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ORIGINAL ARTICLE

Dynamic response of wall-floor joints of wooden light-frame constructions under forced harmonic vibrations

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Abstract Shaking table tests of the wall-floor joints of wooden light-frame constructions under forced harmonic vibrations are conducted in this study so as to observe the dynamic responsive characteristics. The principal results are as follows: The responsive characteristics of timber constructions under strong earthquakes cannot be directly correlated with their resonant frequencies under free or forced vibrations with low input accelerations, because they behave as continuous bodies when the input accelerations are less than the apparent frictional limits of structural joints. The apparent frictional limits are reduced by periodic fluctuation of the effective vertical loads as a result of the vertical motion of the specimens. The characteristic dynamic responses of wall-floor joints depend clearly upon the frequency and input accelerations of forced vibrations. These dependencies arise from the nonlinear load-slip relationship of the wall-floor joints. The equivalent stiffness in their successive transient phases decreases as joint slip increases, which gradually changes the resonant frequencies of the wall-floor joints. This indicates that the frequency components dominant to ultimate or safety-limit resistance should be distinguished from those dominant to allowable or serviceability-limit resistance.

Keywords Wall-floor joints · Harmonic vibration · Responsive acceleration · Frequency dependency · Frictional limit

Introduction

In wooden light-frame constructions, wind or earthquake forces are transmitted through the boundaries between shear walls and lower floors. At these boundaries, nailed wall-floor joints mainly resist the lateral forces occasionally in concert with other supplementary resisting elements. The authors, in previous studies [1, 2], showed the effect of frictional resistance on the lateral resistance of the wall-floor joints of wooden light-frame constructions under static forces. In this study, the authors conducted shaking table tests with the same wall-floor joints to observe their responsive characteristics under dynamic forces.

In most shaking table tests conducted with respect to timber constructions, actual structures or simplified structural models are shaken by actual or simulated earthquake waves or white noise together with sweep waves. The dynamic responses of structures or structural models subjected to waves consisting of random wave components, however, are very complicated and are not easily analyzed in detail without a more fundamental understanding of the dynamic behavior of timber constructions. Therefore in this study, wall-floor joint models were shaken by forced harmonic vibrations at different frequencies on a uniaxial shaking table.

Materials and methods

One-dimensional shaking table tests were conducted on three wall-floor joint specimens as shown in Fig. 1. These

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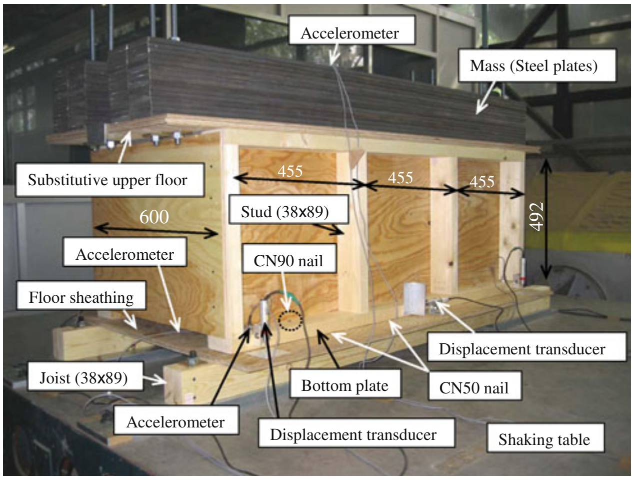


Fig. 1 Shaking table test

three specimens were selected from the six specimens used in the previous static tests and were undamaged except for the nail holes [1]. The average air-dry specific gravity and moisture content of the SPF 204 frame members of the specimens were 0.47 (0.41–0.52) and 12.6% (11.6–13.2%) and those of the floor-sheathing plywood (15-mm thick Karamatsu plywood) were 0.57 (0.54–0.59) and 9.8% (8.7–10.6%), respectively. The apparent frictional coefficient obtained from the previous static tests between the bottom plates of the walls and the floor-sheathing plywood was 0.29 on average and ranged from 0.23 to 0.35 [1].

The floors and walls were fabricated according to standard specification [3], i.e., the floor-sheathing plywood was fastened to the joists with CN50 nails at 150 mm spacing, the bottom plates of the walls were connected to the joists through the sheathing plywood with CN90 nails at 455 mm spacing, and the wall sheathings were connected to the frame members with CN50 nails at 100 mm spacing. Two walls arranged parallel to the shaking axis shown in Fig. 1 were connected with 24-mm thick plywood, which substituted for an upper floor, at the top of the walls and 60 steel plates weighing 0.16 N each were fixed on it to give mass. The total mass applied to the bottom plates of the walls was a little over 1000 kg. This mass was determined in consideration of the approximate static lateral resistance of the nailed wall-floor joints tested in this study. The current design standards for timber structures, however, do not stipulate the allowable lateral resistance of nailed wall-floor joints with bottom plates that are nailed to joists through plywood sheathing. In this study, therefore, the allowable lateral resistance of a standard timber-to-timber joint with six CN90 nails adjusted to the average specific gravity of the frame members was calculated according to the Japan standard for timber structures [4] as an approximation, where the contribution of frictional resistance to the actual lateral resistance was not taken into account [1, 2]. The resultant static allowable lateral resistance was 5797 N per six nails, which roughly corresponded to the acceleration of 0.6 G for the given mass. The design static ultimate resistance of nailed joints is ensured to be at least 1.5 times the allowable resistance, and will in actuality be 1.8 times or more in most cases [4]. The acceleration corresponding to the static ultimate resistance was then estimated to be from 0.87 to 1.05 G, ignoring frictional resistance. The walls were stiffened with 9.5-mm thick plywood panels to avoid out-of plane deformation, and wall-sheathing panels were affixed to the interior sides of the walls to permit re-nailing of the bottom plates to the floor during the process of the shaking table tests as shown in Fig. 1.

The specimens were shaken parallel to the shear walls on a uniaxial electro-dynamic shaking table under harmonic waves of 4, 8 and 12 Hz in an acceleration range from 0.1 to 1.0 G. The full capacity of the shaking table was 2500 kg G for sine waves and 1000 kg G for random waves. The time series of the input acceleration of the shaking table and the responsive accelerations of the floor sheathing, the bottom plates of the walls, and the substitutive upper floor were measured using strain gauge accelerometers with a capacity of 2.0 or 5.0 G for each combination of frequency and acceleration of forced harmonic vibration. The responsive acceleration of the bottom plates was determined as the average of the readings of two accelerometers located at diagonal positions on the bottom plates of the two walls. The average relative slip between the bottom plates of the two walls and the floor sheathing was determined from the readings of two displacement transducers with a capacity of 30 mm fixed at the symmetrical middle positions of the bottom plates of the two walls synchronously with the accelerations. The average relative vertical displacements between the bottom plates and the floor sheathing at the both ends of the two walls were measured with two pairs of displacement transducers with a 20 mm capacity fixed on the same ends of the separate walls.

The shaking table tests were conducted as follows. The assembled specimens were tapped at the tops (substitutive upper floors) with a mallet to measure the resonant frequency in free vibration at a low input acceleration. The impact acceleration given by tapping was about 0.03 G. Next, the specimens were shaken by 8 Hz harmonic waves continuously with increasing input accelerations of roundly 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8 and 1.0 G, with the accelerations kept constant for around ten seconds at each acceleration. After the tests at this frequency, all the CN90 nails were pulled out, regardless of damage, and the bottom plates were re-fixed with new nails placed a little away from the existing nail holes. The re-nailed specimens were tested again using 12 Hz harmonic waves, and then renailed and tested using 4 Hz harmonic waves. After all of the harmonic wave tests were conducted, the resonant frequencies of the specimens were measured again by tapping in the same way as in the free vibration tests before the harmonic wave tests.

Results and discussion

Resonance frequencies in free vibration at low acceleration

The resonant frequencies of the specimens for a given mass, which were measured by tapping their tops, were 9.3, 10.3, 10.3 Hz (9.9 Hz on average) prior to the harmonic wave tests. The resonant frequencies were intermediate between 8 and 12 Hz. The lateral forces corresponded to the impact accelerations, around 0.03 G, were far less than the frictional limits between the bottom plates of the walls and the floor sheathings, which led the specimens to respond as continuous bodies with no slips at the wall-floor joints.

The resonant frequencies of the specimens after all the harmonic wave tests remained at 9.3, 9.3, 9.3 Hz (9.3 Hz on average), although the wall-floor joints had been damaged or broken during the harmonic wave tests as shown in Fig. 2. This slight change in resonance frequency shows that dynamic lateral forces are transmitted by friction through the wall-floor joints with little contribution from the nailed joints in load share if they are sufficiently below the frictional limits [1, 2]. This test result indicates that the responsive characteristics of timber constructions during strong earthquakes cannot be directly correlated with the resonant frequencies observed under free or forced vibrations at very low accelerations, which are regarded as an index of the earthquake resistance of structures.

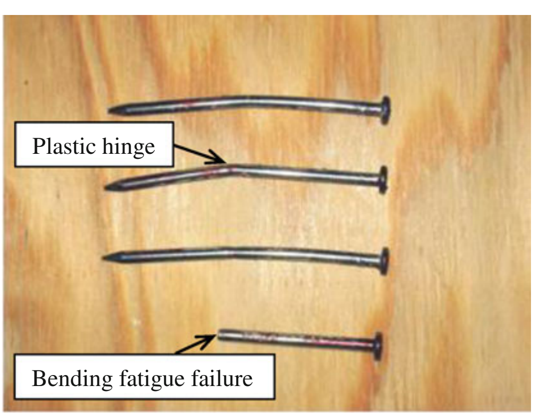
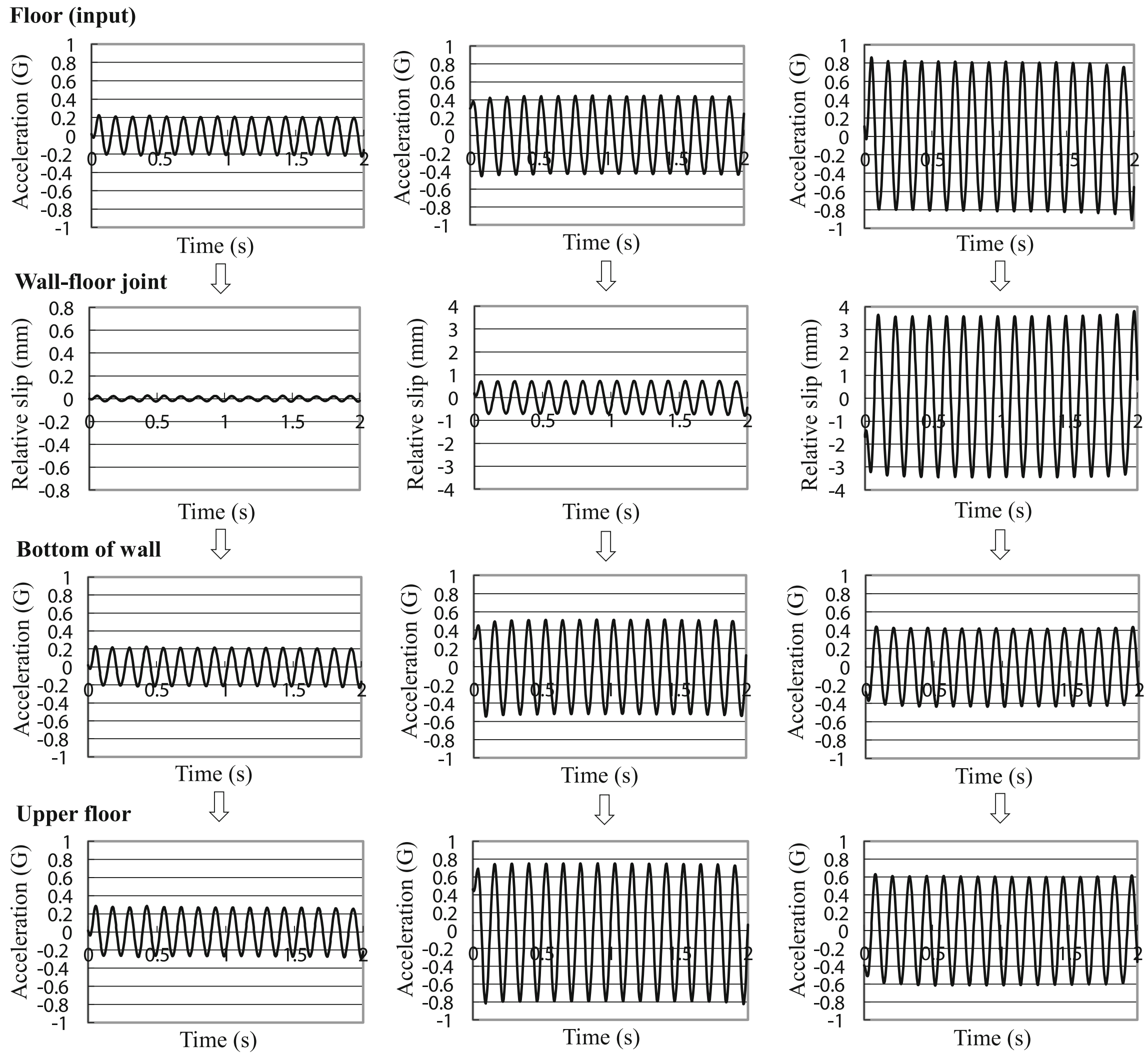


Fig. 2 Observed failures of nails

Responsive accelerations under harmonic vibrations

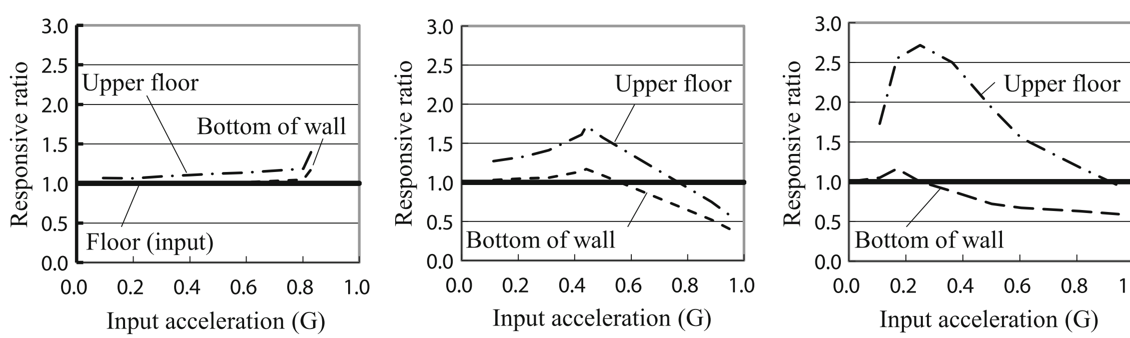
Responsive accelerations on the floor-sheathing panels were regarded as input accelerations at the wall-floor joints because they were almost equal to the acceleration measured on the shaking table throughout the tests. Figure 3 shows examples of a time series of input accelerations at the lower floor and the responsive accelerations at the bottom plates and the substitutive upper floor of one of the specimens shaken by 8 Hz harmonic waves with accelerations of 0.2, 0.5 and 0.8 G. The average relative slips at the wall-floor joints are shown in the figure. When the input acceleration on the floor was 0.2 G, the bottom plates slipped little on the floor sheathing. In this state, the floor, walls and upper floor behaved almost as a continuous body similar to the behavior under free vibration. When the input acceleration increased to 0.5 G, the wall-floor joints slipped distinctly and the responsive acceleration ratios of the bottom plates and upper floor intensified. When the input acceleration reached 0.8 G and the bottom plates slipped more notably, however, the bottom plates responded dully and the responsive acceleration ratios of the bottom plates and upper floor dropped remarkably.

The changes in the responsive acceleration ratios were dependent upon the input acceleration, which reflected the slip behavior of the wall-floor joints, and had different tendencies according to the frequencies of the harmonic waves. The responsive accelerations of the bottom plates and upper floor of the same specimen are shown in Fig. 4 for each frequency. For 4 Hz, the bottom plates responded initially together with the floor, and the responsive acceleration ratios maintained a little more than unity. The responsive ratios finally reached 1.20 at the bottom plates and 1.44 at the upper floor accompanied with large slips of the wall-floor joints. When the input acceleration was comparatively small, the bottom plates and the upper floor responded more sensitively to 8 and 12 Hz, at which the initial resonant frequency 10.3 Hz of this specimen lay between. For 8 Hz, the responsive acceleration ratios intensified to 1.17 at the bottom plates and 1.72 at the upper floor when the input acceleration was about 0.50 G (actually 0.45 G). For 12 Hz, which was a little closer to the resonant frequency of 10.3 Hz than 8 Hz, the responsive acceleration at the bottom plates reached its maximum value of 1.16 when the input acceleration was about 0.20 G (actually 0.17 G) and the responsive acceleration ratios at the upper floor was intensified to 2.72 when the input acceleration was about 0.30 G (actually 0.25 G). The responsive acceleration ratios for these frequencies, however, decreased as the input acceleration increased. They dropped finally to 0.40 at the bottom plates and 0.57 at the upper floor for 8 Hz and 0.59 and 0.95 for 12 Hz. The test results above are restricted within particular test conditions,



(a) Input acceleration: 0.2 G **(b)** Input acceleration: 0.5 G **(c)** Input acceleration: 0.8 G

Fig. 3 Examples of time series of input and responsive accelerations and relative slips



(a) Frequency: 4 Hz **(b)** Frequency: 8 Hz **(c)** Frequency: 12 Hz

Fig. 4 Responsive acceleration ratios for each frequency

of course, because the resonant frequencies of the structural elements or joints vary dependent upon their stiffness and given mass.

The allowable lateral resistance of shear walls similar to the model specimens tested here (Fig. 1) is 15.87 kN per two walls according to the Japanese notification [5], which is equivalent to an acceleration of 1.57 G for the given mass. When these shear walls are installed in actual structures, the earthquake forces bore by them will be less than this value, varying ordinarily between corresponding accelerations of 0.7 and 1.5 G (from less than 50% to nearly 100% of the allowable resistance), because shear walls are usually arranged with safety margins in practical design. The input accelerations that intensified the responses of the specimens for 8 and 12 Hz were less than both the acceleration of 0.6 G that corresponded to the allowable resistance of the wall-floor joints and accelerations varying from 0.7 to 1.5 G estimated above from the allowable resistance of the shear walls derived assuming a standard base shear of 0.2 G [6].

The responsive characteristics dependent upon frequency arise from the nonlinear load-slip relationships of the wall-floor joints as illustrated in Fig. 5. The equivalent secant stiffness of the wall-floor joints, which corresponds to the inclination of each broken line in the figure, decreases as the joint slip increases. This successive transition of equivalent stiffness decreases the resonant frequencies of the wall-floor joints. The wall-floor joints respond sensitively to higher frequencies for small input accelerations in the initial phase of the load-slip curve. When the input accelerations increase, they damage the joints and increase joint slips, which decrease the resonant frequencies of the joints as presumed from Fig. 5. These changes in resonant frequency dull the dynamic responses of the joints to higher frequencies. Because of this dulling of response due to the decrease in resonant frequencies, the

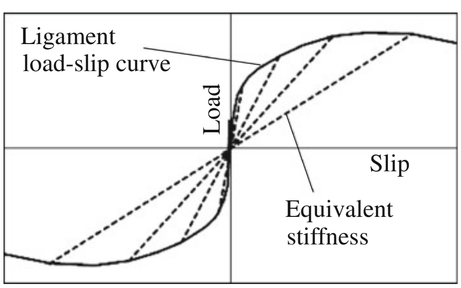


Fig. 5 Equivalent stiffness of a wall-floor joint

wall-floor joints survived under waves of 8 or 12 Hz without critical failures that may result in the collapse of a structure. If the wall-floor joints are shaken by waves of lower frequencies, on the other hand, they respond less sensitively to small input accelerations in the initial phase, but respond more sensitively as the accelerations and slips increase. As a result, the wall-floor joints of two of the three specimens broke in the failure mode of low-cyclic bending fatigue of the nails when subjected to 4 Hz harmonic waves (Fig. 2) in this study. The responsive acceleration ratios of the bottom plates of the walls are shown again in Fig. 6 compared with the relationship between the responsive acceleration ratios and the relative slips of the wall-floor joints for three frequencies.

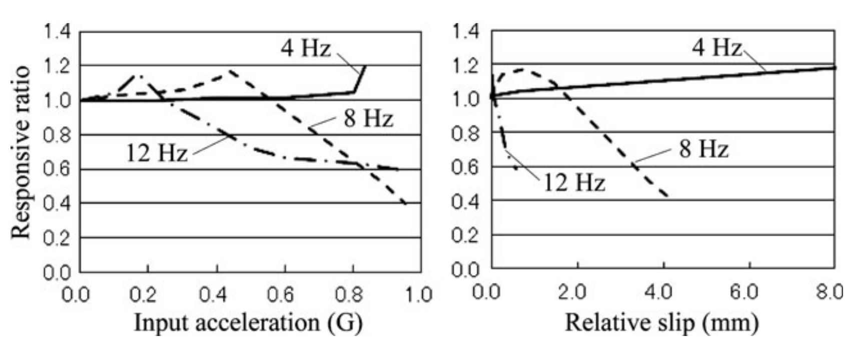
These test results indicate that the frequency components of earthquake motions close to the initial resonant frequencies of structural elements or joints may damage them below the allowable resistance estimated assuming a base shear of 0.2 G. However, they will ultimately be broken by lower-frequency components of strong earthquakes, which cause damaged elements or joints with decreased stiffness to resonate. Although this discussion is derived only from dynamic tests of wall-floor joint of wooden light-frame constructions, a similar transition of the responsive behavior of mechanical timber joints will dominate the earthquake resistance of timber constructions, which will sometimes lead to the collapse of timber buildings or will sometimes allow them to survive strong earthquakes.

The above discussion leads to the conclusion that we should distinguish the frequency components dominant to the ultimate or safety-limit resistance from those which are dominant to the allowable or serviceability-limit resistance [7].

Apparent frictional limits of wall-floor joints under dynamic forces

The apparent frictional coefficients estimated from the relationship between the observed responsive accelerations, which were excited by discrete input accelerations

Fig. 6 Responsive characteristics of bottom plates of walls and relative slips of wall-floor joints



with increments of around 0.1 G, and the relative slips of wall-floor joints were reduced as the frequency increased. Under a harmonic wave of 4 Hz, the average apparent frictional coefficient of the three specimens was 0.30, which was almost equal to the average apparent frictional coefficient 0.29 measured in the previous quasi-static tests. Under waves of 8 and 12 Hz, the wall-floor joints started to slip at lower responsive accelerations corresponded to the average apparent frictional coefficients of 0.22 and 0.14, respectively. These results were not consistent with the results of the previous quasi-static tests [1], which showed that apparent frictional coefficients were stable within the tested range of displacement rate from 2.7 to 82.8 mm/min, although the characteristic stick–slip behavior depended on the displacement rate. The reduction of the apparent frictional coefficients observed in this study seems related to the changes in effective vertical loads resulting from the two-dimensional motion of the specimens. This is because the velocity or displacement rate of each input wave in the shaking table tests, which may possibly affect the frictional coefficients, is lower for a higher frequency at the same acceleration as inferred from the well-known relationships among acceleration, velocity and displacement. This fact is incompatible with the observed apparent frictional coefficients above. The principal components of two-dimensional motion are rocking motion (Fig. 7a) and vertical motion (Fig. 7b). The former component scarcely reduces the apparent frictional coefficients, because the rocking motion changes only the distributions of the vertical loads or reaction forces that are unchanged in total [1]. Then we examined the latter component, the vertical motion of the specimens. Figure 8 shows the absolute peak values of vibrational vertical displacements between the bottom plates and the floor for an input acceleration of 0.2 G, where the fluctuation of displacement resulting from the rocking motion was offset by averaging the measurements of the four displacement transducers located at both ends of the two walls. Vertical displacements were clearly observed and their peak values increased as the frequency increased, as shown in the figure, although the specimens were intended to be shaken only in the horizontal direction parallel to the shear walls on a uniaxial shaking table. This vertical motion causes the effective vertical loads to fluctuate, which allows instantaneous slips of the bottom plates on the floor sheathing under occasional minimized effective vertical loads. It is not clear what caused the vertical motion and its frequency dependency. One probable reason is the particular vibrational characteristics of the shaking table used in this study being dependent on the input frequency, or it may result from the vertical resonant frequencies of the specimens.

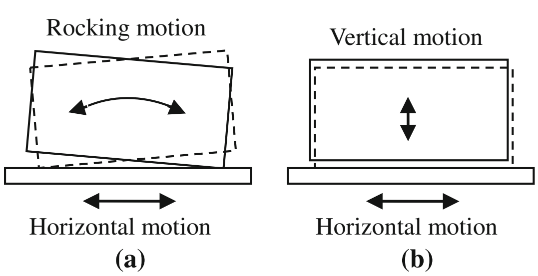


Fig. 7 Presumable two-dimensional motion of specimens

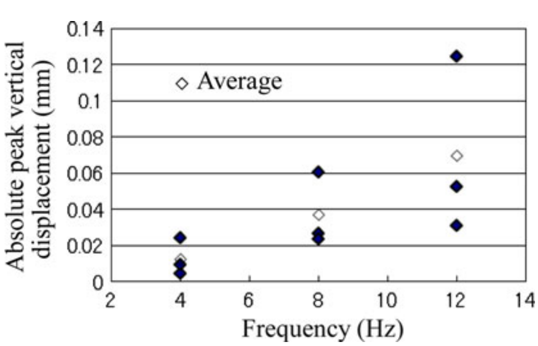


Fig. 8 Absolute peak values of relative vertical displacements between bottom plates and floor sheathing

Actual earthquake forces are naturally three dimensional in any event, thus the vertical motion will fluctuate the effective vertical loads of actual structural elements that cause the instantaneous reduction of frictional resistance [1, 2]. The reduction of the apparent frictional coefficients will also diminish the frictional damping capacities [1, 2, 8–10]. The effect of the decrease in the frictional damping on the dynamic response of the wall-floor joints is not understood in detail at the present.

Conclusions

Shaking table tests of wall-floor joints under forced harmonic vibrations were carried out in this study. The principal conclusions were:

The responsive characteristics of timber constructions during strong earthquakes cannot be directly correlated with their resonant frequencies observed under free or forced vibrations with low input accelerations. This is because the structures behave as continuous bodies when the input accelerations are less than the frictional limits of the structural joints. The apparent frictional limits will be reduced by the periodic fluctuation of the effective vertical loads due to vertical motion.

The characteristic dynamic responses of wall-floor joints depend clearly on the frequency and input accelerations. These dependencies arise from the nonlinear load-slip relationship of the wall-floor joints. The equivalent stiffness in their successive transient phases decreases as joint slip increase, which successively changes the resonant frequencies of the wall-floor joints. This discussion leads to the conclusion that the frequency components dominant to the ultimate or safety-limit resistance should be distinguished from those dominant to the allowable or serviceability-limit resistance.

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