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# 25. *Study on the Earthquake Resistivity of Wooden Houses.*

## *Part 1. On the Aseismic Experiment of a Wooden House in Wakaho Town in Connection with the Damage Due to Matsushiro Earthquake.*

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### Abstract

In order to clarify the earthquake resistivity of wooden houses in the Matsushiro and Wakaho area where the earthquake swarm has been active since 1965, static and free vibration tests on a representative wooden house were carried out. This paper presents the test results including load-deflection curves, natural periods and damping characteristics and, furthermore, some considerations on the relation between the intensity of earthquake motion and the degree of damage observed with reference to the test results, damage investigation and earthquake responses for certain recorded accelerations.

### 1. Introduction

The earthquake resistivity of wooden houses in general is not well known because of its complexity and diversity in construction, the fullsize test of them being relatively rare. T. Saita[1] made vibration and loading tests on a wooden house from small amplitude to failure and concluded that the natural vibration period is nearly proportional to its amplitude.

During the earthquake swarm in Matsushiro and Wakaho area since

1) T. SAITA, "Experiments in the Vibration and Destruction of a Wooden Dwelling House," *Bull. Earthq. Res. Inst.*, **17** (1939), 152.

1965, the damage to wooden houses has been reported[2] and the ground accelerations have been recorded with the strong motion accelerographs.[3] In order to clarify the relationship between the degree of damage and the maximum ground acceleration, an experiment on earthquake resistivity of wooden houses in this area is greatly to be desired.

This paper presents static and free vibration test results on a representative wooden house in Wakaho Town. It is intended that static and dynamic characterestics (such as load-deflection curves, natural frequencies, damping etc.) of the wooden house for horizontal loads be clarified. Further, some considerations on the relation between the intensity of the earthquake motion and the degree of damage are to be given with reference to the test results, damage investigations, earthquake measurements and earthquake response for certain strong earthquake motion records.

## 2. Outline of the experiment

a) Test House

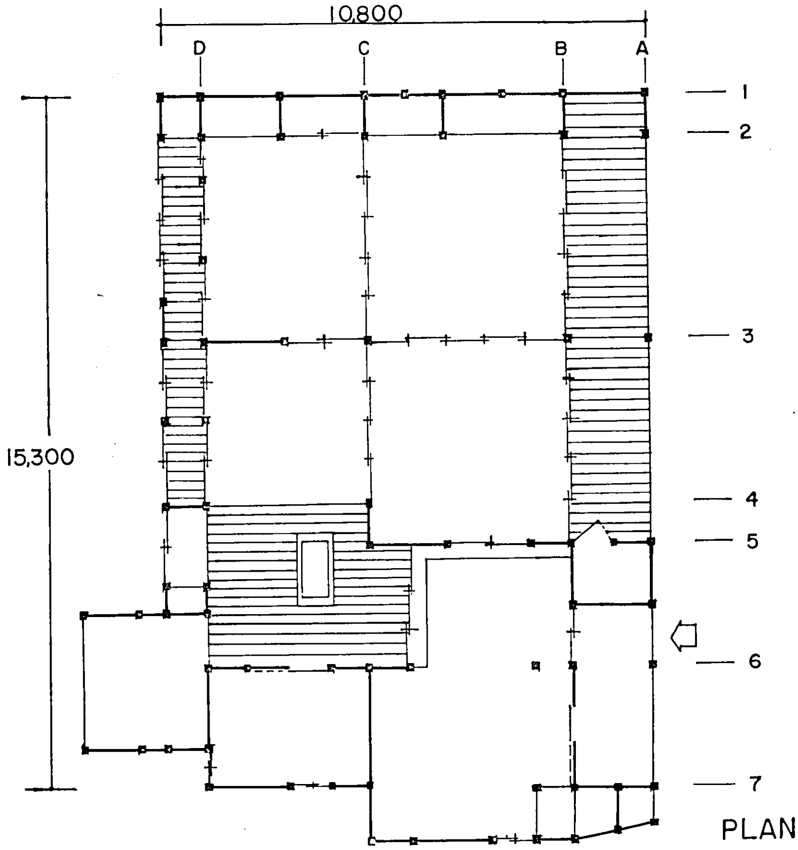
The test house is located at Watauchi area in Wakaho Town, Nagano prefecture. As shown in Fig. 1, there are mud walls on both sides in the NS direction. Roof truss is of heavy construction in the ancient Japanese shrine style and is supposed to have high rigidity. No diagonal member such as bracings is used anywhere. Sections of members are 9–12 cm × 9–12 cm for columns and 18–33 cm for depth of beams.

b) Loading

Horizontal loads were applied simultaneously at 6 points on the test house, namely, to frames 1, 2, 3, 4, 6 and 7, using two sets of composite beams. (see Fig. 2.) Supports of beams and knots on pulling wires were positioned so that the force would be proportional to the distributed dead loads on each frame. Consequently, the distribution ratios of loading are 0.105, 0.105, 0.29, 0.21, 0.165 and 0.125 for frames 1, 2, 3, 4, 6 and 7, respectively. These ratios were kept constant throughout the tests. For free vibration tests, two pulling wires were fastened to the neck and loaded with one pully. The instant release of loads is accomplished by the natural breaking of steel bars whose sections were previously determined. Wooden pillars are used as reaction table sup-

2) M. MURAKAMI, T. MINAMI and Y. OSAWA, "Damage to Houses Caused by the Earthquake Swarm Around Matsushiro," *Bull. Earthq. Res. Inst.*, **45** (1967), 551–557.

3) Strong Earthquake Motion Observation Center, *Strong Earthquake Motion Records in Matsushiro Earthquake Swarm Area* (Earthq. Res. Inst., 1967).



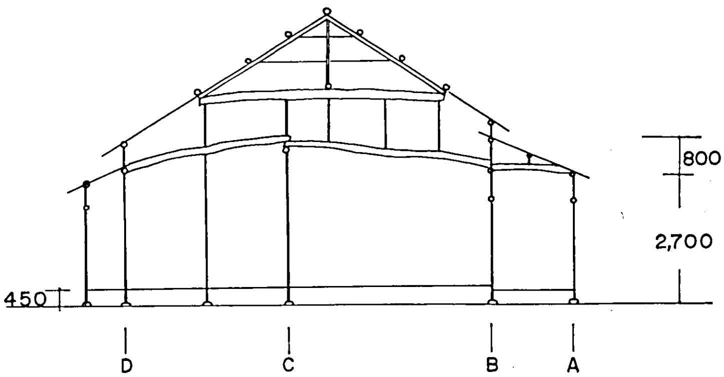
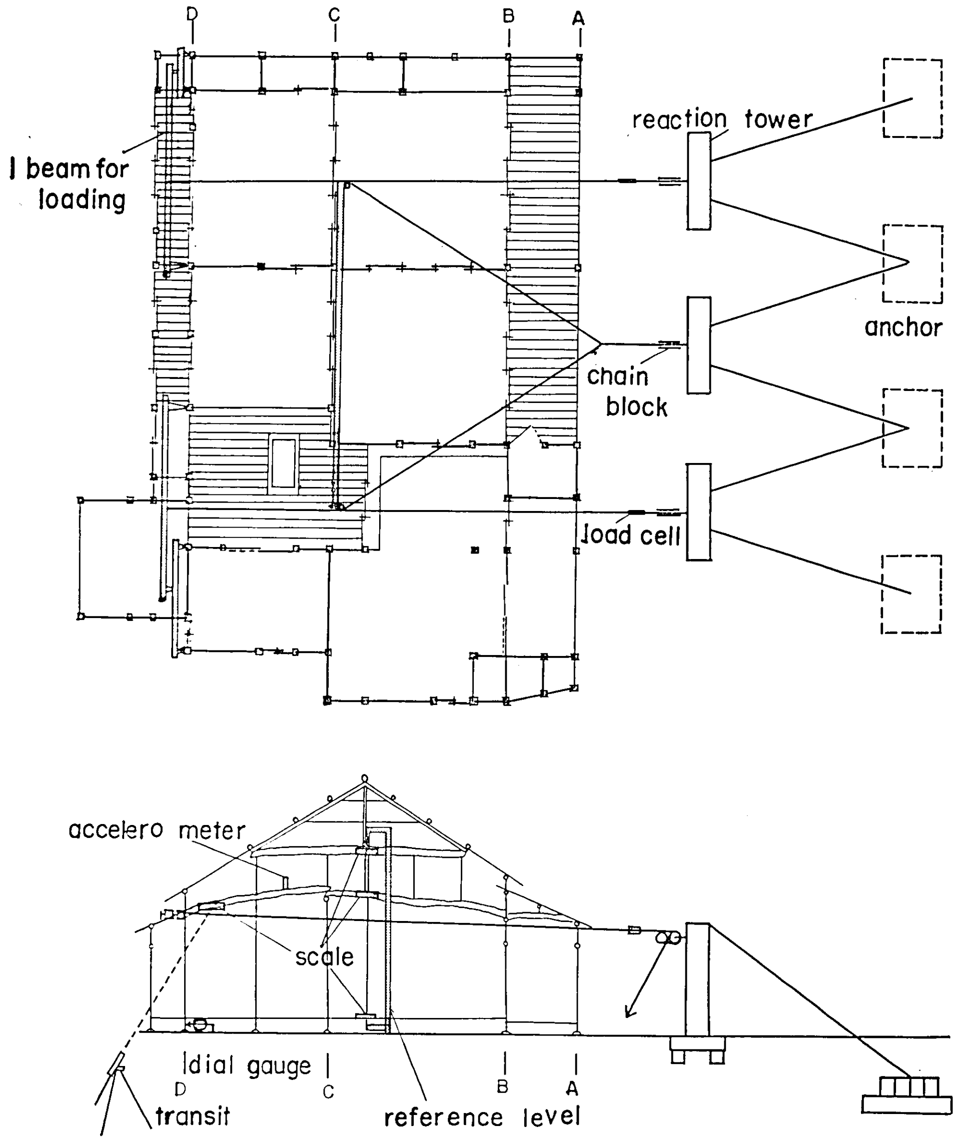




Fig. 1. Plan and Section of the test house. (unit in mm)




Loading and Measurement

Fig. 2.

ported with wires anchored to buried timbers. A hand-made load cell with four wire strain guages was used for load measurements. Eye bolts were inserted in proper positions so as to avoid the effect of

Table 1.

| Test Number | Load (ton) | Data |
|---|---|---|
| S- 1 | 2.69 | displacement (transit), displacement (dial gauge), displacement (scale) |
| S- 2 | 3.00 | displacement (transit), displacement (dial gauge), displacement (scale) |
| D- 3 | 2.50 | displacement (transit) |
| D- 4 | 4.00 | displacement (transit) |
| D- 5 | 4.00 | displacement (transit) |
| D- 6 | 1.50 | displacement (transit), displacement (dynamic) |
| S- 7 | 8.40 | displacement (transit), displacement (dial gauge), displacement (scale) |
| D- 8 | 6.70 | displacement (transit), acceleration |
| D- 9 | 7.30 | displacement (transit), displacement (dynamic), acceleration |
| D-10 | 1.30 | displacement (transit), displacement (dynamic), acceleration |
| S-11 | 8.00 | displacement (transit), displacement (dial gauge), displacement (scale) |
| D-12 | 2.00 | displacement (transit), displacement (dynamic), acceleration |
| S-13 | 10.90 | displacement (transit), displacement (scale), displacement (dial gauge) |
| D-14 | 3.00 | displacement (transit), displacement (dynamic), acceleration |
| D-15 | 3.60 | displacement (transit), displacement (dynamic), acceleration |
| D-16 | 6.00 | displacement (transit), displacement (dynamic), acceleration |
| D-17 | 1.50 | displacement (transit), displacement (dynamic), acceleration |

bending moment.

c) Measurements

Displacements of column heads and beams in frames 1, 3, 4, 6 and 7 on C row were measured with scales and plumb-bobs to obtain distribution of horizontal displacement. The vertical displacement was measured along column C-3. The displacement between the foundation and the bottom of the strut was measured by dial gauges. Displacements of frames 1, 3 and 7 on row D were also measured especially to check the displacement behavior during the loading process in the free vibration tests.

For free vibration tests, four pendulum type accelerometers were conveniently arranged on row C from 1 to 7 frames. A drum type displacement recorder was set at column 3-C.

d) Test Routine

Static tests and free vibration tests were conducted alternately. The test procedure, the outline of each test, and data obtained are shown in Table 1. Initial letters, S and D, on the test number indicate static and dynamic tests, respectively.

## 3. Results of the experiment

a) Results of static tests

Fig. 3 shows the load-deflection curves for frames 1, 3 and 7 on row D (measured with transit and scale). So-called slip effect was found in the loop S-13 especially for frames 1 and 7 which had a considerable amount of mud wall. The ultimate strength of the test house was about 10 tons which corresponds to a seismic coefficient of 0.2.

Typical and horizontal displacement diagrams are shown in Figs. 4 and 5. As to vertical distribution, the column under head jump contributes most of the displacement. Horizontal distribution indicates a triangular shape with the maximum at frame 3. Ratio of displacements of frame 3 to frame 1 and 7 is 2.5 as a maximum in all the tests.

The damage noted during the tests is listed below with the corresponding displacements.

| Displacement | Damage |
|---|---|
| 2-3 cm | Doors of Buddhist alter deformed. |
| | Corner of walls crushed. |
| 5-6 cm | Sliding screen broke. |
| 7 cm | Sliding door buckled. |
| | Cracks in wall. |
| 10-11 cm | Sliding door put out of place. |

b) Results of free vibration tests

The first wave amplitude of displacement data are 1.7 cm maximum and 0.12 cm minimum. Natural periods in the latter stages of the test program are about 1.5 times larger than those in the earlier stages. Variation of natural periods versus displacement where the test was conducted is shown in Fig. 6. Equivalent viscous damping coefficient as measured was rather large, being approximately 20% of critical damping. The maximum value of averaged accelereation is 60 gal and the minimum is 18 gal. The horizontal distribution of acceleration is

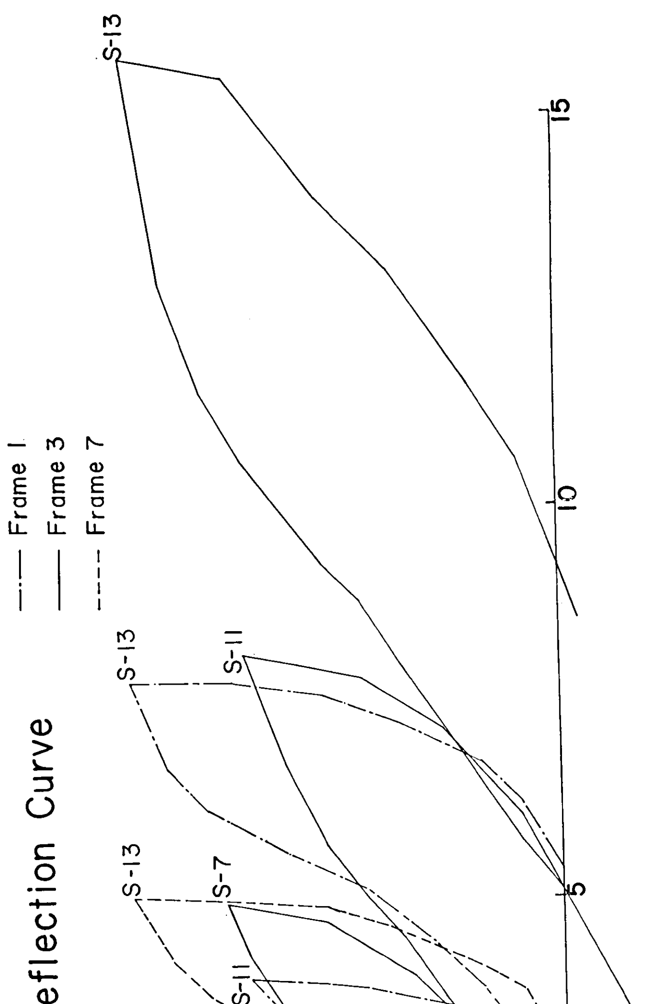

Load Deflection Curve
Frame 1
Frame 3
Frame 7
S-13
S-11
S-7
S-1
P t
δ cm
0
5
10
15

Fig. 3.

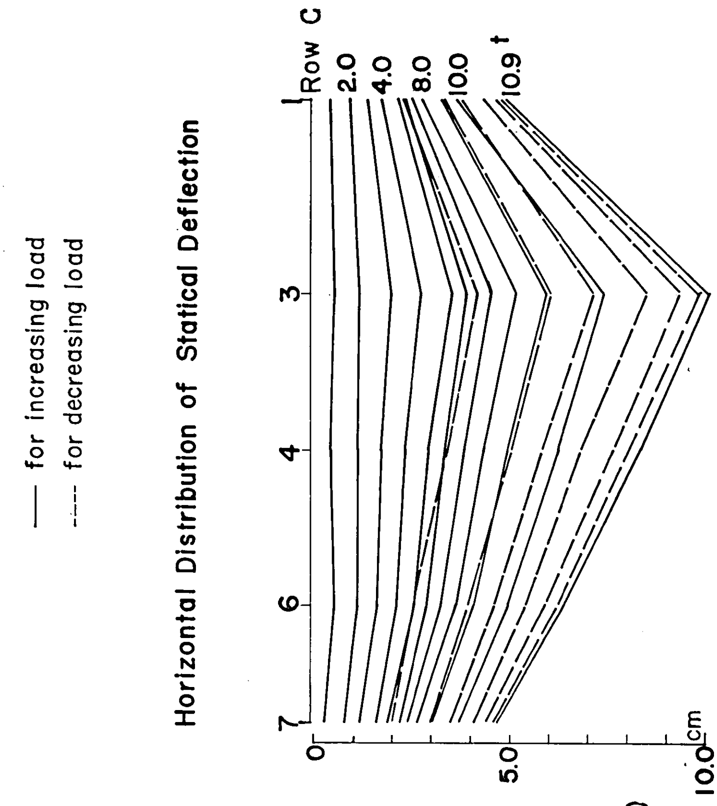

— for increasing load
--- for decreasing load
Horizontal Distribution of Statical Deflection
Row C
2.0
4.0
8.0
10.0
10.9 t
1
3
4
6
7
0
5.0
10.0 cm

Fig. 5.

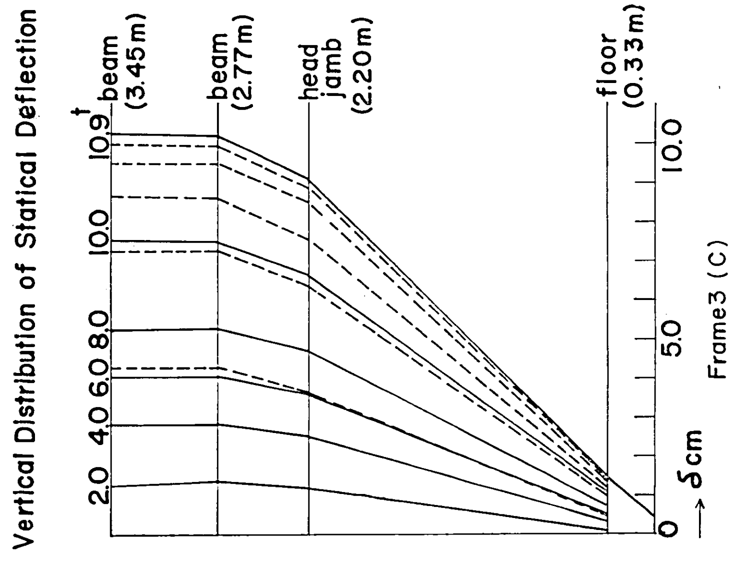

Vertical Distribution of Statical Deflection
2.0
4.0
6.0
8.0
10.0
10.9 t
beam (3.45 m)
beam (2.77 m)
head jamb (2.20 m)
floor (0.33 m)
→ δcm
0
5.0
10.0
Frame3 (C)

Fig. 4.

not as smooth as the displacement distribution.

c) Weight of house

Weight of the test house was calculated in the following manner.

1. Total stiffness was derived from the load deflection curve from the static test results.

2. This value was modified by studying the load deflection curves of frames 1, 3 and 7 in the free vibration test results.

3. Weight of the house was calculated with the stiffness and natural periods obtained from dynamic data.

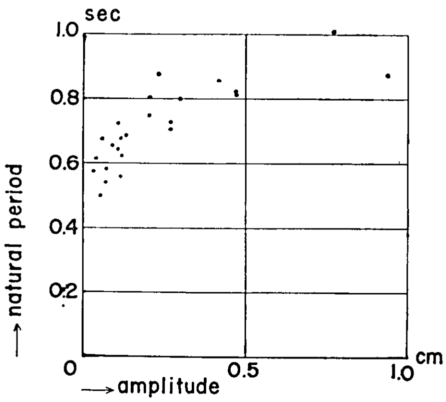


Fig. 6.

Two sets of data and calculated weight are shown below:

S-7 and D-9

| | |
|---|---|
| amplitude of second wave | 0.94 cm |
| natural period | 0.88 sec |
| stiffness (modified) | 2.3 t/cm |
| calculated weight | 42.5 t |

S-13 and D-16

| | |
|---|---|
| amplitude of second wave | 0.77 cm |
| natural period | 1.01 sec |
| stiffness (modified) | 2.1 t/cm |
| calculated weight | 51.4 t |

The average value (47 t) of these two figures seems quite reasonable and will be used later as the weight of the house for the calculation of earthquake response.

d) Earthquake response

Response analysis for one mass tri-linear model was made, where restoring force was determined from the load deflection curves of S-7. (See Fig. 7.) Three earthquake records obtained by the strong motion seismograph at the Wakaho Town Office, located about 2 km south of the test house, were used in the response analysis. Maximum response for 250 gal and 500 gal, maximum acceleration of the ground, are tabulated in Table 2.

The response displacements of 2-3 cm for 250 gal input will cause very slight damage to the house, while for 500 gal input non-destructive damage will be caused such as crushing of wall at corners, breaking of sliding screen and some damage to fittings. (see section 4)

Table 2. Response Displacement

| Earthquake | Maximum Acceleration | Amplification Factor | Input Maximum Acceleration | Maximum Displacement | | |
|---|---|---|---|---|---|---|
| | | | | h=0.05 | h=0.10 | h=0.20 |
| Wakaho-Town (NS) 1966, Apr. 1 | gal 160 | 1.6 | gal 250 | cm 1.70 | cm 1.48 | cm 0.85 |
| | | 3.1 | 500 | 2.75 | 2.80 | 2.50 |
| Wakaho-Town (NS) 1966, Apr. 5 | 250 | 1.0 | 250 | 3.32 | 3.15 | 2.45 |
| | | 2.0 | 500 | 8.45 | 6.58 | 5.05 |
| Wakaho-Town (EW) 1966, Apr. 5 | 250 | 1.0 | 250 | 3.32 | 2.98 | 2.58 |
| | | 2.0 | 500 | 7.50 | 6.35 | 5.25 |

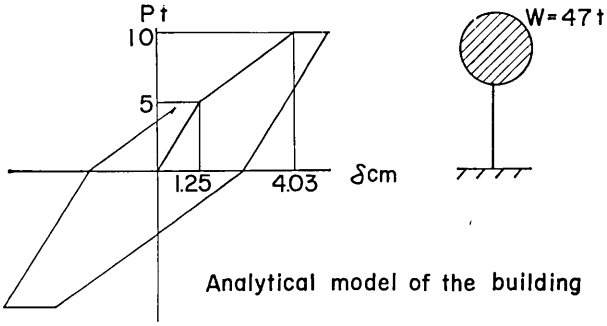



Fig. 7.

## 4. Consideration on earthquake damage

Relation between damage and displacement where the damage occurred in the tests will be extended and applied to the ordinary wooden houses in Matsushiro and Wakaho areas.

Figs. 8 and 9 show the displacement spectra for the accelerograph obtained by the strong motion seismograph at Wakaho Town Offiice on March 5 and at Matsushiro Town Office on August 3, 1966.

Figs. 10 and 11 show the displacement spectra for elasto-plastic models with yield coefficients of 0.1, 0.2, 0.3. (0.2 in the case of the test house.) Input earthquake motion, obtained at Matsushiro Town Office on August 3, 1966 is adjusted so that the maximum acceleration is 250 gal in Fig. 10 and 500 gal in Fig. 11.

As these spectra indicate, the smaller the yield coefficients and the longer the period of houses, the larger the response displacement.

As to the structural damage caused by the earthquake on April 5,

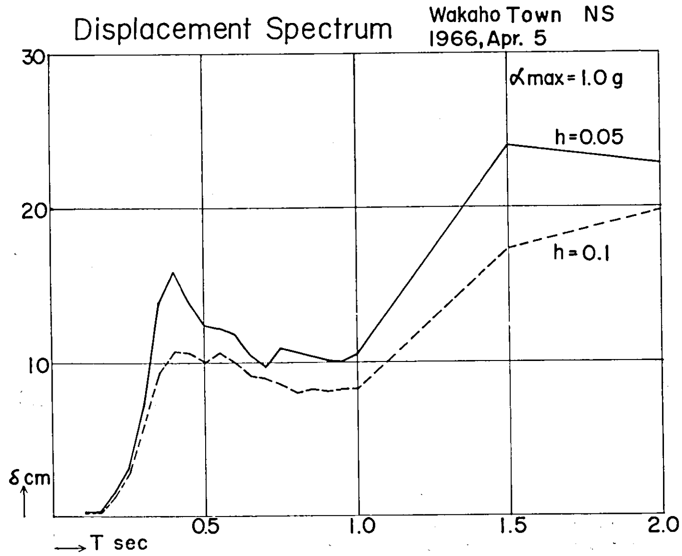

Displacement Spectrum
Wakaho Town NS
1966, Apr. 5
αmax = 1.0 g
h=0.05
h=0.1
δcm
T sec
30
20
10
0.5
1.0
1.5
2.0

Fig. 8.

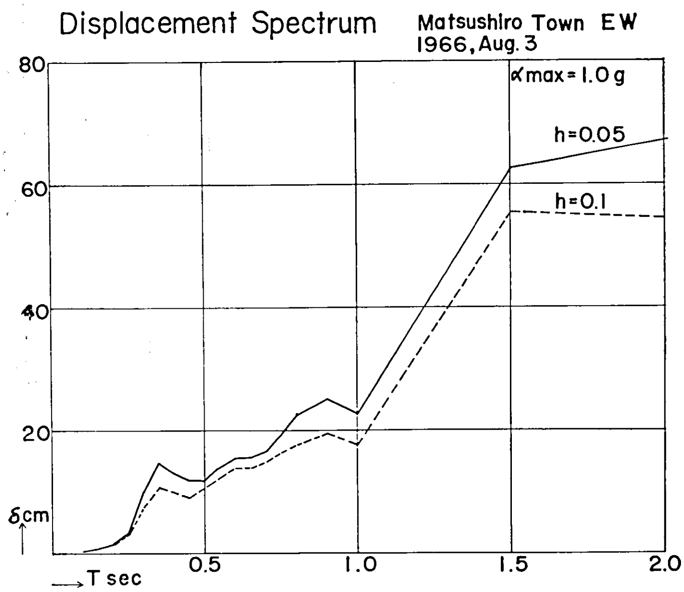

Displacement Spectrum
Matsushiro Town EW
1966, Aug. 3
αmax = 1.0 g
h=0.05
h=0.1
δcm
T sec
80
60
40
20
0.5
1.0
1.5
2.0

Fig. 9.

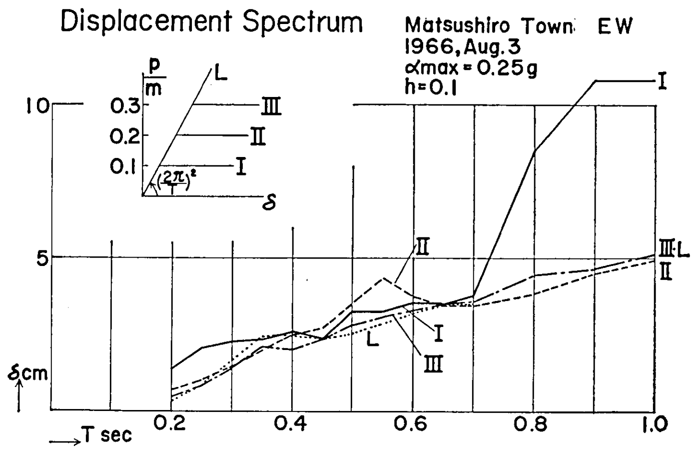



Fig. 10.

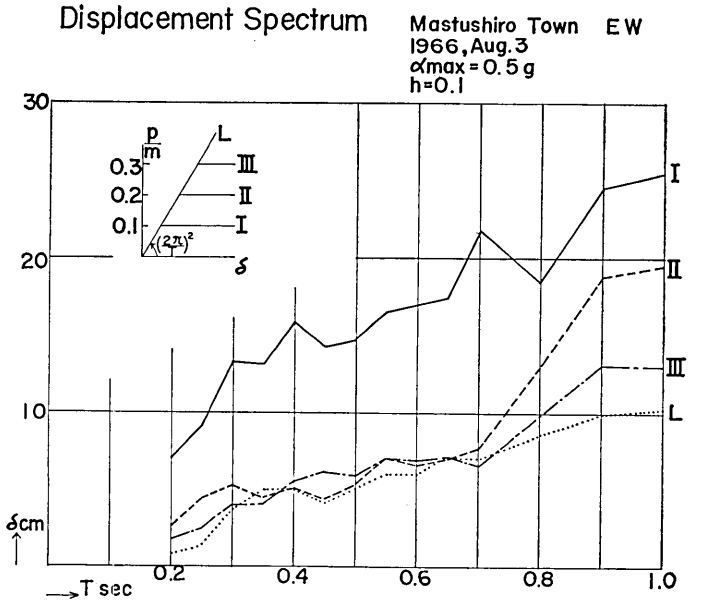



Fig. 11.

1966 slight damage to houses was scattered over a wide area from Matsushiro Town to Nagano City and Suzaka City. Relatively severe damage as observed in the tests was found only in Shimizu area which is located 2 km east of Wakaho Town Office. Failure of sliding screens, large shear cracks on mud walls and buckling of sliding doors were observed.

On the occasion of the earthquake on August 3, damage of the same degree as seen in Shimizu area on April 5 was found in Toyosaka and Hirabayashi area which is located 3 km southeast of Matsushiro Town Office. Cracks in wall, buckling of sliding doors, breakage of sliding screens, and fallen beams were observed in this area. Three non-residential houses in the northern part of Koshoku City were reported to have fallen down whose stiffness and strength are supposed to be very low.

The earthquake damage and the results of response analysis are summarized as follows:

1. No severe damage was seen near Wakaho Town Office on April 5 except for crushing of wall corners and the damage to sliding doors that shut hard. Responsive displacement of 2.5–5 cm just corresponds to the slight damage.
2. Referring to the test results, nearly 10 cm displacement is required to produce the damage as observed in Shimizu area unless the houses in this area differ extraordinarily from those around the Town Office. The ground motion of Shimizu area must consist of predominant waves of low frequency or somewhat larger in magnitude than shown on the record at Wakaho Town Office.
3. Those collopsed houses in Kōhoku City with very low stiffness and strength will easily elongate their natural pariods to more than 1.0 sec, as their deflection becomes large. From response spectrum, they are supposed to have fallen down after suffering considerable deformation.

## 5. Concluding Remarks

For the purpose of studying the earthquake damage to wooden houses in Matsushiro and Wakaho areas under the prolonged earthquake swarm which began in the summer of 1965 around Matsushiro area, an experiment on a representative wooden house in Wakaho City has been conducted.

Static and dynamic characterestics for lateral loads have been studied. Some quantative conclusions were derived on the damage to wooden houses by means of response analysis for certain strong motion earthquake records obtained in this area. A guide for anti-seismic design and reinforcement of wooden houses in these areas is as follows.

Most of the displacement spectra for the strong motion seismograph records obtained in Matsushiro and Wakaho areas do not become large beyond 1.0 second of natural period as shown in Fig. 8. However, the spectra for some records indicate a considerably large displacement in the long period range as shown in Fig. 9.

For earthquakes of the type shown in Fig. 8, more than 10 cm displacement of the house will not be produced even when the maximum ground acceleration becomes 500 gal, as shown in Fig. 8.

For earthquakes of the type shown in Fig. 9, more than 20 cm of displacement may be expected when the maximum ground acceleration is around 500 gal. The houses whose yield coefficient is very low, will fall down in such a case. Reinforcement with bracings and other methods which shorten natural periods and improve yield coefficient, might be quite effective.

## Acknowledgment

The authers wish to express their sincere thanks to officials of the Wakaho Town Office for their kind help during the experiment. Mr. Kaneo Oi, a member of Anti-Seismic Committee in Wakaho Town, accepted the laborious task of communication between Tokyo University and Mr. Yōichi Maruyama, who provided the test house. Great support was given by the Taisei Construction Co., Ltd. The authors wish to thank all the people concerned for their kind assistance.


Fig. 12. View of the test house

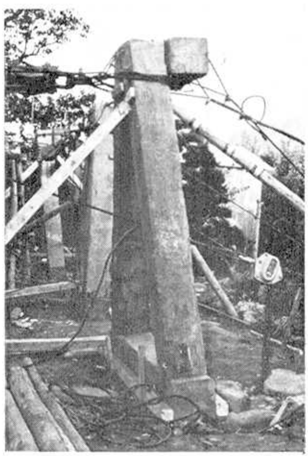


Fig. 13. Reaction towers

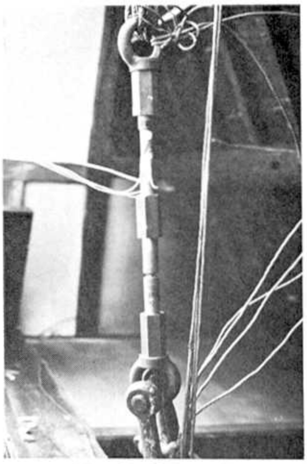


Fig. 14. Notched bar for cutting

Fig. 15. Set of composite beams for loading

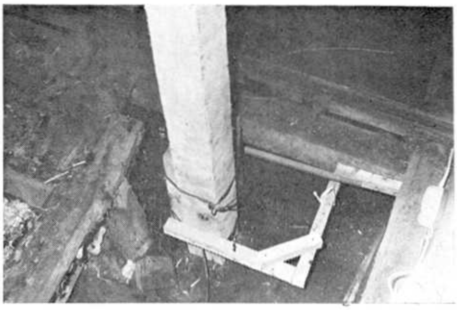


Fig. 16. Foot of standard column

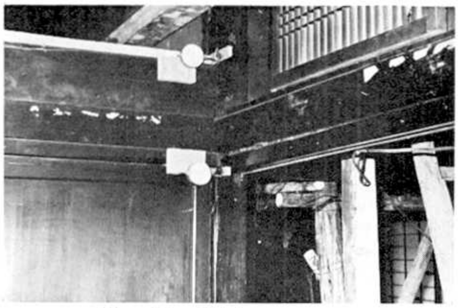


Fig. 17. Dial gauges

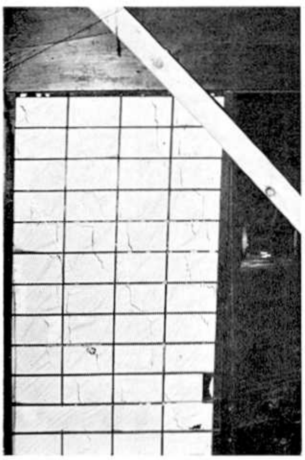


Fig. 18. Break of sliding screen

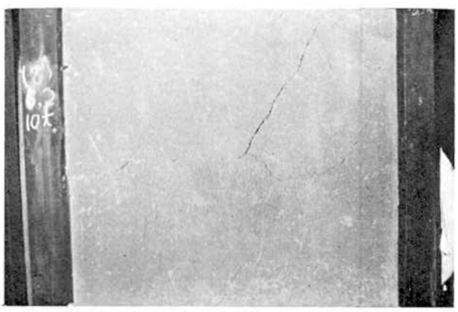


Fig. 19. Cracks in mud wall

## 25. 木造家屋の耐震性に関する研究 (第1報) 松代地震に関連して行なつた木造家屋の耐震試験結果について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昭和40年夏以来北信地方におこつている頻発地震により，木造家屋の被害が多数報告されており，これに対して被害調査，強震計記録の解析，建物の地震観測等行なわれている．しかし，地震動の強さと木造家屋の被害程度の関係を解明するためには，さらにこれら木造家屋の地震力に対する諸性質を知ることがぜひとも必要と思われた．そこで昭和41年10月，この地域の代表的家屋と考えられる木造平屋建物住家一棟について水平加力実験，自由振動実験を行ない，水平力に対する静的ならびに動的特性，すなわち建物の剛性，耐力，復元力特性，固有周期，減衰定数等を実験的に求めた．さらに，以上の実験結果を基にしてこの地域で得られた強震計記録に対する応答計算を行ない，被害調査の結果と比較検討した．応答結果は被害状況とよく対応しており，これまでに記録された程度の地震に対しては，この地域のふつうの木造家屋は破壊的被害を受けないといえる．しかし，さらに大きな地震に対しては，剛性，耐力が低いものは応答変形量が過大となり，倒壊の危険も考えられるので，筋かいなどで補強する必要があろう．