13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 580

EFFECT OF HEAVY DEAD WEIGHT ON EARTHQUAKE DAMAGE OF WOODEN HOUSES BASED ON CHANGE OF NATURAL PERIOD

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SUMMARY

Shaking table test of wooden framed structure was conducted under light, moderate or heavy dead load. Fundamental dynamic behavior of one-story, one-bay wooden framed structure with or without braces and/or plywood bearing walls was investigated. This test program is focusing on changes of damage level, natural period, response magnification factor and damping factor of wooden framed structures under stepwise increasing input accelerations. Dynamic response analysis of wooden structures has been done, in which combination models of tri-linear Masing type and slip type for restoring-force characteristics evaluated from a static loading test, the earthquake acceleration level that the specimen experienced plastic deformation is examined.

INTRODUCTION

In the Hyogoken-Nanbu (Kobe) earthquake in Japan, on January 17th, 1995, about 90,000 wooden houses completely collapsed. Most of damage of wooden houses was that the first story of a two-story house collapsed due to overweight upper floors and heavy roof-tiles of conventional Japanese-style. The objective of this research is to evaluate acceleration level of an input earthquake, in which the wooden houses get into damage in plastic region, by tests and by analytical simulations. Also levels of the dead weight, from light to heavy, effects of the vertical excitation and types of input earthquake wave are investigated.

OUTLINE OF SPECIMENS

Shaking table test of wooden framed structure was conducted under light, moderate or heavy dead load. Size and a specification of test specimens are common as shown in Figure 1. Spatial frames made from a pair of one-story, one-bay wooden structure with or without braces and/or plywood panel walls were investigated. The height from base (sill) to top beam is 1,820 mm, and both columns with 910 mm interval. Five types of specimens were prepared for test; a braced frame (BHD, BHS), a plywood walled-frame with HD (hold-down) connector (WHD, WHS), a plywood walled-frame with cotter connector (WCD, WCS), a pure frame with HD connector (PHD, PHS), and a pure frame with cotter (PCD, PCS).

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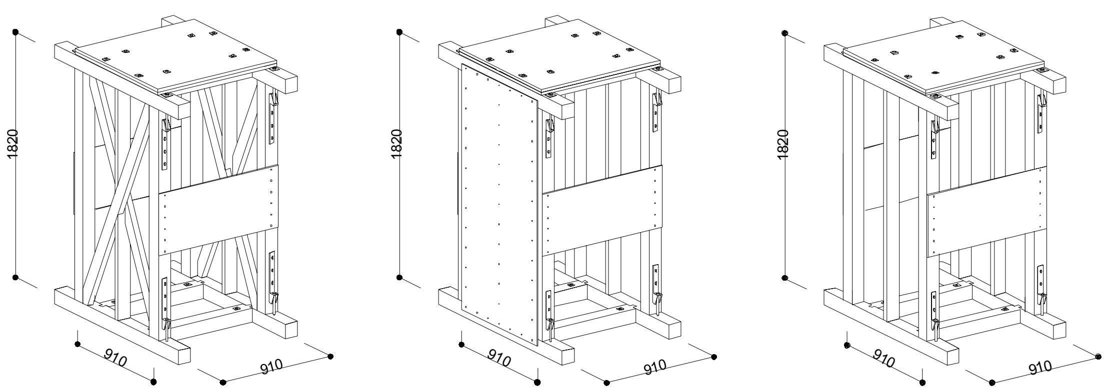
The wall was made from crossed-braces (wall strength magnification factor is 4.0), and/or plywood panel (wall strength magnification factor is 2.5) inside a pure bone frame. An HD metal and a cotter pin were used to fasten for the beam (or sill)-to-column joints. The section size of a column, a beam, and a sill is 105 mm x 105 mm. Also a 45 mm x 90 mm brace is used. The material, air-dried density and water content of each member are shown in Table 1.

Each floor weight per floor-area based on a Building Standard Law in Japan is 2.0 kN/m^2 (200 kg/m^2) on the upper floor of two stories or in one-story house, 4.5 kN/m^2 (460 kg/m^2) the first floor of two stories for a heavy roof, and 3.5 kN/m^2 (360 kg/m^2) for a light roof. Thus, the weight on a top roof of the specimen was changed in three stages for 2.0 kN/m^2, 4.0 kN/m^2, or 5.9 kN/m^2 To present the difference of the dead weight of the building, the specimen name is made as shown in Table 2.

Table 1 Material, air-dried density and water content of each member

Member	Material	Air-dried density (g/cm^3)	Water content (%)
Column, Stud	Redwood	0.60	15.0
Beam, Brace	Douglas fir	0.49	11.0
Sill	Cypress	0.47	11.0
Cotter pin	Zelkova serrata	0.54	11.0



braced frame (BHD) plywood walled-frame (WHD, WCD) pure frame (PHD, PCD)

Figure 1 Test specimen (unit: mm)

EXPERIMENTAL METHOD

Figure 2 shows the loading program in the test. The maximum acceleration level of the input earthquake excitation was changed from 200 cm/s^2 to 2000 cm/s^2 gradually (see Photo 1). The dead weight of the building was loaded from the light to the heavy one, separately for three stages. Fundamental dynamic behavior of the influence on a natural period, a damping factor and a response magnification of the structure was considered. The effect of vertical vibration (up and down) and specifications of beam-to-column joint connectors were also investigated.

The sweep test and the free vibration excitation were used to compare the specimen's behavior before and after the earthquake wave excitation. The input acceleration level was set in 30-50 cm/s^2 in the sweep test, and frequency ranges have been changed among 1-30 Hz in each 1 Hz. A free vibration test was caused given to the top beam by a hammer in man-hand. The earthquake record used as the earthquake wave excitation is the Kobe Marine Observatories record (JMA Kobe) NS and UD component of the 1995 Kobe earthquake. A JR Takatori record-EW component of the 1995 Kobe earthquake and the EW component of the 1978 Miyagiken-oki earthquake record (Kaihoku bridge, Miyagi) was also used against to the specimen at a weight of 5.9 kN/m^2.

Table 2 Test specimen

Specimen name for static test	Specimen name for dynamic test	Dead weight (kN/m^2)
braced frame BHS	BHD-2	2.0
	BHD-4	4.0
	BHD-6	5.9
plywood walled-frame with HD connector WHS	WHD-2	2.0
	WHD-4	4.0
	WHD-6	5.9
plywood walled-frame with cotter connector WCS	WCD-2	2.0
	WCD-4	4.0
	WCD-6	5.9
pure frame with HD connector PHS	PHD-2	2.0
	PHD-4	4.0
	PHD-6	5.9
pure frame with cotter PCS	PCD-2	2.0
	PCD-4	4.0
	PCD-6	5.9

ACCELERATION RESPONSE MAGNIFICATION

Figure 3 is the acceleration response magnification of a braced frame (BHD) is about 1.7-1.9 times as both large as that of in horizontal excitation at 2.0, 4.0, 5.9 kN/m^2 loadings. That of a plywood walled-frame with HD connector (WHD) increases about 1.5 times in 2.0 or 4.0 kN/m^2 loadings, and 2.3 times in 5.9 kN/m^2 loading. It corresponds greatly as the dead weight of the building increases. On the other hand, in the case of a plywood walled-frame with cotter connector (WCD), the acceleration response magnification is about 1.0-1.5 times at 2.0-5.9 kN/m^2 loadings, but does not take a big change. The acceleration response in the case of a pure frame with HD connector (PHD) was about 1.4 times. In the case of a pure frame with cotter (PCD), the response acceleration decreases to about 0.5 times according to the increasing dead weight. The response becomes dull because a fixed degree of columns is loose. All five specimens do not respond as greatly as horizontal excitation due to vertical excitation, as shown in Fig. 4.

NATURAL PERIOD AND RESPONSE MAGNIFICATION

Figure 5 shows the relation of the natural period of the specimen to the maximum input acceleration at the base due to the earthquake excitation by the shaking table. The natural period of the structure becomes long as the input earthquake acceleration increases. In the braced frame specimen (BHD), the natural period was not changed under light weight of 2.0 kN/m^2 and for middle weight of 4.0 kN/m^2, but some changes take place from 0.09 to 0.11 seconds under heavy weight of 5.9kN/m^2 of the building. In the specimen with the plywood wall under the weight of 5.9 N/m^2, it rose especially remarkable from 0.10 to 0.15 seconds for the panel wall with HD connector (WHD), and from 0.10 to 0.25 seconds for the panel wall with cotter connector (WCD). In the case of the pure frames, changes began to take place over the weight of 4.0 kN/m^2, and change was remarkable from 0.30 to 0.46 seconds under the heavy weight of 5.9 kN/m^2. It is found that the response magnification of the top roof against the base tends to decrease with longer natural period of the structure, as shown in Fig. 6.

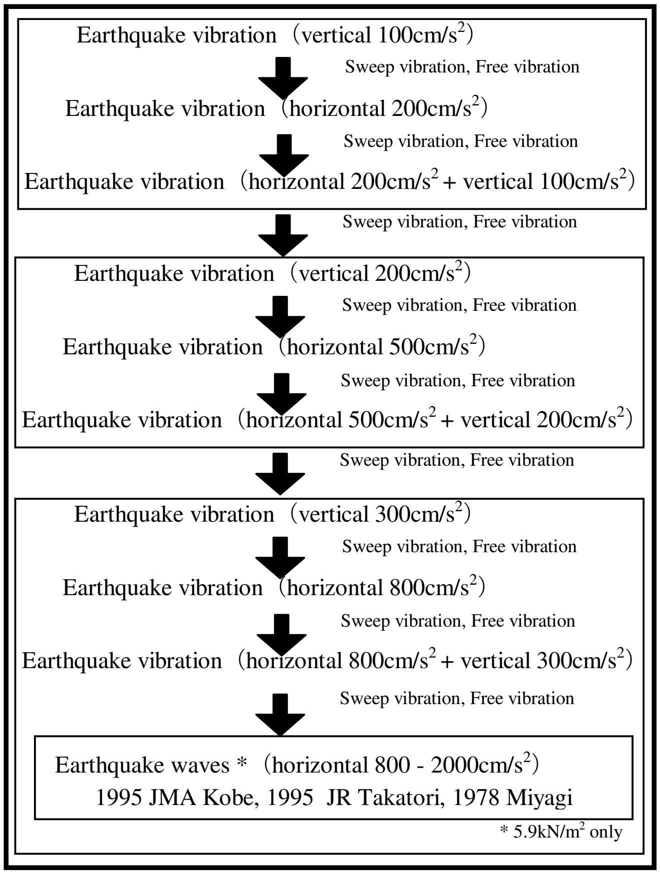


Fig. 2 Shaking test program

Photo 1 Shaking table test

Table 3 Failure mode of the specimen and story drift angle

specimen	Story drift angle in static loading test (failure mode)	Story drift angle in elastic-perfectly plastic model
braced frame (BHS)	1/240 (deformation of connector metal)	1/288
plywood wall with HD connector (WHS)	1/120 (deformation of connector metal)	1/152
plywood wall with cotter connector (WCS)	1/120 (plywood delamination)	1/182
pure frame with HD connector (PHS)	1/60 (deformation of connector metal)	1/46
pure frame with cotter (PCS)	1/30 (pull-out column)	1/28

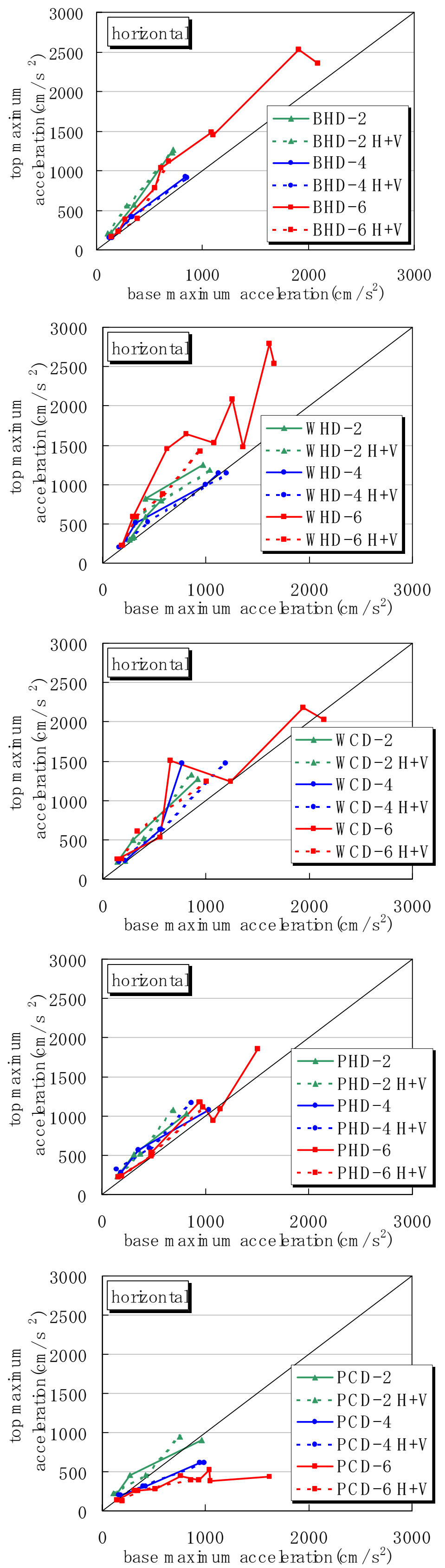


Fig. 3 Acceleration response (horizontal)

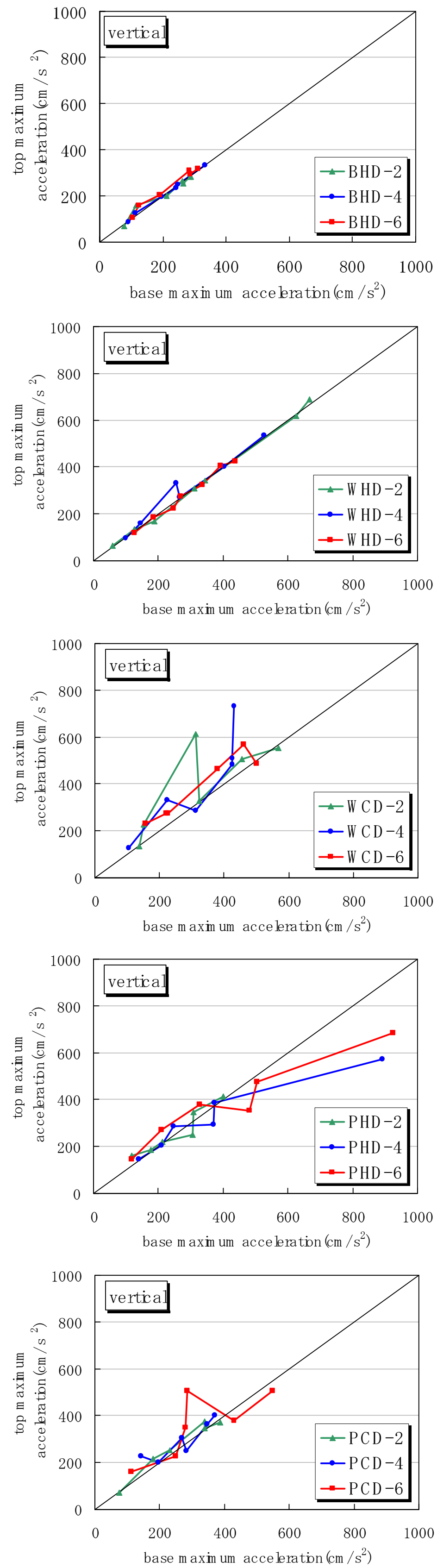


Fig. 4 Acceleration response (vertical)

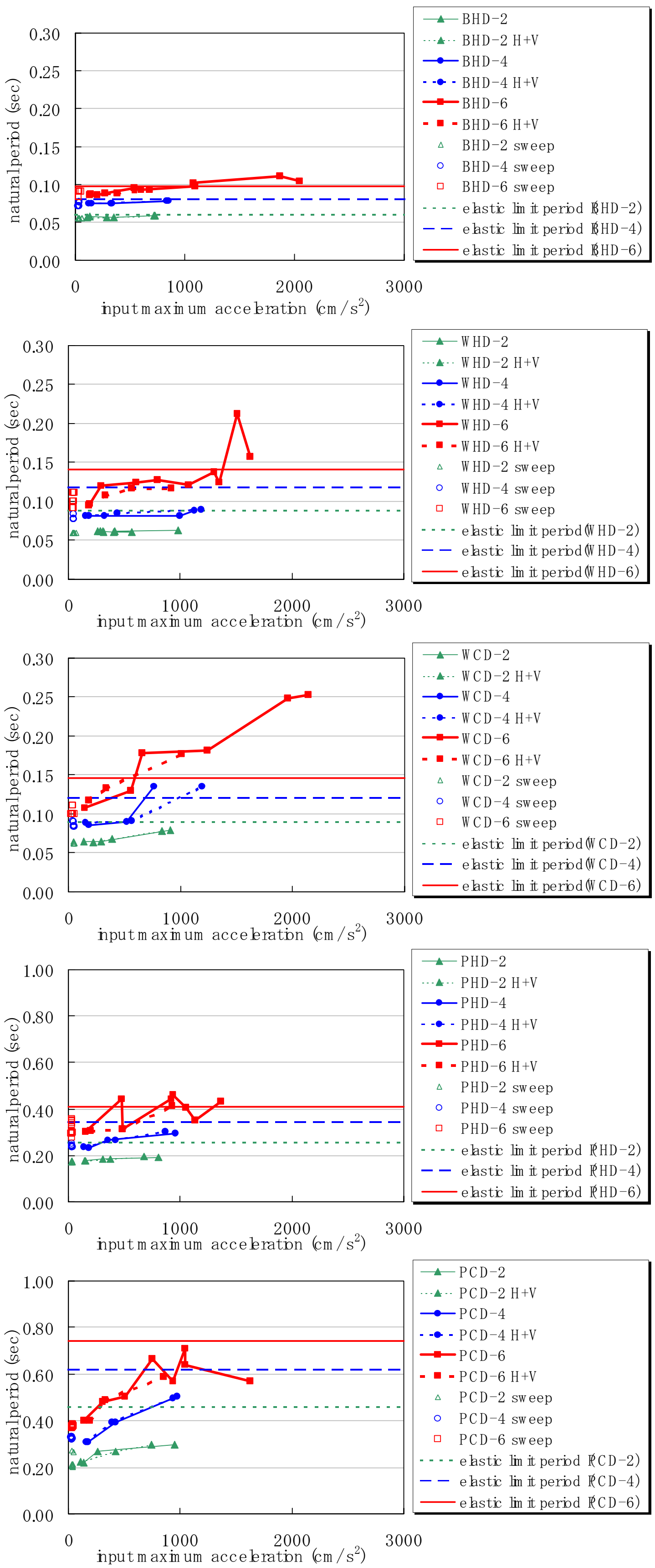


Fig. 5 Natural period-maximum input acceleration

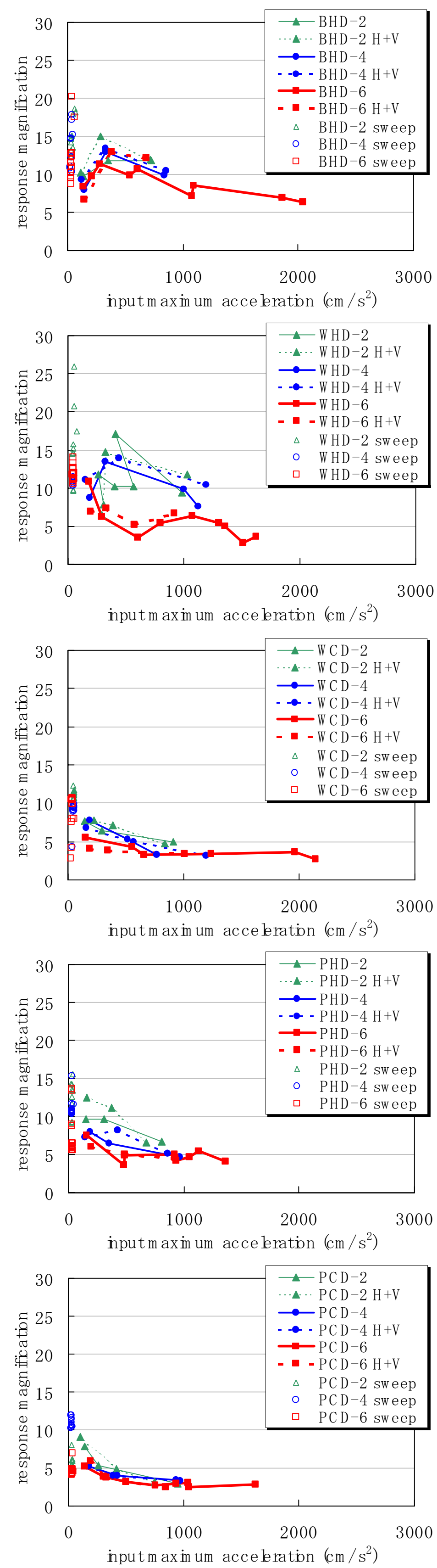


Fig. 6 Response magnification-input acceleration

NATURAL PERIOD TO ELASTIC LIMIT

Natural period of the elastic limit, T_e, is proposed as an evaluation index for damage in an earthquake. Conducting the static loading test, a natural period of the elastic limit, T_e, was calculated (see Eq. 1). Using equivalent elasticity rigidity k_e, corresponding to the first yield displacement δ_y to evaluate the damage condition quantitatively, from the envelope of a restoring force characteristic curve. k_e has been obtained from the static loading test and by using the elastic-perfectly plasticity model (refer to Table 3, Table 4, Fig. 7 and Fig. 8).

$$T_e = 2\pi\sqrt{\frac{m}{k_e}} \qquad (1)$$

The damage condition is quantitatively evaluated by using the natural period of the elastic limit T_e. The natural period of the braced frame (BHD) will exceed T_e over 1000 cm/s^2 under the heavy weight of 5.9 kN/m^2 (see Fig. 5), where loosening of the HD hardware was caused. In the specimens with the plywood wall, the natural period of the elastic limit was exceeded for the HD hardware over 1500cm/s^2 under heavy weight of 5.9 kN/m^2, loosening of the HD hardware was caused similarly. On the other hand, the specimen with cotter joint exceeds T_e over 1000 cm/s^2 under heavy weight of 5.9 kN/m^2. It is defined that a structure is damaged in plastic region when the natural period exceeds T_e. The damage means such as causing from HD connector's loosening and decreasing of rigidity.

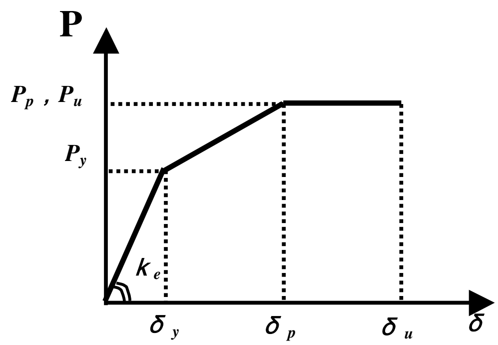


Fig. 7 Restoring force characteristics

Table 4 Restoring force property values

	BHD	WHD	WCD	PHD	PCD
First yield displacement δ_y (cm)	0.8	1.2	1.0	4.0	6.5
Second yield displacement δ_p (cm)	2.1	4.9	3.7	11.8	10.8
Ultimate displacement δ_u (cm)	3.2	9.4	9.2	18.2	18.2
First yield load P_y (kN)	22.1	15.8	12.3	6.2	3.1
Second yield load P_p (kN)	36.3	26.2	18.0	10.5	4.7
Ultimate load P_u (kN)	36.3	26.2	18.0	10.5	4.7

EARTHQUAKE LEVEL REACHING DEFORMATION RESPONSE IN PLASTIC REGION

The elastic-plastic earthquake response analysis, made by Kitahara[1], who used one lumped mass system model was executed, in which combination of tri-linear Masing type and slipping type models for

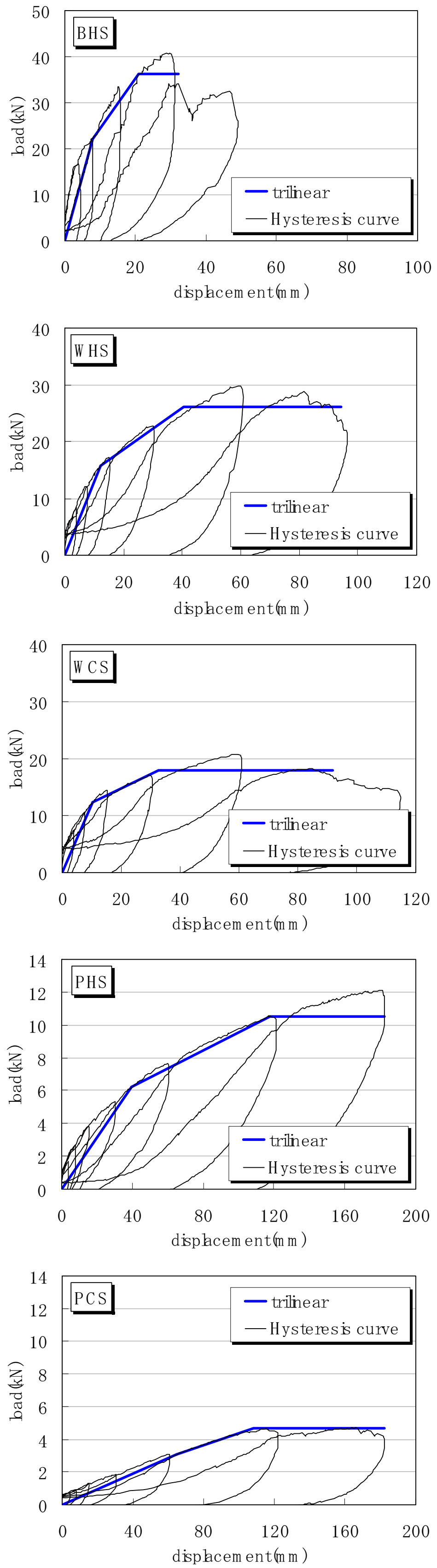


Fig. 8 Load-displacement relations

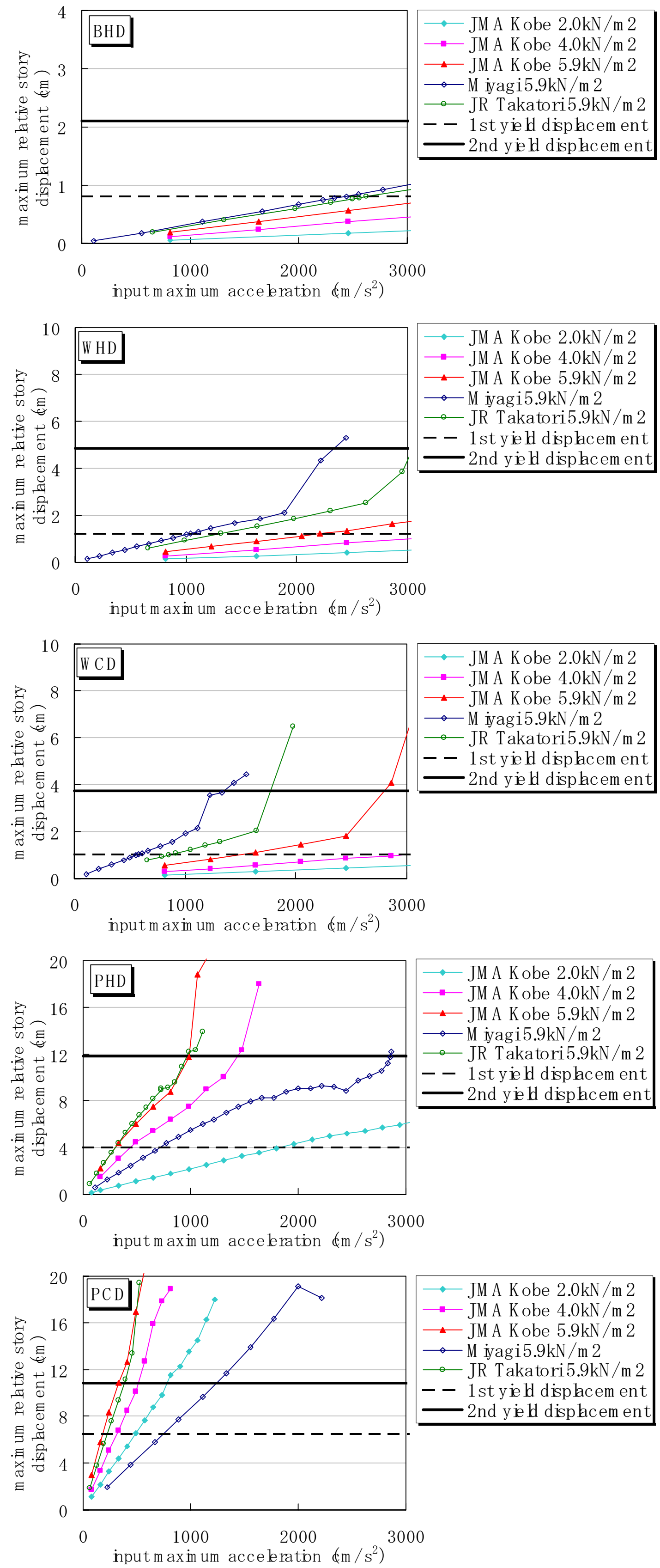


Fig. 9 Story drift-input acceleration relations

restoring-force characteristics was employed (Refer to Table 4). The input earthquake wave used by the analysis is three waves; 1978 Miyagiken-oki earthquake record (Miyagi) EW component, 1995 Kobe Marine Observatories record (JMA Kobe) NS component and of JR Takatori record EW component of the 1995 Kobe earthquake when having used by the shaking table test. The ratio of tri-linear types which occupied to the restoring force characteristic was set to 0.2 as all. The maximum acceleration level in which the specimen reached the yield displacement δ_y coincides that the natural period of the structure rapidly increase by the shaking table test. The story drift and the frame rigidity correspond to the natural period of the elastic limit, T_e, and the analysis confirmed the agreement roughly. The yiled displacement δ_y of the wooden frame to the natural period of elastic limit, T_e, under the dynamic loading test, is corresponding the story drift where damage is watched under the static loading test.

Figure 9 shows the relation between the maximum input acceleration and the maximum story displacement. The yield displacement δ_y of the wooden frame to the natural period of elastic limit, T_e, under the dynamic loading test, is corresponding the story drift where damage is watched under the static loading test. In the case of a braced frame (BHD), a big input acceleration, 4000 cm/s^2 or more, can be estimated under loading at 5.9 kN/m^2. The maximum acceleration level in which the frame reached the yield displacement δ_y coincides that the natural period of the structure rapidly increase by the shaking table test. The story drift and the frame rigidity correspond to the natural period of the elastic limit, T_e, and the analysis confirmed the agreement roughly.

CONCLUSIONS

Shaking table test of wooden framed structure was conducted under light, moderate or heavy dead load. The weight of the building is changed for 2.0 kN/m^2, 4.0 kN/m^2, or 5.9 kN/m^2, and the maximum acceleration level of the input earthquake excitation has been changed from 200 cm/s^2 to 2000 cm/s^2 gradually. Fundamental dynamic behavior of one-story, one-bay wooden framed structure with or without braces and/or plywood panel walls was investigated. The influence on a natural period and a response magnification of the structure was considered. Moreover, the effect due to vertical vibrations (up and down) and specifications of beam-to-column joint connectors were also considered. In conclusions, the following were clarified.

1. The natural period of the structure becomes long as the weight of the structure and the maximum acceleration levels of the input earthquake wave increase. This becomes remarkably longer in the pure frames and the specimen with plywood panel walls under the heavy dead weight of the building. The response magnification of the top roof against the base tends to decrease with longer natural period of the structure. However, it was not so changed in the case of the braced frame even under the heavy dead weight.
2. The above-mentioned behavior becomes remarkable in the case of the frame with HD (hold-down) fasteners in the beam (or sill)-to-column joints. On the other hand, when cotter pin is used to beam (or sill)-to-column joints, there is no increase or, in some cases, decreases in the response acceleration of the top roof, because a fixing rigidity is relatively low.
3. A natural period of the elastic limit, T_e, was proposed as an evaluation index of damage in an earthquake. Executing the static loading test, a natural period of the elastic limit, T_e, was calculated using the equivalent elastic rigidity. It is defined that the structure damages in plasticity when the natural period exceeds T_e. The damage means such as causing the HD fastener's loosening and decreasing of rigidity.
4. The yield displacement δ_y of the wooden frame to the natural period of elastic limit, T_e, under the dynamic loading test, is corresponding the story drift where damage is seen under the static loading test.

5. The elastic-plastic earthquake response analysis which used one lumped mass system model was executed. The maximum acceleration level in which the frame reached the yield displacement δ_y coincides that the natural period of the structure rapidly increases by the shaking table test. The story drift and the frame rigidity correspond to the natural period of the elastic limit, T_e, and the analysis confirmed the agreement roughly.

ACKNOWLEDGEMENTS

The experiment of this research was supported by many students of Department of Civil and Architectural Engineering, Hiroshima Institute of Technology; Kazushi Kandori, Hideaki Koyano, Naoki Nakamura, Chiharu Yagi, Erina Yada, Kohei Isaka, Mami Iwamoto, Mariko Ohmine, Takahiro Orimoto, Takashi Nakahara, Teruo Hukumoto, Kayoko Fujimoto, Koji Yamamoto, Yoko Uehira, Yuji Shimizu, Tomoyuki Shoda, Katsumi Suzuki, and Yuji Takemura. Their efforts are greatly appreciated.

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