Investigation of a Large Wooden Gymnasium Fire

- Its documentation, estimation of the fire scenario by experiments and evaluation of the structural properties of surviving timber elements

Koji Kagiya
National Institute for Land and Infrastructure Management,
Ministry of Land, Infrastructure and Transport
Tachihara-1, Tsukuba, Ibaraki, 305-0802, Japan
kagiya-k92js@nilim.go.jp

Yuji Hasemi and Doggun Nam
Waseda University, Japan
hasemi@mn.waseda.ac.jp; nang@hasemi.arch.waseda.ac.jp

Akihiko Hokugo
Kobe University, Japan
hokugo@kobe-u.ac.jp

Hideaki Masuda
Building Research Institute, Japan
masuda@kenken.go.jp

Toshiro Harada, Atsushi Miyatake and Yasushi Hiramatsu
Forestry and Forest Products Research Institute, Japan
tharada@ffpri.affrc.go.jp; atsushi@ffpri.affrc.go.jp; yash@ffpri.affrc.go.jp

ABSTRACT

This is the first fire in Japan of a large wooden gymnasium with a large-scale glue-laminated timber structure which was totally burnt with a rapid flashover (FO). The fire deserves close attention for not only rapid FO in a large enclosure but also availability of extremely good documentation on the fire.

The extent of carbonization of the members that was collected when the building was dismantled and its structural property were measured. A series of burning tests of the combustibles stored in the source of the fire, conducted to clarify why the fire spread so rapidly in the gymnasium where a FO had been least anticipated and to make guidelines to prevent fire from spreading rapidly.

KEYWORDS: fire investigation, wooden construction, glue-laminated timber, large enclosure, flashover, carbonized layer

1. INTRODUCTION

A fire broke out at a gymnasium of a junior high school in Fukuyama City, Hiroshima Prefecture in October 2000 (Photo 1). It is the first blaze in Japan that has totally burned a large-scale glue-laminated timber structure.

The fire also deserves close attention in terms of fire safety engineering because a flashover (FO) rapidly occurred in the gymnasium, where such which had been considered unlikely.

Combustible materials in storage, their quantity, the source of the fire, the cause of the fire, and the layout of the flammable materials in the room where the fire started are clearly known in addition to the availability of drawings and specifications for the building that suffered from the fire.

There also remain detailed records of what happened during the time from fire detection to fire extinction. All these are valuable data for the study of how a fire spreads in a large space.

The Wooden Architecture Forum (then so called) organized an investigative team to conduct fact-finding on December 2000 and March 2001. The team members measured the extent of carbonization of the arch that was collected when the building was dismantled, its strength, and the burning characteristics of the flammable materials stored in the space where the fire originated.

PHOTO 1 Fire-damaged building in flames

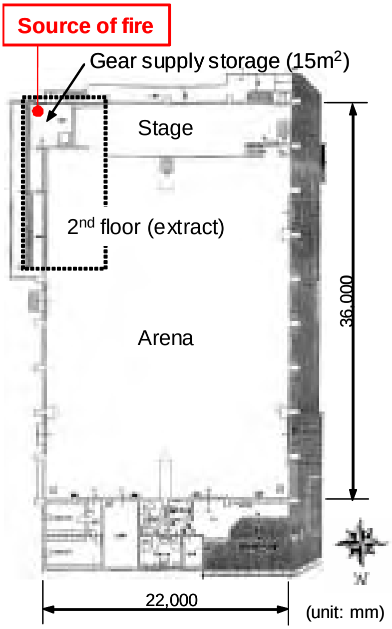

FIGURE 1 Plan of the gymnasium

TABLE 1 Major inner finishes

	Floor	Frame	Wall	Ceiling
Arena	Gypsum board (12), Wooden flooring (15) with polyurethane resin coating	Glue-laminated timber (30)	Cemented excelsior board (30), Finishing plywood (12)	Cemented excelsior board (25) with paint
Stage	Gypsum board (12), Wooden flooring (15) with polyurethane resin coating	Timber (25)	plywood (5.5), mortar on concrete surface	Cemented excelsior board (25) with paint
Gear supply storage	Mortar (30)	Glue-laminated timber (30)	plywood (5.5)	Cemented excelsior board (25) with paint

Note: Parentheses indicates thickness (unit: mm)

2. OUTLINE OF THE FIRE

2.1 Fire-Damaged Building

Completed in February 1997, the fire-damaged building is a gymnasium with its main structure made of large-scale glue-laminated timber and its interior construction consisting of wooden materials. Table 1 shows major inner finishes. The first and second floors of the building are respectively made of reinforced concrete (RC) and wood, with a total floor space of 979m^2. Wide lofts, about 15m^2, were located on both wings of the stage. Of these, the one on the southeast side was used as a gear supply storage (Figure 1) where the fire started.

2.2 Time Lapse of the Fire

Table 2 shows the time lapse from the occurrence of the fire to its extinction based on the information obtained from hearings held at the site of the fire and in the municipal office as well as from newspaper articles about the fire. Photograph 1 also shows the scene immediately after the arrival of the fire-fighting squad. From Table 2 it can be seen that the whole indoor sports arena had a FO within 9 minutes after fire detectors went off. The arch members seem to have been directly exposed to flames for 20 to 30 minutes in the vicinity of the fire source and for 12 to 20 minutes at a place far from that point in the sports arena. Although the whole building suffered from the fire, it is still self-supporting.

TABLE 2 Time lapse of the fire

Time	Event
12:30	A teacher found pupils gathering in the gear supply storage and picked up several cigarette ends from the gap between a urethane mattress and tatami mats. (Newspaper article)
12:49	Though teachers who noticed fire outbreak by fire alarm, tried to suppress the fire, the fire already had reached the ceiling and too large for them to extinguish. (Newspaper article)
12:51	The windows broke and the flame was ejected from the stage side to opposite side of the gymnasium one after another in not so long time. (Newspaper article)
12:58	Fire brigade arrived and began to hose. (Fire department) The whole gymnasium went up in flames. (Fire department)
13:10	Fire was suppressed. (Fire department)

3. INVESTIGATION OF THE MEMBERS

3.1 Depth of Carbonized Layers

Samples of the arch members were collected when the fire-damaged building was pulled down and then transported to the Forestry and Forest Product Research Institute for investigation.

Figure 2 shows the position of the collected members. Because of restriction on the period of the dismantling and

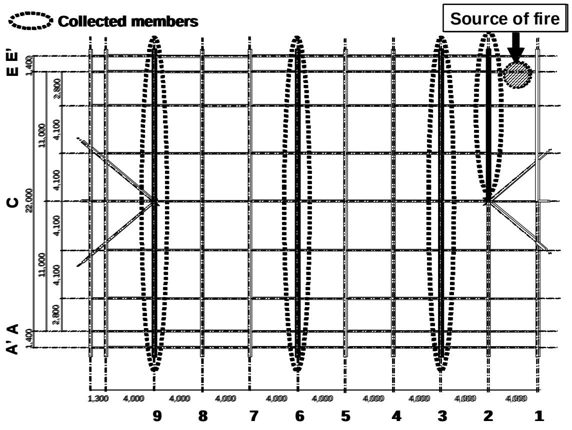

FIGURE 2 Position of the collected members

maximum carrying capacity of the truck for transport, 4 parts of members were collected for estimating of the fire spread from the source of fire to whole building.

Figure 3 illustrates the depth of the carbonized layers. The nearer the carbonized layers to the source of the fire or the higher their location except where the gear supply store is located, the deeper they become. That corresponds to testimony of the eyewitness that the windows broke and the flame was ejected from the stage side to opposite one of the gymnasium.

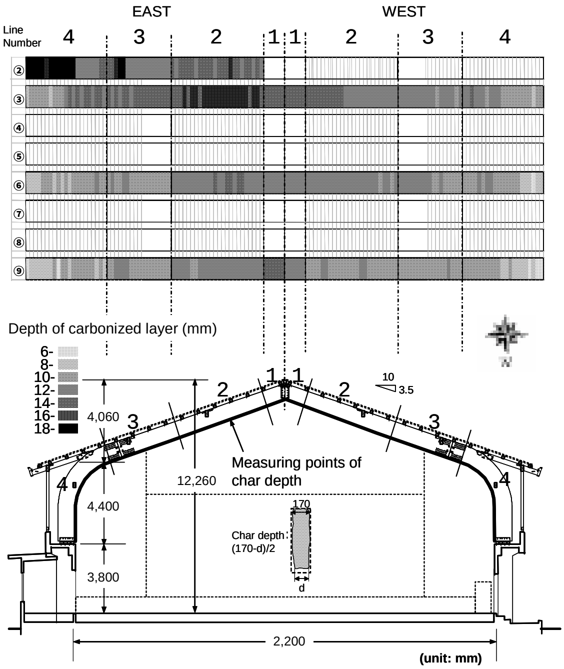

FIGURE 3 Depth of carbonized layer

The carbonization speed of 0.6 mm per minute for glue-laminated timber is normally used based on fireproof heating tests [1]. However, the depth of the carbonized layers almost corresponds to the value obtained by multiplying this carbonization speed by the estimated duration of fire in the vicinity of the fire source and in the gymnasium.

3.2 Structural Property

Structural property tests were conducted to find out how the actual fire will affect the adhesiveness, strength and fire resistance of glue-laminated timber. The tests are bending test, loading and fire resistance tests, test for the deterioration of gluing acceleration, block shear test and material tests of laminas (Figure 4).

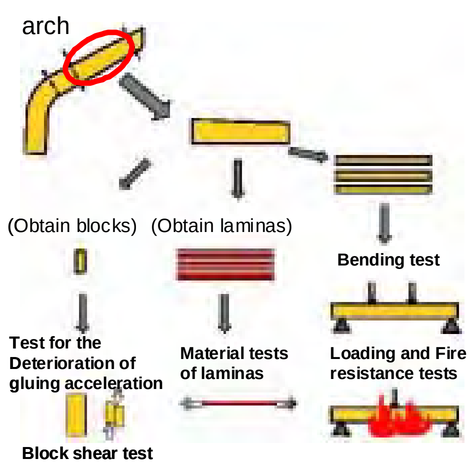

FIGURE 4 Outline of structural property tests

Table 3 summarizes the results of the structural property tests of the members: although the whole building suffered from the fire, members were still self-supporting and the deterioration of their strength was not found and there are no differences between the damaged and normal timber in these characteristics. Especially, in loading and fire resistance tests, all specimens were found to be fire resistant for more than 45 minutes.

It also became clear that the fire-damaged, glue-laminated timber stayed almost as fire resistant as the normal timber and the carbonization speed of the fire-damaged, glue-laminated timber was measured to 0.56 - 0.65 mm per minute in the width direction and 0.55 - 0.71 mm per minute in the beam height direction, which indicates that there are no differences between the fire-damaged and normal timber in the carbonization speed.

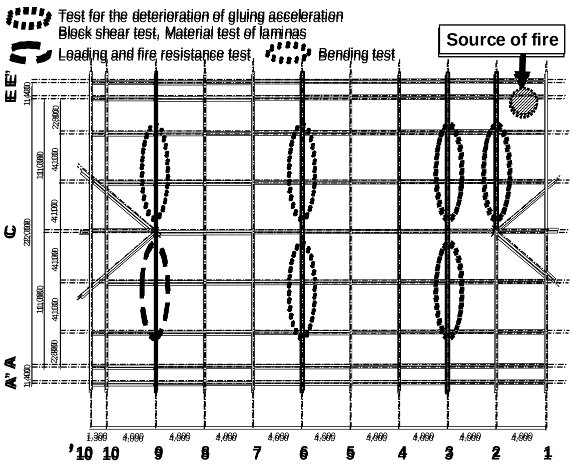

FIGURE 5 Position of the tested members

TABLE 3 Summary of the structural property tests results

Test	Test method	Result
1. Deterioration of gluing acceleration	Boiling and Peeling tests, and decompression, pressurization and peeling tests as specified by JAS*	Some of the specimens were found to be below standard. However, it may be concluded that the adhesiveness of the glue laminated timber does not deteriorate due to exposure to the fire.
2. Block shear test	2 rows on both sides of a member exposed directly to the fire and 2 rows inside of the member were tested in accordance with JAS*	
3. Bending test for glue-laminated timber	A member was divided into three specimens and loaded: loading points as specified by JAS*	Even the performance of the specimens mainly comprising the outer layers did not significantly deteriorate.
4. Loading and fire resistance tests of glue-laminated timber	A member was divided into three specimens and heated according to the heating curve specified by ISO834, while 1/3 of the load required by the JAS*	All specimens were found to be fire resistant for more than 45 minutes. No differences between the damaged and normal timber in the carbonization speed.
5. Material test of laminas	Specimens were cut out along the glued layers and their volume density and elastic coefficient, tensile strength were measured	(In progress)

Note: JAS: Japan Agricultural Standard

4. ESTIMATION OF THE MECHANISM TO FLASHOVER

4.1 Source of the Fire

The fire began is the southeast corner of the gear supply storage on the east side of the second floor. There were 15 athletic tatami mats and one urethane mattress (3 m x 2 m x 0.3 m) in the gear supply storage when the fire broke out. The urethane mattress was rested against the wall. From the testimony of those concerned, it seems that this mattress caught fire (Figure 6).

The storage where the fire started was open to the stage side, but it was surrounded by the plywood wall on the remaining 3 sides. The ceiling of the store was enclosed by a cemented excelsior board and its floor was made of reinforced concrete (RC).

The proscenium arch between the stage side, including the gear supply storage, and the indoor sports arena has plywood finish on the stage side of 2 by 4 studs (5.5 mm thick) and cemented excelsior board finish with vertical grids of glue-laminated timber on the sports arena side.

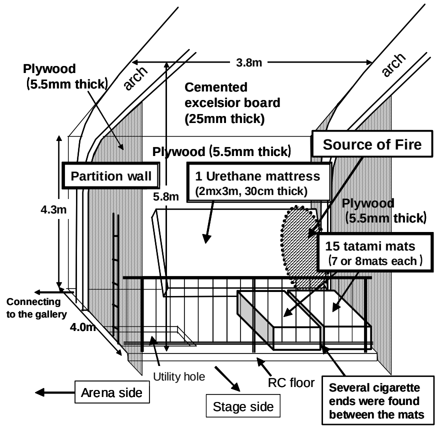

FIGURE 6 Source of fire and its surroundings

4.2 Burn test for Estimation

TABLE 4 Burn test condition

Test number	Specimen	Size (cm)	Propane supply		note
			Quantity (l/min)	time (sec)	
Test 1*	Urethane mattress	100x50x30 (1/12 of full size)	13	80	urethane foam covered with cotton skin
Test 2*		100x100x30 (1/6 of full size)	12	90	
Test 3		100x100x30 (1/6 of full size)	12	90	
Test 4*	Athletic Tatami mat	91x181x6	13	80	plywood with cushion both side and vinyl chloride skin
Test 5*	Partition wall	182x182x25.5	13	80	
Test 6		182x182x25.5	25	Until burn out	

Note: *California State Bulletin 133, Furniture Burning Test's burner was used for the test.

Outline of Test

A series of burning tests conducted to clarify why the fire spread so rapidly in the gymnasium where a FO had been least anticipated.

Specimens of the flammable materials in the gear supply storage were placed under the smoke-collecting hood and gases (CO_2, O_2, and CO) coming from the hood through the exhaust duct were analyzed and the heat release rates were calculated. The flame shapes of the flammable materials in storage were also recorded using a still camera and video camera. Table 4 shows burn test condition.

PHOTO 2 Urethane mattress

Urethane mattress

The same urethane mattress as those in the fire-damaged building was used for the tests. Because of its large size 3 m x 2 m x 0.3 m, the mattress was likely to heat up beyond the capacity of the measuring instrument even if burned totally. Therefore, it was cut to 1/12 of the actual size and burned right under the hood. At Test 1, a mouth-shaped, perforated pipe burner [2] was installed 3 cm above the center of the

PHOTO 3 Athletic tatami mat

specimen that was placed horizontally (Photo 2). Two further tests were made considering the location of a urethane mat of 1/6 size used for the experiment. At Test 2, the mouth-shaped, perforated pipe burner was installed at the same position as at Test 1, with the specimen horizontally placed on the floor. At Test 3, a T-shaped, perforated burner was installed at a position 5 cm away from the lower end, with the specimen resting against the nonflammable wall.

Athletic tatami mat

One of the same tatami mats as those in the gymnasium was used and the mouth-shaped, perforated pipe burner was installed 3 cm above the center of the tatami mat placed horizontally (Photo 3).

Partition wall

A partition wall between the gear store and the arena, which also comprises part of the proscenium, was reproduced according to its drawing and specification. As shown in Figure 7, the partition wall has 5 mm-thick plywood on the front of the gear supply storage side, and on the back of it are 2 x 4 studs at 45 cm intervals. The surface of the arena side has a cemented excelsior board with glue-laminated timber finish vertically pasted at 10 cm intervals.

The test was performed with a nonflammable block placed on the bottom of the wall and the gaps were filled with a fireproof bond to prevent leaking of air into the hollow section. The wooden wall close to the source of the fire in the fire-damaged building was 5.8 m high and its upper part was closed. At the burning test, however, the height of the wall was set at 1.82 m due to the limited height of the testing device and the upper part of the wall was left open because it was not possible to prevent the spread of flames after their passing through the hollow section.

One-piece wall specimen measuring 1.82 m x 1.82 m was produced and subjected to 2 burning tests under different testing conditions. At Test 5, the T-shaped, perforated pipe burner was installed at a height of 5 cm from the lower end of the wall. But the combustion did not spread beyond the studs and therefore Test 6 was made by reusing the intact specimen and installing a 15 cm-square diffusion burner just in front of a row of the neighboring studs and at a height of 5 cm from the lower end of the wall.

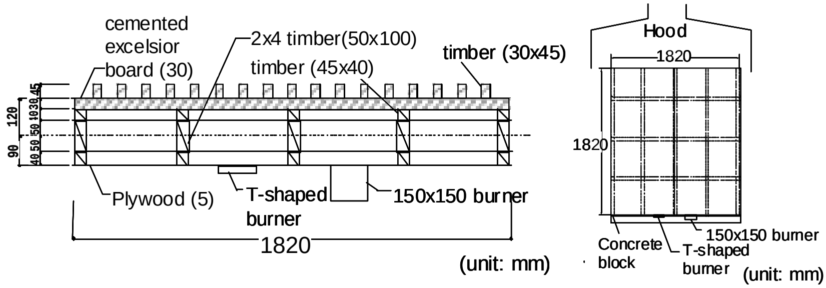

FIGURE 7 Section of the partition wall specimen and experimental setup

4.3 Test Results

Urethane mattress

Test 1: As the specimen heated, it flared up and black smoke developed. Two minutes thereafter the top of the flame reached 2.3 m high. The burning area spread rapidly from the fire source and spread in all directions, almost completely burning the specimen 6 minutes thereafter.

From Figure 8 it is clear that the heat release rate in close proximity to the fire source sharply rose to its peak 2 minutes after the start of the testing, resulting in rapid burnout.

Test 2 and Test 3: Figure 9 and Figure 10 respectively show the heat release rate and the total heat release (THR) at Test 2 where the urethane mattress was horizontally placed and at Test 3 where it rested against the wall.

As at Test 1, the specimen flared up into flames in 2 or 3 minutes, but it is obvious that the peak heat release rate was greater than at Test 1. However, the heat release rate was greater and the spread of the flames faster at Test 3 than at Test 2.

As far as the surface of the flammable materials is concerned, the difference is considered due to the faster spread of the flames on the wall surface than on the upward plane surface, as well as being responsible for the mechanism of the flames.

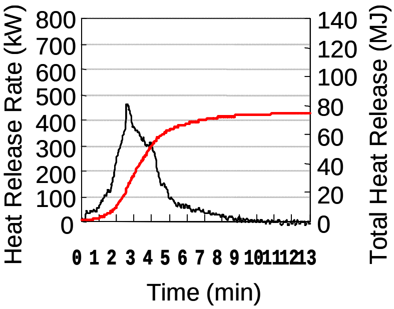

FIGURE 8 Test 1 - Urethane mattress (1/12 of the actual size)

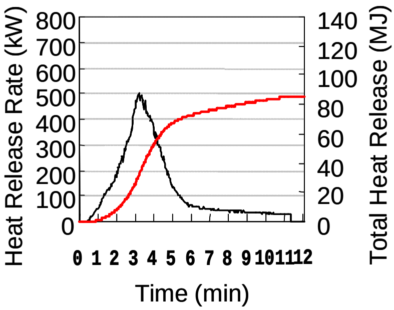

FIGURE 9 Test 2 - Urethane mattress (1/6 of the actual size, horizontally placed)

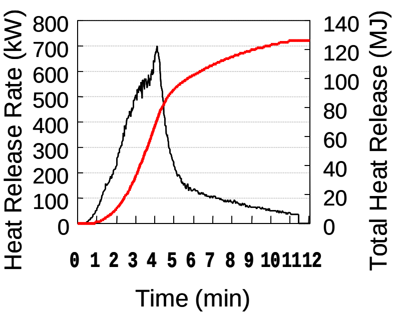

FIGURE 10 Test 3 - Urethane mattress (1/6 of the actual size, rested against a nonflammable wall)

Athletic tatami mat

Test 4: When burning and heating began, the height of flames was 0.3 m - a phenomenon not particularly unusual. The flames spread from the surface to the inner part horizontally over a long period. From Figure 11, it is clear that the heat release rate remained at a low value for 15 minutes after the specimen caught fire.

Partition wall

Test 5: The wall surface started burning first when an ignition burner was brought into contact with the wall. But again there was no fierce flare-up. When heating was discontinued at 80 seconds thereafter, the flames died down in approximately 40 seconds. When the specimen was reignited 3 minutes, 40 seconds thereafter, the flames spread to the upper end of the surface of the specimen in 1 minute.

After the surface burned out 6 minutes thereafter, the hollow section between studs that was in contact with the burner started burning out and the flames continued fiercely. Once the surface of the wall burned out, the flame quickly spread to the upper end of the wall. Heating was discontinued 6 minutes, 30 seconds after re-heating, and the specimen continued burning until it finally died down at 10 minutes, 30 seconds thereafter.

After the tests, the inner part of the wall was checked and it was found that the flames had not spread beyond the studs, with the cemented excelsior board on the reverse side not suffering from serious damage. This phenomenon is reflected in the history of the heat release rate shown in Figure 12.

Test 6**:** A burnout occurred about 5 minutes after the wall caught fire, resulting in fierce flames. Smoke developed from the cemented board 21 minutes after heating. The burner was turned off 33 minutes, 30 seconds after heating and the inside of the wall was checked.

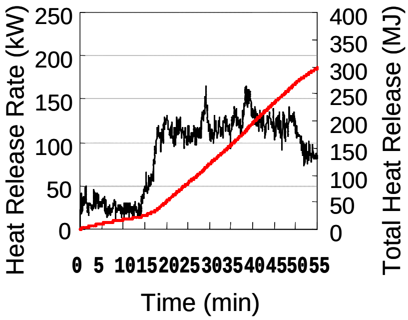

FIGURE 11 Test 4 –Athletic tatami mat

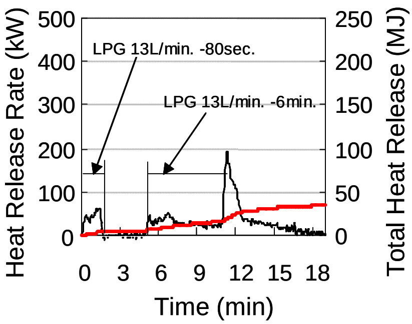

FIGURE 12 Test 5 – partition wall

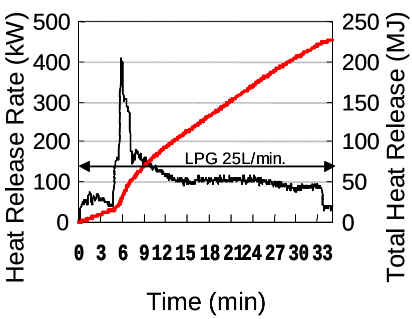

FIGURE 13 Test 6 – partition wall

There was no evidence of the spread of the flames to the studs, but the cemented excelsior board was slightly burned out. Figure 13 shows that the heat release rate climbed sharply to 420 kW 5 minutes after ignition and then declined gradually.

From these test results it is apparent that although it takes some time for the laminated wall to burn out after its ignition, the flames spread rapidly after the burnout. The time required for the burnout to take place will be reduced if the gas flow at the source of ignition is increased, but the flames under the above 2 conditions did not spread to and beyond the studs.

4.4 Estimation of the Mechanism to Flashover

Heat balance of smoke layer

Based on the above findings, an examination will be made as to how the fire spread. However, there exist no data concerning the temperature, heat flux and other factors, although a good record is kept of how the fire developed. Another downside is that specimens of real size and in real quantity were not used for the burning tests because of the constraints on the scale of the experiments and the facilities. However, the test results found that flammability differs significantly among combustible materials.

The cause of the FO will be estimated by comparing the extent of the heat release rate, simply in terms of the real-size specimen, with the extent of the THR of the initial fire required to cause the FO in the whole gymnasium. In consideration of the heat loss resulting from the smoke layer, the heat balance of the smoke layer may be represented by the following equation (1). Heat loss rate (Q_L) is the sum of radiative and convective heat loss and heat loss carried away by ejected flames, however, surface heat transfer rate is unknown and the breakage of windowpanes was immediately before the FO. Therefore, to estimate the heat release required for FO at least, only the radiative heat loss was calculated with $Q_L = rQ$, $r = 0.3$.

$$V_S \Delta T \rho_S C_p = \int_0^t (Q - Q_L) dt = (1-r)\int_0^t Q dt = (1-r)G \quad (1)$$

where G is THR to time t [kJ], Q is heat release rate [kW], Q_L is heat loss rate [kW], V_S is volume of the smoke layer [m^3], ΔT is temperature rise of the smoke layer [K], r is radiative heat loss rate (0.3), ρ_S is density of smoke [kg/m^3] ($\rho_S = 353/T$), C_p is specific heat of the air (=1.0kJ/kgK).

The temperature of smoke layers is generally assumed to be 600 ^oC when a FO occurs in a room, but ΔT in equation (1) is set at a room temperature of 20 ^oC and hence ΔT equals 580 K. Assuming that the windows of the gymnasium will not break until a FO occurs, the height of the smoke layers is set at 3.83 m - higher than the middle of the windows - based on the photograph of the fire (Photo 1).

Although the roof of the gymnasium is triangular, for the convenience of calculation it was converted into a rectangular roof with the height of the triangle halved (Figure 14). To calculate

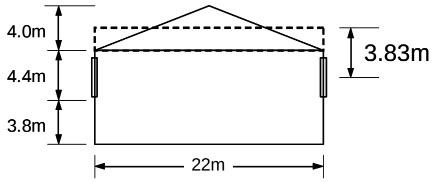

FIGURE 14 Modeling of the height of the smoke layer in the gymnasium

equation (1) from the foregoing $\boldsymbol{G_f}$, a THR that causes a FO in the gymnasium will be 1.3 x 10^3 MJ. Therefore, it may be considered that a FO will not occur unless the integrated THR of flammable materials exceeds this level. In the fire, it took 9 minutes for the FO to occur after the fire detectors went off.

Assuming that the fire detector activates in the initial stage of flaming, a heat release of the specimen accumulated for 9 minutes was used as a standard. At Test 1, a specimen whose size is 1/12 of the real urethane mattress was used and therefore the THR of 1 urethane mattress was estimated by multiplying the THR of the specimen by 12. The THR of the athletic tatami mat was estimated by multiplying the THR of 1 tatami mat by 15 because a total of 15 tatami mats were in the gear supply storage where the fire originated (Figure 6).

In the case of Tests 5 and 6 for the partition wall, the test results represent the THR of 1 plot (45 cm) between studs and therefore the THR of the wooden partition wall (12 m long and 5 m high on average) in the vicinity of the fire source was individually converted to obtain estimated THR. Table 5 shows comparison between $\boldsymbol{G_f}$ that will possibly cause a FO in the gymnasium as calculated from equation (1), and the measured THR of the urethane mattress, athletic tatami mat and partition wall, as well as the estimated THR in terms of real size specimens.

TABLE 5 Comparison between test results

Test Number	Specimen	Total Heat Release in **9 minutes** (MJ)		Gf (MJ)
		Test result	Real size (estimated by volume, area)	
Test 1	Urethane mattress	74	**888**	**1.3x10^3 (=1300)**
Test 2		82	**492**	
Test 3		120	**720**	
Test 4	Athletic tatami mat	17	**255**	
Test 5*	Partition Wall	30	**2430**	
Test 6		70	**5670**	

Note: *start time: re-ignition time

The urethane mattress was quick to catch fire and flame up, with the resultant high THR. Though the estimated THR of 1 urethane mattress differed with each test, it proved to be far smaller than $\boldsymbol{G_f}$ in either case. Therefore, it is highly unlikely that 1 urethane mattress would go up in flames, causing a FO in the gymnasium.

The athletic tatami mat continued burning at a steady heat release rate over a long time, but its THR is small. Even the estimated THR of 15 tatami mats falls far short of $\boldsymbol{G_f}$. If they burn along with the urethane mattress, the THR does not reach $\boldsymbol{G_f}$.

The surface area of the partition wall takes some time before it catches fire and burns out, but the flames expand suddenly after the burnout. It is clear that the estimated THR, when the whole surface area burned, exceeds $\boldsymbol{G_f}$. However, the flames do not easily spread horizontally in the hollow section and therefore the whole area is unlikely to flare up unless subjected to a large flame.

Estimation results

To summarize the above, the direct cause of the FO in terms of the 9 minute-THR is considered attributable to the fact the urethane mattress took acted as a flame-spreading catalyst that caused the wooden partition wall to catch fire over a wide area as it was quick to catch fire and burst into flames, burning the wooden wall in the vicinity of the fire source and quickly producing a large heat release.

The fire is considered to have caused the FO through the following processes: A burning cigarette butt (see Table 2) set fire to the urethane mattress, which flared up rapidly and the flames spread to the nearby wooden wall. The flames of the urethane mattress caused the surface of the nearby wooden wall to flare up over a wide area within 4 to 5 minutes, spreading to the stage curtain and other flammable materials. These combustibles in storage formed a hot gas layer on the ceiling of the gymnasium, causing the FO within 6 to 9 minutes. All this briefly accounts for what happened after the fire detector had been activated, as was covered by Table 2.

5. CONCLUDING REMARKS

There are many gymnasiums of similar construction across the country. It is extremely important to take fire prevention measures against the recurrence of similar fire accidents since the construction demand is expected to continue. For example, the following fire fighting measures will be effective:

1) To fire proof the finish of the partition wall for the gear supply store
2) To control flammable materials near the stage
3) To install sprinklers near the stage
4) To fireproof urethane mattress

In this fire, the whole wooden building suffered from the fire, however, structural members were still self-supporting and the deterioration of their strength was not found.

The carbonization speed of 0.6 mm/min. for glue-laminated timber for normal use corresponds to this fire.

ACKNOWKEDGEMENT

The authors thank to Fukuyama City Municipal office. Especially, the Education Committee and the Fire Department of Fukuyama City offered valuable information of the fire. This investigation and burn tests were supported by the Accident and Disaster Information Center and the Glue-laminated Timber Industry Association of Japan.

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