Fire Resistance of Structural Wooden Walls Covered by Gypsum and Diatomite Board

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The fire resistance of structural wooden walls covered with fire-resisting boards was investigated. A 49-mm-thick gypsum board (No. 1 and No. 2), a 24-mm-thick diatomite (No. 3), and a combination of gypsum and diatomite board (No. 4 and No. 5) were theoretically designed for 2-h fire resistance. As a result, when the gypsum board was fixed to the wood studs with nails (No. 1), there was no damage after 2 h, as predicted. When diatomite boards were used on the surface to face the fire (No. 3 and No. 4), the diatomite boards were destroyed after approximately 50 min because of the cracks of the diatomite board. However, when the diatomite board (6 mm) was placed inside the gypsum board (30 mm), the specimen (No. 5) showed a fire resistance of more than 2 h. Therefore, it is possible to reduce the thickness of the gypsum board using the diatomite board by avoiding placement of the diatomite board in direct contact with heat.

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Keywords: Fire resistance; Fireproof; Gypsum board; Diatomite board; Structural wooden wall

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INTRODUCTION

As a building material, wood has a carbon storage effect and reduces global warming potential (GWP) (Hafner and Schäfer 2018). To increase the carbon storage effect of wood, tall wooden buildings with 5 stories or more are being built in many countries (Foster *et al.* 2016; Safarik *et al*. 2022; Wiegand and Ramage 2022). The buildings must be fire-resistant, which fulfills their designed function in a fire accident (Khoury 2000). The duration of fire resistance depends on the type of building and its structural elements (Green *et al.* 2007). In Korea, a fire-resistant structure is required for 1 h for buildings up to the 4th floor and 2 h for buildings above the 5th floor.

For tall wooden buildings, there are three methods to satisfy the fire performance. The first method is the reduced cross-section method (RCSM), which removes the carbonized layer (zero-strength layer) as much as the thickness of the burning wood (Schmid *et al.* 2015; Xing *et al.* 2021). The RCSM is included in Eurocode 5 (EN 1995-1-1 2004) and the key is to calculate the effective cross-sectional area. Recentely, to provide the RCSM of cross-laminated timber (CLT) used in middle and high-rise buildings, Xing *et al.* (2021) investigated the fire resistance of the CLT and provided a formula to calculate the thickness of the zero-strength layer (Xing *et al.* 2021). The second method is to protect the wood with fireproof boards or coatings so that the wood does not burn. Fire-resistant gypsum board is generally used, and the effect of intumescent coating for wood products has also been reported (Puri and Khanna 2017; Lucherini *et al.* 2019; Pang *et al.* 2022). The third method is to satisfy the fire performance using the above two methods together.

An appropriate method will be selected for the fire resistance design of a building reflecting the concept of the building, economic feasibility, and constructional convenience. In terms of space utilization in a building, it is inefficient to increase the cross-section of the structural member with the carbonized layer. Moreover, if the wood burns in a fire, the burning smell lasts and the member should be replaced. The carbonization layer should be removed or the wood member must be replaced. If there is no damage to the structural wooden members after the fire, then the member can continue to be used. Therefore, reliable protection of wooden members with fire-resisting boards may be an economical way to satisfy the fire-resistance requirement.

In this study, a method to satisfy the fire resistance for 2 h with gypsum and diatomite board on a structural wooden wall was investigated. The thickness of the gypsum and diatomite board was optimized so that there was no damage to the structural member.

EXPERIMENTAL

Determination of the Fireproof Boards Thickness

The thickness of the gypsum board to avoid damaging the wood was determined using the first law of thermodynamics. Theoretically, thermal energy (ΔU) changes by the difference between the heat (Q) and the thermodynamic work (W), as shown in Eq. 1. Because thermodynamic work is negligible for solids, only supplied heat changes the thermal energy, and the temperature changes in inverse proportion to the heat capacity as shown in Eq. 2. This relationship is shown as Eq. 1,

$$\Delta U = Q - W \tag{1}$$

where ΔU is the change in the thermal energy (J), Q is the amount of thermal energy supplied by heat (J), and W is the amount of thermodynamic work (J). The change in thermal energy (J) is given by Eq. 2,

$$\Delta U = c \cdot \rho \cdot V \cdot \Delta T \tag{2}$$

where c is the specific heat capacity (J/kg·°C), ρ is the density of material (kg/m^3), V is the volume of the material (m^3), and ΔT is the temperature difference (°C).

The heat transfer through the gypsum board can be simulated using the finite difference method (Fig. 1) (Zhou *et al.* 2011; Kim *et al.* 2017; Hesthaven 2018; Khouya 2020). The temperature outside the gypsum board where the fire occurred followed the standard fire curve ISO 834-1 (1999)). Heat transferred to the inside was considered only by conduction and convection, and each heat transfer rate can be expressed as Eqs. 3 and 4, respectively,

$$\dot{Q}_{cond} = k \cdot A \cdot (\Delta T / L) \tag{3}$$

where $\dot{Q}_{cond}$ is the conductive heat transfer rate (W), k is the thermal conductivity (W/m·°C), A is the area of thermal conductivity (m^2), ΔT is the temperature difference (°C), and L is the thickness of the material (m); and,

$$\dot{Q}_{conv} = h_c \cdot A \cdot \Delta T \quad (4)$$

where $\dot{Q}_{conv}$ is the convective heat transfer rate (W), h_c is the convective heat transfer coefficient (W/m^2·°C), A is the area of thermal conductivity (m^2), and ΔT is the temperature difference (°C).

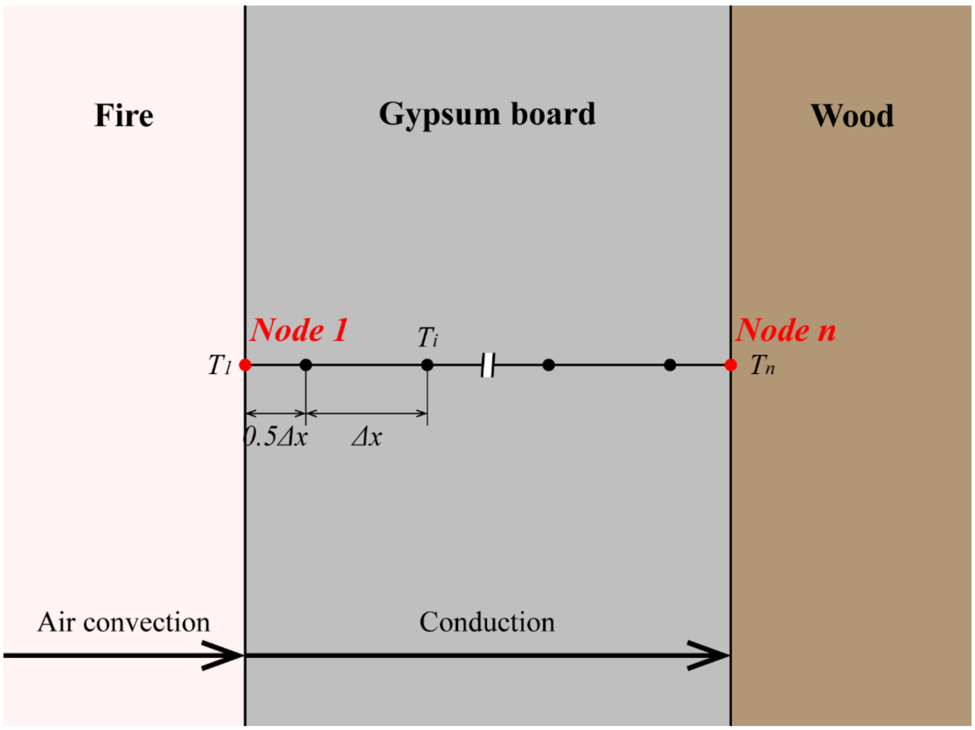


Fig. 1. The node to simulate the temperature in gypsum board by finite difference method

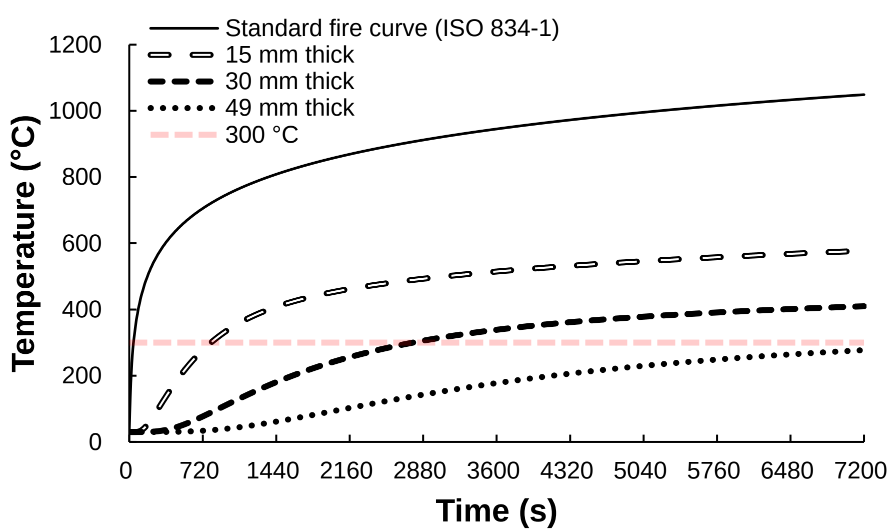


Fig. 2. Temperature-time curve of the back side of gypsum board by its thickness

When heat is continuously supplied from the outside of the gypsum board by fire, the temperature inside increases, and if it is above the wood fire point, the wood burns. The wood fire point was assumed as 300 °C, and the thickness of the gypsum board was simulated so that the temperature of the wood did not increase above the ignition point for 2 h. Figure 2 shows the simulation results of the temperature change of the inside of gypsum board (the surface in contact with the wood) according to the thickness of the gypsum board over time. When the thickness of the gypsum board was 49 mm (two 15-mm-thick boards + one 19-mm board), it did not exceed 300 °C. Therefore, this study applied a 49-mm-thick gypsum board to the specimen.

Experimental Tests

Fire test specimens

A total of 5 specimens were manufactured using lumber (*Larix kaempferi*), oriented strand board (OSB), particle board (PB), and gypsum board or diatomite board (Table 1, Figs. 3 and 4). The nomenclature of the specimen in Table 1 indicates the fire-resistant boards (gypsum board or diatomite board), the fixing of the structural frame (nail or polyurethane (PUR)), and the thickness of the fire-resisting boards. In No. 4, the first letter (DG) of specimen ID indicates a diatomite board is placed on the outside and a gypsum board is placed on the inside. Conversely, in No. 5, the first letter (GD) indicates a gypsum board is placed on the outside and a diatomite board is placed on the inside.

Table 1. Combination of Fire-Resisting Boards for Test Specimens

No	Specimen ID	Frame Joint	Fire-Resisting Boards					Thermal Resistance (m^2k/W)
			Gypsum Board		Diatomite Board		Total Thickness (mm)	
			Thickness (mm)	Thermal Conductivity (W/m·K)	Thickness (mm)	Thermal Conductivity (W/m·K)		
No.1	G-nail-49	Nail	49	0.269	-	0.160	49	0.182
No.2	G-PUR-49	PUR	49		-		49	0.182
No.3	D-nail-24	Nail	-		24		24	0.150
No.4	DG-nail-36	Nail	30		6		36	0.149
No.5	GD-nail-36	Nail	30		6		36	0.149

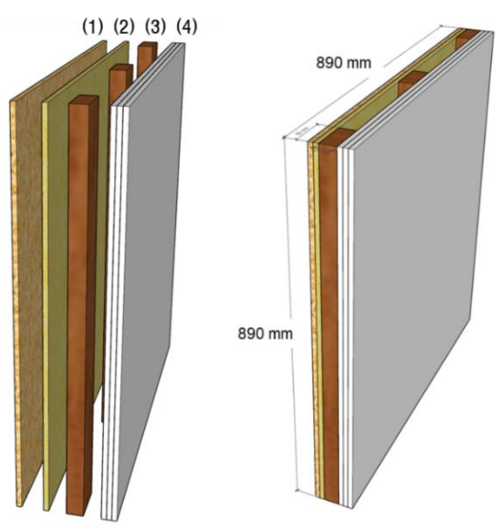
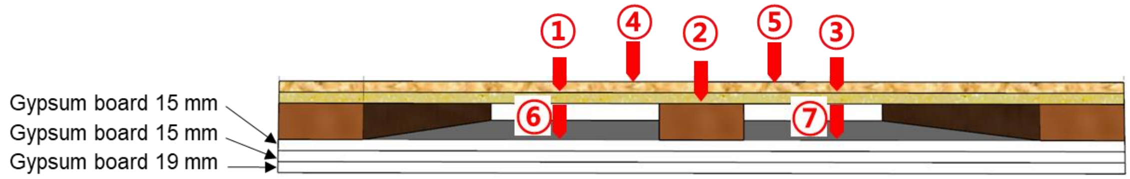
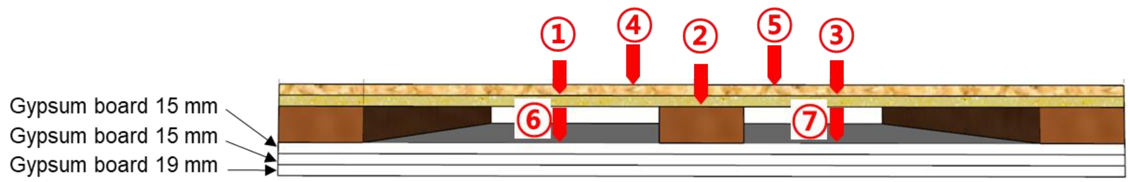


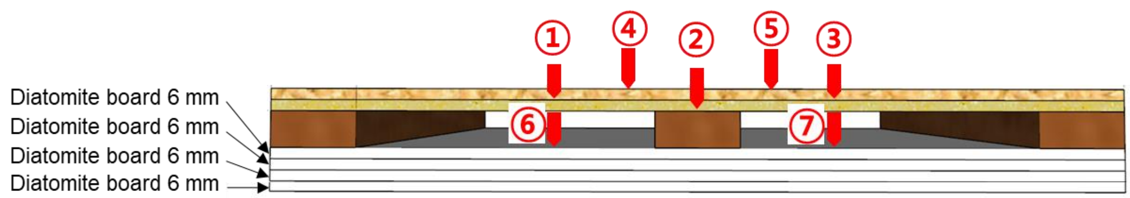
Fig. 3. Test specimen: (1) oriented strand board, (2) particle board, (3) stud (lumber), (4) fire-resistant boards



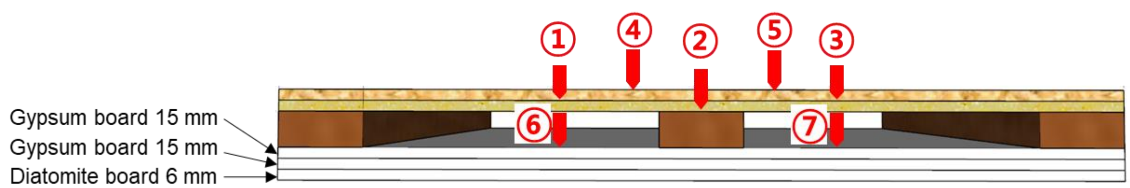
(a) No.1_G-nail-49 (frame was connected by brad nails)



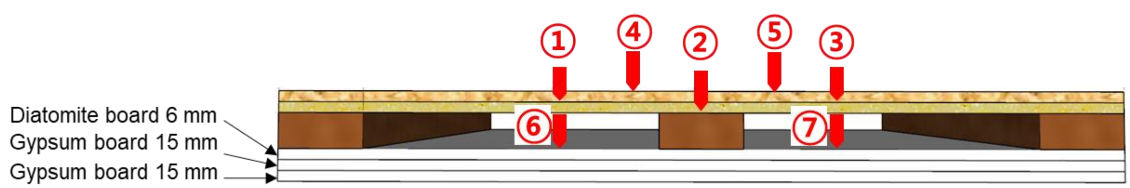
(b) No.2_G-PUR-49 (frame was glued by PUR)



(c) No.3_D-nail-24 (frame was connected by brad nails)



(d) No.4_DG-nail-36 (frame was connected by brad nails)



(e) No.5_GD-nail-36 (frame was connected by brad nails)

Fig. 4. Configuration of test specimen; the position of thermocouples, ① and ③: the back side of particle board, ②: the back of the lumber stud, ④ and ⑤: the back of OSB, ⑥ and ⑦: the back of the fire-resistant board; a: No.1 specimen, b: No.2 specimen, c: No.3 specimen, d: No.4 specimen, e: No.5 specimen

With the exception of No. 2, the structural frame was made by fixing lumber, OSB, and particle board with a brad nail (length: 30 mm, spacing: 50 mm). The frame of No. 2 was glued by PUR. In No. 1 and No. 2, the thickness of the gypsum board was determined so that the temperature of the back side of the gypsum board did not reach the ignition point (300 °C) of the wood stud after 2 h of the fire test. The thickness of the diatomite board was determined so that the thermal resistance (Eq. 5) of No. 3 was lower than that of No. 1 and No. 2. In No. 4 and No. 5, gypsum board and diatomite board were used together, and the thermal resistance of No. 4 and No. 5 was also determined as lower than that of No. 1 and No. 2.

$$R = \sum_{i=1}^{n} \frac{x_i}{k_i} \qquad (5)$$

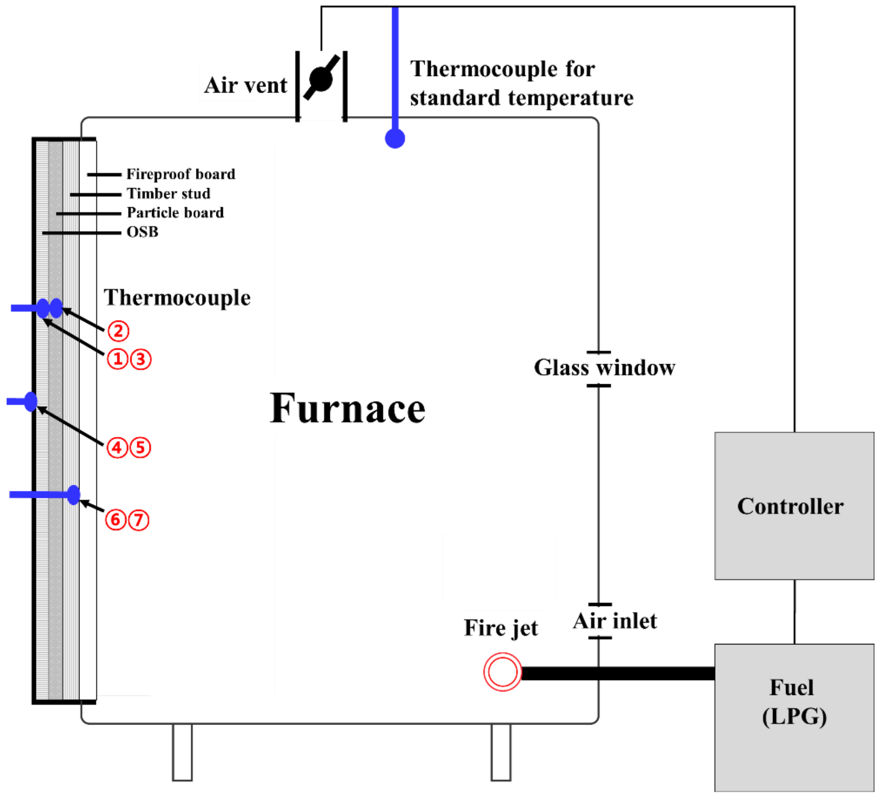
where R is the thermal resistance (m2·k/W), x_i is the thickness of fire-resistance board (mm), and k_i is the thermal conductivity (W/m·K).

Fire Resistance Test

Figure 5 shows the schematic system of the furnace used in this study. The furnace was designed for laboratory-scale experimentation. The fire-exposed volume of the furnace is 1341 mm (door side) × 1486.5 mm (the vertical side of the door) × 1400 mm (height). The temperature inside the furnace was detected by a thermocouple located at the top. A fire jet uses liquefied petroleum gas (LPG) as fuel. The gas injected into the fire jet is automatically controlled so that the internal temperature of the furnace follows the standard temperature curve of ISO 834-1 (1999). It is the same as the experimental equipment used by Pang *et al.* (2022), except for the specimen and the thermocouple installation.

a) Outside photo of the furnace

Fig. 5a. Position of thermocouples and a specimen in furnace (edited by Pang *et al.* 2022): a: outside photo of the furnace, b: schematic diagram of the furnace-burner system



b) Schematic diagram of the furnace-burner system

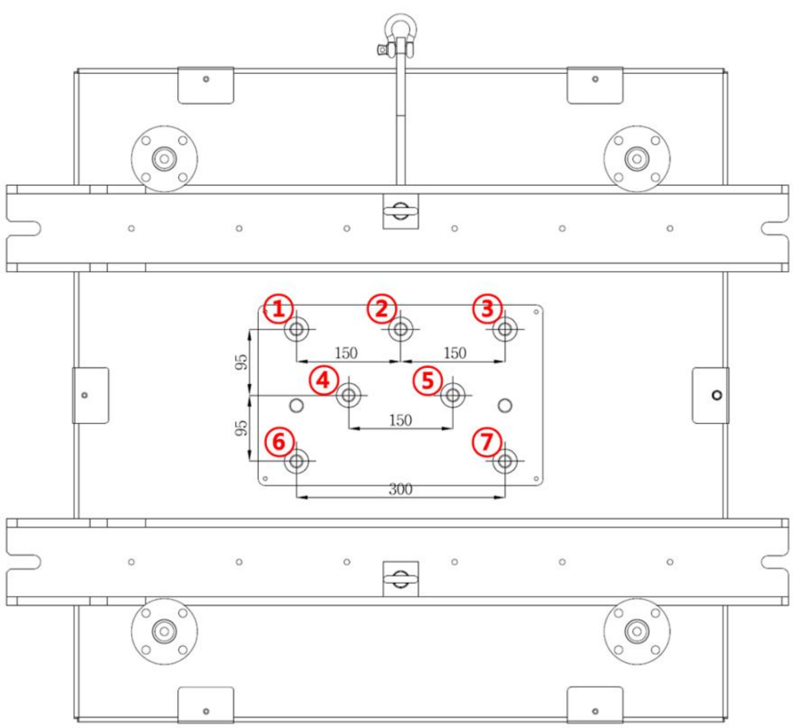
Fig. 5b. Position of thermocouples and a specimen in furnace (edited by Pang *et al.* 2022): a: outside photo of the furnace, b: schematic diagram of the furnace-burner system

A specimen (Table 1) was vertically installed on the furnace door, and the behavior of the specimen was visually observed through the glass window, as shown in Fig. 5. The fire test was conducted for 2 h based on ASTM E119-20 (2020). The temperature of the furnace followed ISO 834-1 (1999), and the temperature of the thermocouples was recorded once a second.

To find out whether each layer was lost by fire, seven thermocouples were installed at the back side of each layer as shown in Fig. 4. Thermocouples ① and ③ were installed to touch the back side of the particle board. Thermocouple ② was installed to touch the back of the lumber stud. Thermocouples ④ and ⑤ were installed to touch the back of OSB. Thermocouples ⑥ and ⑦ were installed to touch the back of the fire-resistant board. Figure 6 shows the location of thermocouples that can be installed through holes in the furnace door.

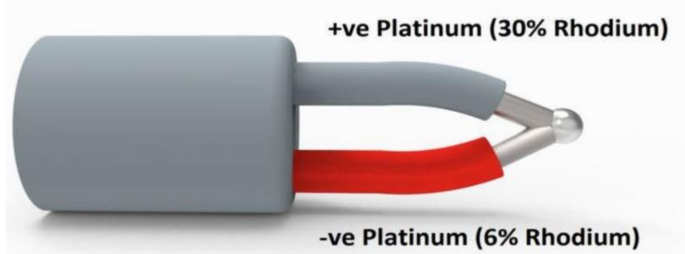
Thermocouples used in this test were TEMPSENS B-Type (Tempsens Instruments Pvt. Ltd., Udaipur, India), which is composed of a positive leg (70% Platinum and 30% Rhodium) and a negative leg (94% platinum and 6% Rhodium), as shown in Fig. 7. The legs were covered with Magnesium Oxide insulation, and the thermocouple has been commercialized for fire resistance test. The B-Type thermocouple has a wide measuring range (0 to 1700 °C, accuracy: ± 5 %) and good pressure-resistant performance. When installing the thermocouples, holes were drilled from the fire-unexposed surface (opposite face to the fire), and the thermocouples were inserted in the holes. A 17-mm diameter drill bit was used in making holes, considering that the diameter of the thermocouples was 16 mm. Thus, the thermocouples were installed so that the longitudinal direction of the thermocouples was parallel to the thickness direction of the specimen.

(a) Specimen on furnace door

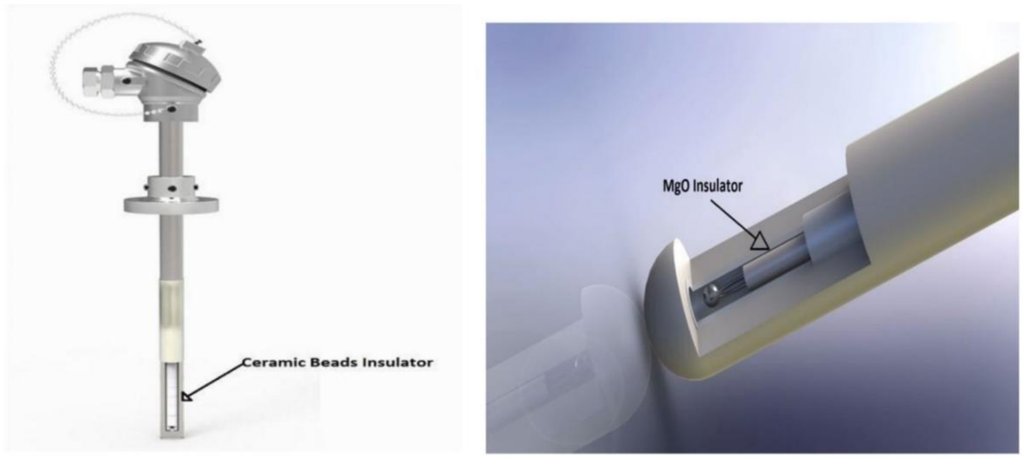


(b) Location of the thermocouples on the door of fire test chamber

Fig. 6. Fire test chamber (a) and location of thermocouples (b)



(a) The positive and negative leg



(b) Magnesium Oxide insulation

Fig. 7. B-Type thermocouple (TEMPSENS 2021)

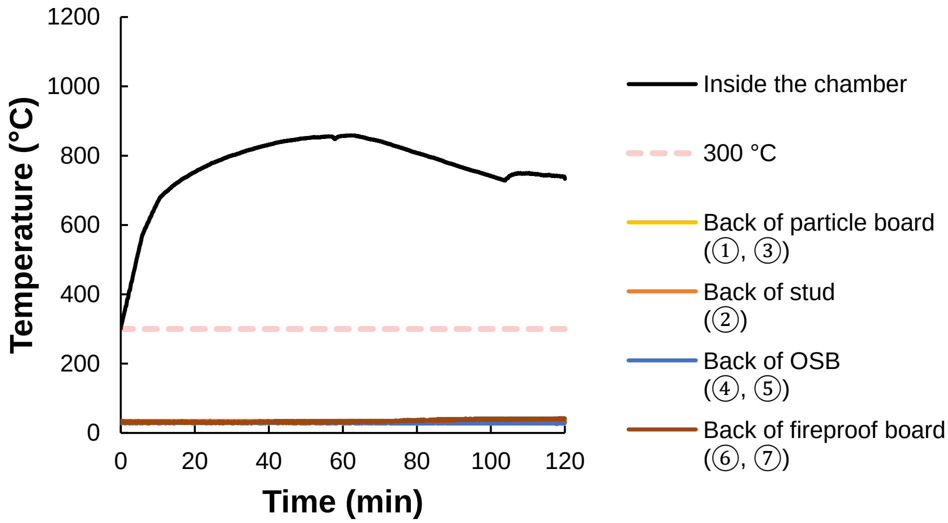
RESULTS AND DISCUSSION

Effect of Gypsum Board

Figures 8 and 9 show the time-temperature curves in specimens covered with gypsum board. When the 49-mm gypsum board was fixed to the wood studs with nails (Fig. 8 (a)), the temperature on the back side of the gypsum board hardly increased even after the 2-h fire test. When the test specimen was removed after the fire test, there was no fire on the specimen, only small cracks on the surface of the gypsum board. This indicates that the specimen has a fire resistance of more than 2 h, and the previous thermodynamically predicted results were validated.

When the 49-mm gypsum board was glued to the wood studs with PUR, the temperature on the back side of the gypsum board started to rise slowly after 80 min (Fig. 9(a)). Before the end of the test, the temperature of the back side of the gypsum board was increased to approximately 100 °C, and the temperature of the other thermocouples was unchanged. When the test specimen was removed after the fire test, there was no damage to the gypsum board, but there was a fire on the back of the gypsum board. During the firefighting process, the gypsum board fell down as shown in Fig. 9(b).

After 60 min there was an increase in internal temperature in Fig. 9(a), which is thought to be caused by a fire in the wood studs. The gypsum boards were glued to the wood studs, and only the studs in the specimen were fixed to the furnace door using screws. Then, the door with the test specimen was lifted by a crane to close the inlet of the furnace. Thus, if the gypsum boards on the specimen were separated before the fire test, the boards would have fallen off when the door was lifted.

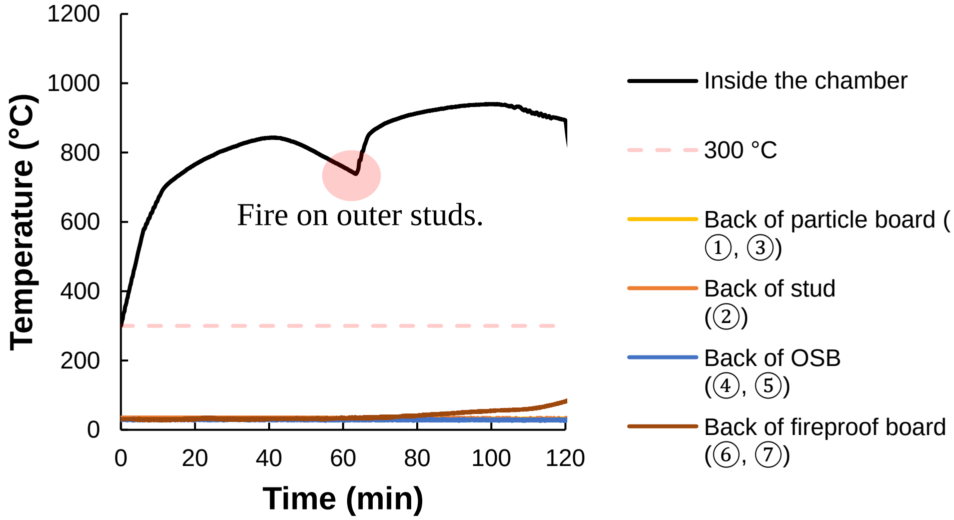


(a) Time-temperature curves

(b) Specimen after 2 h fire test

Fig. 8. Gypsum board fixed to the wood studs with brad nails (No.1): a: time-temperature curves, b: specimen after 2-h fire test

Several researchers (Frangi *et al.* 2012; Klippel 2014; Mäger *et al*. 2021; Just *et al*. 2022) revealed that the tensile strength of PUR decreased when the temperature was increased. Frangi *et al.* (2012) evaluated the tensile strength of finger joints glued with PUR (4 types) according to temperature, and the tensile strength at 100 °C showed approximately 49.2 to 62.8% of the tensile strength at 20 °C. Klippel (2014) also reported that the tensile strength of finger joints glued with PUR (6 types) at 100 °C showed approximately 64.6 to 76.4% of the tensile strength at 20 °C. Thus, the tensile strength between the gypsum board and wood stud glued by PUR would have decreased, when the temperature of the back side of the gypsum board was over 100 °C. In this experiment, the temperature on the back side of the gypsum board did not rise to the ignition point temperature of the wood, since the thermocouples were installed in the center of the test specimen. However, the strength of the adhesive can be decreased and the gap between the gypsum board and the wood studs would be opened. The wood stud and particle board would have caught fire through that space. Therefore, it is recommended to fix the gypsum board to the wood studs with nails.



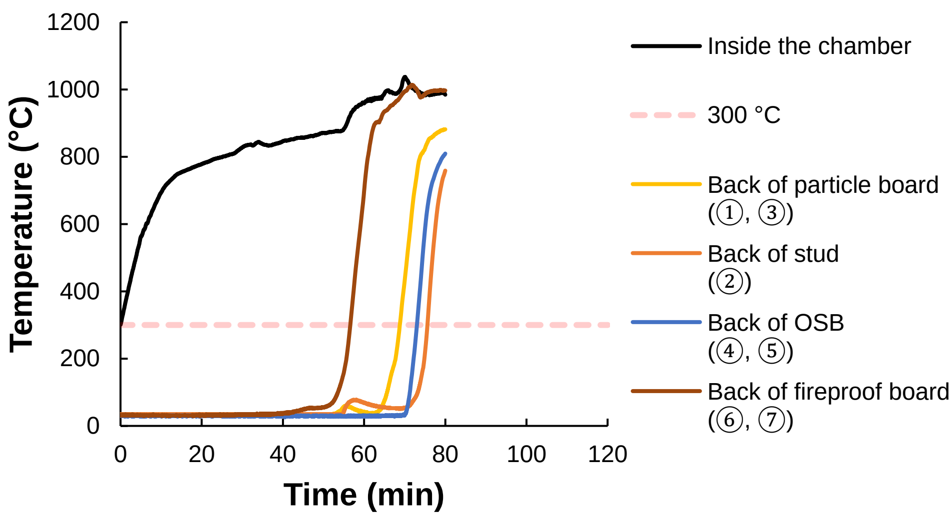
(a) Time-temperature curves

(b) Specimen after 2 h fire test

Fig. 9. Gypsum board glued to the wood studs with PUR (No. 2): a: time-temperature curves, b: specimen after 2-h fire test

Effect of Diatomite Board

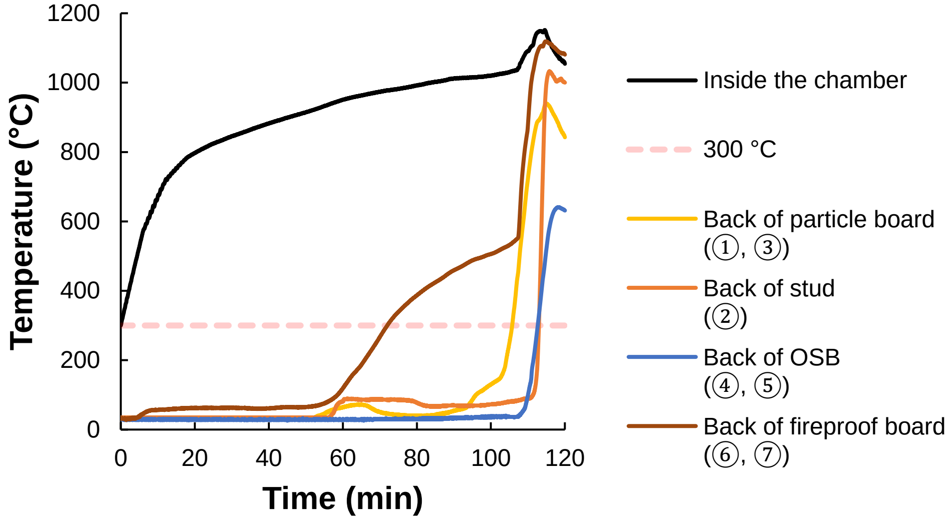
Figures 10 through 11 show the time-temperature curves in specimens covered with diatomite board (No. 3). When the 24 mm diatomite board was fixed to the wood studs with nails, the temperature on the back side of the diatomite board started to rise rapidly after 50 min (Fig. 10(a)). After 60 min, the temperature on the back side of the particleboard, OSB, and wood studs also rapidly increased. When the test specimen was removed after 80 min, the specimen was completely burned, and a piece of diatomite board fell on the floor. Thus, the heat caused cracks in the diatomite board, and the wood materials may have caught fire.



(a) Time-temperature curves

(b) Specimen after 2 h fire test

Fig. 10. Diatomite board (24 mm) nailed to the wood studs (No. 3): a: time-temperature curves, b: specimen after 2-h fire test



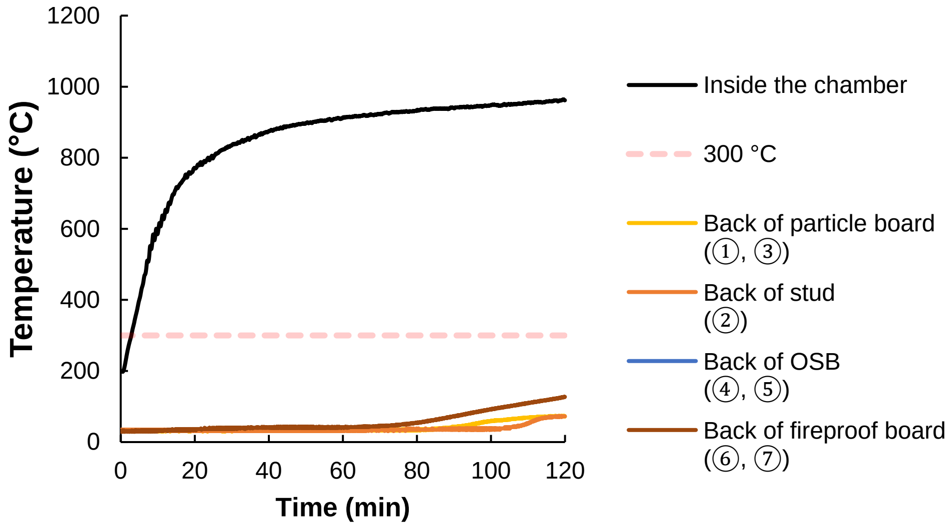
(a) Time-temperature curves

(b) Specimen after 2 h fire test

Fig. 11. Diatomite (6 mm, outside) and gypsum (30 mm, inside) board nailed to the wood studs (No. 4): a: time-temperature curves, b: specimen after 2-h fire test

When the diatomite (6 mm, outside) and gypsum (30 mm, inside) board were nailed to the wood studs, the temperature on the back side of the boards also started to rise after approximately 50 min (Fig. 11(a)). After 100 min, the temperature on the back side of the particle board, OSB, and wood studs also increased over 300 °C. When the test specimen was removed after 120 min, the specimen was also completely burned, and a piece of diatomite board fell on the floor. Compared to No. 3, which had only diatomite board, the temperature rise of the wood material was delayed because the gypsum board delayed the temperature (from approximately 50 min to approximately 100 min). The test results of No. 3 and No. 4 indicate when the diatomite board is in direct contact with heat, the diatomite board is destroyed by cracking after approximately 50 min. Thus, to prevent cracks in the diatomite board, it seems necessary to reinforce it with fibers such as those used in fire-resistant gypsum board (EN 15283-2 2009; Just *et al.* 2010).

To avoid the diatomite board being in direct contact with heat, the diatomite board (6 mm) was placed inside the gypsum board (30 mm), as shown in Fig. 4 (e) (No. 5). As a result, the temperature on the back side of the diatomite board reached approximately 120 °C after the 2-h fire test (Fig. 12(a)). When the test specimen was removed after the fire test, there was only a small crack on the surface of the gypsum board and no other damage. Thus, when the diatomite board is not in direct contact with heat, the specimen had a fire resistance of more than 2 h.



(a) Time-temperature curves

(b) Specimen after 2 h fire test

Fig. 12. Diatomite (6 mm, inside) and gypsum (30 mm, outside) board nailed to the wood studs (No. 5): a: time-temperature curves, b: specimen after 2-h fire test

The thermal conductivity of the diatomite board is lower than that of the gypsum board. When the thickness of fire-resistant board was theoretically designed to have a similar thermal resistance, the thickness of the No. 5 specimen (36 mm) was 13 mm thinner than when only the gypsum board (49 mm) was used in No. 1. Therefore, the experimental results indicate the possibility of reducing the thickness of gypsum board using the diatomite board and the theoretically predicted result from Eq. 5 was validated.

If fireproof boards are not used, structural wood walls for 2-h fire resistance can be designed based on the charring rate of the wood. In this case, 96 mm thick wood should be added for 2-hour fire resistance because the three-sided carbonization rate of the species is 0.78 to 0.80 mm/min (Pang *et al.* 2022, EN 1995-1-2 2004). This is twice as thick as gypsum board (49 mm, No. 1) and 2.7 times thicker than the diatomite and gypsum board (36 mm, No. 5). Therefore, it is shown that the thickness of the wall required for 2-hour fire resistance can be reduced by using the fireproof board.

CONCLUSIONS

In this study, the fire resistance of structural wooden walls with fire-resistant boards was investigated, and the main findings were as follows.

1. A 49-mm-thick gypsum board was theoretically designed for 2-h fire resistance. As a result of the experiment, when the gypsum board was fixed to the wood studs with nails (No. 1), there was no damage after 2 h, as predicted. However, when gypsum boards were attached to wood studs by gluing (PUR, No. 2), there was a decrease in the performance of the adhesive. Therefore, fixing with nails rather than gluing is recommended.
2. The diatomite boards in specimen No. 3 and No. 4 were destroyed after approximately 50 min. This was because cracks developed when the diatomite board was in direct contact with heat. Therefore, reinforcing the diatomite board with fibers to prevent it from cracking due to heat would be more effective in improving fire resistance than increasing the thickness of the diatomite board.
3. When the diatomite board (6 mm) was placed inside the gypsum board (30 mm), the specimen (No. 5) showed a fire resistance of more than 2 h. Through avoiding the diatomite board being in direct contact with heat, the effect of thickness of the boards theoretically predicted by thermal resistance was validated. Therefore, it is possible to reduce the thickness of the gypsum board using the diatomite board, if the diatomite board is not in direct contact with heat.

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Competing Interests

The authors declare they have no competing interest.

Authors' Contributions

Sung-Jun Pang analyzed the test results and wrote this manuscript. Kyung-Sun Ahn and Jae-Won Oh established the formulas and simulated the temperature of the specimens. Han Shik Lee designed and manufactured the test specimens. Seog Goo Kang designed an experimental test procedure and operated the test facility. Jung-Kwon Oh managed this research project and approved the final manuscript.

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