Ignition Behavior of Firebrands Landed on Roofs with Roof-tile Deficit after an Earthquake

Hideki Yoshioka[1], Yoshihiko Hayashi[2], Yoshifumi Ohmiya[3], and Takafumi Noguchi[1]

[1]The University of Tokyo, Japan
[2]Building Research Institute, Japan
[3]Tokyo University of Science, Japan

Abstract

Multiple fires may break out simultaneously with or immediately after a large earthquake. They may result in a large urban fire. In particular, many firebrands may occur under strong wind conditions and disperse to distant places, thereby engendering spreading damage by leaping flames. Past records of large fires indicate that roofs are most likely to suffer damage from leaping flames. The probable reason is that roof tiles fall off and wood portions that constitute a roof are exposed just after a large earthquake. Therefore, this study made an aerial photography analysis on roof tile falling after the Kobe earthquake, and also conducted Fire Wind Tunnel experiments to investigate leaping flame damage on roofs with roof tile deficit.

1. Introduction

Today the number of houses subjected to structural damage is predictable in a certain area according to structural type and the extent of structural damage based on epicenter information such as the place, hypocentral depth, and magnitude. This study develops this estimation further: it is intended to realize prediction of the number of houses subjected to roof tile damage according to the extent of structural damage and roof tile damage. The outcome of this study will be applicable for determining the roof tile deficit situation as an initial condition for a future simulation model of leaping fire spread caused by firebrands using Computational Fluid Dynamics (CFD).

With regard to Fire Wind Tunnel experiments, the ignited crib was placed on the upper face of the test roof as a fire seed. And combustion behavior of both a crib and a test roof was observed. Experimental parameters were wind velocity and the damage extent of roof tiles.

2. Aerial photography analysis on roof-tile falling after the Kobe earthquake

2.1 Analysis Outline

Corresponding Author- Tel.: +81-298-79-0720;
Fax: +81-295-64-6775
E-mail address: yoshioka@kenken.go.jp

2.1.1 Analysis method

Six survey areas are selected as shown in Figure 1. They include three zones each in Nada-ku and Higashinada-ku, Kobe-shi, Hyogo prefecture (about 63 km^2) that were subjected to heavy and light structural damage. That area experienced particularly severe damage during the Kobe earthquake in January, 1995. Areas 1, 3, and 4 suffered minor structural damage, while areas 2, 5, and 6 suffered severe structural damage.

The relationship between the extents of roof tile deficit and structural damage was studied about the same building in the survey areas. The extent of roof tile deficit was determined visually for each building based on aerial photography (Photo 1) taken from the sky after the earthquake. The extent of structural damage was determined according to structural damage survey results for each house[Note1)] conducted by the Building Research Institute on site soon after the earthquake [1, 2]. Note that this analysis addresses only wooden houses with tiled roofs. The number of such houses are 302, 191, and 130 in areas 1, 3, and 4, respectively, and 336, 156, and 315 in areas 2, 5, and 6, respectively. These houses constitute a large portion of all buildings in every area.

2.1.2 Classifying the extent of roof tile deficit

The extent of roof tile deficit is classified into the following six classes: "No damage", "Less than half tiles missing", "Not all, but more than half of tiles missing", "All tiles lost", "Roof collapse", and "Covered by blue sheet." "All tiles lost" means that all tiles have fallen and are lost, but that the roof remains; it refers to the condition that roof boards and asphalt roofing are exposed. "Roof collapse" indicates a condition in which the roof itself has collapsed. "Covered by blue sheet" is the condition in which the roof is covered by a blue sheet; therefore, it is assumed that the roof is damaged considerably.

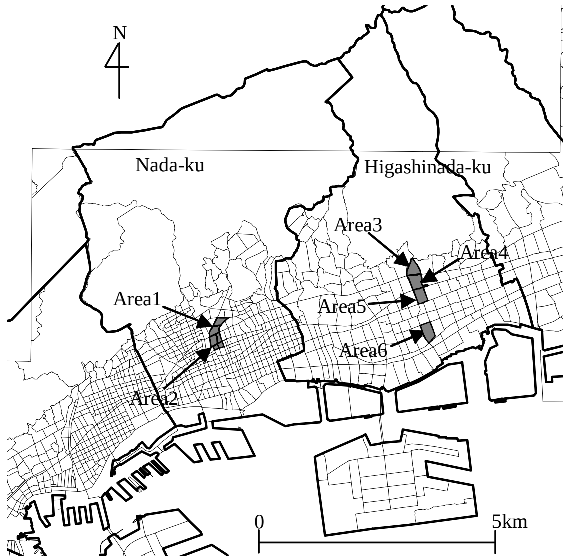

Figure 1. Survey area.

Photo 1. Portion of aerial photography (area 1 is shown as framed).

2.2 Analysis Results

2.2.1 General trend

The relationship between the extent of structural damage and roof tile deficit of a wooden house differs greatly in areas with little and severe structural damage (Figs. 2.1 and 3.1). Nevertheless, there is little difference in the extent of roof tile deficit in every structural damage class (Figs. 2.2 and 3.2). Cases of "Complete collapse or serious damage" are extremely few in areas with little structural damage (Fig. 2.1), while cases of "No apparent damage" are few in areas where structural damage is severe (Fig. 3.1). It is noteworthy that there is little difference in the extent of roof tile deficit in each class in both areas (Fig. 2.2, 3.2). Hereinafter, each rate of roof tile deficit is presented as a suggested value according to the extent of structural damage of a wooden structure.

2.2.2 Case: "No apparent damage"

The results in areas with little and severe structural damage (Tables 1 and 2, Figs. 2.2 and 3.2) show little significant difference, such as 27.0% and 41.3% for "Less than half tiles missing", 6.9% and 8.8% for "Not all, but more than half of tiles missing", and 1.4% and 1.3% for "All tiles lost", respectively. The results of all areas (Table 3, Fig. 4.2) indicate 29.3%, 7.2%, and 1.4% for "Less than half tiles missing" "Not all, but more than half of tiles missing", and "All tiles lost", respectively.

2.2.3 Case: "Slight damage"

Results in areas with little and severe structural damage (Tables 1 and 2, Figs. 2.2 and 3.2) show little significant difference, such as 36.2% and 43.1% for "Less than half tiles missing", 16.9% and 19.9% for "Not all, but more than half of tiles missing", and 13.1% and 9.9% for "All tiles lost", respectively. Results of all areas (Table 3, Fig. 4.2) indicate results of 40.2%, 18.6%, and 11.3% for "Less than half tiles missing" "Not all, but more than half of tiles missing", and "All tiles lost", respectively.

2.2.4 Case: "Medium damage"

Results for areas with little and severe structural damage (Tables 1 and 2, Figs. 2.2 and 3.2) show little significant difference, such as 28.6% and 52.1% for "Less than half tiles missing", 33.3% and 22.9% for "Not all, but more than half of tiles missing", and 16.7% and 16.0% for "All tiles lost", respectively. Results of all areas (Table 3, Fig. 4.2) indicate 47.3%, 24.8%, and 16.1% for "Less than half tiles missing" "Not all, but more than half of tiles missing", and "All tiles lost", respectively.

2.3 Summary of Aerial photography analysis on roof-tile falling after the Kobe earthquake

1. The situation of roof tile deficit after the Kobe earthquake was determined for every house using aerial photography, which was verified with results of a structural damage survey conducted on-site after the earthquake. Then, the roof tile deficit rate was estimated according to the extent of structural damage of wooden houses.

2. If the number of wooden houses subjected to structural damage becomes available, the suggested values in this study will indicate the number of houses having potential risk of leaping fire spread by firebrands .

3. The outcome of this study will be applicable for determining roof tile deficit as the initial conditions for a simulation model on leaping fire spread caused by firebrands in the future.

Table 1: Analysis results for less damaged areas (Areas 1, 3, 4) (number of houses).

Roof \ Structure	No apparent damage	Slight damage	Medium damage	Complete collapse or serious damage
No damage	273(64.7%)	40(30.8%)	7(16.7%)	4(14.8%)
Less than half tiles missing	114(27.0)	47(36.2)	12(28.6)	10(37.0)
Not all, but more than half tiles missing	29(6.9)	22(16.9)	14(33.3)	7(25.9)
All tiles lost	6(1.4)	17(13.1)	7(16.7)	4(14.8)
Roof collapse	0(0)	1(0.8)	2(4.8)	2(7.4)
Covered by blue sheet	0(0)	3(2.3)	0(0)	0(0)
Total	422(100)	130(100)	42(100)	27(100)

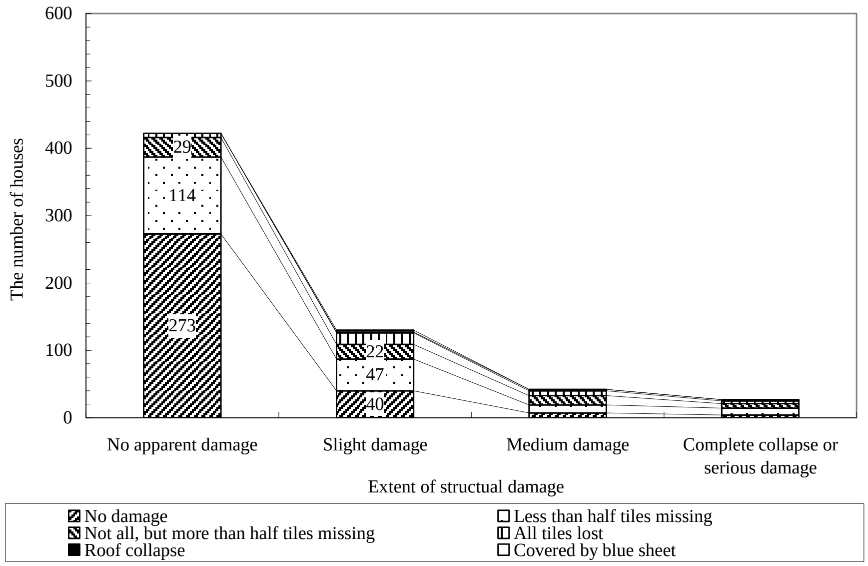

Figure 2.1: Roof tile deficit according to the extent of structural damage (the number of houses) (for less damaged areas (Areas 1, 3, 4)).

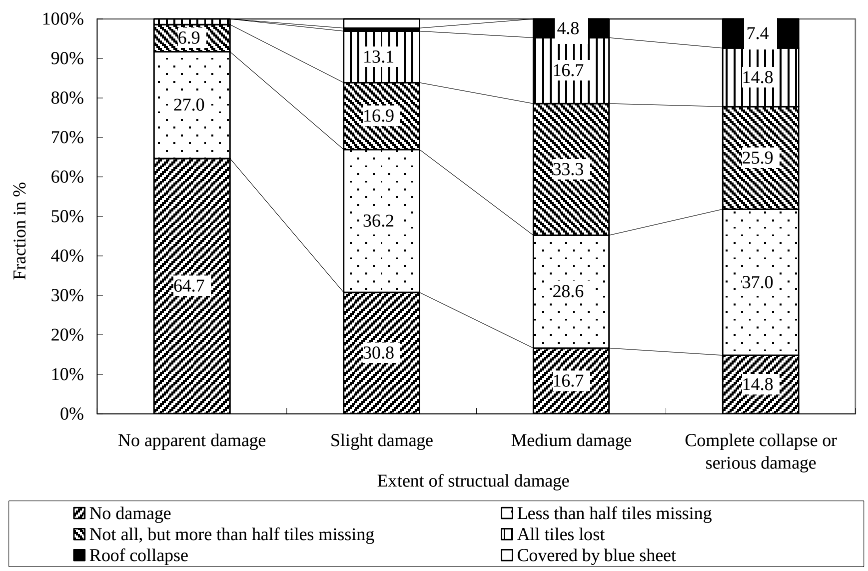

Figure 2.2: Roof tile deficit according to the extent of structural damage (fraction in %) (for less damaged areas (Areas 1, 3, 4)).

Table 2: Analysis results for severely damaged areas (Areas 2, 5, 6) (number of houses).

Roof \ Structure	No apparent damage	Slight damage	Medium damage	Complete collapase or serious damage
No damage	39(48.8%)	45(24.9%)	12(6.4%)	29(8.1%)
Less than half tiles missing	33(41.3)	78(43.1)	98(52.1)	96(27.0)
Not all, but more than half tiles missing	7(8.8)	36(19.9)	43(22.9)	92(25.8)
All tiles lost	1(1.3)	18(9.9)	30(16.0)	71(19.9)
Roof collapse	0(0)	4(2.2)	5(2.7)	68(19.1)
Covered by blue sheet	0(0)	0(0)	0(0)	0(0)
Total	80(100)	181(100)	188(100)	356(100)

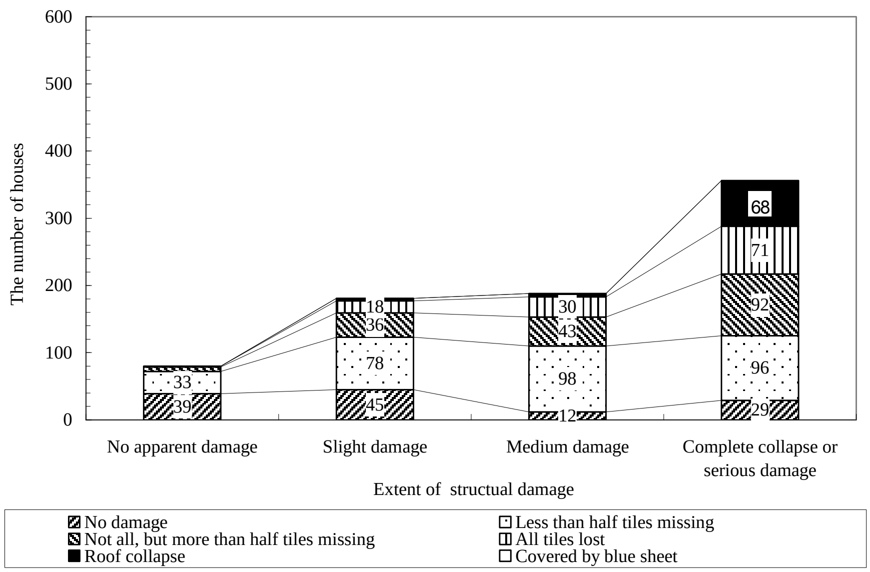

Figure 3.1: Roof tile deficit according to the extent of structural damage (the number of houses) (for severely damaged areas (Areas 2, 5, 6)).

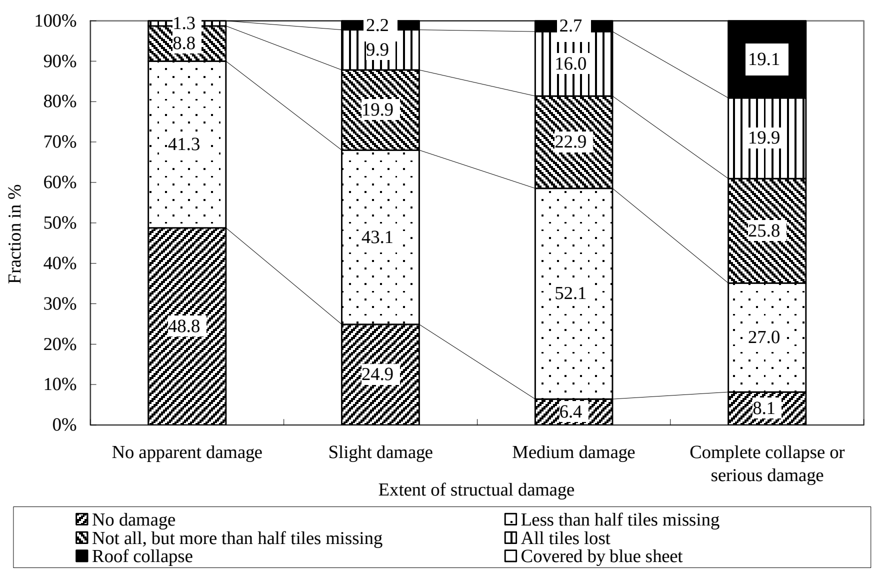

Figure 3.2: Roof tile deficit according to the extent of structural damage (fraction in %) (for severely damaged areas (Areas 2, 5, 6)).

Table 3: Overall analysis results (Areas 1-6) (number of houses).

Roof \ Structure	No apparent damage	Slight damage	Medium damage	Complete collapase or serious damage
No damage	312(62.2%)	85(27.3%)	19(8.3%)	33(8.6%)
Less than half tiles missing	147(29.3)	125(40.2)	110(47.8)	106(27.7)
Not all, but more than half tiles missing	36(7.2)	58(18.6)	57(24.8)	99(25.8)
All tiles lost	7(1.4)	35(11.3)	37(16.1)	75(19.6)
Roof collapse	0(0)	5(1.6)	7(3.0)	70(18.3)
Covered by blue sheet	0(0)	3(1.0)	0(0)	0(0)
Total	502(100)	311(100)	230(100)	383(100)

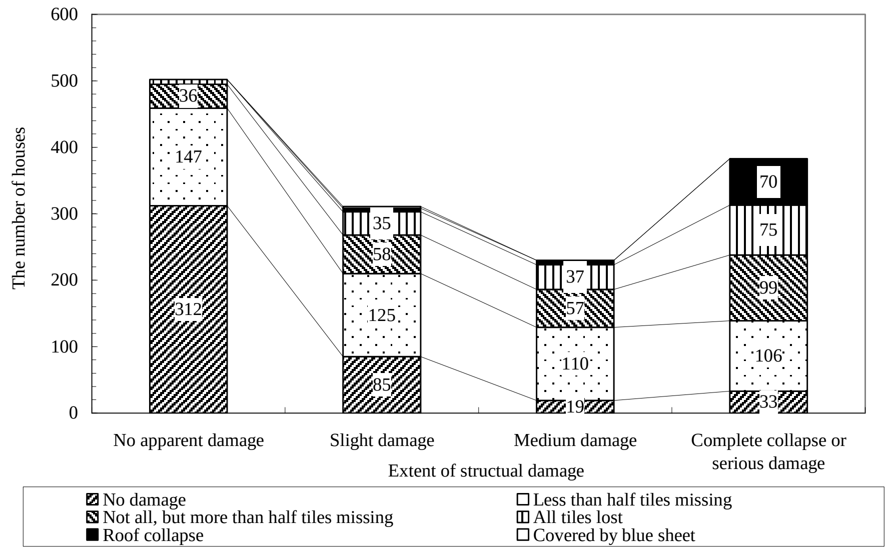

Figure 4.1: Roof tile deficit according to the extent of structural damage (the number of houses) (for all areas (Areas 1-6)).

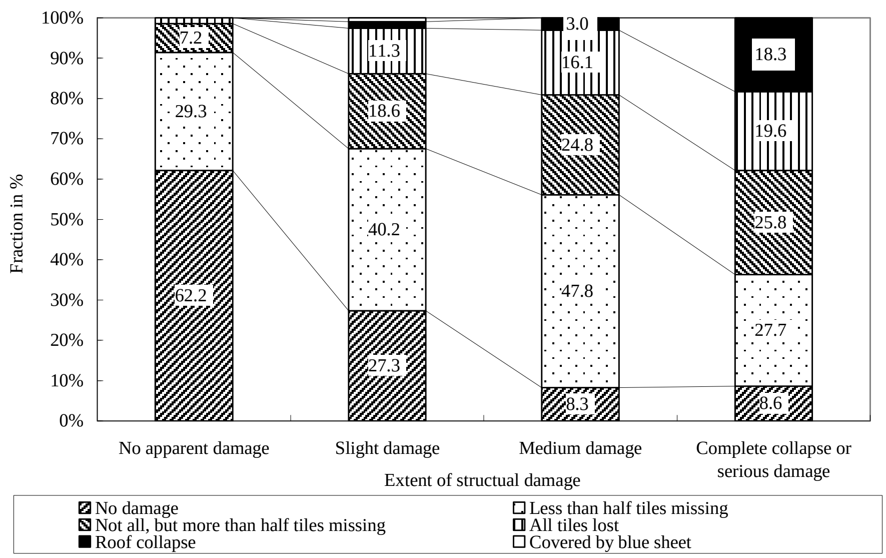

Figure 4.2: Roof tile deficit according to the extent of structural damage (fraction in %) (for all areas (Areas 1-6)).

3. Real-scale Fire Wind Tunnel Experiment on ignition behavior of firebrands landed on roofs

3.1 Experiment Outline

3.1.1 Experimental conditions

Table 4 describes the experimental cases and experimental conditions. A test roof was a 825 × 1717 mm piece cut from a general wooden tiled roof, consisting of rafters, roof boards (12-mm-thick plywood), asphalt roofing, counter battens, and tiles. The test roofs in Cases 1–3 (Table 4) were not tiled on the assumption that all the tiles had been lost because of an earthquake (Photo 2). The test roof in Case 4 (Table 4) had a missing tile where a fire seed was placed on the assumption of slight damage (Photo 3). These test roofs were installed on a frame inclined by 30°. (Photos 2 and 3).

A wooden crib was prepared as follows: beech wood (density: 560 kg/m^3) was fabricated into 19 × 19 × 80 mm pieces; three of them were arranged at an equal interval as a layer; three layers of them were piled crossing each other, and fixed with nails; the outside dimension and weight were 80 × 80 × 60 mm and 155 g, respectively. This crib was exposed to fire on its two faces of 80 × 80 mm at a distance of 65 mm from a burner for 1 min for each face (2 min total)[Note 2]. The ignited crib was placed on the upper face of the test roof as a fire seed. Figure 6 shows the experimental layout.

As combustion behavior of a fallen firebrand is greatly influenced by wind velocity, wind velocity should be considered as an experimental parameter as well as the damage extent of roof tiles. Three levels of wind velocity: no wind, 3 m/s, and 6 m/s, were set at the fire seed installation point (O in Fig. 5). First, the correlation between the wind velocity at the fire seed installation point (O in Fig. 5) and the wind velocity at 6 m upwind (x in Fig. 5) was examined (Table 5). Then, the wind velocity at 6 m upwind (x in Fig. 5) was controlled so that the predetermined wind velocity in Table 4 was obtained during the experiment. Wind measurement at the fire seed installation point was conducted with the frame removed.

3.1.2 Measurement

Combustion behavior of the fire seed and test roof was recorded using two digital camcorders located windward and at the side of the test roof [(1) and (2) in Fig. 5], respectively, and a miniature CCD camera at the rear face of the test roof [(3) in Fig. 5]. Temperature change during the experiment was measured using 36 thermocouples: 18 on the top face of a test roof (on the asphalt roofing) (Fig. 6), and 18 on the rear face (the bottom face of the roof board) (Fig. 7).

Table 4: Experimental conditions.

Experiment Case	Wind velocity	Tile
Case 1	0 m/s	None
Case 2	3 m/s	None
Case 3	6 m/s	None
Case 4	6 m/s	Yes (one tile missing)

Photo 2: Test roof (Case1-3).

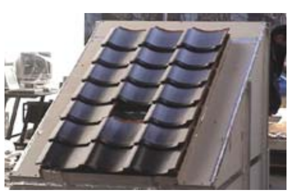

Photo 3: Test roof (Case4).

Photo 4: Rear face of test roof.

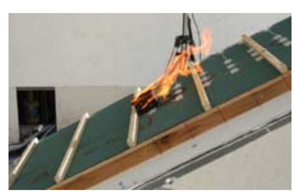

Photo 5: Placed fire seed.

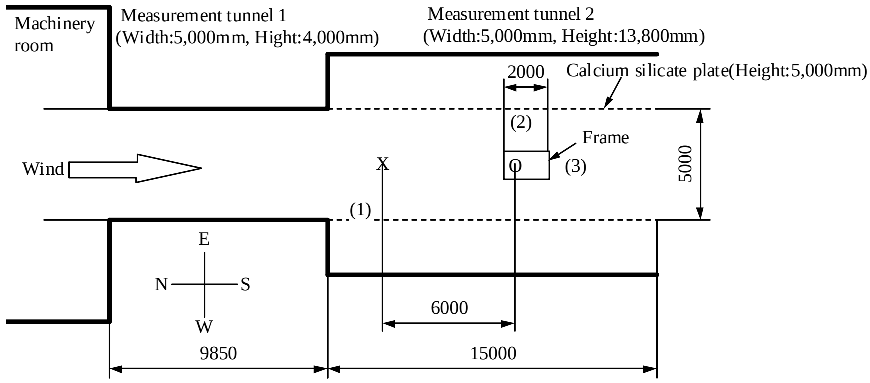

Figure 5: Layout in Fire Wind Tunnel (unit: mm).

Table 5: Wind velocities at each measurement point before experiment

Aimed wind velocity	Wind velocity at the firebrand installation site marked with O	Wind velocity at upwind location marked with X
3 m/s	2.99 m/s	3.41 m/s
6 m/s	5.98 m/s	6.64 m/s

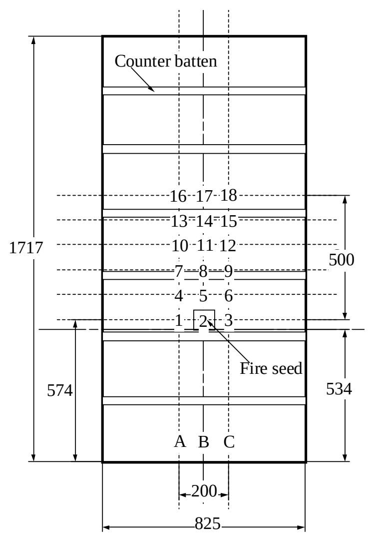

Figure 6: Top face of test roof (unit: mm).

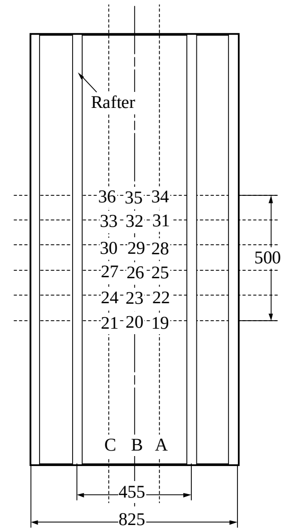

Figure 7: Rear face of test roof (unit: mm).

3.2 Experimental Results

3.2.1 Progress status of the experiment

The progress status of each case is listed in Tables 6–9. The moment when a burner started the fire seed was set as the experiment start time. Accordingly, when a fire seed was installed on a test roof, 2 min or more will have passed (including transfer time of the fire seed from the burner to the installation point) from the experiment start time.

3.2.2 Fire damage of test roofs

Table 10 shows measured maximum lengths in longitudinal and transverse directions of the range in which the asphalt-roofing surface blackened by melting or combustion, and of the range in which fire penetrated the roof board. Surface conditions of the test roofs after the experiment are shown in Photos 6 (Case 1) and 7 (Case 2).

3.2.3 Temperature variation & maximum temperature distribution on roof surfaces

Figures 8-11 show temperature variation of each case, and figures 12-15 illustrate maximum temperature distribution on roof surfaces.

Table 6: Progress status in Case 1.

Time	Progress status
00'00"	One side of a wood crib is heated.
01'00"	The reverse side of the crib is heated.
02'00"	Heating of the crib is finished and it is placed on the top of the test roof. The fire seed is already in flames.
15'00"	The flame of the fire seed has already been extinguished; however, the test roof has not been penetrated.

Table 7: Progress status in Case 2.

Time	Progress status
00'00"	One side of a wood crib is heated.
01'00"	The reverse side of the crib is heated.
02'00"	Heating of the crib is finished and it is placed on the top of the test roof. The fire seed is already in flames.
14'00"	Smoke occurs from the rear face of the test roof.
29'18"	Flame penetrates the test roof at fire seed installation point.
41'44"	Combustion of the fire seed and the test roof stops.
42'58"	Smoke also stops.

Table 8: Progress status in Case 3.

Time	Progress status
00'00"	One side of a wood crib is heated.
01'00"	The reverse side of the crib is heated.
02'00"	Heating of the crib is finished and it is placed on the top face of the test roof. Due to high wind velocity, the fire seed is smoldering, but no flame has occurred yet.
04'48"	The fire seed catches flames.
06'20"	Smoke has already occurred from the rear face of the test roof.
14'24"	Flame penetrates the test roof at fire seed installation point.
17'20"	Combustion of the fire seed and the test roof stops.

Table 9: Progress status in Case 4.

Time	Progress status
00'00"	One side of a wood crib is heated.
01'00"	The reverse side of the crib is heated.
02'00"	Heating of the crib is finished and it is placed on the top of the test roof. The fire seed is already in flames.
11'49"	Smoke takes place from a test specimen rear face.
17'12"	Flame penetrates the test roof at fire seed installation point.
18'07"	A flame spouts from the rear face of the test roof.
39'50"	Smoke stops.

Photo 6: Damage on the surface (Case 1).

Photo 7: Damage on the surface (Case 2).

Table 10: Fire damaged range of the test roof.

Experimental Case	Surface fire-damaged range		Fire penetration range	
	Longitudinal direction	Transverse direction	Longitudinal direction	Transverse direction
Case 1	19cm	21cm	-	-
Case 2	34cm	42cm	4cm	5cm
Case 3	38cm	42cm	8cm	11cm
Case 4	22cm	52cm	8cm	9cm

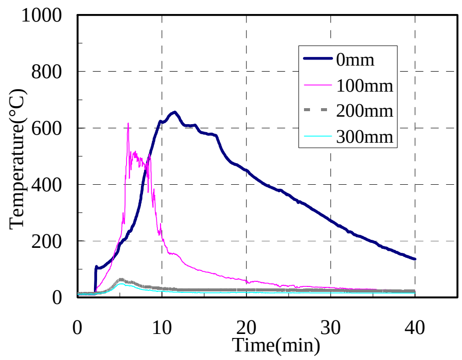

Figure 8: Surface temperature along line B (Case 1).

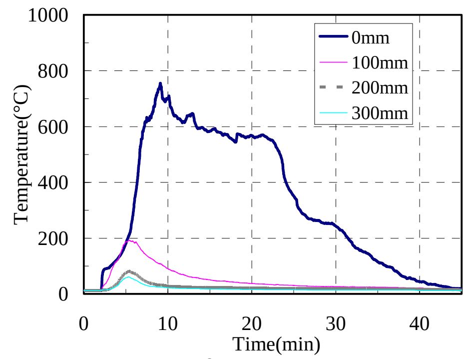

Figure 9: Surface temperature along line B (Case 2).

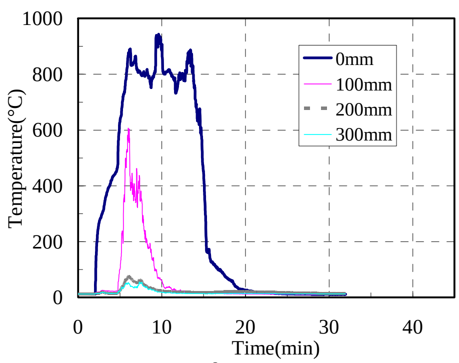

Figure 10: Surface temperature along line B (Case 3).

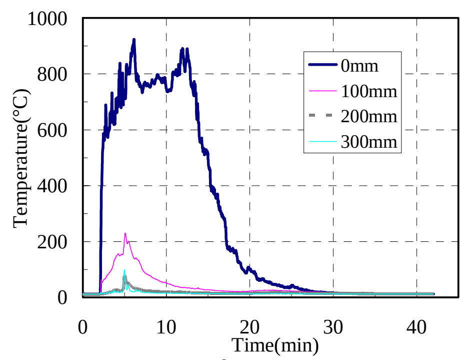

Figure 11: Surface temperature along line B (Case 4).

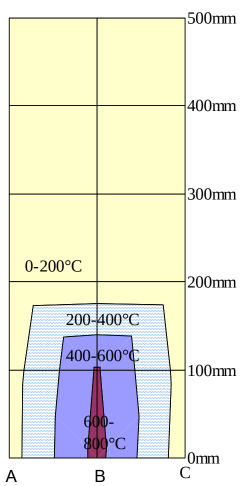

Figure 12: Max temperature distribution (Case1).

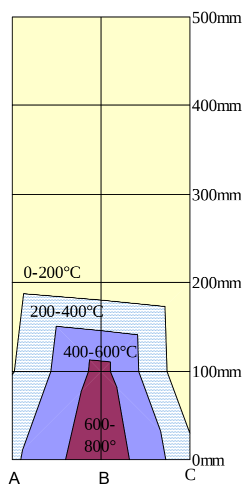

Figure 13: Max temperature distribution (Case2).

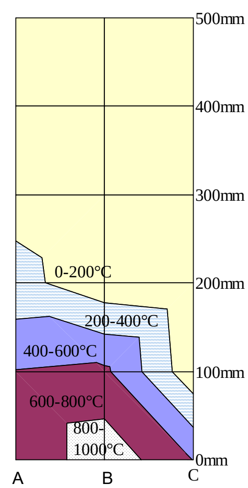

Figure 14: Max temperature distribution (Case3).

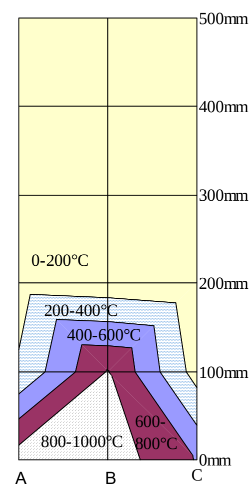

Figure 15: Max temperature distribution (Case4).

3.3 Discussion

3.3.1 Relationship between wind velocity and combustion behavior

This experiment employed a relatively thin, 12-mm-thick plywood as a roof board. No flame penetration was observed in the windless condition of Case 1, while fire penetration occurred directly under the fire seed under windy conditions of Cases 2–4 (Table10). Flame penetration was observed at about 29 min and 14 min after the test start at a wind velocity of 3 m/s in Case 2, and 6 m/s in Case 3, respectively. These results suggest that wind greatly changes the attacking nature of a firebrand in the range of wind velocity up to about 6 m/s[Note3)]. Therefore, such a risk is enhanced as wind velocity increases. However, combustion of the roof itself is limited in all cases in the range near the fire seed, which is the fire source. After fire seed combustion is completed, roof combustion also follows. For this reason, more than fire spreading to the roof, it is considered a rather more serious risk that the fire seed penetrates the roof board, falls into the attic, igniting the indoor combustibles directly beneath.

3.3.2 Relationship between combustion behavior and surface temperature

Surface temperatures near the fire seed are compared (Figs. 8, 9, and 10): at a wind velocity of 3 m/s, combustion time is a little shorter compared with a windless condition, while the maximum temperature rises to about 700°C compared with about 600°C at a windless condition (Figs. 8 and 9). Furthermore, at wind velocity of 6 m/s, the combustion time decreases to 20 min and the maximum temperature reaches about 900°C (Fig. 10). Temperature increases and decreases are rapid.

Maximum temperature distribution measured in each part (Figs. 12–15) indicates that the temperature near the fire seed rises as wind velocity increases.

These results, in consideration of the combustion behavior of the roof board, imply that conditions with wind and rapid heating, even for a short time, would rather more likely engender fire expansion than gentle and prolonged heating.

3.3.3 Relationship between tile missing and combustion behavior

In Cases 3 and 4, both with 6 m/s wind velocity, fire penetration took place in 14 min and 17 min in Case 3 with all tiles missing, and in Case 4 with one tile missing, respectively.

In Case 3, fire penetration time is slightly shorter. In addition, the fire penetration range is a little larger (Table10). The maximum temperature distribution (Figs. 14 and 15) indicates that the area with a range at 200°C or above is larger in Case 3, while that at 800°C or above is larger in Case 4. In Case 4, with only one tile missing, the fire seed, placed at the tile-less area, is surrounded by tiles. Therefore, it is inferred that the airflow into the tile-less area concentrated fire heat to that area.

4. Conclusions

Because tiles are made of a noncombustible material, it is hardly assumed that a firebrand landing on a tiled roof in a sound condition engenders a great risk of fire. However, a firebrand that lands on a roof with all tiles missing or on one with a tile deficit is likely to cause fire penetration through the roof board irrespective of the damage extent of tiles. Fire penetration through a roof board depends on wind velocity, and fire damage extends as wind velocity increases up to about 6 m/s.

5. Future Subjects

This study employed a relatively large fire seed adopted in the roof strength test according to the Building Standard Law. It is possible that firebrands of various sizes occur [3] and fly in an actual leaping flame phenomenon. Our experiments will be conducted successively with respect to the firebrand size, wind velocity, and the damage extent in settings other than this experiment. Moreover, the process that results in structural destruction by fire after roof board penetration will be investigated.

Acknowledgments

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Notes

1. Classification of damage observed on-site comprises four classes: "No apparent damage", "Slight damage", "Medium damage", and "Complete collapse or serious damage." This classification is according to inhabitability, specifically: "No apparent damage" means there is no damage visible; "Slight damage" is a condition in which the house is inhabitable with repair; "Medium damage" is the condition in which a house is inhabitable with major repair; and "Complete collapse or serious damage" means the house is uninhabitable.
2. Flame temperature at 65 mm from the burner top face was 800 ± 100°C.
3. Tadao Moriya reported a drop in the ignition rate at wind velocities of 3–4 m/s and above in an experiment on firebrand ignition conditions. However, as no further information is available, the reference is under examination.

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3. Yoshioka H., Hayashi Y., Masuda H., and Noguchi T., “Rear-scale Fire Wind Tunnel Experiment on Generation of Firebrands from a House on Fire”, Proceedings of the Second International Symposium on New Technologies for Urban Safety of Mega Cities in Asia, 2003, pp.95-102.