A Study on the Influence of Non-Structural Member Timber Staircases on Seismic Performance

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SUMMARY:

This study aimed to obtain a quantitative understanding of the seismic performance provided by the staircase which a wooden building with two or more stories always has, through static lateral loading tests and numerical analysis based on structural dynamics models. It has been revealed by recent studies that among such non-structural members, staircases especially have a considerably high initial stiffness and maximum bearing strength, and that they should not be ignored. A total of four buildings by two construction methods; post-and-beam and light-frame, and with two types of staircases; U-shape winding staircase and straight flight staircase, were used as specimens. The "light-frame winding staircase specimen" recorded 53.74kN at 1/36rad. The test results revealed that the seismic performance of the staircases resulted from the fact that the sideboards incidentally serve as non-buckling braces combined with the treads. This demonstrates how the fasteners joining the timber frame and side panels are of crucial importance.

Keywords: Timber Staircases, Non-Structural Member, Wooden Structure, Seismic Performance, Static Lateral Loading Test

1. INTRODUCTION

This study aimed to obtain a quantitative understanding of the seismic performance provided by the staircase which a wooden building with two or more stories always has, through static loading tests and numerical analysis based on structural dynamics models. As the maximum restoring force of wooden buildings is small, the bearing strength of non-structural members, which is of no significance in Reinforced-Concrete and Steel structures can have great effect. It has been revealed by recent studies that among such non-structural members, staircases especially have a considerably high initial stiffness and maximum bearing strength, and that they should not be ignored. It will be very useful to elucidate the formation mechanism of the bearing strength of staircases, not only for seismic design when building new dwellings, but also for existing dwellings as it is applicable to retrofitting. A total of four buildings by two construction methods; post-and-beam and light-frame, and with two types of staircases; U-shape winding staircase and straight flight staircase, were used as specimens.

2. POST-AND-BEAM WOODEN STRUCTURE STAIRCASE SPECIMENS

2.1. Outline of Static Lateral Loading Tests

Static lateral loading tests on full-scale models of wooden frames were carried out at the Research Institute for Sustainable Humanosphere, Kyoto University. The static lateral loading tests used the tie rod style. In the static tests, all specimens were tested in order to show the restoring force more clearly. The lateral force was applied at the middle of the beam in X-direction with the control quantity being

the displacement. A load cell was installed at the top of the actuator, and the measured horizontal force was used to calculate the restoring forces of the whole specimen. The experiments were performed three times in tie rode type peak-to-peak alternative loading under displacement control. Force application was made in the long side direction. And, in the case of the U-shape winding staircase specimen, force application was made in the long and short side directions.

2.2. Straight flight staircase specimen

The basic specimen was composed of two planar frames connected to each other by a horizontal wooden staircase shown in Figure 1. Each frame consisted of a pair of columns and two beams connecting them at the base level and the roof level, respectively, by using stud tenons with nail plates. The basic specimen will be called "post-and-beam structure with straight flight staircase specimens" in this paper. The straight flight staircase specimen has a 2.73m (length) x 2.73m (height) staircase sandwiched by two planes arranged in parallel at an interval of 0.91m. The cross-sections of all columns and base sizes are 120mm square. Two bases were fastened to the base plate by bolts. The column-beam joints of all specimens were secured by metal connectors. All columns and beams were made of glued laminated timber (E95-F315); the beams of Japanese cypress, and studs (short tenons) of Japanese cedar. The side panels were fastened with two nails (4.2 x 75mm) to all columns and studs. The total number of nails was 27. After construction of the side panels, the adhesive (vinyl acetate resin emulsion) was applied to the side panels, columns and studs. The steps and side panels were fastened with adhesive and nails (3.8 x 38mm).

The experiment was conducted in three stages. At the first experiment stage, the specimen consisted of a frame structure (columns, base, beam and studs) only, while the second stage experiment specimen consisted of a frame structure and side panels. During the Stage 1 and 2 experiments, deformation drift angle was made less than 1/150rad to minimize damage to the specimen. In the final third experiment stage, the specimen consisted of a frame structure and staircase (side panels and steps). In this Stage 3, all nails and adhesive between the columns and side panels used in Stage 2 were renewed.

Damage to the specimen in Stage 2, i.e. a gap with a maximum of 7mm between the side panel and the column occurred, and the nails were found broken as shown in Figure 2 b). The fracture surface was near the boundary surfaces of the side panel and set about 30mm from the axis of the nail head. In the experiment of Stage 3, separation of surfaces fastened with adhesive as well as breaking of the nails were found as shown in Figure 2 a). Because all damage occurred on the back side of the staircase only, it appeared from the front that the staircase had received no damage.

Figure 3 shows the restoring force and backbone curves of the staircase in each stage. The horizontal axis in Figure 3 is a value corrected to the true deformation angle. The maximum restoring force of Stage 2, was a very large value, about 10 times that of Stage 1. The reason for the maximum restoring force increase was considered to have been caused by adhesive and nails. In Stage 1 with the specimen consisting only of the frame structure, the maximum restoring force. In Stage 2 where side panels were installed, the maximum restoring force was increased to 14.8kN, while slip characteristic became prominent when story drift angle exceeded 1/500rad. The maximum restoring force of Stage 3 was 28.0kN (1/85rad). In the range where story drift angle exceeded 1/70rad, the maximum restoring force was increased in two steps. The adhesive is considered to have had a great influence on the initial stiffness and deformation performance. In addition, the experimental results of Stage 3 showed that compression produced between the columns and side panels also had a significant impact.

2.3. U-shape winding staircase specimen

The basic specimen shown in Figure 4 is called "post-and-beam structure with U-shape winding staircase specimen" in this paper. The U-shape winding staircase specimen has a staircase on a plane of 2.73m x 2.73m, sandwiched by two planes arranged in parallel 1.82m apart. The specimen and staircase details are more or less the same as in section 2.2. The main difference from the straight





flight staircase is the joining method of the part where the side panels are perpendicular to the staircase.

Figure 5 shows the typical damage to the specimen. Much of the damage was the same as that of the straight flight staircase specimen. Separation of the junction occurred between the column base and side panels at about 1/30rad. When the story drift angle deformation was large, a nail at the edge of the side panel came out, and the studs had large bends, and as shown in Figure 5 b) a gap at the side panel joint occurred which grew as large story drift angle increased.



Figure 6. Restoring force characteristics of the post-and-beam structure U-shape staircase specimen

Figure 6 shows the restoring force and backbone curves of the U-shape winding staircase specimen, in the long and short directions. The maximum restoring force of the long direction was recorded as 16.43kN at 1/30rad. With respect to the short direction, a certain initial stiffness was observed, showing a load of 5.14kN with a loading of up to 1/150rad. Figure 6 includes a comparison with the backbone curves of the straight flight staircase specimen. Compared with the straight flight staircase specimen, the deformability performance was good, but there was low initial stiffness and maximum restoring force. The joining method of the side panel where the staircase is at right angles to the landing is considered to contribute greatly to such results.



Figure 7. Light-frame wooden construction straight staircase specimen

Figure 8. Light-frame wooden construction U-shape staircase specimen



Figure 12. Restoring force characteristics of the light-frame wooden construction staircase specimen

3. LIGHT-FRAME WOODEN CONSTRUCTION STAIRCASE SPECIMENS

A "light-frame wooden construction straight staircase specimen" and a "light-frame wooden construction U-shape winding staircase specimen" were constructed by referring to the Japanese two-by-four standard construction specifications. The two specimens are shown in Figures 7 and 8. The straight staircase specimen was installed between two parallel plaster boards with an interval of 0.91m, placed in a plane of 2.73 x 2.73m. The U-shape winding staircase specimen was likewise installed with an interval of 1.82m, placed in a plane of 2.73 x 2.73m. SPF and OSB were used for the stude of the specimen and the side panel respectively.

CN75 nails were used for joining the studs and the side panel. Before attaching the side panel, plaster boards (thickness: 12mm) were installed using nails (with intervals of 100mm for the outer periphery and 150mm for the center part). Six plaster boards were used for the straight staircases specimen, and

10 boards and 3 boards were used for the longitudinal and short directions respectively of the U-shape winding staircase specimen. At first, the side panel was attached to the plaster board with adhesive (urethane resin), which was further fixed to the studs by driving two or three nails (@4.2 x 65mm) through the plaster board. Threads and risers were joined to the side panel that was cut into a saw-tooth as shown in Figure 9, using the steel plates. Nails used for the steel plates did not reach the studs.

Damage was observed at the nail joints in the outer periphery of the plaster board at 1/100rad. As shown in Figures 10 and 11, cracks occurred on the plaster boards along the side panel, which became larger as deformation increased. Also, a significant bend was observed in the stud.

Figure 12 shows restoring force characteristics and backbone curves of the light-frame wooden construction staircase specimen. The restoring force of the straight staircase specimen recorded 50.16kN at 1/66rad. As for the U-shape winding staircase specimen, the restoring force was recorded as 53.74kN at 1/36rad in the longitudinal direction, and 12.95kN with applied load up to 1/200rad in the short direction, showing a certain initial stiffness. Figure 12 c) shows a comparison with the backbone curves of the post-and-beam structure staircase specimen stated in Chapter 2. The maximum restoring force is larger in the light-frame construction staircase specimen compared to the post-and-beam structure staircase specimen. This is due largely to the inclusion of the restoring force of the plaster boards.

4. RELATIONSHIP BETWEEN ANALYSIS AND EXPERIMENT

To implement the analytical study, a specimen for the element experiment was created (Figure 13). Because the test results in Chapter 2 showed that the joining of the side panel and the frame structure was important, the subject part was reproduced. The element tests were carried out as vertical loading tests, and a total of 12 specimens consisted of three each of four types. Experimental parameters were the use of nails only (Specimen A), adhesive only (Specimen B), adhesive and nails (Specimen C), and adhesive, nails and compression by steel plates (Specimen D) (Figure 13 a). Specimen A, C and D had four nails each. The adhesive drying time was more than 10 days following the experiment. The applied area of the adhesive was 7,000mm² each side (70 x 100mm).

Figure 13b) shows the typical damage of each specimen for the element experiment. Specimen A showed broken nails. Specimens B, C and D showed separation of the column from the panel, and breaking of the nails as shown in Figure 13 b). The separation of the column from the panel occurred in the form of peeling of the surface of the side panel (MDF).

Figure 14 shows the restoring force characteristics of each specimen for the element experiment. The maximum restoring force and the initial stiffness are shown in Table 1. The initial stiffness was represented by the angle produced by a straight line connecting the points of 0.4 times and 0.1 times that of the maximum restoring force. Specimen B-2 was not shown in Figure 14, as no appropriate restoring force was obtained due to defect of the experiment.

Average values of the maximum restoring force were 6.3kN of Specimen A with only four nails, 25.1kN of Specimen B with adhesive only, 17.9kN of Specimen C with four nails and adhesive, and 23.8kN of Specimen D with nails, adhesive and compression by steel plates. Average values of the initial stiffness were 2.1kN/mm, 15.5kN/mm, 9.7kN/mm, and 14.9kN/mm respectively. As shown in Figures 14 a) and b), specimens with either the nails or adhesive only showed poor deformability and the maximum restoring force. Specimen C using both adhesive and nails showed a smaller maximum restoring force than that of Specimen B which used only adhesive, however deformability was increased. Specimen D showed a greater maximum restoring force and deformability than those of Specimen C. In addition, the initial stiffness of the Specimen D was comparable to those of Specimen B.

From the results, the effect of nails, adhesives and compression force have a significant impact on the seismic performance of the element experiment specimen. In other words, it was confirmed that the effect was an important component of the seismic performance of the staircases.

An incremental analysis was conducted on specimens of the post-and-beam method through the use of stiffness matrix based on the frame with no out of plane deformation in the side panel, and with the replaced spring of fasteners between the side panels. To replace the spring of fasteners, the load-



Table 1. Maximum restoring force and stiffness of element specimen

Name		Maximum force (kN)		Stiffness (kN/mm)	
A−1	Specimen A	6.3	6.3	2.0	
A-2		6.1		2.0	2.1
A-3		6.6		2.3	
B-1	Specimen B	23.8	25.1	13.9	
B-2					15.5
B-3		26.4		17.0	
C-1	Specimen C	20.3	17.9	8.8	9.7
C-2		17.6		9.8	
C-3		15.8		10.5	
D-1	Specimen D	22.7	23.8	10.5	14.9
D-2		23.8		18.1	
D-3		25.0		16.1	

displacement relationship obtained by the element tests was used, while placing the spring in parallel with the side panel angle. Although the analysis showed results with a slightly lower initial stiffness and a tendency in maximum load to be higher by about 3kN compared with the test results, they more or less follow the actual values.

5. CONCLUSIONS

This study aimed to obtain quantitative understanding of the seismic performance provided by the staircase, through static loading tests and numerical analysis based on structural dynamics models. A total of four buildings by two construction methods; post-and-beam and light-frame, and with two types of staircase; U-shape winding staircase and straight flight staircase, were used as specimens. From the results of the static lateral loading tests, the following conclusions can be drawn.

1) The "post-and-beam U-shape staircase specimen" recorded a maximum bearing strength of 16.43kN at 1/30rad. In the case of the "post-and-beam straight staircase specimen", it was 28.0kN (1/85rad).

2) The "two-by-four straight flight staircase specimen" recorded a maximum bearing strength of



gure 15. Analysis model of post and bean structure U-shape staircase specimen

Figure 16. Comparison of test and analysis of post and beam structure U-shape staircase specimen

50.16kN at 1/66rad. The "two-by-four winding staircase specimen" recorded 53.74kN at 1/36rad.3) The element tests confirmed that the seismic performance of the staircases were produced by the

- effect of the side panels incidentally serving as non-buckling braces combined with the treads. This demonstrates how the fasteners joining the timber frame and side panels are of crucial importance.
- 4) Staircases among such non-structural members have a considerably high initial stiffness and maximum bearing strength, and they should not be ignored.
- 5) An incremental analytical method to model the replaced spring of fasteners between the side panels was proposed. Although the analysis showed results with a slightly lower initial stiffness and a tendency in maximum load to be higher than the experiment by 3kN, the analytical model more or less represents the restoring force of the structure.

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