Dynamic Response of Timber-Plywood Joints under Forced Harmonic Vibrations

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SUMMARY:
In past our various structural experiments, bending fatigue failure of nails and wood screws has been confirmed. The purpose of this study is to research how dynamic loads affect bending fatigue failure of nailed timber-plywood joints. First, in order to establish the test method and experimental design, the fixture was designed, fabricated and adjusted. Next, using this jig, harmonic vibration tests are conducted to understand the dynamic response of the joint for different frequencies and input levels. These tests confirm that vibration response behavior of the joint is complex and flexural fatigue failure occurs cannot be estimated in static test. Here, it is suspected that harmonic vibration is more excessive than random vibration as input. Therefore, random vibration tests are conducted and the dependence of frequency is characterized.

Keywords: Shaking table tests, wooden joints, flexural fatigue failure

1. INTRODUCTION

In recent years, small or large earthquakes occur frequently in Japan and buildings are shaken many times. In general, structural members are joined by nails in wood frame construction in Japan. The current allowable shear-stress design method for the wooden joints is based on the modes of shear failure of joints on the assumption that flexural fatigue failure of joints does not occur. Although the risk of flexural fatigue fracture by earthquake for wooden joints has been mentioned in the current design method, the data for evaluating the dynamic responsive characteristics is not enough. In past our various structural experiments, the flexural fatigue fracture of nails sometimes was confirmed (Figure 1.1). However, the condition this fracture occurs does not become clear.

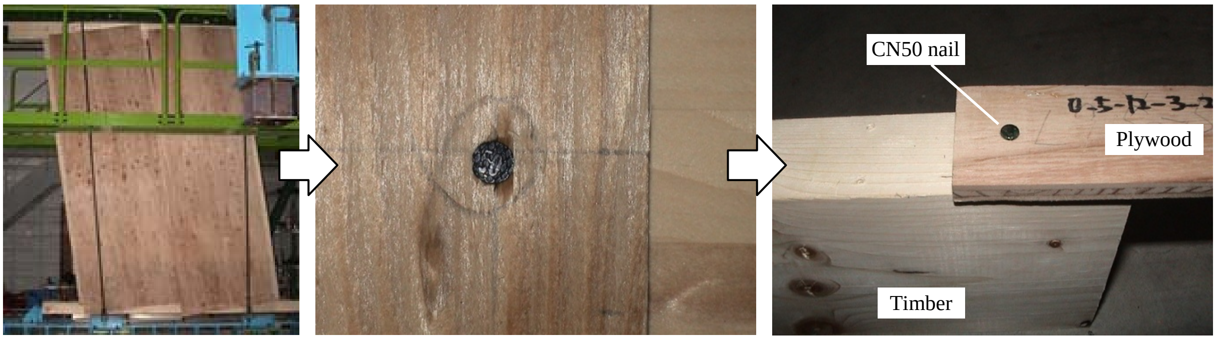
Figure 1.1. General deformation and flexural fatigue fracture of nails in our past experiments

In view of this situation, shaking table tests of the timber-plywood joints fastened with nail under forced harmonic or random vibrations are conducted in this study so as to observe the basic dynamic responsive characteristics.

2. EXPERIMENT

2.1. Materials and Specimens

Figure 2.1 shows the test specimen. The specimen is composed of CN50 common nail, Karamatsu(Larix kaempferi) plywood and Todomatsu(Abies sachalinensis) timber. CN50 common nail is 2.87mm in diameter and 51.0mm in length. Karamatsu plywood is 9.5mm in thickness. These are commonly used in shear walls in Japanese wood-frame construction. The specimen used in this study is a basic joint element of the share wall. Incidentally, the specific gravity and the moisture content of the Karamatsu plywood ranged from 0.47 to 0.54 (0.51 on average) and from 6.9 % to 8.3 % (7.5 % on average), and those of the Todomatsu timber ranged from 0.36 to 0.45 (0.40 on average) and from 7.3 % to 8.9 % (8.2 % on average), respectively. These test materials were divided evenly among all test conditions including preliminary static tests based on the specific gravities of the materials.



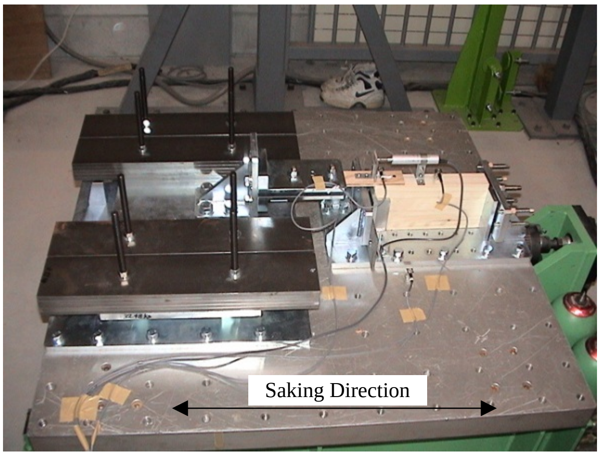
Shear walls with plywoods | Nailed plywood-timber joints in the shear wall | Outline of the specimens

Figure 2.1. Overview of test specimens

2.2. Method of Shaking Test

Figure 2.2 shows the outline of shaking test. The full capacity, the maximum displacement and the maximum velocity of the shaking table were ±9.6 kN, ±50 mm, and 590 mm/sec, respectively. The specimens were assembled in the same way as the preliminary static tests referred to in the following sections except for the depth of the timber main-members, which was altered to 125 mm to fit the steel base (A) fixed onto the shaking table as shown in Figure 2.2 The timber main-member was supported tightly on this steel base. The plywood side-member was fixed to the steel base (B) on the opposite side, which was placed on a pair of sliding rails with two pairs of bearings as shown in Figure 2.2 to allow the smooth motion of mass free from the motion of the shaking table. The mass was adjusted using removable steel plates fixed to the steel base (B)

The input acceleration at the timber main-member fixed to the shaking table and the responsive acceleration at the plywood side-member fixed to the sliding mass were measured using strain gauge accelerometers with a capacity of 2G. The relative slip between the side-member and the main-member was measured synchronously with the accelerations using a displacement transducer with a 50-mm stroke. The acceleration on the shaking table was also measured to verify that the timber main-member was firmly fixed onto the shaking table.



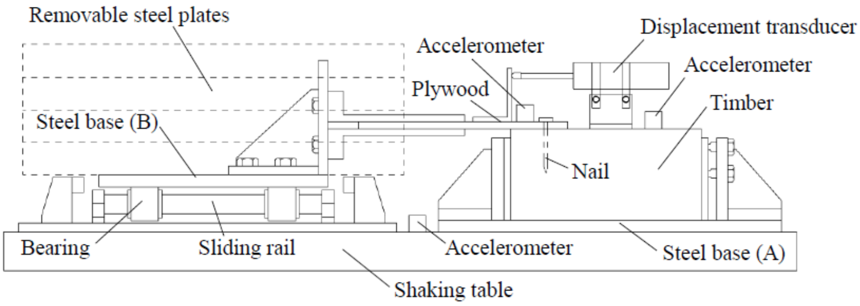


Figure 2.2. Outline of the shaking test

2.3. Plan of Shaking Test

The excitation was two types: sine wave and random vibration. Table 2.1 and Table 2.2 show the characteristics of the sine waves and the random vibration and the number of specimens, respectively.

Each frequency of the sine waves was determined to be 2, 3, 4, 5, 6 and 7 Hz. These frequencies were within the general distribution of base shear spectra. The given mass and the input accelerations were determined to be 202 kg and 165 gal (0.17G), 330 gal (0.34G) and 495 gal (0.51G). The products of the given mass by the input accelerations above were equivalent to one-third, two-thirds and the whole of maximum load of a preliminary static single-shear test, respectively. Here, twelve nailed plywood-timber joints were tested in static single-shear in advance of the dynamic tests and the static load-slip curves of the 12 specimens were averaged into the control load-slip curve. Figure 2.3 shows the relation between the control curve and the input accelerations. Each displacement for shaking test was calculated from the frequency and acceleration.

The random vibration covered frequencies 1Hz to 8Hz in increments of 0.5Hz and all of the amplitude of these component waves was same. Input acceleration and displacement amplitude of random vibration was determined in the same method as described above.

For each testing condition, 6 specimens were tested one-dimensionally in the direction parallel to both the grains of the timber main-members and the surface veneers of the plywood side-members. The specimens were shaken continuously to failure or for 150 seconds if clear failures were not found.

Table 2.1. Shaking condition and the number of specimens (sine wave)

Input Level	frequency[Hz]					
	2	3	4	5	6	7
(3/3)P_{max}	6	6	6	6	6	6
(2/3)P_{max}	6	6	6	6	6	6
(1/3)P_{max}	6	6	6	6	6	6

Table 2.2. Shaking condition and the number of specimens (random vibration)

Input Level	frequency[Hz]
	1-8Hz, $\triangle f$=0.5Hz
(3/3)P_{max}	6
(2/3)P_{max}	6
(1/3)P_{max}	6

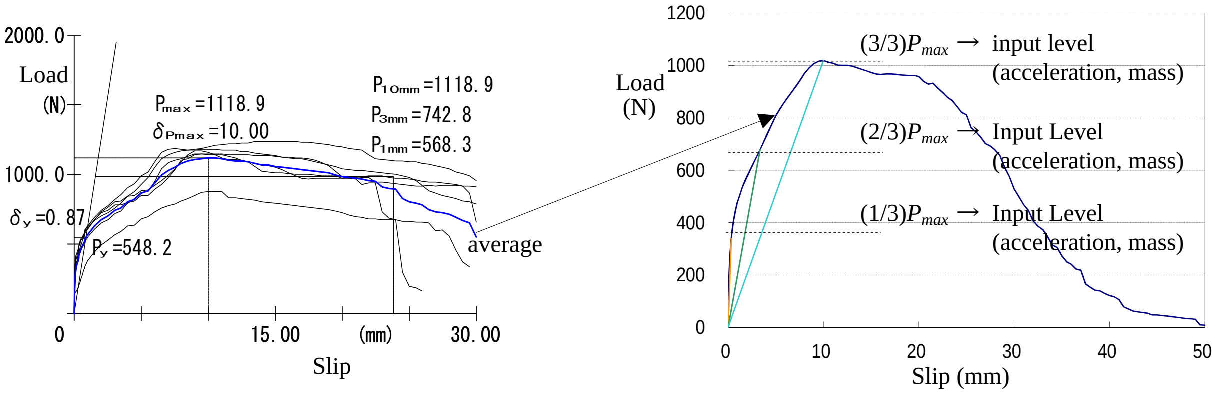


Figure 2.3. Control load-slip curve by preliminary static tests and input level on shaking tests

3. TEST RESULTS AND STUDY

3.1. Frequency Dependence on acceleration-slip curves

The characteristic dynamic responses of the joints depending upon the input frequency are made clearer by observing the responsive acceleration-slip curves shown in Figure 3.1. In this figure, the control static load-slip curves (see Figure 2.3) are shown again by converting static loads into equivalent accelerations together with the equivalent slips and secants resonant to each input frequency from 2 Hz to 7 Hz. Figure 3.1 shows that the dynamic cyclic loops shift gradually to nearly inside the static envelope curves. In this figure, a characteristic difference can be seen in the dynamic response between the frequencies of 2 Hz and 3 Hz. For the frequency of 2 Hz, both the responsive acceleration and slip increased with every cycle accompanied by a cyclic impairment of the equivalent linear stiffness. This behavior was gradual in the early phase of the cyclic response, and became more intense as the resultant equivalent linear stiffness came closer to the equivalent secant stiffness in Figure 3.1 (a).

3.2. Frequency Dependence on failure modes

The frequency dependencies of the responsive accelerations and slips resulted in the cycles at the ultimate failures of the specimens and their failure modes as shown in Figure 3.2. The boldface (red) and italic (blue) entries in Figure 3.2 show, respectively, low-cyclic bending fatigue failure and nail-head-pull-through with occasional plywood shear. The cycles with “+” symbols show that no critical failures were observed after shaking for 150 seconds. This results show the relative sensitivities of the dynamic responses and the obvious frequency dependency of the nailed plywood-timber joints among the combinations of input acceleration and frequency. The input

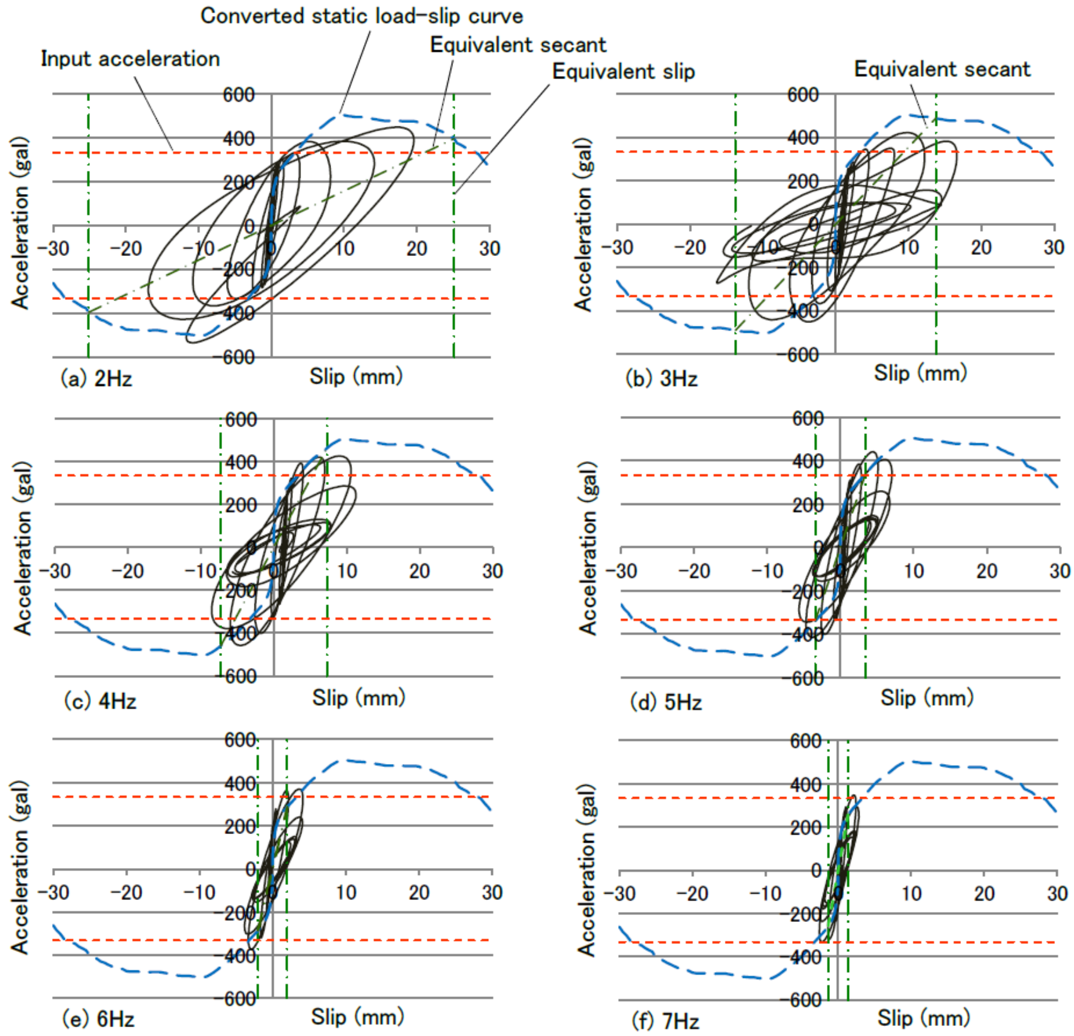


Figure 3.1. Examples of dynamic responsive acceleration-slip loops (sinusodial, 330gal)

acceleration equivalent to the standard short-term allowable lateral resistance adjusted to the specific gravities of the test materials is about 244 gal, which lies between 167 gal and 330 gal. An important result in Figure 3.2 is that the dynamic response of the nailed plywood-timber joints is relatively more sensitive to input frequency than input acceleration. Another important result is that the most severe frequency that causes the bending fatigue failure of nails does not coincide with the most severe frequency that causes a typical failure in static loading, nail-head-pull-through.

Figure 3.3 shows an example of the results of the shaking tests by the random vibration. The natural frequency of the specimen is reduced if the input level rises. At this time, the transition of the natural frequency is non-linear and the stiffness calculated from the frequency consistent with the equivalent stiffness by the preliminary static tests.

On the other hand, the incidence of bending fatigue fracture was reduced compared with the case in the sine wave tests. These results mean that the sine wave is convenient to identify trends but excessive input in order to evaluate the destruction.

Cycles at failue						
Equivalent static	Frequency (Hz)					
	2	3	4	5	6	7
$P_{max}/3$	300+	118	343	750+	900+	1050+
	35	157	167	344	900+	1050+
	300+	130	128	387	900+	1050+
	300+	52	157	720	900+	1050+
	56	141	284	750+	900+	1050+
	300+	199	368	750+	900+	1050+
Av.	215+	133	241	617+	900+	1050+
$2P_{max}/3$	*18*	17	94	306	266	1050+
	12	33	108	307	455	1050+
	11	51	49	240	900+	1050+
	14	43	61	191	309	1050+
	17	57	43	178	416	501
	12	21	98	426	859	1050+
Av.	14	37	76	275	534+	959+
P_{max}	*9*	27	27	60	215	334
	10	15	64	143	268	468
	10	26	29	100	78	342
	12	17	27	51	81	277
	11	26	39	146	152	1043
	8	16	35	340	358	524
Av.	10	21	37	140	192	498

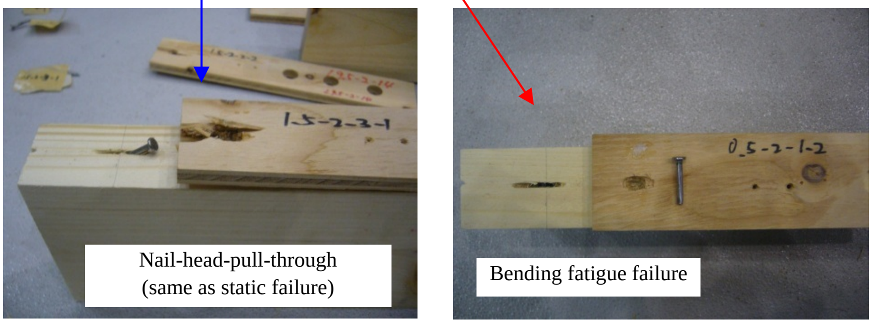


Figure 3.2. Cycles at failure of each specimen and failure modes (sine wave test)

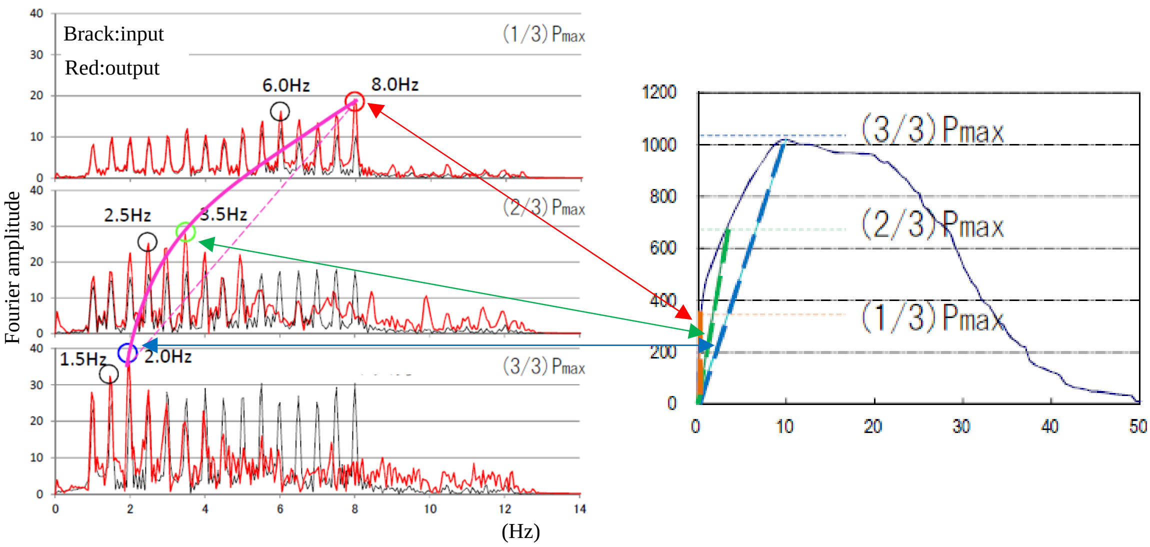


Figure 3.3. Comparison between input levels and transition of natural frequency (random vibration test)

4. CONCLUTION

In this study, we maintained the data more than 120 about dynamic behavior of nailed plywood-timber joint which has not been revealed until now. The principal results obtained from the above experiments are as follows:

- Flexural fatigue failure of joints may occur in harmonic vibration.
- In random vibration, a similar failure is observed but the incidence is low compared with the case in harmonic vibration.
- Frequency-domain independent of input level to flexural fatigue failure is confirmed.
- Non-linearity of natural frequency is observed according to the input level.
- The frequency characteristics of the case seems a good response to equivalent linear line obtained from the static load-slip curves.

The detailed analysis of these enormous data is an urgent problem in the future.

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