A STUDY ON EARTHQUAKE DAMAGES OF TIMBER HOUSING AND SIMULATION BY THE THREE DIMENSIONAL VIBRATION ANALYSIS

Katushiko KOHARA[1], Yoichiro OHKI[2] And Kenji MIYAZAWA[3]

SUMMARY

The 1995 Hyogo-Ken Nanbu Earthquake caused a large scale of damage on wooden dwelling houses [1]. This damage showed us the necessity of the new seismic design procedures considering the severe earthquake and investigation on dynamic behavior of wooden structures. The new seismic design method of wooden structures for a severe earthquake becomes the focus of researcher's and designer's attention. Our research group conducted the field survey [1] on seismic damage of wooden houses in Kobe, experimental studies of wooden shear elements, the real scale shaking table tests [2~4] and response analytical study. In this study, the comparative study and the verification of cause of damage were conducted for the damaged wooden houses in the 1995 Hyogo-Ken Nanbu Earthquake, the real scale shaking table tests and slender and narrow dangerous wooden houses which was build in Japan. The static theoretical investigation and response analysis were carried out on these houses. The results show that response analysis could simulate the dynamic properties but there are many problems on modeling of non-structural elements.

INTRODUCTION

The damage of Wooden houses in Kobe showed us the necessity of the seismic design procedures considering the severe earthquake and study on dynamic behavior of wooden structures. But Japanese wooden frame constructions are very complicated in structural performance. After the 1995 Hyogo-Ken Nanbu Earthquake, extreme experimental studies were carried out. The properties of structural performance were made clear [5]. The share of shearing force with non-structural elements is unbelievable large [3,5]. More over, the eccentricity factor is ordinary very large in according to our disaster investigation [1]. One of the aims of this study is the eccentricity of wall arrangements. Almost all of damages of wooden houses are explicable with effective wall length, the eccentricity factor and performance of fastener of wooden elements each other. Many examples which suffered from the severe earthquake and the structural specification were known, were investigated by the response analysis. But unfortunately almost all of response analysis were linear one. Therefor, results of almost all of analysis have to restrict the specified scope.

1 *Grad. Student, Dept. of Architecture, Kogakuin University, Tokyo, Japan Email wwd10192@ccs.koggakuin.ac.jp*
2 *Grad. Student, Dept. of Architecture, Kogakuin University, Tokyo, Japan*
3 *Prof., Dept. of Architecture, Kogakuin University, Tokyo, Japan Email: miyazawa@cc.kogakuin.ac.jp*

2. JAPANESE WOODEN DWELLING HOUSES AND INVESTIGATION PROCEDURE

2.1 Japanese Wooden Dwelling Frame Constructions

Fig.1 shows ordinary Japanese wooden dwelling frame Constructions. Wooden braces and wall constructed by wood lath, mortar exterior (mortar are excluded as structural element) and gypsum board are structural elements for horizontal forces. Recently, the siding are ordinarily used on exterior wall.

2.2 Seismic Damage Survey[1]

Grate many severe damaged houses were investigated. The two types of them were used in this study for to discover the cause of collapse. One of them was suffered from the 1995 Hyogo-Ken Nanbu Earthquake within two month after the complete building. The drawing was kept and damage was clearly recorded(see Photo.1). Another damaged house was built in 1957 (extension work in 1968). This house has the eccentricity factor of 0.35 and has insufficient wall length (left side in Fig.8). These two houses were conducted the response analysis by three dimensional linear analysis.

2.3 Narrow And Slender 3 Story Wooden House

According to the situation of land price, dangerous narrow and slender 3 story wooden dwelling houses are frequently build in a city area. One of them shows Photo.5 and isn't suffered from the severe earthquake. This building has the eccentricity factor of 0.47. Three dimensional linear response analysis was carried out to grasp the dynamic behavior.

2.4 Full Scale Shaking Table Test[2-6]

After the 1995 Hyogo-Ken Nanbu Earthquake, full scale shaking table tests of 6 houses were carried out in Japan. Results of two of them are used for comparative investigation. The shaking table test is three dimensional shaking, and shaken by recorded strong motion obtained at Kobe of Japan Meteorological Agency.

2.5 Model for Response Analysis

Table 1 shows response analytical model adopted in this study.

Table 1 Analytical model for response

No.	Contents
1	Three dimensional Equivalent linear
2	Pseudo three dimensional Equivalent linear
3	One way spring mass dumper Degrading tri-linear

*) Equivalent linear is secant sttifeness considering Non linearity.

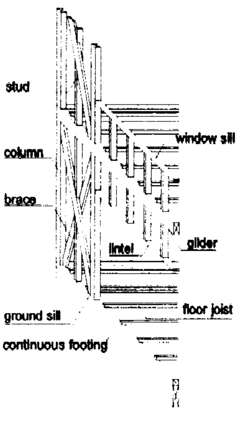


Fig.1 Japanese frame construction

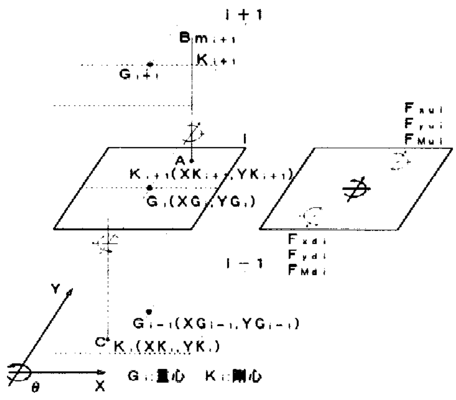


Fig.2 Pseudo-three dimensional mode

2.6 Input Seismic Wave

Fig. 3 shows input seismic wave of accelerations in direction of N-S and E-W. This data is measured in JMA Kobe.

For one way direction analysis, the wave of N-S. For three dimensional analysis, both wave is used for actual directions.

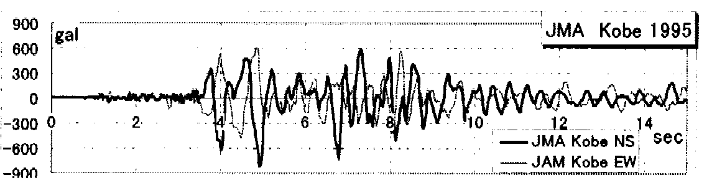


Fig.3 Input seismic wave (JMA Kobe N-S and E-W)

3. RESPONSE ANALYSIS

3.1 Example No.1

The collapsed wooden house (shown in Photo. 1) was suffered in Kobe [1], has floor plan of Fig.4 and the structural model for response analysis shows Photo.2. The model is quasi-three dimensional one shown in Fig.2. The natural periods and vibration modes are shown in Fig.5. The blank circle is the center of gravity and the black circle is the center of rigidity of each story. Results of response analysis with 3-dimensional input seismic wave recorded in Kobe are shown in Fig.6. Fig.7 shows the orbits of four corner points on the roof. Photo.2 is one scene of televised computer graphics on Japan Broadcasting Corporation, is at maximum response displacement and is shown with magnification of five times.

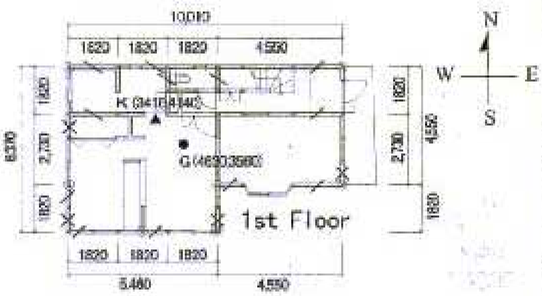


Fig.4 First floor plan

Photo.1 Collapsed 2 story house in Kobe

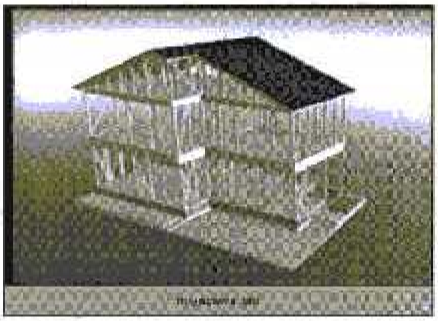
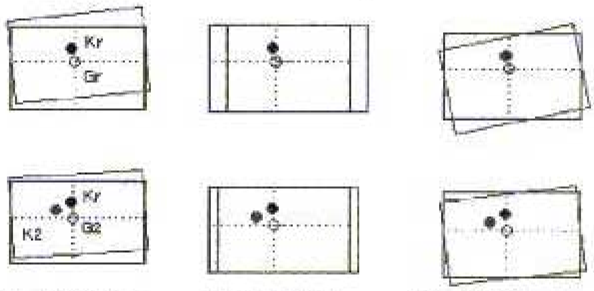


Photo.2 Deformation at Maximum Displacement



T_1=0.5018sec T_2=0.4502sec T_3=0.3442sec

Fig.5 Natural vibration mode

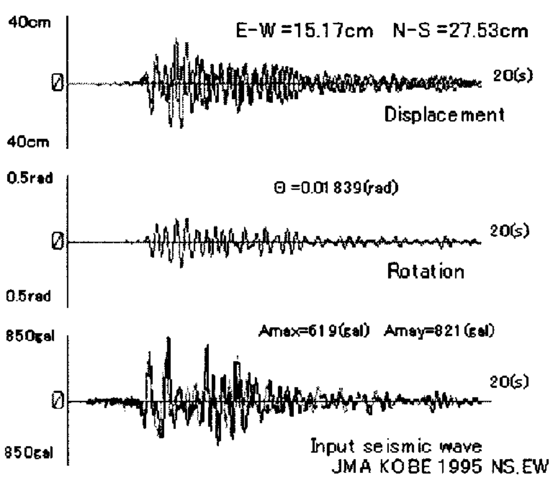


Fig.6 Response of displacement

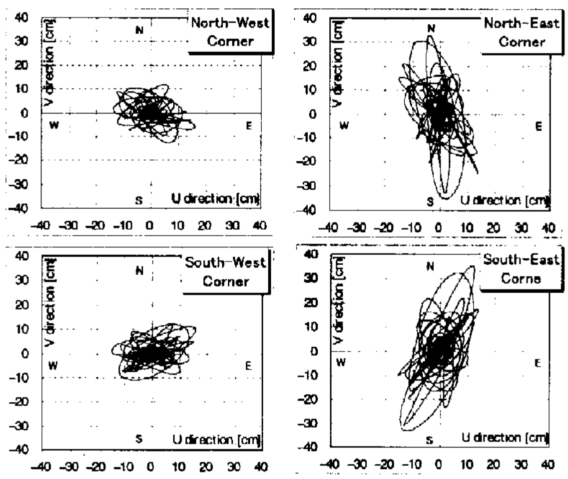


Fig.7 Orbit of four corner point on roof level

3.2 Example No.2

The house of Photo.3 was collapsed to north direction, and had a fatality due to the 1995 Hyogo-Ken Nanbu Earthquake[1]. The effective wall lengths of each direction in this house were 14.34 cm/m^2 (N-S direction) and 11.47 cm/m^2 (E-W direction); these wall length ratios were 0.43 (N-S) and 0.34 (E-W) to the value prescribed by 1995 Japanese Building Code. The S32-Model was modelled from this actual house (plan of left side in Fig.8), and the H10-Model was drastically revised house to conform the 1995 Code (plan of right side in Fig.8).

FIg.9 shows the three dimensional analytical model of S32-Model; the horizontal and vertical planes and wooden braces of structure are substituted to equivalent braces with an appropriate stiffness. The lateral stiffness of braced wall is estimated that story shear strength of a wall is 130 kg/m, and a story deformation angle is 1/120 rad. Fig.10 shows the natural vibration mode. Fig.11 and Fig.12 show the orbit of response displacement on four corner points when JMA KOBE 1995 waves (Fig.3) were inputted. Fig.11 is S32-Model and Fig.12 is H10-Model. The displacement of east-west direction on the south side is larger than the displacement of east-west direction on the north side in S32-Model.

On the other hand, the response of H10-Model is small and the torsional displacement is negligible small.

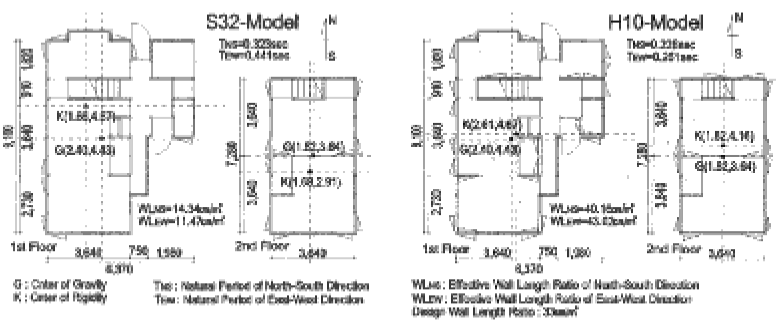


Fig.8 Floor plan of S32-Model and H10-Model

Photo.3 Seismic damage of S32-House in Kobe

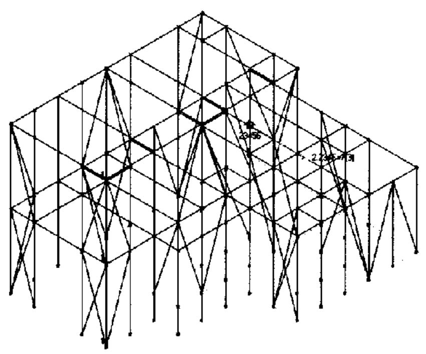


Fig.9 Analytical model of S32-Model

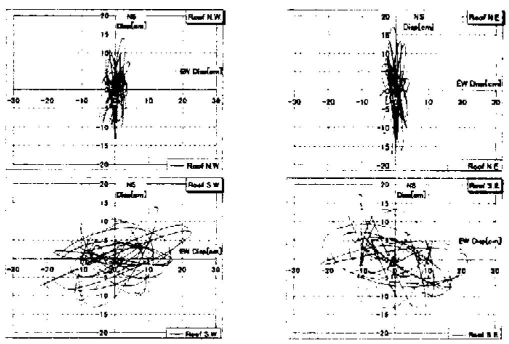


Fig.11 Displacement of roof on S32-Model

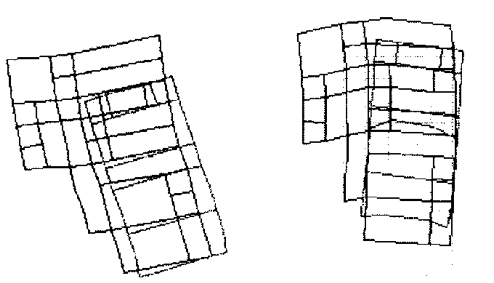


Fig.10 Natural vibration mode on S32-Model

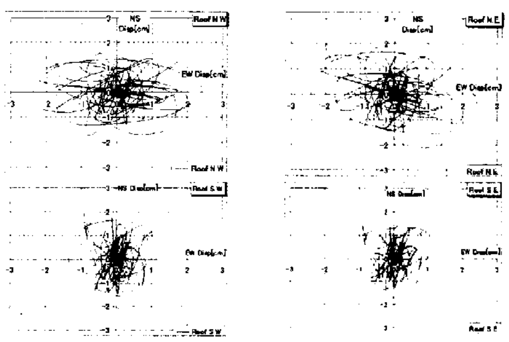


Fig.12 Displacement of roof on H10-Model

3.3 Example No.3 (3 story slender house)

Many 3 story slender wooden houses are built on small and narrow site in a city area. A 3 story slender house with drastically eccentric arrangement of bearing walls and without hold-down metal fasteners at the bottom of columns was collapsed due to heavy earthquake in Kobe (shown in Photo.4) [1]. The eccentricity factor of this house was 0.59 for seismic force in direction of north-south with only considering effective wall length. Although the minimum length of effective wall was 91 cm according to the ordinary design specification, the width of a slender wall on the east side, in which there is a lack of wall, was 50 cm.

The house shown in Photo.5 was constructed in Osaka (not suffered from the 1995 Hyogo-Ken Nanbu Earthquake) and the new detestable problem. Fig. 13 is model for response analysis, but equivalent horizontal and vertical braces were omitted in this figure. Model 1 in Fig.14 is original plan with the eccentricity factor of 0.47, and Model 2 in Fig.14 is the revised plan for suitable arrangement of bearing walls with the eccentricity factor of 0.05. The frequency of 1st natural vibration mode of Model 2 is two times of Model 1 (shown in Fig.15). The displacement response of four corner points on roof level of both models are shown in Fig.16 and Fig.17.

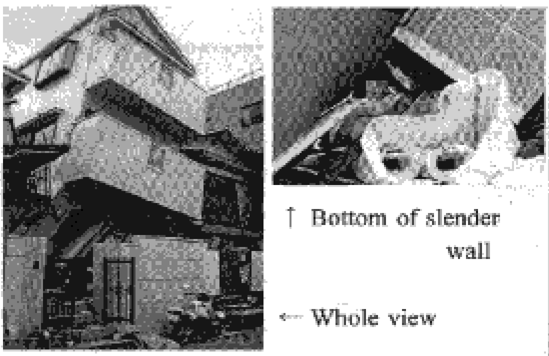


Photo.4 Damage of 3 story house in Kobe[1]

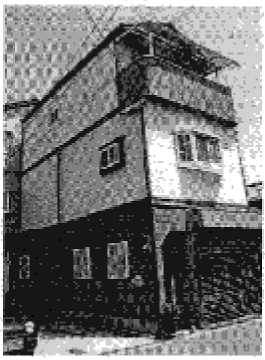


Photo.5 House for analysis

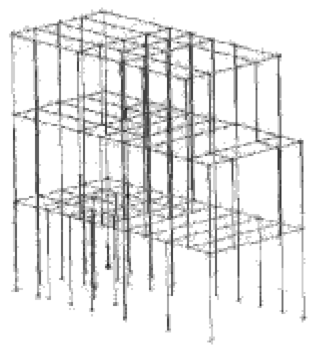


Fig.13 Analytical model

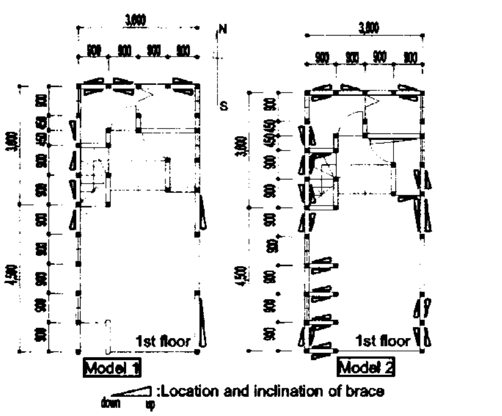


Fig.14 First floor plan of Model 1 and Model 2

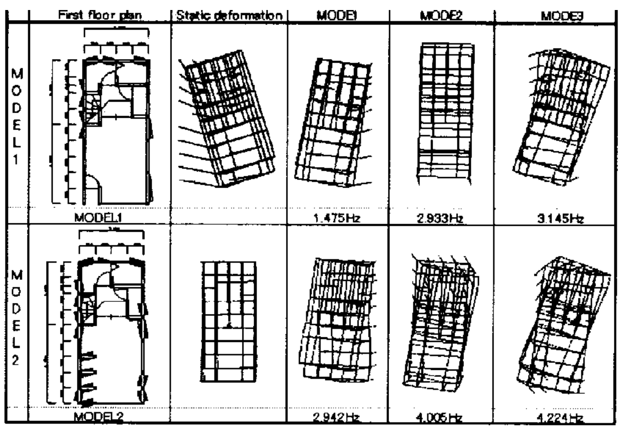


Fig.15 Natural vibration modes

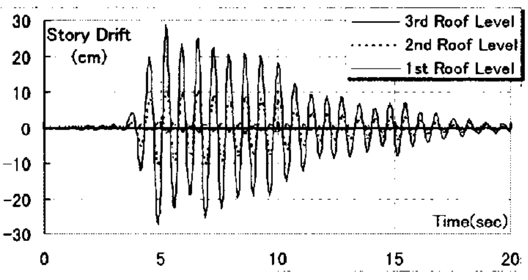


Fig.16 Floor response displacement of Model 1

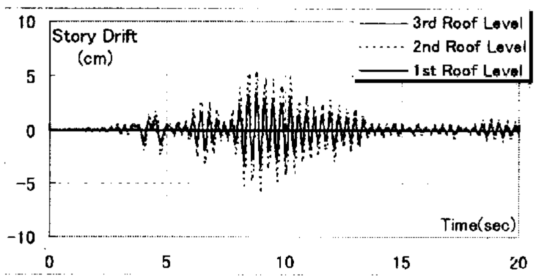


Fig.17 Floor response displacement of Model 2

3.4 Example No.4 (shaking table test: Type A)

The type A of Fig.18 and Photo.6 is one of six full scale two story wooden houses that shaking table tests were executed in 1995[12,4]. The total floor area of the type A is about 104 m^2. The external facing is a siding finishing. In the shaking table tests, three components of JMA Kobe (see Fig.3) were used. Two analytical models were adopted as response analysis for comparison with the experiments. One of them is a degrading tri-linear model of three freedom system that the hystersis model is shown in the right upper part of Fig.19 and parameters were decided from static experiments. Results and comparisons with experiment are shown in Fig.19. Response analysis could fairly simulate the hystersis of story shear - story drift. Another model is three dimensional linear model as like as Fig.9 and 13. Input seismic wave in the direction of E-D of the specimen is N-S component of JMA Kobe. Results and comparisons with experiment are shown in Fig.20. Response analysis could fairly simulate results of experiment except for displacements.

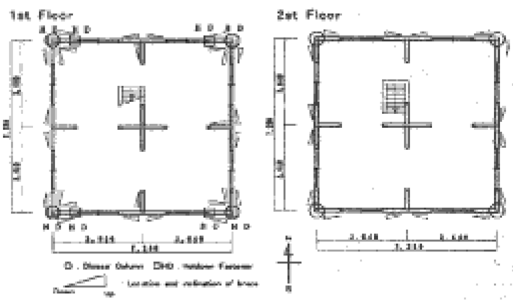


Fig.18 Floor plan of Type A for shaking table test

Photo.6 Perspective of shaking table test

2nd Story			
k1	7020	k2	4000
k3	300	Y1	0.5
Y2	1.5	Y3	1.725
Weight		8.2	t
1st Story			
k1	12270	k2	7700
k3	800	Y1	0.5
Y2	1.5	Y3	1.725
Weight		9.1	t
Natural Period			
Primary		0.354	sec
Secondary		0.146	sec

	Analysis	Experiment	
Maximum Story Shear Force			
2nd	13.18	15	t
1st	19.53	20	t
Maximum Story Drift			
2nd	4.63	3.54	cm
1st	6.86	7.72	cm

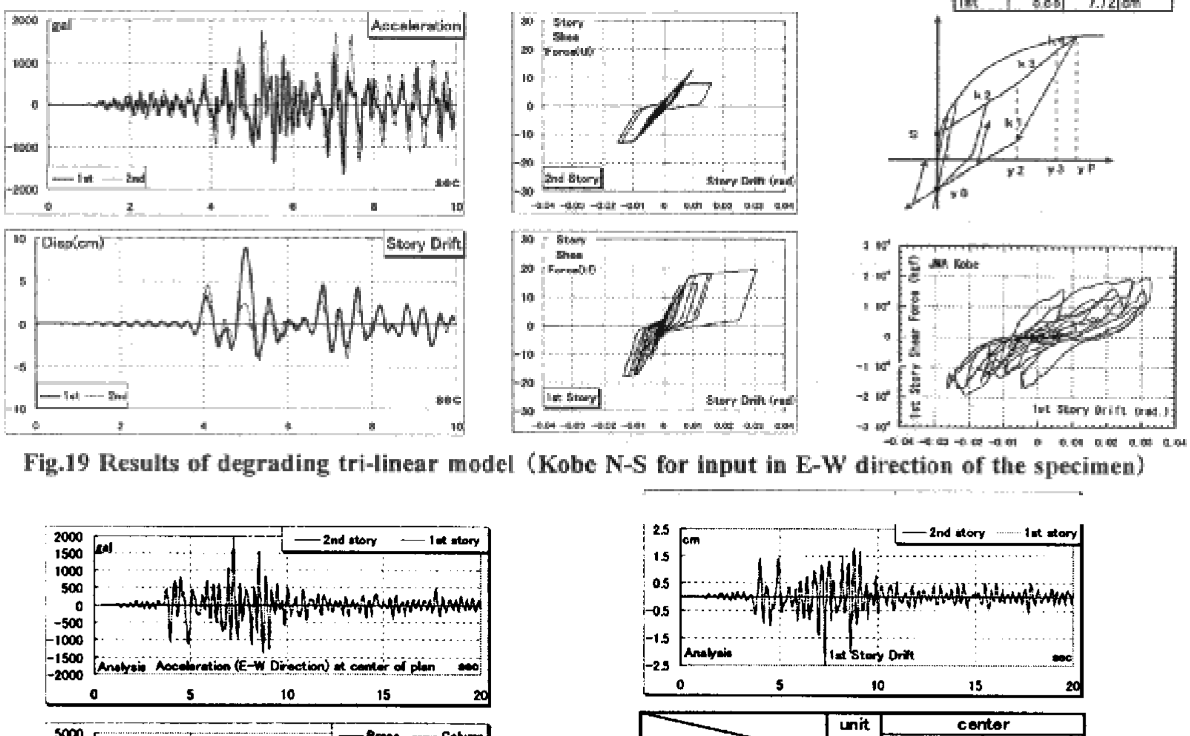
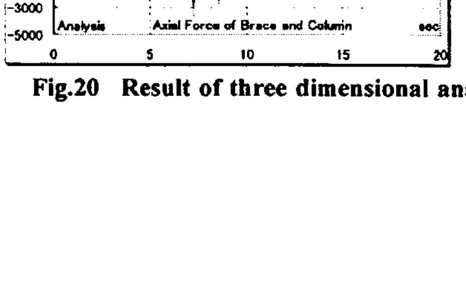
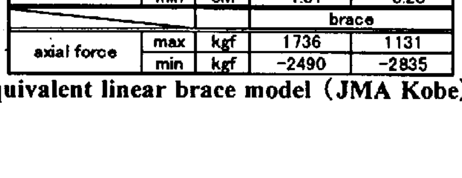


Fig.19 Results of degrading tri-linear model (Kobe N-S for input in E-W direction of the specimen)





		unit	center	
			analysis	experiment
acceleration	max	gal	1367	1575
	min	gal	-1995	-1890
story drift	max	cm	2.58	3.22
	min	cm	-1.81	-3.28
			brace	
axial force	max	kgf	1736	1131
	min	kgf	-2490	-2835

Fig.20 Result of three dimensional analysis by equivalent linear brace model (JMA Kobe)

3.5 Example No.5 (shaking table test: Type B)

The type B of Fig.21 and Photo.7 is one of six full scale 2 story wooden houses that shaking table tests were executed in 1995[2-4]. The total floor area of type B is about 133 ㎡. The external facing is a mortar finishing. After the first Phase test, mortar and plaster board was removed (Phase 2) as Fig.21. Three components of JMA Kobe 1995 wave were inputted to the shaking table as Fig.21, but in response analysis, only one component of N-S was inputted in the longitudinal direction. Fig.23 shows the results of experiments and analysis. For the results of brace, results of experiment of the Phase 2 is added. The response acceleration and story drift of the analysis are close value of the experiment, though the axial force of brace and column are not close values. The share of story shearing force by braces was 7 % in experiment of Phase 1 and 12 % in Phase 2. The share of story shear by non-structural elements was extremely large. Therefor, investigation on non-structural elements is very important.

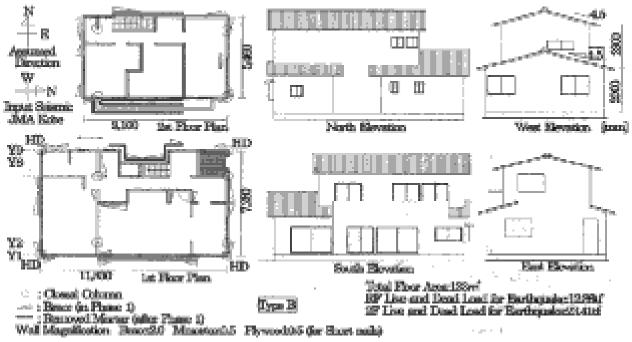


Fig.21 Floor plan of type B for shaking table test

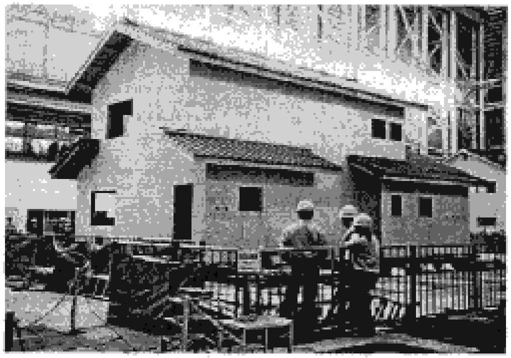


Photo.7 Perspective of shaking table test

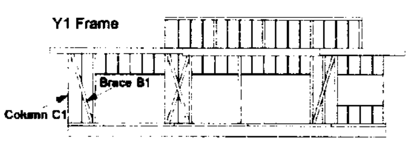


Fig.22 Location of brace and column

Table 2 Result of response acc., story drift, axial force of B1&C1

		unit	south side		northside	
			analysis	experiment	analysis	experiment
acceleration	max	gal	1393	1513	1029	1075
	min	gal	-1351	-1308	-993	-1083
story drift	max	cm	1.34	3.40	0.99	1.38
	min	cm	-1.32	-2.02	-1.03	-2.41
			brace B1		column C1	
axial force	max	kgf	3589	419	3678	341
	min	kgf	-3628	-717	-3748	-554

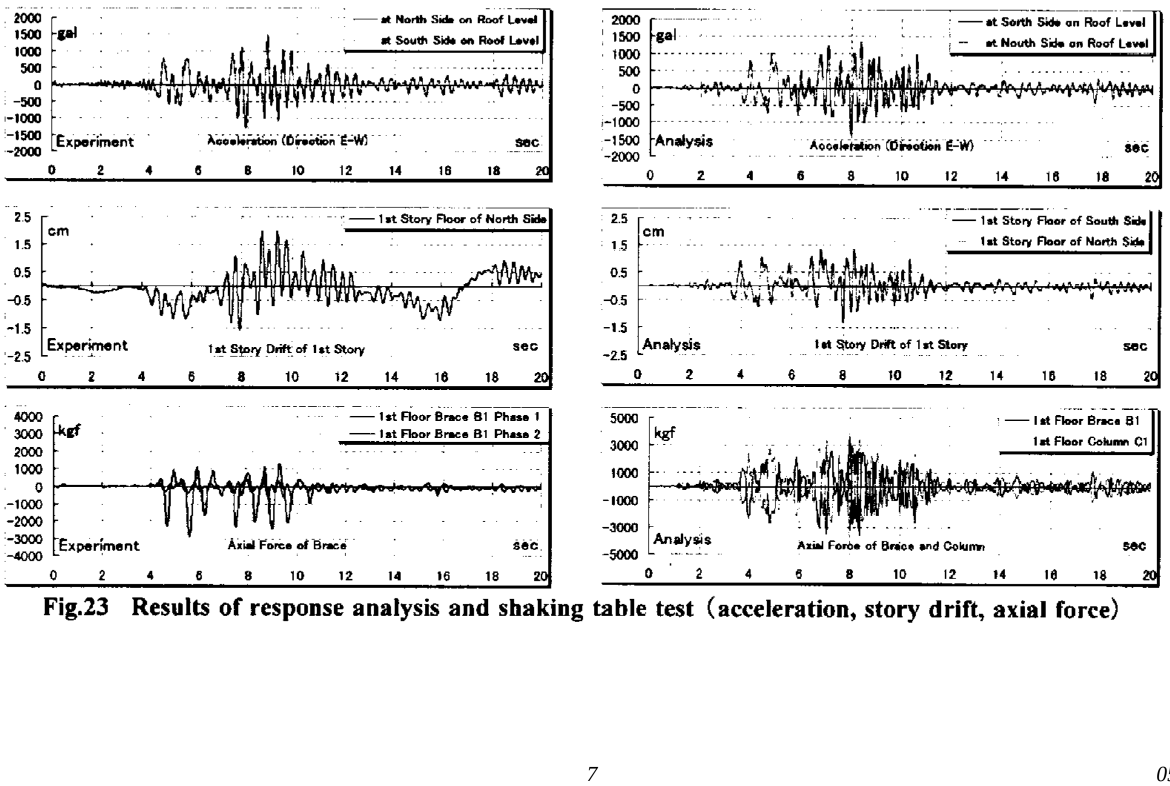


Fig.23 Results of response analysis and shaking table test (acceleration, story drift, axial force)

4. CONCLUSIONS

From the earthquake damage investigation, shaking table tests and response analyses, the following conclusions can be drawn.

1) From the earthquake damage investigation, causes of damage of wooden dwelling houses were a lack of effective wall length and performance of fastener, and a large value of eccentricity factor.

2) From the shaking table tests, conventional wooden houses with suitable fastener wouldn't collapse by severe earthquake like as the 1995 Hyogo-Ken Nanbu Earthquake.

3) Even the linear response analysis could simulate the dynamic behavior of torsional vibration, and is effective procedure for a structural planing. In this case, estimation of equivalent braces is very important. Reduction of axial stiffness of brace by the fastener and non-structural elements should be considered based on experiments.

4) Degrading tri-linear model could fairly simulate the story shear force - story drift relationship of shaking table test.

5) To grasp the properties of each stress - displacement relationship of elements and parts, three dimensional model with each element of degrading tri-linear are desired.

REFERENCES

[1] Kenji Miyazawa and Katsuhiko Kohara, "A Study on Damages of Wooden Houses due to the 1995 Hyogo-Ken Nanbu Earthquake ", International Wood Engineering Conference, Vol.1, 1-339~1-346, 1996.10

[2] Isao Sakamoto, Yoshimitsu Ohashi, Kenji Miyazawa and et al, "A Survey Report on Real Scale Shaking Table Tests of Wooden houses", The Experimental Report of Japan House and Wood Technology Center, 1996.10

[3] Kenji Miyazawa and Katsuhiko Kohara, "A Study on Shaking Test of Full-scale Wooden Dwelling Houses", The Annual Report No.4 (1997/1998) of Research Institute for Sciences and Technology, Kogakuin University, 1998.3

[4] Katsuhiko Kohara and Kenji Miyazawa, "Full-scale Shaking Table Test of Two story Wooden Dwelling Houses", Proceedings of 5th World Conference on Timber Engineering, Vol.2, 548-555, 1998.8

[5] Kenji Miyazawa and Katsuhiko Kohara, "Seismic Performance of Wooden Structures and Dynamic Behavior of Joints", Pacific Timber Engineering Conference, Vol.3, 73~80, 1999.3

[6] Yoshimitsu Ohashi, Isao Sakamoto and et al., "Pseudo-Dynamic and Shaking Table Tests on a Japanese Wooden House", Pacific Timber Engineering Conference, Vol.3, 213~220, 1999.3

[7] Kenji Miyazawa and Katsuhiko Kohara, "Evaluation of Seismic Performance and New Seismic Design Method of Wooden Dwelling Houses", Proceedings of 5th World Conference on Timber Engineering, Vol.1, 836-837, 1998.8

ACKNOWLEDGEMENT

The seismic damage field survey and the shaking table tests were founded by Foundation of the Japan House and Wood Technology Center and Kogakuin University in Japan. The authors wish to express their thanks to the Japan House and Wood Technology Center and Kogakuin University. And they also would like to express their appreciation (especially Japan Broadcasting Corporation in computer graphic and site investigation, and Messrs. Sato, Agawa and Shigeto in our laboratory for response analysis) to the collaborators who participated to the these investigations.