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STRUCTURAL PERFORMANCE EVALUATION OF A TIMBER HOUSE USING NEW CONSTRUCTION SYSTEM WITH CLT HORIZONTAL DIAPHRAGM

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KEYWORDS: Post-and-beam construction system, CLT, Horizontal diaphragm, Braced shear wall

1 INTRODUCTION

Japanese forest resources have been abandoned and accumulated for a long time. Making much use of CLT(Cross Laminated Timber) leads to consuming the forest resources effectively, it is necessary to develop various ways to use CLT.
As one of the ways to use CLT, authors have developed a new post-and-beam construction system with a CLT horizontal diaphragm. In the developed construction system, CLTs are used as a horizontal diaphragm, whereas beams are omitted. It may realize a short construction period, high structural performance, and high sound insulation.
This paper presents the structural performance evaluation of the newly developed construction system through the static incremental analysis of a prototype timber house.

2 OUTLINE OF PROTOTYPE HOUSE

Figure 1 shows the conventional post-and-beam construction system and the new construction system with a CLT horizontal diaphragm. In the new construction system, the floor system of the conventional post-and-beam construction system is replaced by CLTs. Because CLT has mortises, tenons of the end of columns can be joined to CLTs directly.
Figures 2 to 4 show a prototype house with the new construction system. Thanks to the rigidity of CLT, a large balcony can be placed on the southern part of the house, and it is tolerated that the external wall of the second story is not arranged just above the one on the first story. The CLT grade of the horizontal diaphragm at the floor level on the second story is Mx60-5-5[1]. The species of the CLTs is Japanese cedar.
Braces are used as the shear wall in the prototype house while the plywood shear wall is not used. The ends of the braces are connected by newly developed ductile brace connectors. 15kN hold-down connectors are installed on the ends of columns. CLTs as the second story floor are arranged as shown in Figure 5.
A half-lapped joint was adopted as the joint between CLTs of the horizontal diaphragm. Screws, 7 mm in diameter and 200 mm long, are driven at an angle of 45 degrees on the joint for reinforcement.

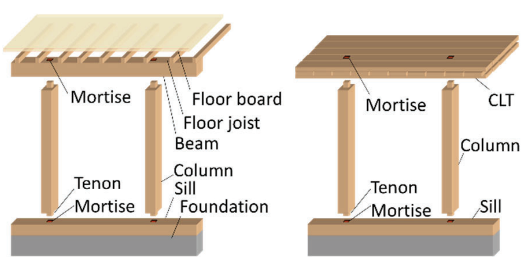

Figure 1: *Conventional post-and-beam construction system(left) and new construction system with CLT horizontal diaphragm(right)*

Figure 2: *South elevation of the prototype house*

Figure 3: *East elevation of the prototype house*

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The weight of the first story of the prototype house is estimated as 191.1 kN, while the one of the second story is 120.7 kN, where the live load was assumed as 600 N/m^2[2].

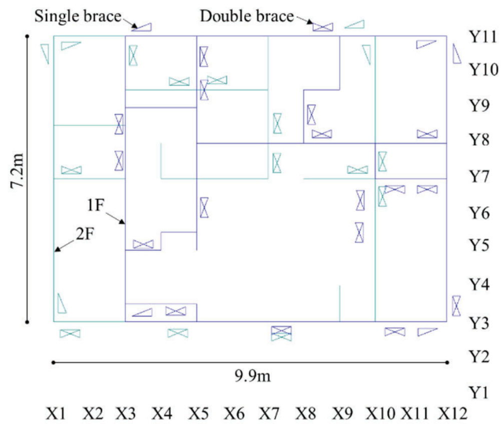


Figure 4: *Plan of the prototype house*

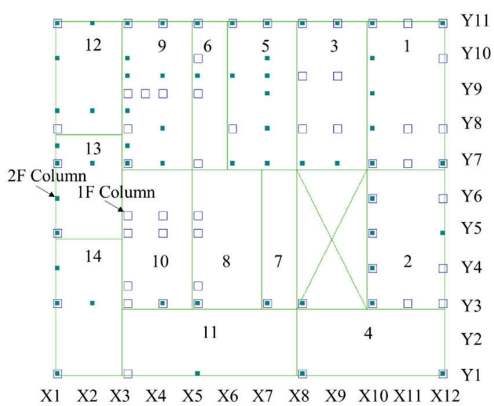


Figure 5: *Arrangement of CLTs at the floor level on the second story*

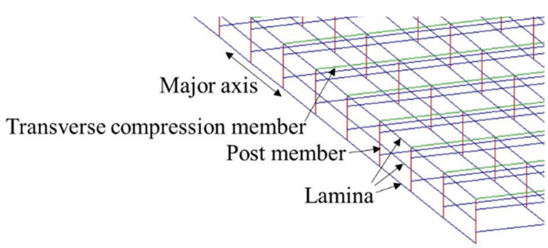


Figure 6: *Analysis Model of CLT*

Table 1: *Young's modulus and shear modulus of CLT analysis model*

	Young's modulus (N/mm^2)	Shear modulus (N/mm^2)
Lamina	7350	637
Post member	590	326
Trans. comp. mem.	590	637

3 PROTOTYPE HOUSE MODELING AND INCREMENTAL ANALYSIS

To evaluate the structural performance of the prototype house, a 3D structural model for static incremental analysis was built.

3.1 CLT AS HORIZONTAL DIAPHRAGM

Because an evaluation method of the out-plane two-way bending stiffness of CLT is not established, the CLT model that consists of laminas as shown in Figure 6 was adopted. The section of the lamina was 227.5mm x 30mm, and the laminas were connected by the post members. On the top layer, the side of the lamina is expected to touch the next lamina under a bending moment of minor direction. Therefore, transverse compression members were arranged between laminas on the top layer. Young's modulus and shear modulus of the members that compose the CLT are listed in Table 1, where every member is assumed as elastic.

3.2 CLT-CLT JOINT

3.2.1 Tensile direction

To evaluate the tensile force-displacement relationship of a CLT-CLT joint of the second-story floor diaphragm, a tensile loading test was conducted. The joint type is a half-lapped joint with long screws that is 7mm in diameter and 200mm long. Figure 7 shows the specimen. There were major axis specimens and minor axis specimens regarding the lamina direction as shown in Figure 8, and three specimens were prepared for each axis. Two screws were driven to the specimen. Figure 9 shows a specimen set in the test apparatus. One directional tensile load was applied to the specimen.

Figure 10 shows the tensile force-displacement relationships of all specimens. The variation of minor axis specimens is relatively large, while the average curve of major axis specimens and of minor axis specimens are about the same level. The average maximum tensile force per screw was approximately 12.5kN. For major axis specimens, failure around the screw occurred, while split along the edge occurred in minor axis specimens as shown in Figure 11. Large plastic deformation of the screws was not found in both major axis or minor axis specimens.

The spring which represents the screw on the joint between CLTs was set to 4 kN/mm of stiffness for tensile direction considering the experimental data. Because a large axial force is not expected to be produced through the incremental analysis, the spring was elastic. Regarding the compression side, the stiffness was set to 4kN/mm same as the tensile direction.

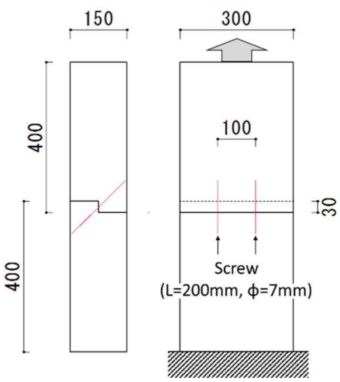
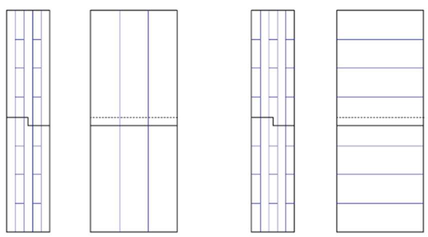


Figure 7: *Specimen of tensile loading test*



(a) Major axis specimen *(b) Minor axis specimen*
Figure 8: *Direction of lamina*

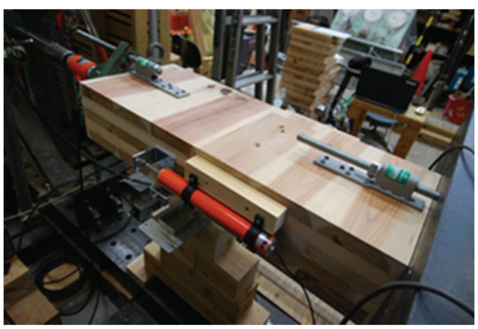


Figure 9: *Tensile loading test of CLT-CLT joint*

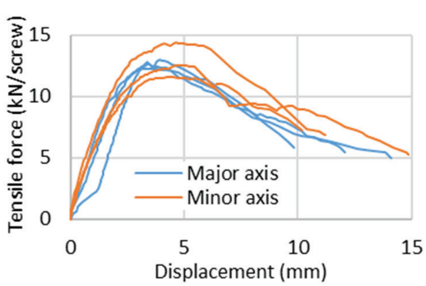


Figure 10: *Tensile force-disp. relationship of CLT-CLT joint*

(a) Major axis specimen *(b) Minor axis specimen*
Figure 11: *Specimen after tensile loading test*

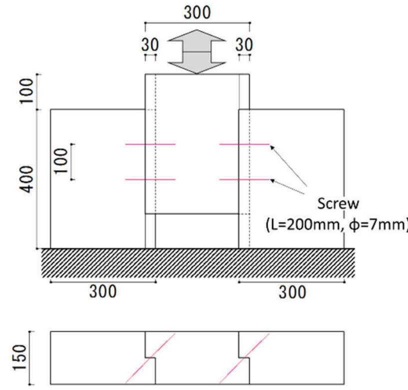
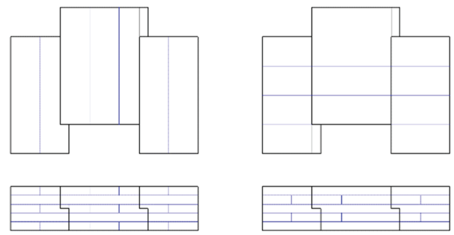


Figure 12: *Specimen of shear loading test*



(a) Major axis specimen *(b) Minor axis specimen*
Figure 13: *Direction of lamina*

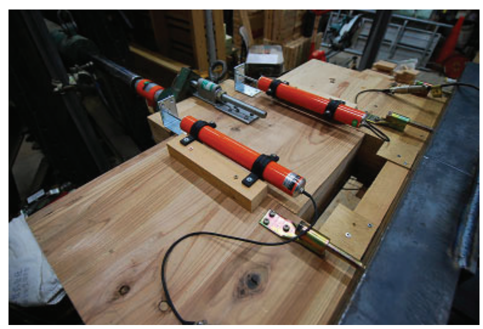


Figure 14: *Shear loading test of CLT-CLT joint*

3.2.2 Shear direction

To evaluate the shear force-displace relationship of a CLT-CLT joint of the second story floor diaphragm, a shear loading test was conducted. The joint type is also a half-lapped joint with long screws.

Figure 12 shows the specimen. There were major axis specimens and minor axis specimens regarding the lamina direction as shown in Figure. 13, and three specimens were prepared for each axis. Four screws were driven to Major axis 1 and Minor axis 1 specimens, while two screws were driven in the other specimens. Figure 14 shows a specimen set in the test apparatus. The repeated load was applied to the center peace of the specimen.

The results of the tests are shown in Figure 15. The maximum shear force per screw was approximately 10kN, and the screw was bent largely or fractured as shown in Figure 16. Figure 17 shows the skeleton curves of all specimens. The variation of major axis specimens is relatively large, while the average curve of the major axis specimens and the one of the minor axis specimens are about the same level.

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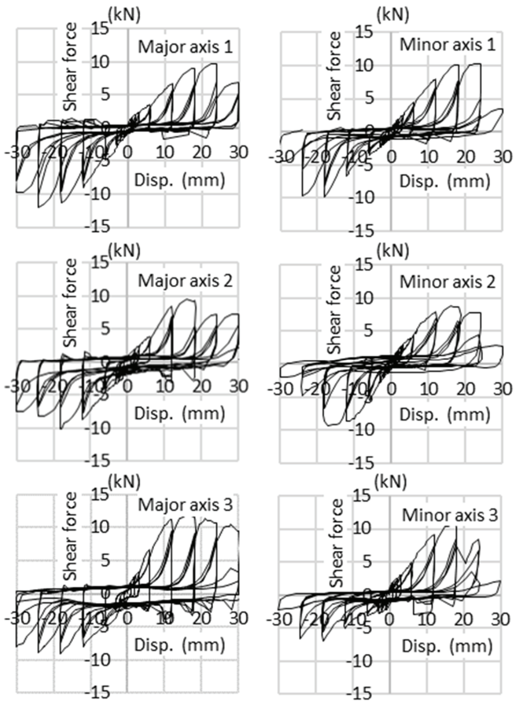

Figure 15: Shear force-disp. relationship of CLT-CLT joint

(a) Major axis specimen *(b) Minor axis specimen*

Figure 16: Specimen after shear loading test

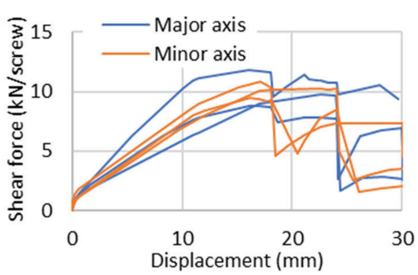

Figure 17: Skeleton curves of shear force-disp. relationship

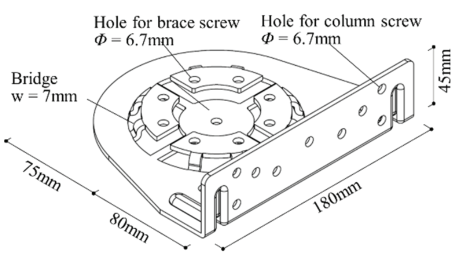

Figure 18: Steel core of ductile brace connector
(To use as a brace connector, this steel core is covered with high damping rubber.)

The spring which represents the screw on the joint between CLTs had 0.8 kN/mm of stiffness for in-plane shear direction. The spring was elastic, and the stiffness was derived from the experimental data.

3.3 BRACE

Regarding shear walls, braced shear walls are arranged in the prototype house. For reinforcing the joint between the end of a brace and a column, the ductile brace connector was used.

The ductile brace connector, as shown in Figure 18, includes a damping mechanism. The thickness of the steel for the connector is 3.2mm. As the lateral displacement of the braced shear wall increases, the bridges deform to absorb a displacement between a brace and a column. Damping force is produced by the plastic deformation of the bridges. To use as a brace connector, the steel core is covered with high-damping rubber.

Figure 19 shows a shear force-drift angle relationship of a single braced shear wall specimen as shown in Figure 20. Repeated lateral shear load was applied to the beam up to 0.02rad. After that, a one-directional shear force that causes tensile failure at the joint between the end of a brace and a column was applied.

The axial force-displacement relationship model of the brace with the ductile brace connectors is shown in Figure 21, where the compressive yield force of the model is the buckling strength of the brace.

3.4 COLUMN-CLT JOINT

To evaluate the tensile force-displace relationship of a joint between the end of the column and the CLT of the floor diaphragm on the second story, a tensile loading test was conducted.

Figure 22 shows the specimen, which has a tenon on the end of the column and a mortise on the CLT. A connector to prevent pull-out of the column was installed at the joint. Three specimens were prepared for the test, and a repeated load was applied to the column.

Figure 23 shows the axial force-displacement relationship of the joint between the end of the column and the CLT. Screws driven to the CLT were pulled out as shown in Figure 24, and the applied load decreased.

After the tensile loading test, a compressive loading test was conducted with the same specimen as the tensile loading test. The compressive load was applied to the specimen up to 50kN due to a limitation of the test apparatus, and relationships between compressive force and relative displacement between the end of the column and the CLT were derived as shown in Figure 25.

From the test results, an axial force-displacement relationship model at the end of the column, as shown in Figure 26, was set, and applied to the 3D prototype house model.

3.5 BUILDING UP OF 3D PROTOTYPE HOUSE MODEL

The 3D structural model of the prototype house is shown in Figure 27, which contains 8944 nodes and 16747 members, where the out-plane shear stiffness of the CLT-CLT joint was set as 10 kN/mm.

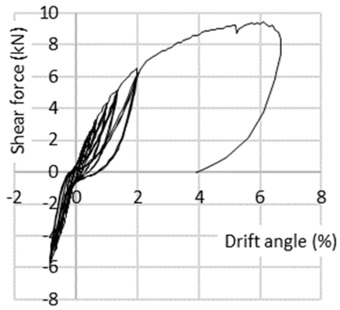

Figure 19: Shear force-drift angle relationship

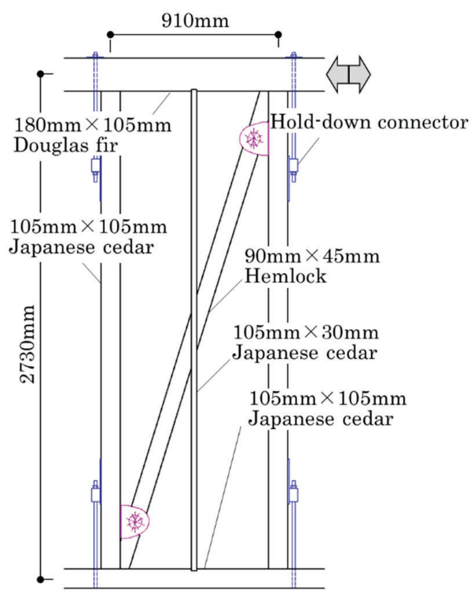

Figure 20: Single brace shear wall specimen

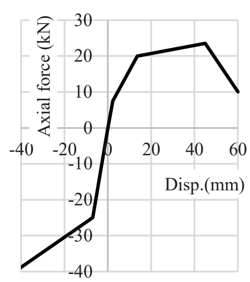

Figure 21: Axial force-disp. relationship of brace

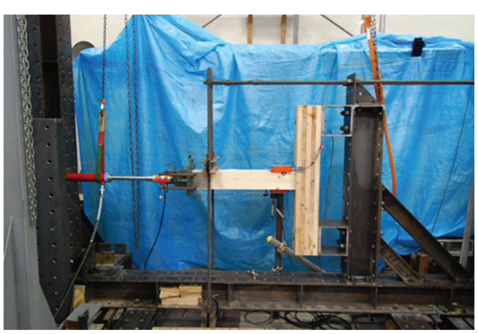

Figure 22: Tensile loading test of column-CLT joint

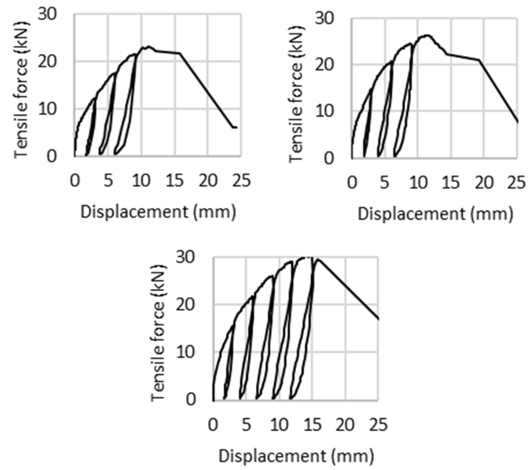

Figure 23: Tensile force-disp. relationship of column-CLT joint

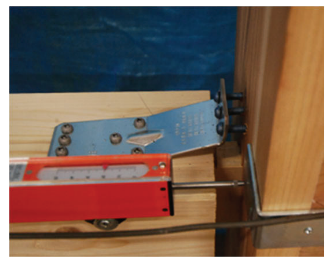

Figure 24: Joint of specimen after tensile loading test

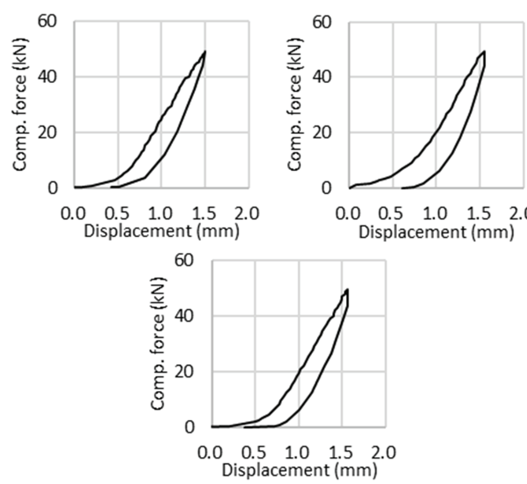

Figure 25: Compressive force-disp. relationship of column-CLT joint

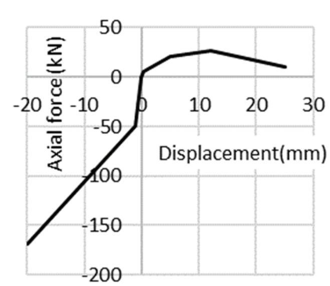

Figure 26: Axial force-disp. relationship of column-CLT joint

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4 RESULT OF INCREMENTAL ANALYSIS

Figure 28 shows the story shear force-story displacement relationship from the static incremental analysis. Though the shear force along the Y-direction is slightly low compared to the one along the X-direction.

Regarding C_0=0.2 and C_0=0.3, where C_0 is the value of the story shear force divided by the weight the story carries, the maximum stress of the laminas and the maximum force of the screws on the CLT-CLT joint are listed in Table 2. The maximum bending stress of all laminas is 77% of the lower limit strength under C_0=0.3 shear force. For the maximum tensile stress, it is 21% of the lower limit strength, therefore CLTs are not considered to have damage even under relatively large earthquakes.

Regarding the tensile and shear forces carried by the spring at the CLT-CLT joint, they are considered to be in the elastic range compared to the test results such as Figures 10 and 17. As for the out-plane shear force, because no experimental data exist, an out-plane shear loading test will be planned to be conducted.

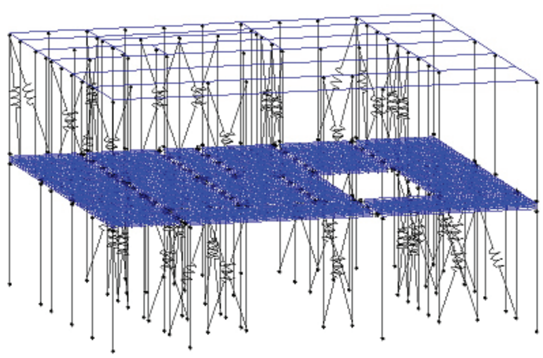

Figure 27: *3D structural model of the prototype house*

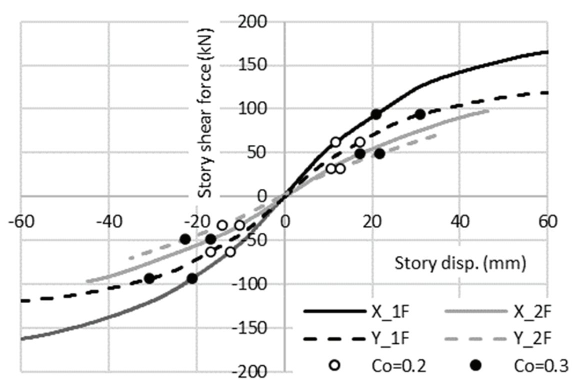

Figure 28: *Story shear force-story displacement relationship*

Table 2: *Maximum stress and force*

	Lamina (N/mm^2)		Spring between CLTs (kN)		
	Bending	Tension	Tension	In-plane shear	Out-plane shear
C_0=0.2	10.89	1.57	5.19	2.16	5.30
C_0=0.3	15.49	2.56	7.80	3.33	7.24

5 CONCLUSIONS

Static incremental analysis of the prototype timber house which is designed with the new post-and-beam construction system with a CLT horizontal diaphragm was conducted. From the experimental and numerical test results, it was confirmed that no damage to the CLT horizontal diaphragm was expected even under relatively large earthquakes.

REFERENCES

[1] Japanese Agricultural Standard of Closs Laminated Timber. Notification No.683 of the Ministry of Agriculture, Forestry and Fisheries, 2018. (in Japanese)

[2] Structural Design and Construction Manual using CLT. Japan Housing and Wood Technology Center, 2018. (in Japanese)

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