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AN EXPERIMENTAL STUDY ON THE CHARACTERISTICS OF A HORIZONTAL RESISTANT MECHANISM USING A CHECKERED PATTERN HYBRID BEARING WALL WITH A PLYWOOD AND STEEL FRAME

Rieko NAGAO[1], Akihiro MORI[2], Takumi ITO[3], Natsuhiko SAKIYAMA[4]

ABSTRACT: In recent years, the use of natural resources has been recognized as a means towards reducing environmental impacts, such as climate change. This paper examines the resistance mechanism and structural performance of a sandwich panel, where a steel column is positioned between structural plywood sheets and connected to steel frames through rings welded to the steel columns. In this paper, horizontal loading tests were conducted to clarify the mechanisms of bearing resistance, destructive properties, and stress transfer. The results show that the specimen with structural plywood exhibits higher strength and rigidity compared to the steel specimen.

KEYWORDS: Sandwich panel, Horizontal resistant mechanism, Hybrid structure, Seismic wall

1 – INTRODUCTION

The Japanese government has been promoting the use of domestically produced timber, as wood helps absorb and store carbon dioxide from the air [1]. A wide variety of proposals have been made regardless of the size of the building. Composite structures combining wood and steel offer various patterns and provide a wide range of characteristics, including design, environmental friendliness, and structural integrity. Composite structures are expected to have a promising future in high-rise and large-space buildings. Combining wood and steel frames can produce design features that are not possible with either material alone.

In Japan, an earthquake-prone country, it is essential to find ways to prevent delays in restoration and to recover efficiently from unavoidable damage. Damaged walls caused by natural disasters, such as earthquakes, can be restored through wood panel replacement. The use of familiar materials in construction is expected to shorten the waiting time for repair in the event of a disaster.

Therefore, the use of easily accessible materials for buildings, not only because of environmental issues but also because of resource issues, is worthy of consideration. However, under current Japanese regulations, it is difficult to obtain approval for a composite structure of wood and steel frames. Therefore, we conducted horizontal loading tests of composite walls to research their mechanical properties, which is a motivation for this study.

Fig. 1 Case using the hybrid bearing wall

2 – BACKGROUND

The authors propose synthetic structures in which steel square columns are sandwiched between two pieces of plywood. Previous studies have clarified the resistance mechanism using diagonal braces on plywood [2, 3, 4]. The structure has been modified from a closed pattern to a checkered one to provide wider openings for design and lighting purposes [5, 6, 7, 8]. However, the clearance between the plywood and the steel column has been an issue because of the difficulty in transferring stress at the joint position. This study proposes a new joint method,

[1] Rieko NAGAO, Graduate Student, Dept of Architecture, Tokyo University of Science, Tokyo, Japan, rieko_nagao@me.com
[2] Akihoro MORI, Master in Eng., Tokyo, Japan, 4122527@alumni.tus.ac.jp
[3] Takumi ITO, Professor., Dr. Eng., Dept of Architecture, Tokyo University of Science, Tokyo, Japan, t-ito@rs.tus.ac.jp
[4] Natsuhiko SAKIYAMA, Assistant Professor., Dr. Eng., Dept of Architecture, Tokyo University of Science, Tokyo, Japan, n.sakiyama@rs.tus.ac.jp

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where the plywood panel is connected to the steel frame through rings welded to the steel column.

2.1 Previous studies (sandwiched panel of steel stub and plywood)

The authors have proposed a hybrid bearing wall (hereinafter referred to as a composite hybrid bearing wall) in which plywood (thick plywood or structural plywood) is bolted to a steel frame and have examined the structural properties of mechanical behavior and resilience characteristics, as well as productivity and workability (Figs. 1and 2).

The purpose of this study was to improve the structural performance of the panel by using steel bolts and other steel elements as joint elements. When screws are used, the bearing capacity is determined by pull-through and shear failure (screws affect the bearing capacity). In such cases, the performance of wood cannot be fully utilized.
The deformation of the framing under force is transmitted to the plywood through hardware and bolts, and the shear resistance of the plywood and the axial force on the diagonal of the bolts, or brace resistance mechanism, improve the structural performance (strength and stiffness) of the plywood bearing wall (hereinafter referred to as the composite effect).

The joints between the steel frame and plywood using hardware and bolts cause the plywood to cave in, deform out-of-plane, and warp due to bearing pressure. The restoring force characteristics of the plywood can be used for bearing pressure without the joints being damaged. In addition, the shape and size of the joints can be utilized to adjust the bearing capacity and rigidity. From the viewpoints of structure, workability, and design, two methods of steel and wood construction have been proposed: one is to sandwich the steel frame between the plywood, and the other is to sandwich the plywood between the steel frame and the plywood. In the former method, the plywood can be used entirely as a facade. However, it is desirable to provide a mechanism to restrain out-of-plane deformation and edge warping of the plywood with hardware and screws. In the latter, the steel frame partially hides the plywood, but it is expected to be effective in restraining the out-of-plane behavior and plywood warping.

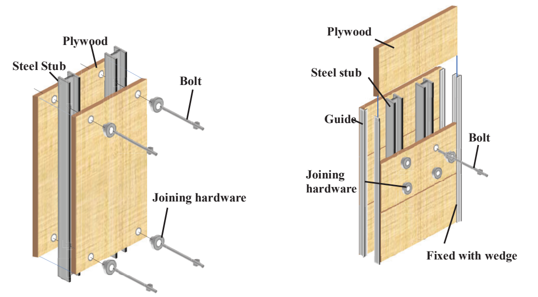

Fig.2 Configuration of sandwiched panel of steel stub and plywood (previous model)

2.2 Checkered pattern sandwiched panel (previous model)

In previous studies, high earthquake resistance was achieved by covering the entire structural wall with plywood, but there were no openings, resulting in a closed facade. In a subsequent study, a checkered arrangement was proposed to provide adequate openings, to secure lighting, and to consider the design aspect (Fig. 3).

This structural system aims to control the stress distribution and loading of the steel frame members, provide appropriate hybrid bearing capacity, and provide a fail-safe mechanism against loss of structural performance due to buckling of the steel members and frame in large deformation regions, based on the steel frame and the contribution of wood facing materials as structural elements. Note that this structural system is intended for comparison with low-rise, steel-framed, system, and prefabricated buildings.

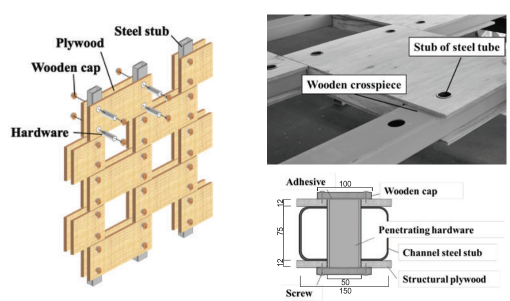

Fig.3 Checkered pattern sandwiched panel (previous model)

3 – PROJECT DESCRIPTION

3.1 Overview of project

This study aims to provide a method for achieving the composite effect of plywood within the scope of elastic structural design. Furthermore, the use of timber plates is examined to prevent the plywood from falling out of the steel frame. Horizontal loading testing was conducted to clarify the mechanisms of bearing resistance, destructive properties, and stress transfer by comparing two types of full-scale specimens: one with a steel frame and the other with a bearing wall using timber and steel.

3.2 New model (Checkered pattern sandwiched panel)

Previous studies have clarified the resistance mechanism using diagonal braces on plywood. The structure has been modified from a closed pattern to a checkered one to provide wider openings for design and lighting purposes [9, 11]. However, the clearance between the plywood and the steel column has been an issue because of the difficulty in transferring stress at the joint position. This study proposes a new joint method, where the plywood panel is connected to the steel frame through rings welded to the steel column (Fig. 4).

When wood is used as a seismic element, screws and other small-diameter joint elements are generally used to connect to the framework. In that case, the bearing capacity of the structure is determined by the shear and pullout of these elements. The composite hybrid bearing wall in this study is expected to avoid yielding or rupture of the joint elements using hardware, and it is expected the bearing capacity develop due to the bearing pressure of the plywood. This can be achieved by connecting through steel columns. The layout of the plywood and the shape and size of the through-hardware allows for the control of the collapse mode and the adjustment and control of the resilience characteristics. Furthermore, the checkered pattern is expected to increase the number of resisting areas and reduce the burden on the steel members.

If plywood is damaged, it can be easily replaced or repaired due to its small size. When wood members are subjected to bearing pressure, the load is expected to continue to increase. The wood members are expected to exhibit more stable resilience characteristics compared to damage to screws and other joints unless rupturing occurs.

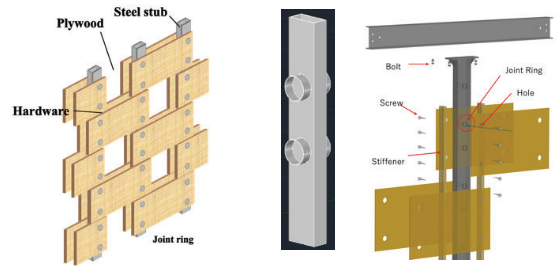

Fig.4 Checkered pattern sandwiched panel (current model)

3.3 Composition of specimen

Fig. 5 shows the configuration of test specimen of hybrid-resistant wall panel. The specimen is full-scale, spanning 2200 mm and a height of 3450 mm. The steel framework consists of main columns (JIS grade, STKR400, □-100×100×9) that imitates the building framework and intermediate columns (JIS grade, STKR400, □-150×75×4.5) that constitutes the composite wall. End plates (JIS grade, SS400, EP-300×120×16, hereafter referred to as main column BPL) are corner-welded (S=7mm) to the column legs, and gusset plates (JIS grade, SS400, PL-6) are corner-welded (S=5mm) to the column heads (Fig. 2). End plates (column heads: JIS grade, SS400, EP-300 x 120×16; column legs: JIS grade, SN490B, EP-350×115×25; hereafter referred to as TPL and BPL, respectively) are corner-welded (S=6mm) to the column heads and column legs of the intermediate columns. The girders are made of H-girder (JIS grade, SS400, H-200×100×5.5×8) and joined to the columns using ordinary bolts (M16 for the studs and M20 for the main columns, strength class 4.8). The bottom flange of the girders is stiffened with square washers (JIS grade, SS400, 60×30×12, Φ=17). The plywood is 12-mm-thick structural plywood (JAS Class 2, larch).The plywood is joined to the steel columns by corner-welding the inside of a circular steel pipe (JIS grade, STK400, 0-48.6 x 3.2, L-11.5 mm, hereinafter referred to as a joining ring) to the column flange (S=3.2 mm) and fitting the joining ring into a hole (Φ=50 mm) previously made in the plywood. Vertical cleats (75 mm x 30 mm, cypress) are placed on both sides of the columns, and the plywood and the vertical cleats are fastened with slender screws.

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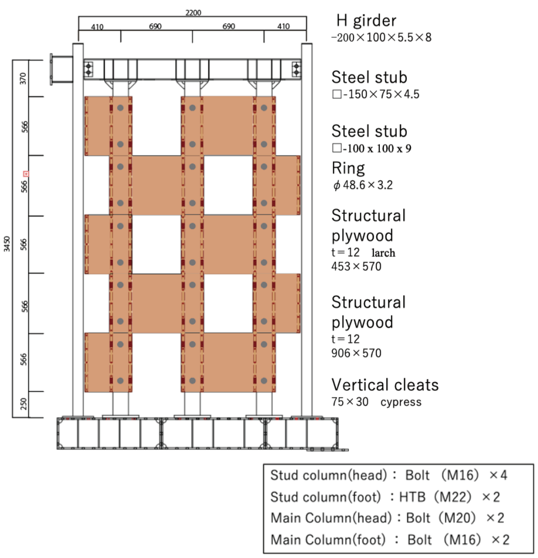

Fig. 5 Configuration of test specimen of hybrid-resistant wall panel

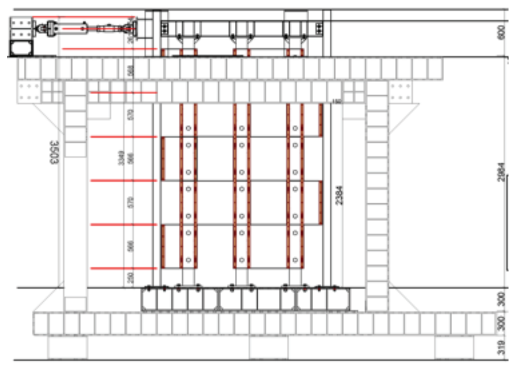

Fig.6 Experimental setup of specimen (unit: mm)

Table 1.	Summary of Experiment Parameters and Specimen ID		
Specimen ID	Plywood	Joint	Stiffening Stud Top
W-RJ-NRF	Wear	Rigid (Bolt joint with EPL)	None
W-RJ-RF			Stiffening
S-RJ-NRF	None		None
S-RJ-RF			Stiffening

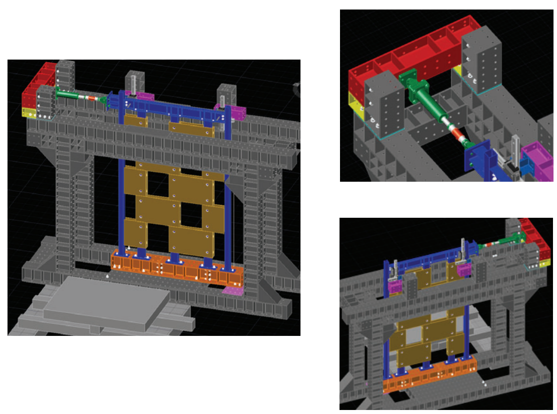

Fig. 7 Setup image (3D CAD) [10]

4 – EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 6. The horizontal loading test has been conducted under incremental cyclic loading. The loading was controlled by story drift angles: (1/450, 1/300, 1/200, and 1/150) rad. were loaded once each, and (1/100, 1/75, 1/50, and 1/30) rad. were loaded three times each until the jack stroke reached the limit.

Steel specimen

Hybrid bearing wall specimen

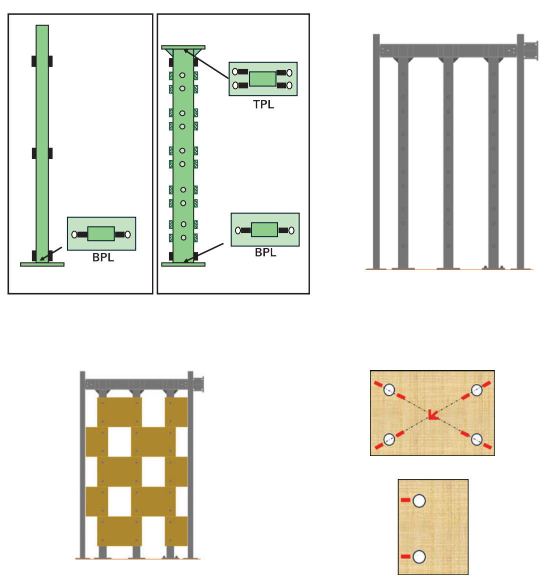

Fig. 8 Layout of strain gauge

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5 – RESULTS

The specimen with structural plywood presents higher strength and rigidity, compared to the steel specimen. All specimens showed column bending and yielding, and the joint rings penetrated the plywood in the specimens with plywood.

5.1 Summary of test results

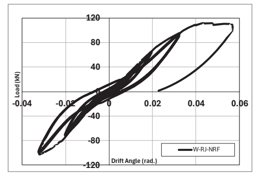
The yield load and maximum load were obtained. The results are listed in Table 2. Fig. 9 shows the hysteresis loop of restoring force obtained from the cyclic loading test, and Fig. 10 shows the skeleton curve obtained by joining the envelopes of the history curves.

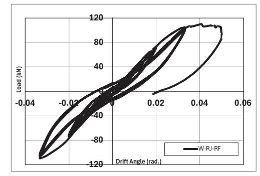
In the experiments on steel columns, bending yielding of the columns and end plates at the column-leg joints was observed (Fig. 11). Fig. 9(2) shows a small amount of unloading-point-oriented historical behavior with pinching. This is consistent with the endplate collapse-type resilience characteristics of steel semi-rigid joints.

In the composite hybrid bearing wall experiment, bending and yielding of the end plates of the steel column footings, the penetration of the joint ring into the plywood, and out-of-plane bending due to warping of the plywood were observed. Fig. 9(1) shows pinching behavior and stiffness-degraded and reverse S-shaped history behaviors. This may be due to the expansion of the holes in the plywood due to the penetration of the joint ring into the plywood.

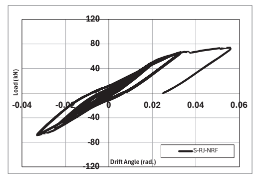
These results show that unstable seismic behavior, such as progressive slip caused by buckling of turnbuckle braces, is not observed, and the superiority of this structural system in stable behavior can be confirmed. It is expected that by adjusting the contribution of the steel frame and plywood according to their geometry and cross-sectional dimensions, the restoring force characteristics can be stabilized by increasing the proportion of the spindle-shaped steel frame.

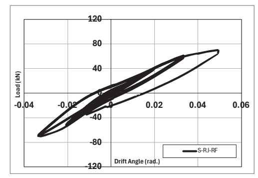
Table 2.	Summary of test results			
Specimen ID	Rigidity	Yield strength	Maximum load	Wall magnification
W-RJ-NRF	3450kN/rad.	74.0kN	111.5kN	6.7
W-RJ-RF	3817kN/rad.	76.1kN	115.5kN	7.4
S-RJ-NRF	2642kN/rad.	51.1kN	79.1kN	5.1
S-RJ-RF	1950kN/rad.	46.4kN	70.3kN	4.1


(a)W-RJ-NRF


(b)W-RJ-RF

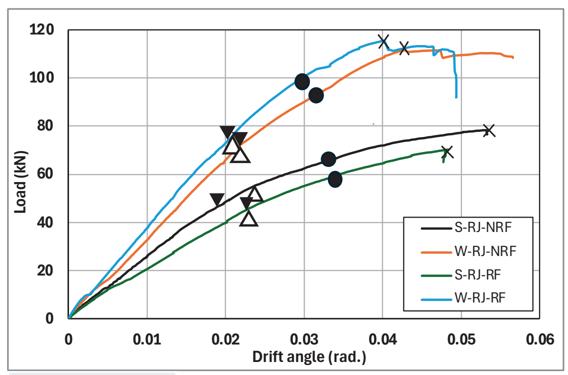
(1) Hybrid panel test specimen


(c)S-RJ-NRF


(d)S-RJ-RF

(2) Steel stub test specimen

Fig.9 Test result of hysteresis loop of restoring force



▼ : Elastic Limit
× : Maximum Strength
● : Plastic Moment
△ : Yield Strength

Fig. 10 Test result of skeleton curve of restoring force vs story drift

5.2 Collapse mode

Fig. 11 shows the collapse modes observed in the experiments. Bending yielding of the columns was observed in all specimens, and penetration of the joint rings into the plywood was observed in the specimens with plywood. For the collapse modes of the steel girders, local deformation of the girder flange was observed at 1/30 rad in the W-RJ-NRF and S-RJ-NRF specimens without stiffening of the girder flange due to the pullout of the ordinary bolts. The main column BPL rotation was also observed in the end state after 1/30 rad. The plywood

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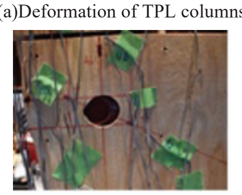
was observed to have progressive gouging where it was subjected to bearing forces from the joint rings, resulting in out-of-plane deformation due to deformation by delamination of the plywood from the vertical piers and out-of-plane deformation of the plywood due to warping and contact between the plywood.

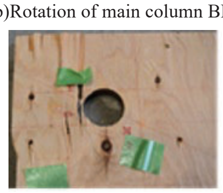
From the observations of the experiment, when the load was applied in the forward direction, the failure due to the joint ring penetration was observed at the upper right and lower left. It is considered that the load-bearing mechanism of the brace field is generated in the plywood by the bearing force generated by the penetration of the joint rings into the plywood and that the plywood resists the horizontal force.

(a)Deformation of TPL columns

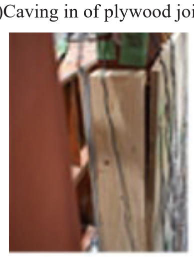
(b)Rotation of main column BPL



(c)Caving in of plywood joints



(d) Failure of plywood to push through



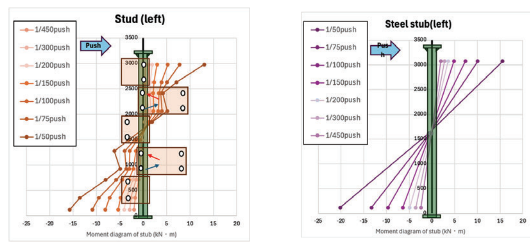
(e)Delamination of plywood from vertical piers

(f)Out-of-plane deformation of plywood

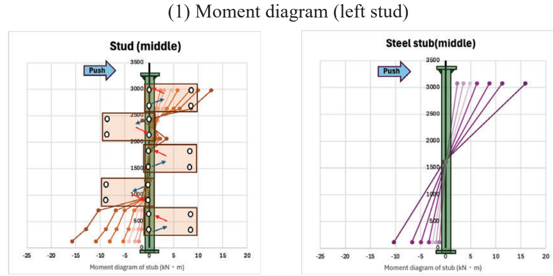
Fig. 11 Fracture properties

5.3 Rigidification effect

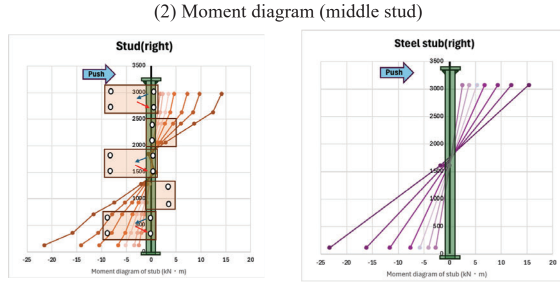
In the composite bearing wall specimen, the tilting of the moment of the studs has the opposite direction, indicating that the studs are bending back. On the other hand, in the steel frame specimen, the moment inclination is straight. Fig.10 shows that the diagram inclination of the hybrid bearing wall specimen changes in inverse position (inverse shear). This means that although the bending and strain burdens of the steel columns are partially more significant than those of the steel-only specimens, they are all within the elastic range, indicating that the plywood is effectively suppresses strain and deformation. The plywood on the outer face of the specimen is not joined diagonally, so it can be confirmed that the plywood does not provide any bending resistance to the steel columns.



(1) Moment diagram (left stud)



(2) Moment diagram (middle stud)



(3) Moment diagram (right stud)

Fig. 12 Moment diagram of stub (hybrid vs steel)

6 – CONCLUSION

In this study, we proposed a composite hybrid bearing wall structure consisting of steel and wood sandwich panels arranged in a checkerboard pattern. To clarify the mechanism and resilience characteristics under horizontal forces, a full-scale horizontal loading test of the composite hybrid wall was conducted. The results of this study reveal the failure mode of full-scale wood-steel composite walls under cyclic loading tests. The hybrid specimen using plywood presents high strength and rigidity. It is also suggested that the plywood contributes to an increase the bearing capacity. In conclusion, it is confirmed that stress transfer from the steel frame to the plywood occurs within the scope of elastic deformation due to the composite effect.

1) From the results of the horizontal loading tests, bending yielding of the bottom of the columns, bending yielding of the end plates of the column legs, penetration joint ring into the plywood, out-of-plane deformation of the plywood, and rotation of the joints of the column legs were observed.

2) The experimental results of the composite hybrid bearing wall showed that the stiffness and bearing capacity were larger than those of the steel column specimens. This indicates that the plywood has a stiffening effect and contributes to the increase in stiffness and bearing capacity.

3) Out-of-plane bending due to warping of the plywood and the penetration of the joint ring into the plywood were observed. Due to these effects, pinching behavior was observed in the historical behavior.

5) A comparison of the moment diagram of the studs in the composite hybrid bearing wall specimens and steel column specimens showed that the plywood resistance caused reverse shear in the studs, which resulted in bending back.

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