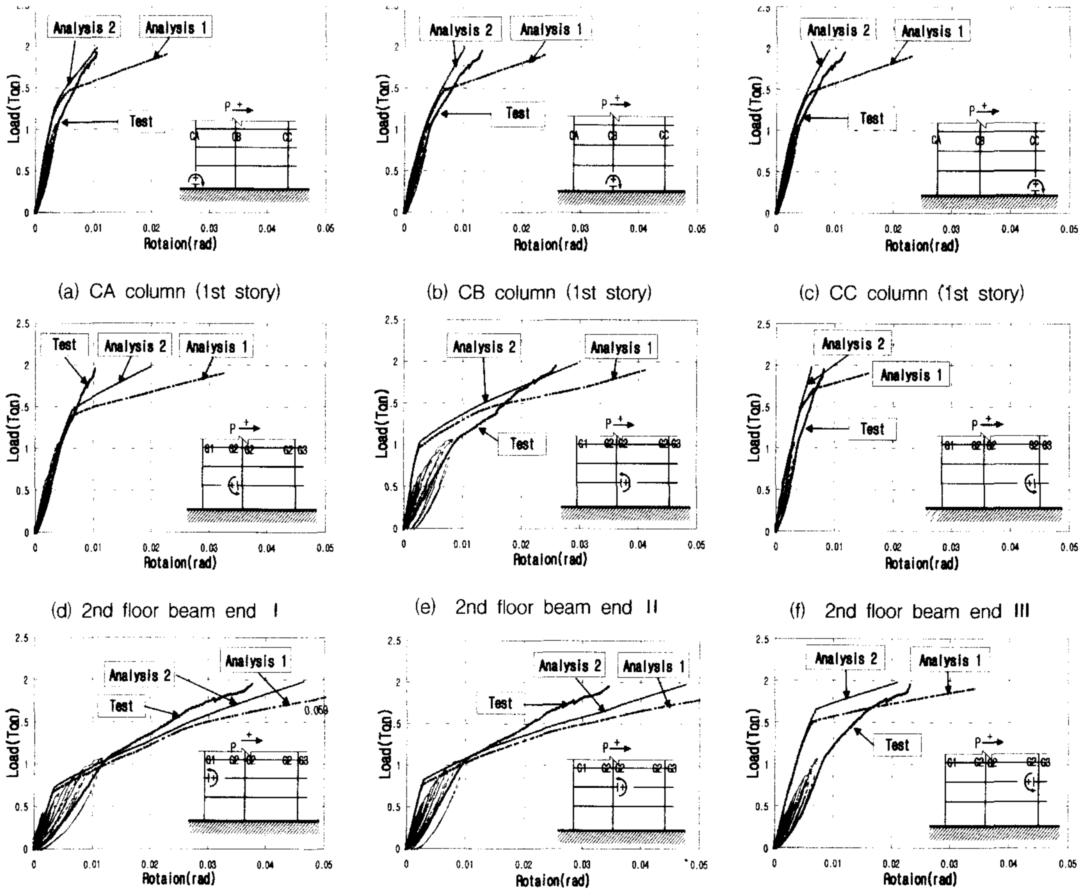


Fig. 8 Calculation of rotation at CA column

3.3 Development of plastic hinges and crack patterns

The development of plastic hinges throughout the structure predicted by analysis 2 is shown in **Fig. 10**. When we investigate the curves in **Fig. 9(g)**, **(e)** and **(i)** which correspond to the plastic hinges 2, 14 and 30 respectively in **Fig. 10**, it can be found that the sequence of the occurrence of plastic hinges predicted by analysis 2 is quite reliable. Also when the curves of **Fig. 9(f)** and the final distribution of plastic hinges as shown in **Fig. 10(f)** are compared, we can observe that no plastic hinge has occurred in the right end of the right beam at the second floor. This means again that the prediction by analysis 2 is highly reliable. Finally, when we compare the final distribution of plastic hinges as shown in **Fig. 10(f)** with the crack patterns after the completion of the test, the damage predicted by analysis 2 is also credible to a reasonable extent. It is interesting to note that where the external joints have plastic hinges both at the beam and at the lower column connected, the joint have diagonal shear cracks as shown in **Fig. 11**. Where the internal joints have plastic hinges at both beams and one of the columns, the joints have also shown diagonal shear cracks. Here, it is important to note that the analysis 2 does not mean this type of failure by two plastic hinges adjacent to a certain joint. This is a sort of limitation of the type 02 model in DRAIN-2DX.



(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. 9 Comparison of rotation

4. Conclusions

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

(1) Though the analytic model, Type 02, for the plastic hinge beam-column element is simple and easy to apply, the prediction by using this model turns out to be quite reliable in the following aspects.

- The ultimate strength of the whole structure and the vertical distribution of story drifts can be predicted with high reliability though there may be some errors in the input information on the section properties.

- The sequence of occurrence and the distribution of plastic hinges are quite similar to the test results.

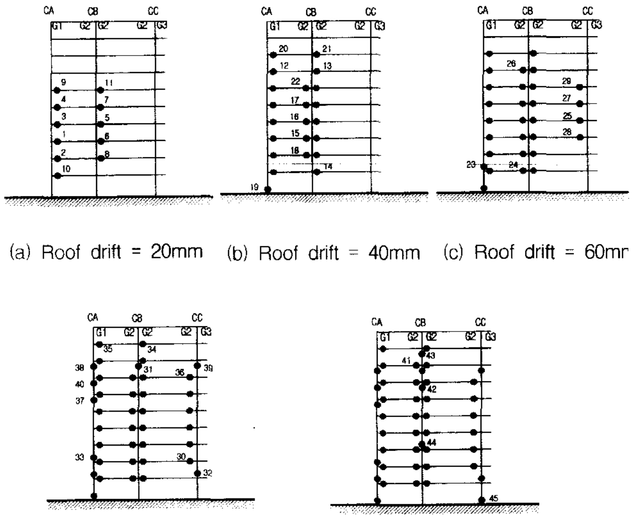


Fig. 10 Development of plastic hinges by Analysis 2
(The number denotes the sequence of occurrence.)

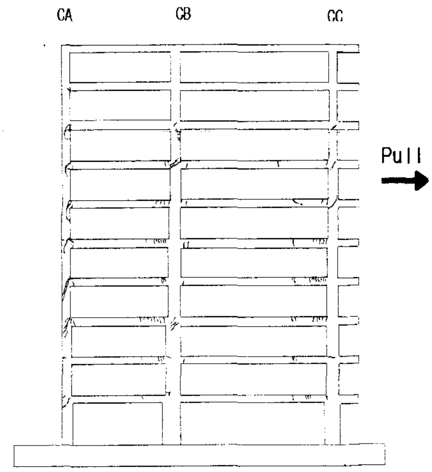


Fig. 11 Crack pattern after test

(2) However, DRAIN-2DX seems to have some limitations in the exact prediction of local inelastic behavior or damage patterns in the following aspects.

- 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. Therefore, the results of DRAIN-2DX tends to underestimate the rotational angle in the elastic range and overestimate in the inelastic range.

- The plastic hinge beam-column model reflects the flexural behavior only. Therefore, the shear failures in the joints where the connected members may have plastic hinges can not be predicted with this model. In particular, if the beam-column joints have the nonseismic details, it may be necessary to perform the experiment to clarify the characteristics of inelastic behaviors of these special details and to establish the appropriate analytic model to those elements, and finally to incorporate this model to the basic module in DRAIN-2DX.

Acknowledgements

The research stated herein was supported by STRESS at Hanyang University. The writers appreciate this support gratefully.

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요 약

현재 일방향 가력 해석기법은 세계적으로 기존 건물의 지진평가를 위해 구조물의 탄성 및 비탄성 거동을 예측하는데 가장 유용한 방법이다. 그러나, 이 해석기법은 특히 비내진 상세를 가진 철근콘크리트 골조에 대해 실험결과와 충분히 검토되지 않았다. 본 연구의 목적은 비내진 상세를 가진 고층 R.C. 골조에 대해 실험과 해석의 상관성을 검증하는데 있다. 본 연구의 목적은 DRAIN-2DX를 이용한 해석결과와 이미 수행된 비내진 상세를 가진 1:12축소 10층 철근콘크리트 골조의 실험결과를 서로 비교, 검토함으로써 그 응용상의 문제점과 신뢰성을 확인하는 데 있다.

본 연구는 실험과 해석의 상호 비교결과 다음과 같은 결론을 얻었다. 층전단력과 층간변위 및 소성회전각 같은 국부 변형의 전체적인 거동은 실험결과와 해석결과가 잘 일치하는 것으로 나타났다.

(접수일자 : 1998. 12. 7)