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EFFECT OF THE SACRIFICIAL LAYER THICKNESS AND THE BARRIER LAYER TYPE ON SELF-EXTINGUISHING FOR WOODEN FIREPROOF-STRUCTURAL ELEMENTS

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ABSTRACT: The effects of the thickness of the sacrificial layer and the type of barrier layer on the self-extinguishing performance of wooden fireproof structural elements made from Japanese cedar were clarified. Three series of small fireproof heating tests were conducted. It was clarified that with a wood-based protection layer, there was an optimum thickness of the sacrificial layer regardless of the heating time. The use of gypsum and fire-retardant wood as the barrier layer was then compared in terms of suppressing the temperature rise through the latent heat of the barrier layer, and the effect of the sacrificial layer thickness on the self-extinguishing performance was clarified.

KEYWORDS: Japanese cedar, glowing combustion, Flame die-out, Fire-resistive construction

1 INTRODUCTION

High-rise wooden structures must be fireproof. The fire-resistant performance in Japan, as an earthquake-prone country that does not assume firefighting activities, requires high-rise wooden structures to self-extinguish and become independent after a fire.

In recent years, there have been frequent international examples of fires rapidly spreading to the upper floors of high-rise buildings and causing enormous damage[1]. Fire-resistant structures that self-extinguish in the event of a fire should thus be considered even for high-rise wooden buildings.

The authors have clarified the specifications of fire-resistive structures that achieve 1 and 2-hour fire resistance adopting the concept of the sacrificial layer as shown in **Figure 1** and clarified the self-extinguishing performance of the sacrificial layer[2][3]. They showed that if the sacrificial layer is designed to be thick according to the required fire resistance time, the performance of the barrier layer can be minimized and an efficient member design achieved[2].

Meanwhile, when a long fire resistance time is required in the case of a high-rise building, the actual fire heating time may be shorter than the required fire resistance time. In this case, the sacrificial layer designed to be thick according to the fire resistance time may maintain glowing combustion after the fire. The fire resistance structure must perform even when it is heated by fire for a time shorter than the required fire resistance time. The present study thus examines the optimum thickness of the sacrificial layer regardless of the required fire resistance time.

The optimum thickness of the sacrificial layer depends on the suppression of the temperature rise through the latent heat of the barrier layer, and the appropriate thickness of the sacrificial layer when the barrier layer is gypsum is thus also examined in the present paper.

Three series of tests were conducted to examine the effects of the thickness of the sacrificial layer and the type of barrier layer on the self-extinguishing performance of the sacrificial layer. In all tests, specimens were heated following the ISO834 fire temperature–time curve and then left in a quiescent environment. All specimens were made from Japanese cedar, the wood most used for construction in Japan.

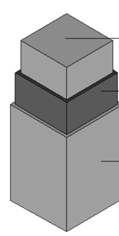

Figure 1: *Wooden fireproof structural elements*

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2 EFFECT OF THE THICKNESS OF THE SACRIFICIAL LAYER ON SELF-EXTINGUISHING WITH A WOOD-BASED PROTECTION LAYER

2.1 THICKNESS AND SELF-EXTINGUISHING OF THE SACRIFICIAL LAYER

2.1.1 Purpose

The first series of tests was conducted to clarify whether fireproof-structural elements with a sacrificial layer thickness designed for the required fire-resistant time will self-extinguish when exposed to heating for a time shorter than the required fire-resistant time.
Specifically, test pieces with sacrificial layers of 50 mm, which were designed to have fire resistance for 120 minutes, were heated for 60 and 120 minutes to verify whether they self-extinguished even after 60 minutes of heating.

2.1.2 Outline of tests

In the first series of tests, using a small furnace at the Forestry and Forest Products Research Institute, test pieces were heated for 1 or 2 hours according to the ISO834 standard heating curve and allowed to cool in the furnace for 6 hours. **Figure 2** is a schematic diagram of the furnace and the layout of the test specimen.
Two specimens were prepared with a sacrificial layer having a thickness of 50 mm and fire-retardant plywood for the barrier having a thickness of 50 mm. The materials of barrier layer, fire-retardant plywood, were rated as quasi-incombustible materials. The fire-retarding agent injected 180 kg/m^3 into the fire-retardant plywood.
The measurement items were the internal temperature of the specimen and the furnace temperature. The temperature measurement points are shown in **Figure 3**.

2.1.3 Test results and discussion

Table 1 shows that the sacrificial layer with the 120-minute heating specification extinguished itself after heating whereas the sacrificial layer with the 60-minute heating specification continued to burn. Previous studies [2] have shown that the self-extinguishing of the sacrificial layer is greatly affected by a rise in the barrier layer temperature to the decomposition temperature of the fire retarding agent (195 °C) during heating. **Figures 4 and 5** show that the temperature within the barrier of self-extinguishing specimen S50-120 exceeded the decomposition temperature 97 minutes after the start of heating, whereas the non-self-extinguishing specimen S50-60 did not even reach 100 °C.

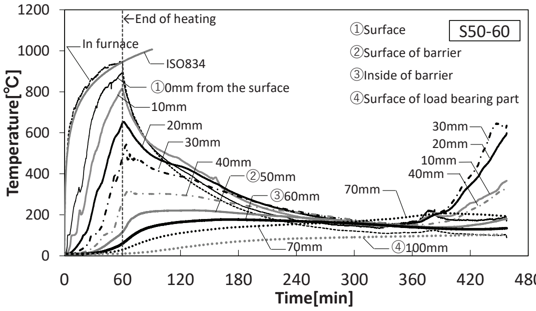


Figure4: *Temperature (S50-60)*

This is probably because the sacrificial layer was too thick and the barrier layer did not reach the decomposition temperature of the fire retarding agent during heating and did not self-extinguish.

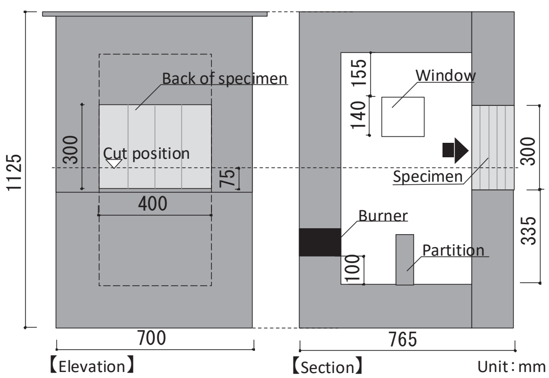


Figure 2: *Specimen layout in the first and second series of tests*

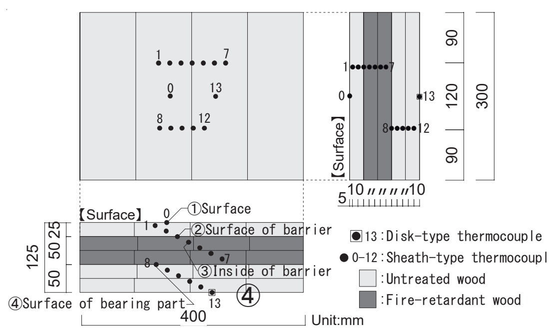
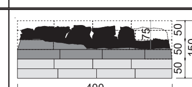
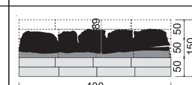


Figure 3: *Specimens in the first series of tests*

Table 1: *Results of the first series of tests*

	Specimen	Sacrificial layer thickness [mm]	Heating time [min]	Carbonization [mm]	Results*1
series(1)tests	S50-60	50	60		× (Continued to burn)
	S50-120		120		○ (Extinguished)

:Untreated wood　: Fire-retardant wood　: Char layer

*1: ○:Glowing combustion stopped after end of the test, ×:Glowing combustion continued after end of the test

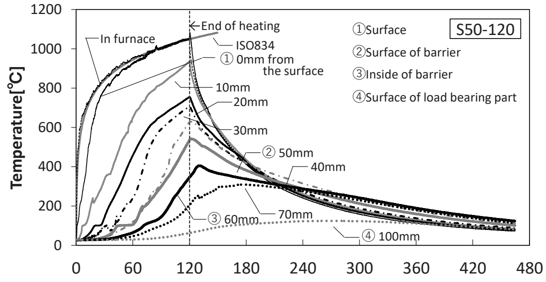


Figure 5: *Temperature (S50-120)*

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The results show that for the same thickness of the sacrificial layer, self-extinguishing depends on the heating time. It is considered that there are two reasons for the continuation of combustion in the sacrificial layer.

(1) The barrier layer did not reach the decomposition temperature of the retarding agent during heating and could not contribute to suppressing the temperature rise inside the sacrificial layer.

(2) The carbonized layer on the surface of the specimen suppressed the heat loss to the outside, and the combustion of the uncarbonized part of the sacrificial layer continued.

Therefore, in the next section, the optimum thickness of the self-extinguishing sacrificial layer is examined regardless of the heating time.

2.2 OPTIMUM SACRIFICIAL LAYER THICKNESS REGARDLESS OF THE HEATING TIME

2.2.1 Purpose

The second series of tests was conducted to examine the optimum thickness of the sacrificial layer regardless of the heating time. From the results of past experiments[2], it is thought that if the carbonization depth is under 10–20 mm, a specimen will self-extinguish through heat loss from the surface. The carbonization rate of Japanese cedar is 0.6–0.8 mm/min[4], and it is thus presumed that fire heating for 12.5–33.3 min will result in the specimen self-extinguishing through heat loss from the surface. Additionally, in the case of heating for 30 minutes or longer, the temperature of the barrier layer must reach the decomposition temperature of the retarding agent during heating. **Figure 4** shows that the depth reaching the decomposition temperature of the fire retarding agent (195 °C) after heating for 30 minutes was 20–30 mm, and it is thus estimated that the optimum thickness of the sacrificial layer is 20–30 mm.

2.2.2 Outline of the tests

In the second series of tests, four specimens with a sacrificial layer thickness of 25 mm were prepared for self-extinguishing regardless of the heating time. The fire-retarding agent was injected 180 kg/m^3 into the fire-retardant plywood at as in section 2.1. Following the ISO834 standard heating curve, heating tests were conducted with heating times of 30, 45, 60 and 120 minutes.

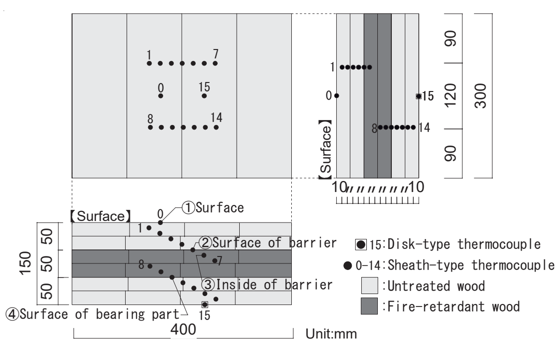
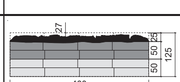
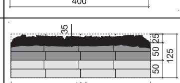
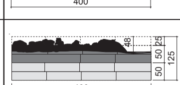
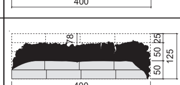


Figure 6: *Specimens in the second series of tests*

Table 2: *Results of the second series of tests*

	Specimen	Sacrificial layer thickness [mm]	Heating time [min]	Carbonization	Char layer depth [mm] Heating end*1 / Test end	Results*2
series(2)tests	S25-30	25	30		22 / 27 (+5mm)	Succeeded (Non exists)
	S25-45		45		31 / 35 (+4mm)	Succeeded (Non exists)
	S25-60		60		33 / 48 (+15mm)	Succeeded (Non exists)
	S25-120		120		58 / 78 (+20mm)	Succeeded* (Non exists)

:Untreated wood : Fire-retardant wood : Char layer

*1:Char layer depth is calculated linear interpolation of internal tempreture. Carboonization tempreture is 260°C for untreated wood, 195°C for fire-retardant wood.

*2: ○:Glowing combustion stopped after end of the test, ×:Glowing combustion continued after end of the test

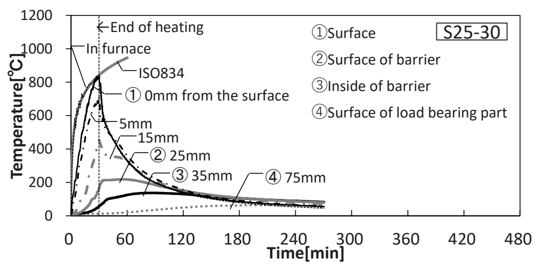


Figure 7: *Temperature (S25-30)*

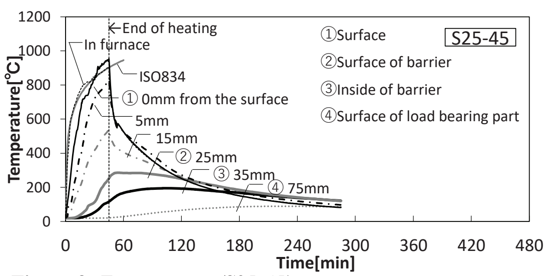


Figure 8: *Temperature (S25-45)*

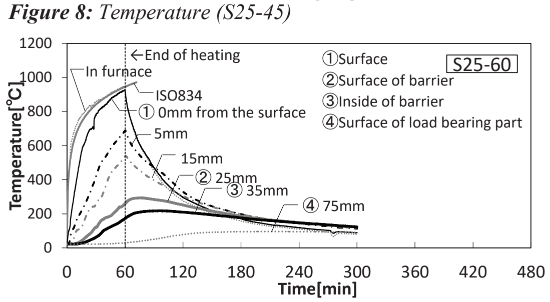


Figure 9: *Temperature (S25-60)*

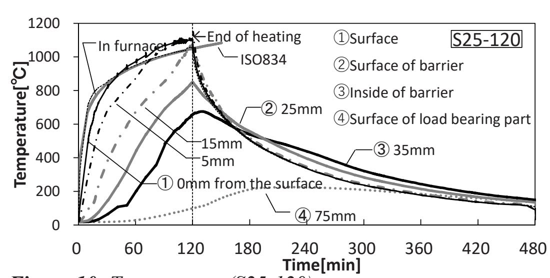


Figure 10: *Temperature (S25-120)*

Specimens were then allowed to cool in the furnace for a time longer than three times the heating time. The layout of the furnace and test specimen and the measurement items were the same as those in section 2.1. The temperature measurement points are shown in **Figure 6**.

2.2.3 Test results and discussion

Table 2 presents the cross section of each specimen, the carbonization depth, and whether glowing combustion continued at the end of the test. There was self-extinguishing for all heating times. **Figures 7** to **10** show the internal temperatures.

Table 2 reveals that carbonization progressed to the load-bearing part after heating for 2 hours. The temperature of the load-bearing part decreased with the temperature inside the furnace, and it is thus considered that the progress of combustion after heating was due not to the glowing combustion of the sacrificial layer but to the insufficient performance of the barrier layer. Additionally, the burning of the ends was due to the poor coating of the ends.

In the specimen heated for 30 minutes, the carbonization depths at the end of heating and at the end of the test were 22 and 27 mm, respectively (**Table 2**). It can be said that the sacrificial layer was generally carbonized entirely during heating and that the barrier layer was hardly carbonized and extinguished by itself after the heating. Meanwhile, because the barrier layer did not reach 100 °C at the end of heating, it is thought that if the sacrificial layer is 25 mm, the sacrificial layer will self-extinguish through heat loss from the surface, regardless of the self-extinguishing effect of the barrier layer.

In the specimen heated for 45 minutes, the sacrificial layer was completely carbonized at the end of heating, and the barrier layer reached the retarding agent decomposition temperature (195 °C) (**Figure 8**). It is thus presumed that an self-extinguishing effect of the barrier layer was exerted.

On the basis of these results, it can be said that the performance of the barrier layer determines whether the specimen can self-extinguish when exposed to fire heating for 45 minutes or longer. Therefore, the thickness of the sacrificial layer that reliably self-extinguishes regardless of the heating time is estimated to be 25 mm from the heat loss from the surface and the effect of the barrier layer.

3 EFFECT OF THE THICKNESS OF THE SACRIFICIAL LAYER ON SELF-EXTINGUISHING IN THE CASE OF A GYPSUM-BASED PROTECTION LAYER

3.1 Purpose

The results obtained in section 2 revealed that the self-extinguishing performance is affected by whether the effect of suppressing the temperature rise due to the latent heat of the barrier layer is exerted during heating.

Gypsum exposed to heat suppresses a temperature rise of the sacrificial layer through the heat of vaporization of the water of crystallization within.

In a third series of tests, with gypsum used as the barrier layer, the thickness of the sacrificial layer was prepared from 0 to 95 mm, to clarify the effect of the thickness of the sacrificial layer on the self-extinguishing performance.

3.2 Outline of tests

In the third series of tests, using a wall furnace (3 m × 3 m) at the Takenaka Co. Research & Development Institute, specimens were heated for 1 hour following the ISO834 standard heating curve and allowed to cool in the furnace for 4 hours. **Figure 11** is a schematic diagram of the furnace and the layout of the test specimen.

Eleven test specimens were prepared with the thickness of the sacrificial layer ranging from 0 to 95 mm in increments of 10 mm. Gypsum-based self-leveling material and Japanese larch were used for the barrier layer. The thickness of the barrier layer was set at 40 mm. The load bearing part and sacrificial layer were integrated, and the gypsum-to-larch length ratio of the barrier layer was set at 2:1 considering the minimum width that could bear the shear force that needs to be borne by a structural member. The measurement items were the internal temperature of the specimen and the furnace temperature. Specimens and the temperature measurement points are shown in **Figure 12**.

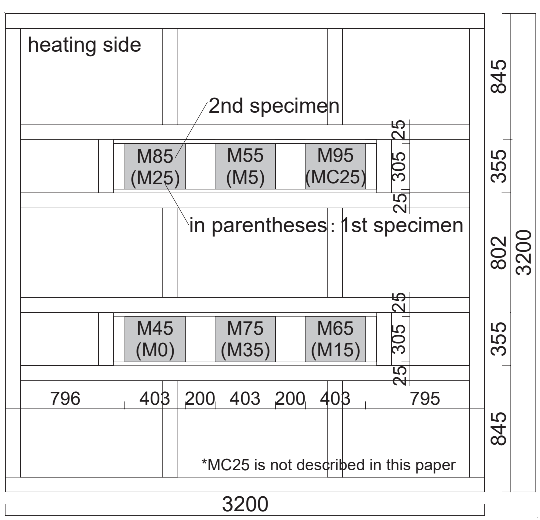


Figure 11: *Specimen layout in the third series of tests*

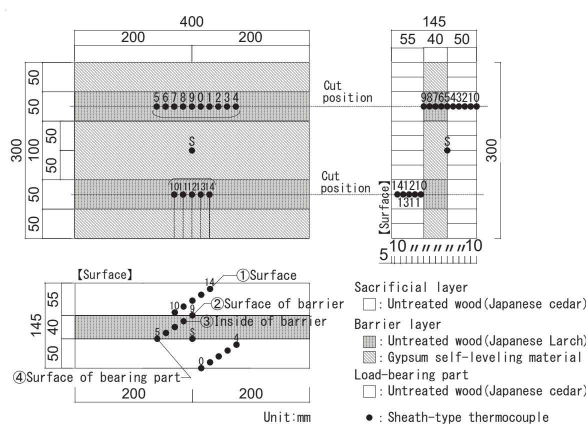


Figure 12: *Specimens in the third series of tests (M55)*

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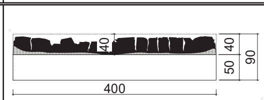
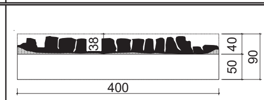
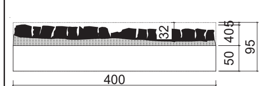
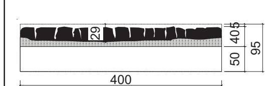
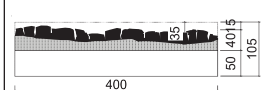
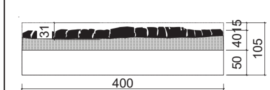
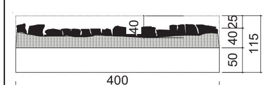
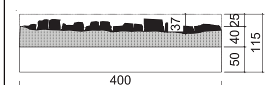
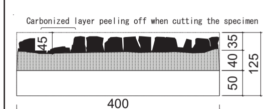
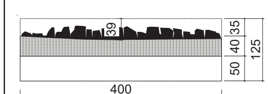
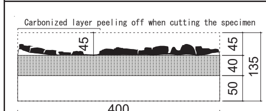
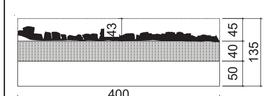
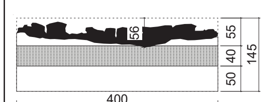
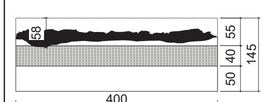
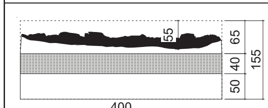
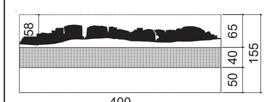
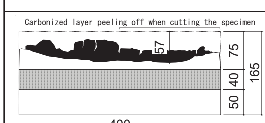
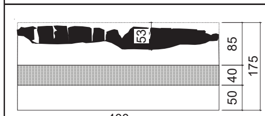
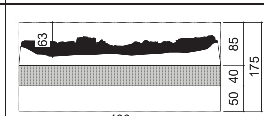
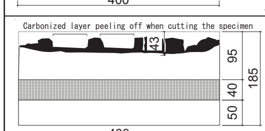
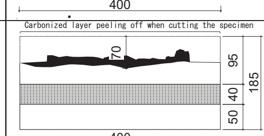
Table 3: Results of the third series of tests

	Specimen	Sacrificial layer thickness [mm]	Heating time [min]	Carbonization: upper side	Carbonization: underside	Char layer depth: Heating end*1 / Test end (upper/under)	Results*2
series(3)tests	M0	0	60			29mm / 40mm / 38mm	○ (Extinguished)
	M5	5				32mm / 32mm / 29mm	○ (Extinguished)
	M15	15				29mm / 35mm / 31mm	○ (Extinguished)
	M25	25				33mm / 40mm / 37mm	○ (Extinguished)
	M35	35				35mm / 45mm / 39mm	○ (Extinguished)
	M45	45				32mm / 45mm / 43mm	○ (Extinguished)
	M55	55				39mm / 56mm / 58mm	○ (Extinguished)
	M65	65				35mm / 55mm / 58mm	× (Continued to burn)
	M75	75				34mm / 57mm / -	× (Continued to burn)
	M75	85				36mm / 53mm / 63mm	× (Continued to burn)
	M75	95				36mm / 43mm / 70mm	× (Continued to burn)

:Untreated wood   : Gypsum self-leveling material   : Char layer

*1:Char layer depth is calculated linear interpolation of internal tempreture. Carboonization tempreture is 260℃ for untreated wood, 195℃ for fire-retardant wood.

*2: ○:Glowing combustion stopped after end of the test, ×:Glowing combustion continued after end of the test

3.3 Test results and discussion

Table 3 presents the cross section of the specimen, the carbonization depth, and whether glowing combustion continued at the end of the test. No specimen carbonized up to the load-bearing part. Self-extinguishing was confirmed when the thickness of the sacrificial layer was 55 mm or less, but with a sacrificial layer having a thickness of 65 mm or more, glowing combustion continued and the sacrificial layer did not self-extinguish. **Figure 8** shows the temperature of the barrier layer and **Figure 9** shows the temperature of the sacrificial layer for M35 to M85, which became the boundary of self-extinguishing. **Table 3** shows that the sacrificial layers of self-extinguished of M0 to M45 were uniformly carbonized. After heating, the temperature at the inside of the barrier layer (55 to 85 mm deep surface from) of M45 quickly reached 100℃ and was maintained until the end of the test (**Figure 14**). It is thus considered that the carbonization of the sacrificial layer was completed by heat conduction after the end of heating, and the continuation of combustion was suppressed by the heat of vaporization of the barrier layer.

As shown in **Figure 14**, the temperature of M55, which also extinguished itself, gradually increased to a maximum of 150 °C inside the barrier layer more than 1 hour after the end of heating.

In M55, after heating, the temperature of the inside of the sacrificial layer (15 to 35 mm in **Figure 13**) decreased as the temperature inside the furnace decreased, and then increased again to a maximum of approximately 500 °C. Furthermore, **Table 3** shows there were variations in the carbonization depth within the cross section of a specimen. It is thus considered that the temperature of the barrier layer rises owing to glowing combustion in the sacrificial layer after heating, and the heat of vaporization of the moisture present in the gypsum suppresses the continuation of combustion.

Meanwhile, in M65, which continued burning, the temperature of the barrier layer rose owing to heat conduction after heating, but the temperature of the barrier layer deeper than 95 mm from the heating surface did not reach 100 °C. Additionally, **Table 3** shows that an uncarbonized sacrificial layer with thickness of approximately 10 to 20 mm remained after the test was

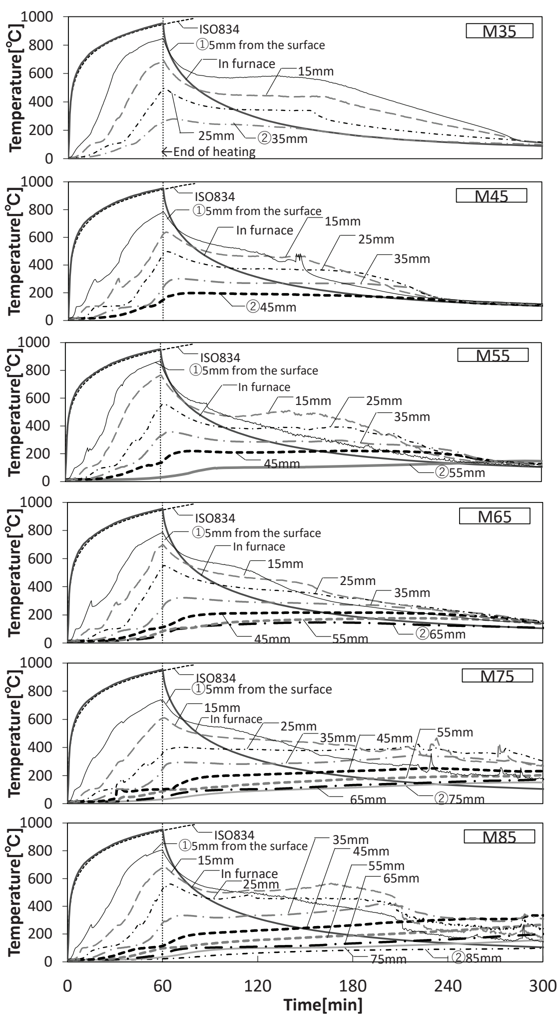


Figure 13: Temperature of the sacrificial layer (M35, M45, M55, M65, M75, M85)

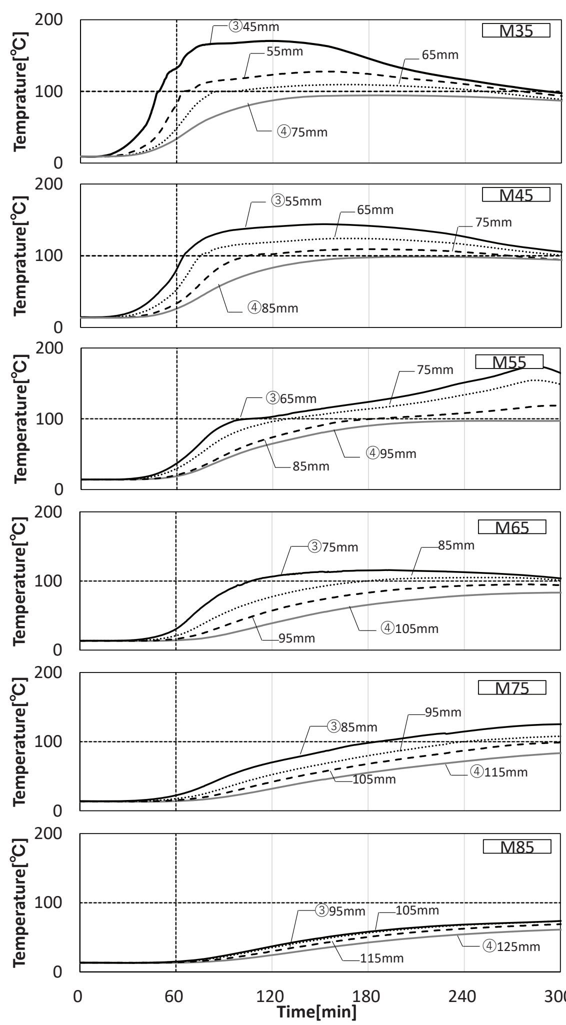


Figure 14: Temperature of the barrier layer (M35, M45, M55, M65, M75, M85)

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complete. It is thus considered that the sacrificial layer was so thick that the temperature did not rise to the vaporization temperature (100 °C) of the moisture present in the gypsum and did not self-extinguish within the test time.

4 EFFECT OF THE DIFFERENCE IN THE BARRIER LAYER TYPE ON ACHIEVING SELF-EXTINGUISHING

The results presented in sections 2 and 3 reveal that the self-extinguishing performance is determined by whether or not there is latent heat of the barrier layer during heating. In the specimens with a barrier layer made from fire-retardant plywood, the thickness of the sacrificial layer was set at 25 mm or less, and the sacrificial layer extinguished regardless of the heating time.

In the test specimens with a gypsum barrier layer, the sacrificial layer reached the vaporization temperature through refractory heating at a thickness of the sacrificial layer of 45 mm or less and the sacrificial layer extinguished by itself.

With the gypsum barrier layer, the sacrificial layer self-extinguished even if it remained uncarbonized by approximately 20 mm. The water evaporation temperature in gypsum is lower than the decomposition temperature of the fire-retardant wood, and it is thus thought that the temperature control effect appears earlier for gypsum.

Furthermore, from the relationship between the heating time and the carbonization depth in **Tables 2 and 3**, the minimum thickness of the coating layer of the sacrificial layer + the barrier layer can be found with respect to the required fire resistance time. For example, in the case that the fire resistance time is 60 minutes, when the barrier layer is wood (as in the second series of tests), the minimum thickness of the covering layer is 48 mm, whereas when the barrier layer is gypsum (as in the third series of tests), the minimum thickness of the covering layer is approximately 32 to 58 mm, which is not so different.

Therefore, if the required fire resistance time increases, it will be necessary to consider changing the thickness of the sacrificial layer according to the type of barrier layer and improving the performance of the barrier layer.

5 CONCLUSIONS

The following conclusions are drawn from the results of the study.

(1) If the heating time is shorter than the required fire resistance time, it may not be possible to ensure self-extinguishing of the sacrificial layer.
(2) The optimum thickness of the sacrificial layer is 25 mm when using fire-retardant wood as the barrier layer.
(3) The gypsum barrier layer self-extinguished even if the sacrificial layer was about 20 mm thicker compared to the fire retardant wood-based barrier layer in the case of heating for 1 hour. It is thought that the effect of suppressing the temperature rise through the latent heat of water in the gypsum appears earlier.

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