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Dynamic excitation and static loading tests of glulam lattice floor

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Abstract A wooden lattice floor with high stiffness and damping capacity has been developed to solve noise problems in wooden apartment houses. The lattice floor consisted of Douglas fir glulam beams with inserted steel plate joints and drift pins. To examine the structural performance of the floor, dynamic excitation and static loading tests were conducted on the full size floor. The first and second order resonance frequencies of the floor were 13.5 Hz and 27.0 Hz, respectively. These frequencies are similar to the peak frequency of a conventional wooden floor and the combined floor fabricated from glued laminated timber and iron. The maximum static load of the floor was 127 kN. The apparent flexural rigidity was less than half the value of several floors studied in the past. However, it is considered that the stiffness is improved by constructing panels and this floor has almost equivalent performance. Relative deflection was not affected by the loading history.

Key words Lattice Floor · Drift pin · Static deflection · Dynamic deflection · Resonance frequency

Introduction

In wooden apartment houses, various noises generated on upper floors can become serious lifestyle issues for inhabitants on the lower floors. Generally, there are four methods to solve this problem: mass addition onto structural members,[1] restraint of vibration by stiffening of joints, an increase of energy consumption at joints by damping, and raising the rigidity of joints. Although the effect of mass addition had been studied in the field of wooden structures, the other methods have not been examined at all. Thus, we chose to study a lattice floor[2] in which many metal fasteners can restrain the vibration and increase damping properties.

In this study, we designed a glulam lattice floor (GLF) with mechanical joints using drift pins, and carried out a dynamic excitation test and a static loading test. We then estimated static loading capacity, static deflection, resonance frequency, and dynamic deflection.

Materials and methods

Shape of GLF

Figure 1 shows a schematic overview of the GLF which consisted of 12 center beams (0.15 m wide, 0.23 m high, 0.86 m long), 12 side beams (0.15 m wide, 0.23 m high, 1.14 m long), 4 frames (0.12 m wide, 0.3 m high, 3.8 m long), and 4 columns (0.4 m × 0.4 m in cross section, 1.0 m long). All members were Douglas fir (*Pseudotsuga menziesii* Franco) glulam beams. In Fig. 1, the symbols X_0 to X_4 and Y_0 to Y_4 shows grid lines. Hereafter, these letters are used for expressing the intersection points (e.g., X_1Y_3). The dynamic modulus of elasticity (dynamic MOE, E') of all members was measured by the flexural vibration method. Table 1 shows the fundamental properties of the members.

Figure 2 shows a beam and joints. The joints were the so-called inserted steel plate with drift pins type in which a steel plate was inserted into a member and fixed with many drift pins. The diameter of the drift pins was 12 mm. The thickness of the inserted steel plate was 9 mm.

The arrangement of drift pins was determined in the following stepwise manner. At first, the largest moment of glued laminated timber was defined as a moment generated 1.5 times as large as the allowable bending stress.[3] Next, the stresses that occurred at individual drift pins were

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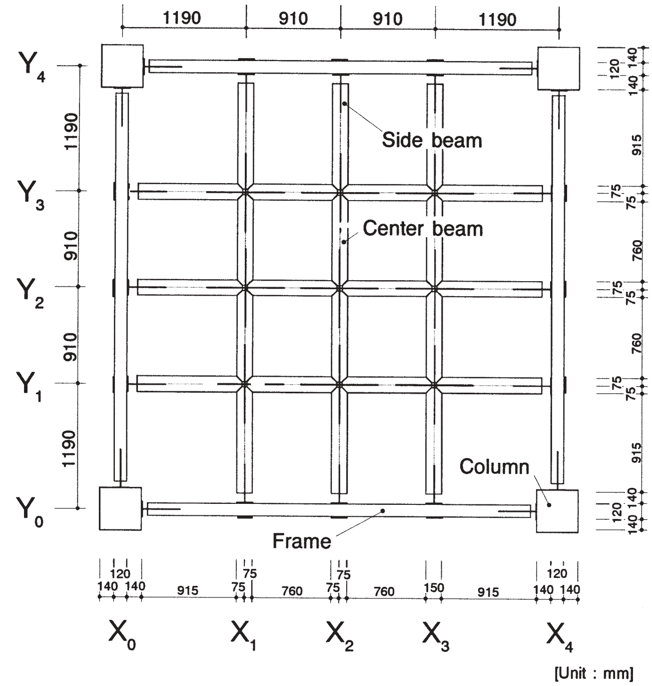

Fig. 1. Overview of glulam lattice floor (GLF)

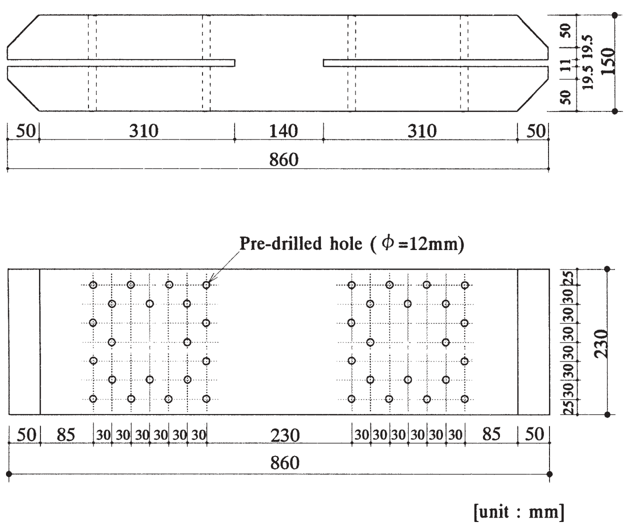

Fig. 2. Detail of the joint

Table 1. Fundamental properties of members

Property	Mean	Coefficient of variation (%)
Dynamic elasticity (MPa)	12.1	6.03
Air-dried density (kg/m^3)	511	5.28
Moisture content (%)	11.2	6.25

calculated by assuming that 80% of the largest moment affected the joint. Then, the number and arrangement were adjusted until the calculated stresses of all drift pins fell below the yield stress.

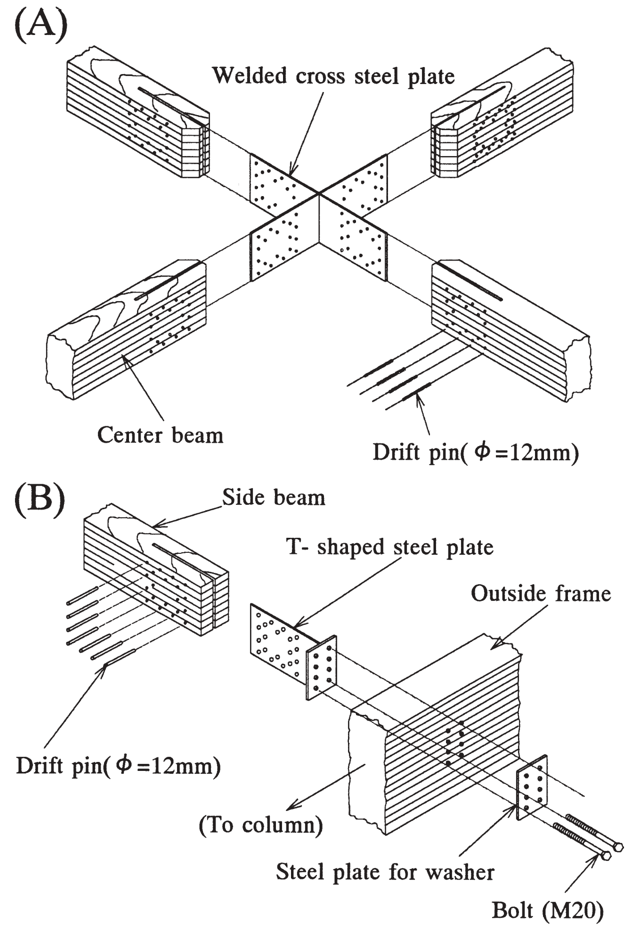

Fig. 3. Assembly methods at intersection (**A**) and at edge section (**B**)

Assembly of GLF

There were four processes in the assembly of the GLF. At first, the center beams were connected together. Four center beams were connected with a welded-cross steel plate. The steel plate and members were fixed with 20 drift pins in a joint (see Fig. 3A). The side beams were then connected to center beams using the same method. Side beams and outside frames were connected with welded T-shaped steel plates and drift pins. Eight bolts were used to connect the steel plate and the outside frame (see Fig. 3B). As the final step, outside frames and columns were fixed with eight bolts (M20) in a joint.

Dynamic excitation test

A portable vibration generator (Reliance RD-200B, frequency: 2–25 Hz, moment: 0.0981 Nm) was used for applying vibrations to the GLF. Initially, the generator was put on the center of the GLF (X_2Y_2). This was defined as center excitation (see Fig. 4) and hereafter, is referred to as "Center". In another case, the generator was placed on point X_1Y_1. This was defined as an eccentric excitation (Eccentric).

Dynamic load was applied to the GLF in two ways. One was a "steady-state test" in which excitation with a certain

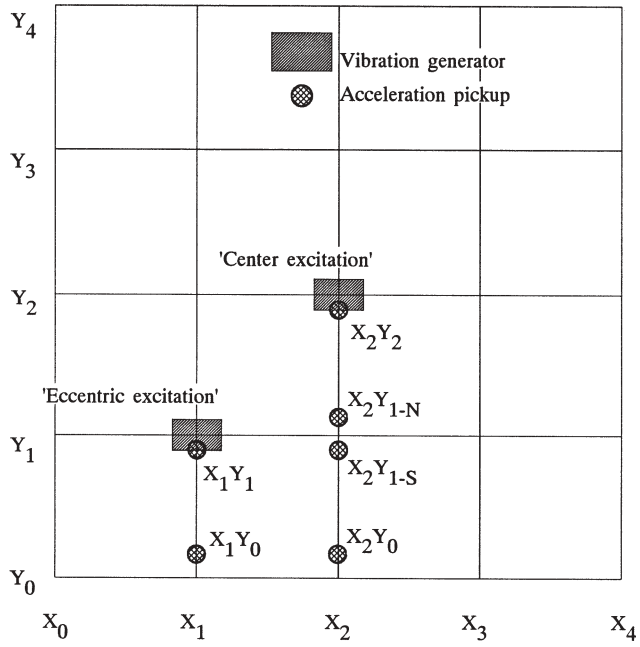

Fig. 4. Locations of vibration generator and acceleration pickups. X_2Y_2, X_2Y_0, X_1Y_1, X_2Y_1, X_1Y_0 represent locations of acceleration pickups

frequency was applied to the GLF until the vibration attained stationary status for 20–30s. Acceleration was measured continuously during excitation. The applied frequency was changed from 1Hz to 29Hz. It was considered that the effect of the weight of the generator could be disregarded, because the weight is about 3% of total weight of the floor.

The second application of dynamic load to the GLF was a "damping test" in which vibration of resonance frequency was applied for 20–30s, and then turned off. The damping process was measured for about 3s. Acceleration was converted into a displacement value by a numerical integration apparatus installed in a dynamic data processing system. Acceleration pickup devices were set on the points vertically where the center of rotation was expected to occur with dynamic deflection. The locations of acceleration measurements are shown in Fig. 4.

Static loading test

After dynamic excitation testing, static concentrated cyclic load was applied to the center of the GLF by an oil jack with a capacity of 196kN (20ton-force). Four load levels were set: 29.4kN (3ton-force), 58.8kN (6ton-force), 88.3kN (9ton-force), and 118kN (12ton-force). After attaining each load level, the load was released. In the case of the fourth loading cycle, partial failure took place during loading, but the GLF did not fail completely until the load attained 118kN.

The loading process can be depicted as:

$0 \rightarrow 29.4 \rightarrow 0 \rightarrow 58.8 \rightarrow 0 \rightarrow 88.3 \rightarrow 0 \rightarrow 118 \rightarrow 0 \rightarrow$ failure (unit: kN)

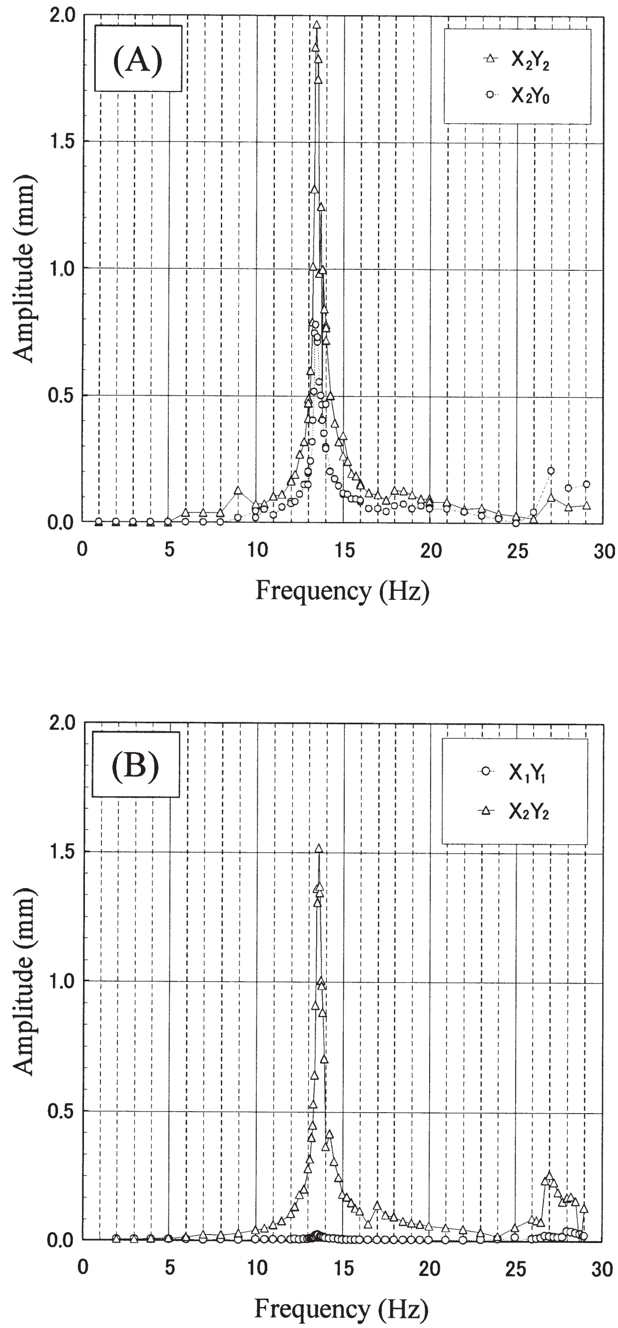

Fig. 5. Typical resonance curves for Center excitation (**A**) and Eccentric excitation (**B**)

The applied load was monitored with a load cell on the loading apparatus and absolute deflections at intersection points were measured with displacement meters.

Results and discussion

Dynamic properties

Typical resonance curves obtained by the excitation test are shown in Fig. 5. Sharp rises were observed in both Center and Eccentric tests.

In the case of the Center test, the first and second order resonance frequencies were 13.5 Hz and 27.0 Hz, respectively. The shape of the curves did not depend on the locations of excitation. With increasing distance from the center, the amplitude of dynamic deflection decreased. In the case of the Eccentric test, the curves were similar to those of the Center test. The first and second order resonance frequencies were the same as those of the Center test.

The natural frequency, assuming the member of the floor continued as a single glued laminated timber, was 1.4 Hz under the double-end free condition. The resonant frequency of the lattice floor (measured value) was 13.5 Hz, and by arranging the member in a lattice, the natural frequency of the floor was able to be increased. When stiffness of the single beam was weighted by volume ratio of the glued laminated timber and steel plate, the frequency became 15.7 Hz and it was almost equal to the measured value. Therefore, it was proven that the dynamic properties of the lattice floor could be approximately explained by vibration characteristics of glued laminated timber and steel plate. In spite of not constructing a panel, the natural frequency of the lattice floor was similar to the peak frequency of the wooden floor of the traditional Japanese wooden house (10 Hz)[4] and the natural frequency of the floor constructed with glued laminated timber and iron (14.2 Hz).[5] Therefore, it was possible to prove the excellent performance of this floor.

The damping factor of GLF was calculated with the half-width method ($1/\sqrt{2}$ method)[6] and was found to be 0.89%. This value is approximately the same as measured values of stressed-skin panels (1%).[7]

Figure 6 shows the dynamic deflection of the GLF. At the first order resonance frequency of the Center test, the deflection shape was parabolic and the maximum deflection was observed at the center. At the second order resonance, the shape of the deflection was similar to the form at the first resonance, but the amplitude was lower.

In the case of the Eccentric test, deflections of the center decreased and the shape of deflection became flat. At the second order resonance, deflection of the center decreased and the shape became concave. A node was produced at the center of the GLF.

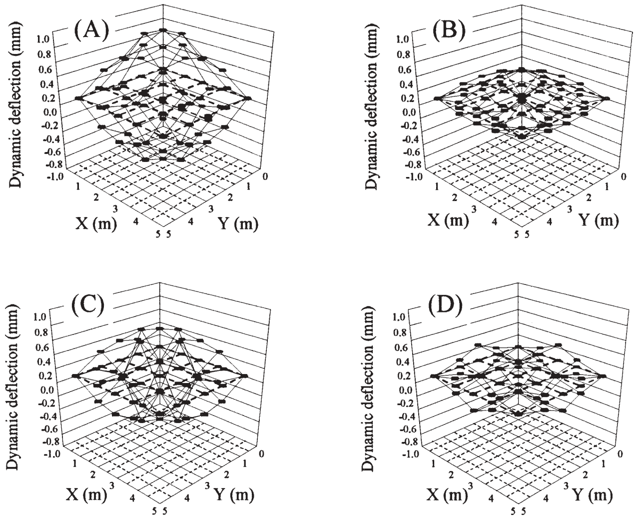

Fig. 6A–D. Dynamic deflections. Deflection at first order resonance (**A**), second order resonance (**B**) for Center excitation. Deflection at first order resonance (**C**), at second order resonance (**D**) for Eccentric excitation

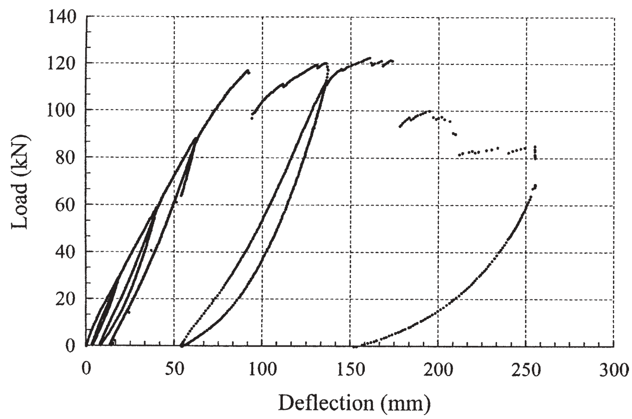

Fig. 7. Relation between applied load and the deflections at the center of GLF

Static properties

The relationship between load and deflection at the center of the GLF is shown in Fig. 7. The first failure took place just before the load reached the maximum load of the fourth loop (117 kN, 11.9 ton-force). The load decreased to 96.8 kN (9.87 ton-force), but it recovered to the previous level, and the fourth loading loop was completed. The final failure took place in the fifth loading. The maximum load was 127 kN (12.5 ton-force). Figure 8 shows the static deflection of the GLF at 58.8 kN (6 ton-force) and 118 kN (12 ton-force). It should be noted that deflection is expressed as a parabolic curve.

The apparent flexural rigidity (EI) was calculated using the span of the floor and value of the initial stiffness obtained in the static loading test. The distance between columns was used as the span of the floor, and for the initial stiffness, the gradient of the straight line which connected two points corresponding to 40% and 10% of maximum load in load-center deflection curve was used. As the result, the apparent flexural rigidity of the lattice floor was 228 MPa. From past research, the apparent stiffness of several wooden floors ranged between 490 and 2451 MPa.[8] The value for the lattice floor obtained in this study was less than half by comparison. However, an increase in stiffness can be expected by constructing panels, and, therefore, it can be assumed that near-equivalent performance could be obtained.

Relative deflection (deflection at each grid point/deflection at center) was used for the uniform evaluation of the deflection shapes. Relative deflections in the GLF are shown in Fig. 9. In Fig. 9, deflections at the start and end of each loading loop were drawn for each grid line. The values for X_1 and X_3 were almost equal, and it is possible that they

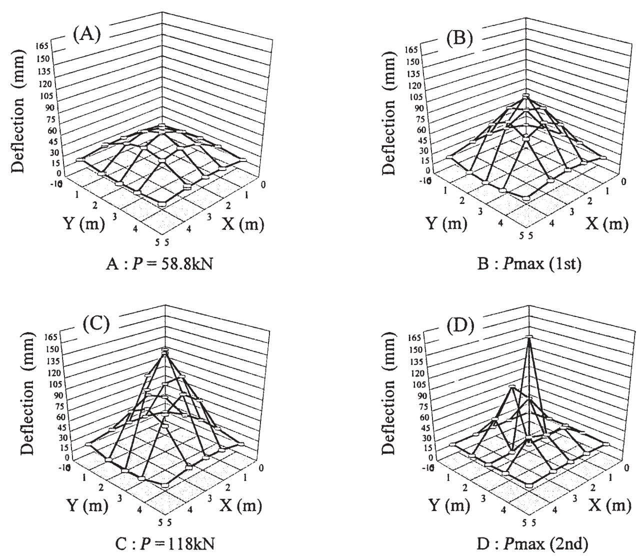

Fig. 8A–D. Static deflection of GLF. **A–D** show several stages (2nd loop, 1st failure, 4th loop and final failure)

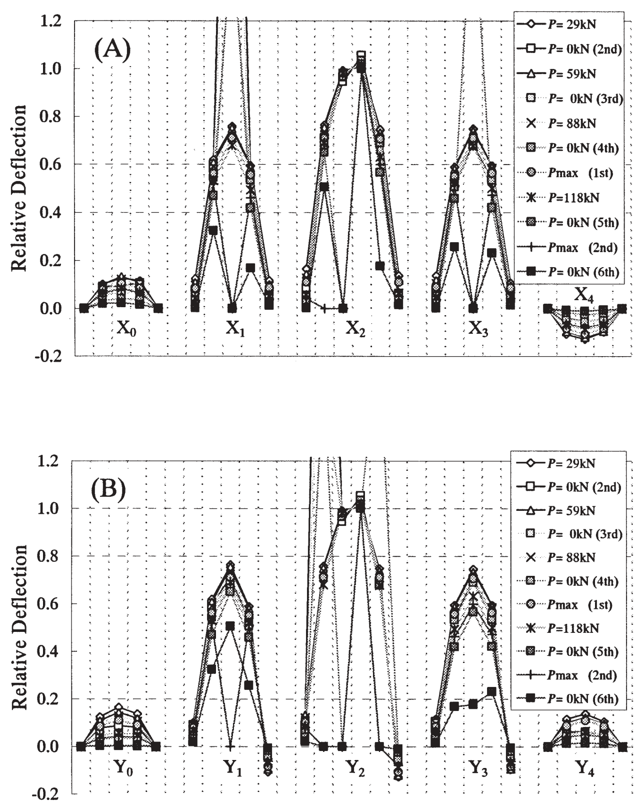

Fig. 9A,B. Relative deflections. Deflections in the X-direction (**A**) and Y-direction (**B**). Relative deflection = (Deflection at optional grid point)/(Deflection at center)

were symmetrical with respect to X_2. The phase of the deflection at X_4 was reversed which may be because the four frames were out of balance as a result of the construction. On the Y-lines, perfect bilateral symmetry was observed. Because the shape of deflection was equal in each of the lines, regardless of loading history, deflection at all grid points in each loop could be calculated using the center deflection.

Conclusions

The first and the second order resonance frequencies of the floor were 13.5 Hz and 27.0 Hz, respectively. These frequencies are very similar to the peak frequency of conventional wooden floor and the combined floor fabricated from glued laminated timber and iron. Therefore, it was possible to demonstrate the excellent performance of this floor.

The maximum static load of the GLF was 127 kN. The apparent flexural rigidity of the lattice floor was less than half in comparison with several floors studied in the past. However, an increase in stiffness can be expected by constructing panels, and, therefore, it can be assumed that near-equivalent performance could be obtained. The relative deflection was not affected by the loading history.

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