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ORIGINAL ARTICLE

Dynamic responses of nailed plywood-timber joints under a band-limited white-noise wave

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Abstract In this study, dynamic tests of nailed plywood-timber joints are conducted under a band-limited white-noise wave using a uniaxial hydraulic shaking table. The principal results are as follows: dynamic responses of nailed plywood-timber joints under a band-limited white-noise wave are reasonably related to the static load-slip relationships and the dynamic responses under harmonic waves of them. When nailed plywood-timber joints are shaken under a composite wave of wide frequency range, they resonate transitionally with one of the frequency components one after another decreasing their equivalent resonant frequencies along their static load-slip curves. Nailed plywood-timber joints are in danger of ultimate failures even though the input maximum accelerations do not exceed their damage limits, if they are shaken for long times with or without intermittences. In this case, nailed plywood-timber joints are prone to fail in low-cyclic bending fatigue failure of nails. Nailed plywood-timber joints, on the other hand, are prone to fail in typical static failure modes when they are shaken under strong input maximum accelerations equivalent to their ultimate limits.

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Introduction

Dynamic responses of timber joints depend upon frequency characteristics of input waves. In the previous study [1], shaking table tests of nailed plywood-timber joints were conducted under harmonic waves of various frequencies, which clarified characteristic frequency dependence in responsive behavior of them. Dynamic tests under harmonic waves are suitable for understanding the fundamental frequency dependence of timber joints in dynamic response. Harmonic waves of single frequencies, however, affect them in a different way from actual seismic waves of the same peak input accelerations, because a seismic wave is composed of various frequency components. A difference between the dynamic responses under harmonic waves and those under seismic waves may be the successive transition of responsive behavior related to the characteristic nonlinear load-slip relationships and cyclic stiffness degradation of nailed timber joints [1]. In this study, therefore, shaking table tests were conducted on nailed plywood-timber joints under a band-limited white-noise wave, which was a simple basic model of composite waves of multiple frequency components.

Experimental

Nailed plywood-timber joints were tested under a band-limited white-noise wave [2–4] using a uniaxial hydraulic shaking table. In a shaking table test, a Karamatsu (*Larix*

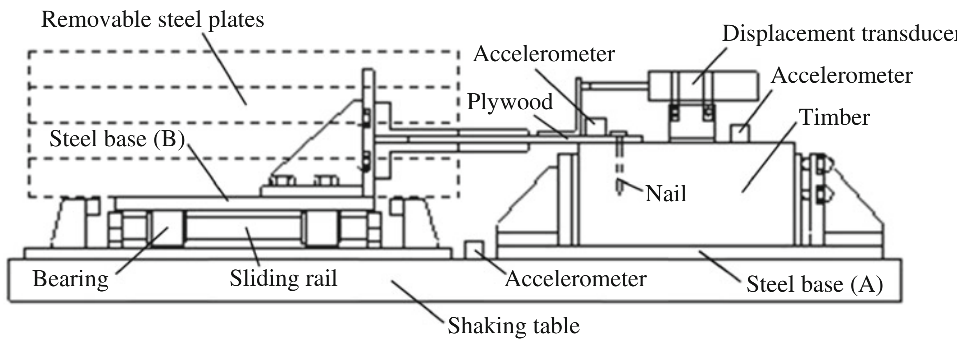

Fig. 1 Details of dynamic single-shear test [1]

kaempferi) plywood (JAS for plywood: structural plywood, type special, class 2) side-member was fastened with a CN50 common nail (JIS A 5508: 2.87 mm in nominal diameter and 50.8 mm in nominal length) onto a Todomatsu (*Abies sachalinensis*) timber main-member as shown in Fig. 1 [1]. Timber main-members were prepared to avoid knots or other defects. The plywood side-member was 9.5 mm in thickness, 45 mm in width and 255 mm in length, and the timber main-member was 40 mm in width, 125 mm in depth and 240 mm in length. The end distance from the nail was 6 times the nail diameter in the side-member and 15 times in the main-member, and the side distance was 7.8 times the nail diameter in the side-member and 7 times in the main-member [5]. The air-dry density and the moisture content of the Karamatsu plywood ranged from 0.47 to 0.52 g/cm^3 (0.50 g/cm^3 on average) and from 10.1 to 10.6 % (10.4 % on average) and those of the Todomatsu timber ranged from 0.37 to 0.41 g/cm^3 (0.40 g/cm^3 on average) and from 11.2 to 11.8 % (11.4 % on average). These test materials had been prepared in advance of the previous static and dynamic tests [1] to make the densities of the test materials even among all the tests. This procedure was adopted to enable the fair comparison between the test results of previous and this study, particularly to use the static load-slip curve determined in the previous study as the control.

The full capacity, the maximum displacement and the maximum velocity of the shaking table were ±9.6 kN, ±50 mm and 590 mm/s, respectively. The timber main-member of a specimen was supported tightly on the steel base (A) in Fig. 1 [1]. The plywood side-member, on the other hand, was fixed to the steel base (B) in the same figure. The steel base (B) with removable steel plates bolted onto it, which gave a mass of 202 kg in total [1], was placed on a pair of sliding rails to allow the smooth motion of mass free from the shaking table. The input acceleration at the timber main-member and the responsive acceleration at the plywood side-member were measured using strain gauge accelerometers with a capacity of 2 G. The relative slip between the side-member and the main-member was measured using a displacement transducer with a 50 mm stroke. The acceleration on the shaking table was also monitored to verify the firm fixing of the timber main-member onto the shaking table. In this study, a band-limited white-noise wave was generated as follows. A frequency range from 1.0 to 8.0 Hz was adopted considering the responsive characteristics of the nailed plywood-timber joints under harmonic waves [1] and the general distribution of base shear spectra of most seismic waves [6, 7]. A flat white-noise wave of this frequency range was substituted with a composite wave of discrete frequency components of 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5 and 8.0 Hz. These frequency components with an even acceleration were integrated into a composite wave assuming quasi random phases so as to generate peak accelerations of 165 gal (cm/s^2) (0.17 G), 330 gal (cm/s^2) (0.34 G) and 495 gal (cm/s^2) (0.51 G) [4]. The products of these maximum accelerations and the given mass of 202 kg were equivalent to one-third, two-thirds and three-thirds of the control static maximum load, which were determined to be 333, 667 and 1000 N in the previous study [1].

For each testing condition, 6 specimens were shaken 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 first shaken for 20 s in consideration for effective duration of principal earthquake motion [4, 8] and then kept stationary for 20 s. This intermittent shake was repeated up to five times if clear failures were not found.

Results and discussion

Figure 2 shows examples of the time series of the actual input accelerations at the timber main-members, the responsive accelerations at the plywood side-members and the responsive joint slips for the initial 10 s. Flat broken lines in the figure show the designed input maximum accelerations, 165 gal (cm/s^2), 330 gal (cm/s^2) and 495 gal (cm/s^2), which are equivalent to one-third, two-thirds and three-thirds of the control static maximum load, respectively. The time series data will be arranged or

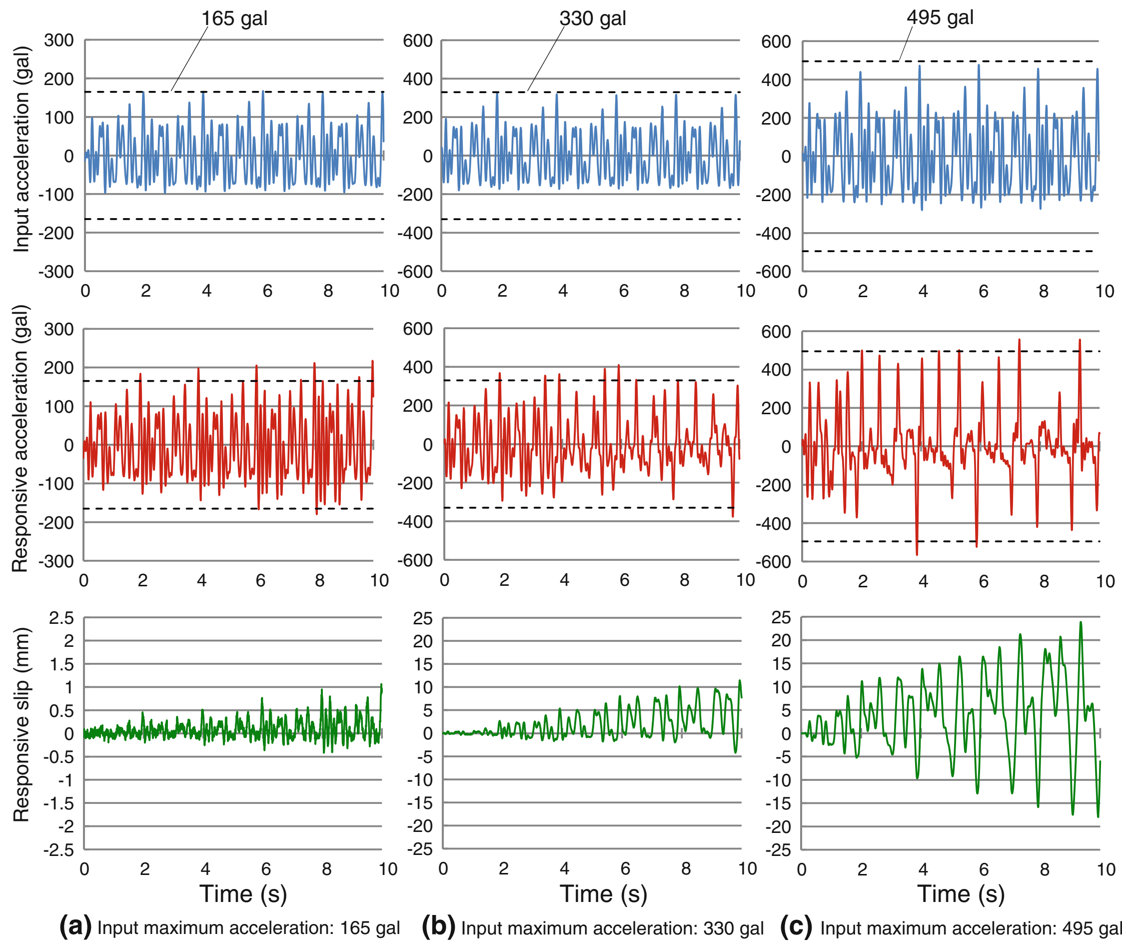

Fig. 2 Examples of time series of input accelerations, responsive accelerations and responsive joint slips

Table 1 Time at failure and failure mode

Input maximum acceleration (gal: cm/s^2)	Equivalent static load	Time at failure (s)	Failure mode
165	$P_{max}/3$	More than 100	NF: 6/6
330	$2P_{max}/3$	27.27–40.61 (Av. 34.22)	PO: 2/6, BF: 4/6
495	P_{max}	9.01–11.03 (Av. 10.03)	PO: 4/6, BF: 2/6

Numerator for each failure mode shows number of specimens failed in that mode per 6 specimens

P_{max} static maximum load, *NF* no critical failure, *PO* nail-pull-off, *BF* bending fatigue failure of nail

transformed here after, because the dynamic responses caused by combined action of multiple frequency components are not clarified in detail simply from the raw time series.

Table 1 shows time at failure and failure modes of the specimens. In this study, a shake for a period of 20 s was repeated intermittently at a regular interval of 20 s. The time at failure in Table 1 shows the cumulative seconds of active shakes. When the input maximum acceleration was 165 gal, which was equivalent to one-third of the control static maximum load, all the specimens survived five active periods of 20 s with no conspicuous failure. When the input maximum acceleration was 330 gal, which was equivalent to two-thirds of the control static maximum load, 5 of the 6 specimens failed during the second period and a specimen failed early in the third period. For this input acceleration, 2 specimens failed in nail-pull-off and 4 specimens failed in low-cyclic bending fatigue failure of nails [9]. For the input maximum acceleration of 495 gal, which was equivalent to the control static maximum load, all the specimens failed during the first period. For this input acceleration, 4 specimens failed in nail-pull-off and 2 specimens failed in low-cyclic bending fatigue failure of nails.

Figure 3 shows examples of the responsive acceleration-slip loops. The acceleration-slip loops in this figure cover the initial 20 s for the input maximum accelerations of 165 and 330 gal and just before the failure for the maximum

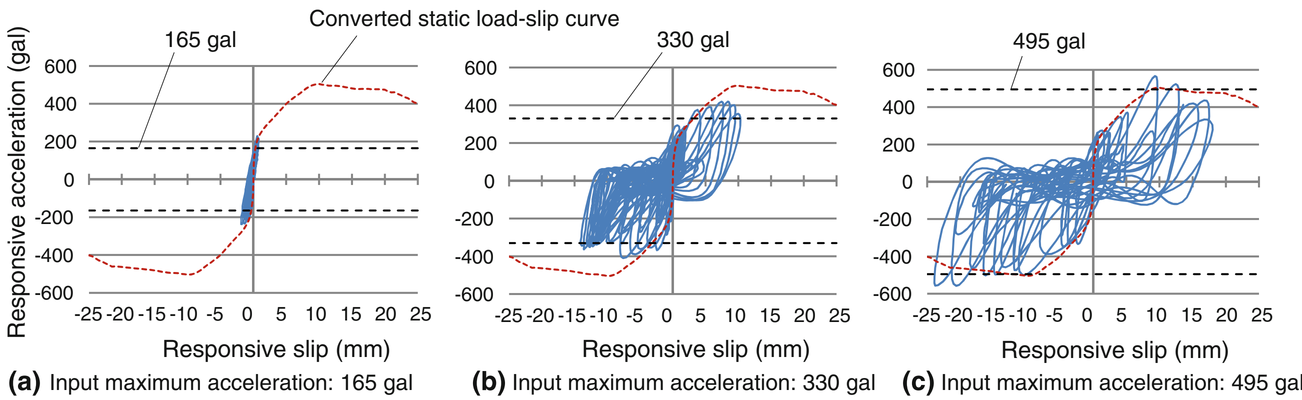

Fig. 3 Examples of responsive acceleration-slip loops

acceleration of 495 gal. The broken curved lines show the equivalent acceleration-slip curve converted from the control static load-slip curve, in which the equivalent acceleration ($m/s^2 = 10^2\ cm/s^2$) is given by dividing the static load (N) by the given mass (kg), and the horizontal dot and dash lines show the actual input maximum accelerations (see Fig. 2). The equivalent acceleration-slip curve or the converted static load-slip curve in the figure nearly envelops the dynamic cyclic loops. This result confirms that the dynamic responsive behavior of the nailed plywood-timber joints under a band-limited white-noise wave is reasonably related to the static load-slip curves of them [1].

Both the responsive acceleration and slip increased every cycle nearly along the equivalent acceleration-slip curve when the input maximum acceleration was 495 gal. This responsive behavior finally caused nail-pull-off, which was a typical static failure, in relatively higher probability (see Table 1). When the input maximum acceleration was 330 gal, the responsive acceleration and slip also increased every cycle partway; however, the peaks of cyclic loops did not trace the equivalent acceleration-slip curve through the end but kept below it as shown in Fig. 3. The resultant lower maximum acceleration allowed the specimens to withstand comparatively longer the typical static failures.

The test results shown in Fig. 3; Table 1 will indicate the following characteristic behavior of nailed plywood-timber joints under composite waves: (1) Nailed plywood-timber joints are prone to fail in typical static failure modes in relatively higher probability, when they are shaken under strong input maximum accelerations equivalent to their ultimate limits. (2) When input maximum accelerations are not so strong, they can withstand comparatively longer the typical static failures. If active shakes continue only for short time under the input maximum accelerations within their damage limits, then, nailed plywood-timber joints are able to survive with no fatal failures. If active shakes continue for long time or repeat intermittently, however, they are in danger of fatal failures even though the input maximum accelerations do not exceed their damage limits. In this case, nailed plywood-timber joints are prone to fail in relatively higher probability of low-cyclic bending fatigue failure of nails than typical static failures.

Figure 4 shows examples of the linear spectra of the input and responsive waves. In this figure, the accelerations of the actual input waves are not ideally even among the frequency components, though the input wave was confirmed beforehand with fixing the sliding mass directly onto the shaking table. This unevenness comes from an unavoidable interaction between the shaking table and the sliding mass. Three periods of 6 s were picked up from the first 20 s to observe the transition of the characteristic responses under a band-limited white-noise wave; that is, from 1 to 7 s, from 7 to 13 s, and from 13 to 19 s. Linear spectra of the input and responsive waves were calculated for these three periods for the input maximum accelerations of 165 and 330 gal. The linear spectra are shown only for the first period from 1 to 7 s for the input maximum acceleration of 495 gal, because all the specimens failed before reaching 13 s under this input maximum acceleration. The average responsive acceleration ratios of 6 specimens, which were defined as the average ratios of the responsive accelerations to the input accelerations, are shown in Fig. 5.

In the previous dynamic tests under harmonic waves of frequencies from 2 to 7 Hz, the authors observed clear frequency dependence of the dynamic responses of nailed plywood-timber joints [1]. The test results shown in Figs. 4 and 5 also confirmed the frequency dependence of the same nailed joints under a band-limited white-noise wave composed of discrete frequencies from 1 to 8 Hz. Under the input maximum acceleration of 165 gal, the nailed plywood-timber joints responded most sensitively to the highest frequency component of 8 Hz for the first period from 1 to 7 s and the sensitive frequencies became gradually lower as the cumulative shake increased from the first

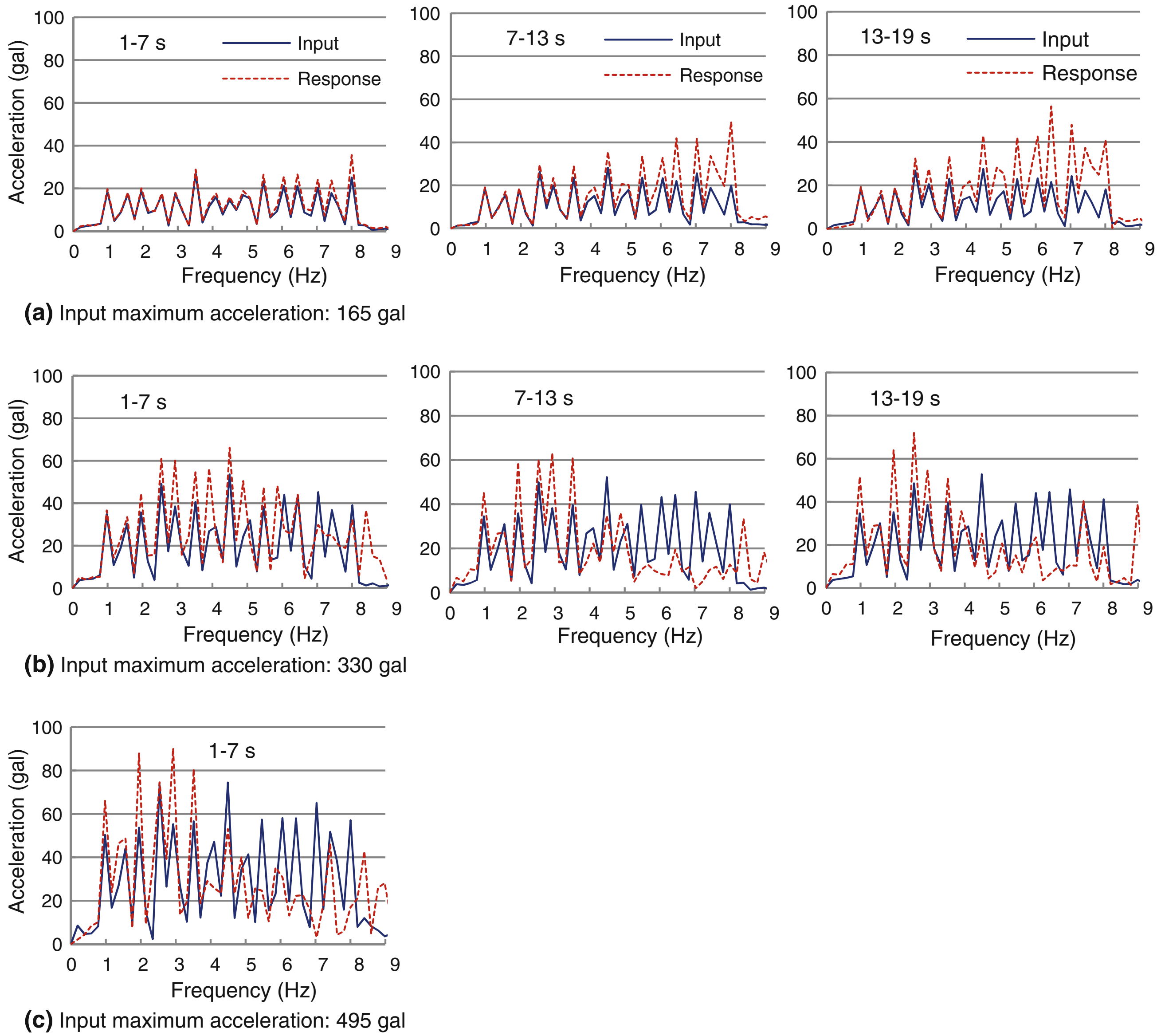

Fig. 4 Examples of linear spectra of input and responsive waves

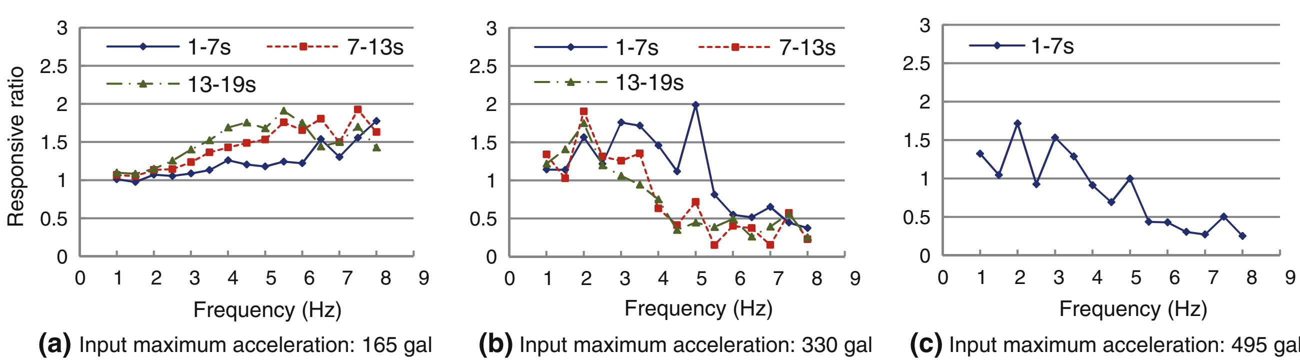

Fig. 5 Responsive acceleration ratios

period to the third period as shown in Fig. 5. This transition of the sensitive frequencies is the result of the nonlinear load-slip relationships and the cyclic stiffness degradation of nailed timber joints, which are commonly observed both under static and dynamic loadings [1, 10–14]. As the input maximum acceleration increased, the sensitive frequencies at the first period became lower as shown in Fig. 5. The sensitive frequencies to the input maximum accelerations of 165, 330 and 495 gal are related to the equivalent linear secant stiffness at these accelerations on the equivalent envelope acceleration-slip curves in Fig. 3 [1]. When the input maximum acceleration was 330 gal, they responded most sensitively to the frequency of 5 Hz for the first period, and the most sensitive frequency decreased to 2 Hz for the second and third periods on the average. An important result shown in Fig. 5 is that the distribution of responsive acceleration ratios under the wave of the input maximum acceleration of 330 gal for the second and third periods are close to that under the wave of the input maximum acceleration of 495 gal for the first period. This result indicates that nailed timber joints are in danger of resonating with the frequency components equivalent to the linear secant stiffness at their ultimate limits, if they are shaken for long times with or without intermittences, even though the input maximum accelerations do not exceed their damage limit accelerations.

The test results above show that the characteristic dynamic responses of nailed plywood-timber joints under composite waves of multiple frequency components are reasonably related to the dynamic responses of them under harmonic waves of single frequencies. Generally speaking, a harmonic wave of a single frequency affects a joint stronger than a composite wave, if the frequency of the harmonic wave is close to the stationary resonant frequency of the joint. However, it cannot simply be applied to understand the dynamic responses of nailed timber joints. When a nailed timber joint is shaken under a harmonic wave, it never resonates long with it, because the cyclic stiffness degradation decreases gradually the resonant frequency of the joint [1]. When a nailed timber joint is shaken under a composite wave that covers the full range of transitional resonant frequencies of it from the initial phase to the final phase of its load-slip curve (see Fig. 3), on the other hand, it must resonates with one of the frequency components one after another decreasing its transitional resonant frequency every cycle.

The transitional dynamic behavior of nailed timber joints depends upon the composition of the frequency components of input waves, which may be an essential key to understand the actual responsive behavior of timber constructions under earthquakes of various wave characteristics. Timber constructions are composite structural systems composed of multi-members and multi-joints, therefore, the dynamic responsive characteristics of them, which are related to the lateral load-deformation characteristics or the restoring force characteristics of them, are the integrated results of all members and joints. The element dynamic tests of mechanical timber joints, however, are very important because nonlinearity, cyclic degradation and hysteretic damping of timber constructions are generally determined by them.

Conclusions

In this study, dynamic tests of nailed plywood-timber joints were carried out under a band-limited white-noise wave, which gave the following conclusions:

1. Dynamic responses of nailed plywood-timber joints under a band-limited white-noise wave are reasonably related to the static load-slip relationships and the dynamic responses under harmonic waves of them.
2. When nailed plywood-timber joints are shaken under a composite wave of wide frequency range, they resonate transitionally with one of the frequency components one after another decreasing their equivalent resonant frequencies along their static load-slip curves.
3. Nailed plywood-timber joints are in danger of ultimate failures even though the input maximum accelerations do not exceed their damage limits, if they are shaken for long times with or without intermittences. In this case, nailed plywood-timber joints are prone to fail in low-cyclic bending fatigue failure of nails in relatively higher probability.
4. Nailed plywood-timber joints are prone to fail in typical static failure modes in relatively higher probability, when they are shaken under strong input maximum accelerations equivalent to their ultimate limits.

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