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Experimental study on vulnerabilities of Japanese-style tile roof assemblies to firebrand exposures

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Abstract

Roof assemblies are known to be vulnerable to firebrands in urban and wildland-urban interface fires. In the 2016 urban fire in Japan (Itoigawa-City Fire), at least 10 structures were ignited by firebrand showers and three of these structures were ignited by firebrand penetration under tile roof assemblies. In this study, the vulnerabilities of Japanese-style roof tile assemblies to firebrand exposures were investigated by using a continuous-feed firebrand generator with applied nominal wind speeds of 6 m/s and 9 m/s. It was observed that Japanese-style roof tile assemblies were more vulnerable than concrete flat, concrete profile, and terracotta flat roof tiles for applied wind speeds of 6 m/s. When the experiments were performed with debris placed underneath the roof tiles, penetrated firebrands ignited debris. Flaming ignition was observed under 9 m/s where flame was observed to protrude from the tiles in an effort to reach necessary oxygen for combustion.

Introduction

Large outdoor fires, such as wildland fires, wildland-urban interface (WUI) fires, and urban fires, have been an international problem in recent years. The property losses are staggering in large outdoor fires [1], and efforts to reduce such destruction are desired by hardening houses or communities to such fire exposures. Fire spread occurs via three mechanisms: flame contact, thermal radiation, and firebrands. Post-fire investigations have suggested that firebrands were a major cause of rapid fire spread in large outdoor fires [2, 3] and that roofing assemblies, in particular, were one of the vulnerable components of houses to firebrands [4]. A post-fire investigation of the 2016 Itoigawa-city Fire in Niigata, Japan concluded at least three houses were ignited by firebrand penetration under tile roof assemblies [5, 6].

In Japan, due to frequent earthquakes and the ensuing post-earthquake fires, vulnerabilities of roof assemblies to firebrands were investigated by focusing on sheathing materials, as it was assumed roof tiles would be destroyed from the intense shaking due to earthquakes [4]. Most of the prior research performed in Japan has used wood cribs as a surrogate for firebrand exposure and current standard testing methodologies are predicated on use of wood crib exposure [7]. One or two cribs of a specific size were placed on mock-ups of roof assemblies to observe the flame spread or penetration of fire through the assemblies. ‘A shower of firebrands’, which was often reported in actual large outdoor fire events, is not

simulated in test methods [4]. A firebrand generator, called the NIST Dragon, was developed by NIST to simulate firebrand showers often seen in large outdoor fires [8]. This technology was applied to study the vulnerabilities of roof assemblies for the first time for Spanish tiles, then other kind of tiles and showed ignitions under the roof [9-12].

In this study, experiments were performed with Japanese-style roof tile assemblies (see Figs. 1 and 2) in order to investigate firebrand penetration and subsequent ignition of all types of roof designs and roof tile assemblies. The results were compared with those in the literature [12], and efforts were made to obtain insights on firebrand shower exposures to Japanese roof tile assemblies.

Experimental Description

Traditionally, Japanese-style roof tiles have been manufactured locally and are somewhat unique and made from local materials. More recently, roof tiles have been manufactured based on well-defined Japanese Industrial Standards (JIS) [13]. As roof tiles have a long expected service life, it is possible to find old style roof tiles in many locations all over Japan. 'Japanese-style' tiles receive their name due to the shape of roof tiles. In this study, disaster-prevention style roof tiles (Japanese-style) were used to begin to characterize the effect of dimensional variability and under tile debris on ignition by firebrands. This style is designed to prevent tiles from being blown away in case of strong winds (standard wind speed of 46 m/s) or less easily removed from earthquake shaking. These specific roof tile designs have joints which loosely secure the connection between tiles, as shown in Figures 1 and 2.

As detailed experimental procedures to expose roof tile assemblies to wind driven firebrand showers have been described by the authors for non-Japanese roof assemblies, [11, 12] only a short description is provided here. Roof tile assemblies were placed at 2.0 m from the NIST continuous-feed Dragon and the angle of roof tile assemblies is 25° (pitch angle) as it is common in USA and Japan [11, 12]. This version of the NIST Dragon has the capability of producing a firebrand shower for a desired duration. Experiments were performed under nominal 6 m/s and 9 m/s wind speeds. Wood chips were used to simulate firebrands produced from structure combustion [14]. The combustion state of firebrands was adjusted to all glowing, and 10 % flaming and 90 % glowing (which is simply referred to as flaming firebrand exposure later), depending on the experiments. The ratio of flaming/glowing was confirmed manually and uncertainties are $\pm 10\%$. As described in [11, 12], the combustion state of firebrands may be adjusted by a blower coupled to the NIST Dragon. The wind speed at the exit of the NIST Dragon was adjusted to 2.3 m/s for flaming firebrands, and 2.0 m/s for glowing firebrands, respectively. The firebrands arriving on roof tile assemblies were uniform on any location on roof tile assemblies, the same as [11]. The firebrand flux arriving on roof tile assemblies under 6 m/s and 9 m/s wind is 10.3 /m² s and 9.3 /m² s respectively (for glowing and flaming). The size and mass of firebrands for this experimental series are provided in Figure 3. Sections of roof assemblies, similar to those described in [11] were used for this experimental series; these were designed to focus on the field area of roofing assemblies and not edge effects. The roof slope of 25 degree was used for this experimental series as well as [11]. Adjustment was made to follow the construction methods for

Japanese-style roof tile assemblies [15]. Only horizontal battens were used (Figure 2). Information on Japanese-style roof tiles as well as concrete profile tiles, concrete flat tiles and terracotta flat tiles in [11] are provided for completeness in Table 1. The dimensions of tiles were measured shown in Figure 4.

The first series of experiments were performed without debris and the second series with debris (oven-dried pine needles/fir needles) placed under the roof tiles to simulate a scenario which often occurs when no maintenance, such as cleaning or replacement, has been taken for long time. Debris was placed along 2nd (fir needles) and 3rd (pine needles) battens from bottom, 12.5 (± 10 % standard deviation) g/m shown in Figure 5. Firebrand exposure time for first and second series of experiments was 20 min and 15 min (6 m/s) respectively. For second series of experiments under a 9 m/s wind, firebrand exposure was stopped when flame was observed between roof tiles. Experiments were repeated at least twice for all conditions. The experimental conditions are provided in Table 2.

Experiments were performed in Building Research Institute's Fire Research Wind Tunnel Facility (FRWTF), and an image of atypical experiment is provided in Figure 6.

Results & Discussions

Experiments without debris

During 20 min of glowing firebrand exposure, neither flame nor smoke was observed emanating from the roof tile assembly. This was the same as all other roof tile assemblies exposed to firebrands in the past [12]. The roof tiles were removed after the completion of the firebrand exposure. It was observed that firebrands penetrated, smoldering ignitions were observed on the battens, but no sustained ignition was observed.

The number of firebrands that penetrated under the Japanese roof tiles was counted and compared with those from past experiments as shown in Figure 7. The number of firebrands was counted after the experiments. For 6 m/s wind, the number of firebrands that penetrated under Japanese style roof tile was found to be the largest out of all roof tiles tested in the same manner [11, 12]. With wind speed increased to 9 m/s, the number of firebrands that penetrate the tiles decreased, which shows the same trend as all other roof tiles studied previously by the authors. Compared with concrete tiles which often used in North America and Australia, Japanese style tiles and terracotta tiles have the largest number of firebrand penetration, both at 6 m/s and 9 m/s, mostly likely due to the manufacturing process (baked in oven) as baking process would result in some non-uniformity in nature [11, 12].

The penetration ratio of firebrands for Japanese style tile was compared with the previous results and is shown in Figure 8. The penetration ratio was defined as the percentage of the number of firebrands that penetrated under roof tiles versus the total number of firebrands that landed roof tiles for experimental duration $\frac{\text{The number of firebrands penetrated under roof tiles}}{\text{The number of firebrands landed roof tiles}}$.

The penetration ratio was introduced in this study in order to adjust the difference of firebrand arriving flux under 6 m/s and 9 m/s in Figure 7. While the penetration ratio of firebrands under flat tiles remains similar (or only slightly decreased) from 6 m/s to 9 m/s, it is clear that profiled tiles (both concrete and Japanese style) decreased significantly with a

wind speed increase. Wind speed has a strong effect on firebrand penetration on profiled tiles compared to flat tiles. The same trend was observed in our previous studies, and it was found that the same trend also applies to Japanese roof tiles [12].

The penetration ratio was compared with the thickness and the height of tiles, as shown in Figures 9 (a), and (b) respectively. The thickness and the height of each tile, shown in Figure 4, were measured with calipers and sampled from at least three locations. It was observed in [12] that firebrands landed on the roof tiles and then accumulated in front of roof tiles, thus, thickness of tile may be important for firebrands to stay in front of roof tiles and combust until firebrands become small enough to penetrate under roof tiles. The height of tile was selected as one of parameter to describe the 'profile' of tile. Figure 9(a) demonstrates that as the thickness of tile increases, the penetration ratio decreases for 6 m/s wind. With an increase of wind speed to 9 m/s wind speed, no relationship is observed. Figure 9(a) shows that the thickness of tiles may be an important parameter for lower wind speed while for a higher wind speed, this may be not the case. Firebrands were accumulated in front of roof tiles first in experiments under 6 m/s wind, while under 9 m/s wind, it was observed that it was difficult for firebrands to accumulate due to higher wind speed. Figure 9(b) shows that if the hip (profile) part of tile is higher, the penetration increases, which means more firebrands may penetrate under the roof tiles. Figure 9(b) includes data from flat tiles, terracotta flat tiles and concrete flat tiles (tile height 0 mm) for the references while it is not applicable for comparison. It is also shown more firebrands penetrate at higher wind speed in this experimental series.

Figures 10(a) and (b) show the relationship between the ratio of the penetration ratio at 6 m/s and at 9 m/s, $\frac{\text{The penetration ratio at } 9 \text{ m/s}}{\text{The penetration ratio at } 6 \text{ m/s}}$, and the thickness and the height of tile. The ratio of the penetration ratio at 6 m/s and at 9 m/s, $\frac{\text{The penetration ratio at } 9 \text{ m/s}}{\text{The penetration ratio at } 6 \text{ m/s}}$, and the thickness of the tile is shown to have no relationship (Figure 10(a)). Figure 10(b) shows the higher the profile of tile, the ratio of the penetration ratio at 6 m/s and at 9 m/s, $\frac{\text{The penetration ratio at } 9 \text{ m/s}}{\text{The penetration ratio at } 6 \text{ m/s}}$, was less, which means wind effect was less. This is interesting that if there is no profile at all (flat tiles), the wind has little effect on the change of penetration ratio itself, and within the two heights tested in this experimental series, the wind did have an effect on penetration ratio of difference of height of profiles. More experiments will be desired to understand this relationship.

The difference of firebrands collected from under the roof tiles is shown in Figure 11. The collected firebrands that penetrated under Japanese style roof tiles were found to be overall larger than those that penetrated under flat tiles (concrete and terracotta) under the same wind speed (6 m/s). While information on the thickness of firebrands collected under flat tiles is limited to 'less than 1 mm' [11], the thickness of firebrands collected under Japanese-style tiles was measured to be $2.2 \text{ mm} \pm 0.9 \text{ mm}$ (average $\pm$ standard deviation), which is thicker than those collected under flat tiles. This could be explained as Japanese-style tile has profile, the gaps between tiles tend to be larger, thus, overall the firebrands penetrated under tiles are bigger. Figure 12 shows the difference between firebrands under roof tiles from experiments under 6 m/s and 9 m/s wind speed, respectively. There were no firebrands

left on the tiles after experiments under 9 m/s wind speed. Overall relationship between the size and the mass of firebrands is found to be similar. The flaming firebrands under 6 m/s wind speed are slightly bigger than others; however, the relationship between the size and mass of firebrands is similar to the other glowing firebrands.

Experiments with debris

Debris was dried in the oven and placed just prior to the wind driven firebrand exposures, as shown in Figure 5. Experiments were terminated if flames were observed to protrude from the tiles (for experiments at 9 m/s wind). The firebrand exposure time was set to 15 min if no visible trace of flaming or smouldering ignition was observed (for experiments at 6 m/s wind).

No visible sign of smoke was observed during the experiments with debris under the tiles at a 6 m/s wind, when exposed to glowing firebrand showers. After the completion of the experiments, firebrands were collected under tiles, and smoldering ignition on debris was observed. The battens were charred, the underlayment was melted, but the OSB sheathing was not ignited.

Experiments with debris at 6 m/s wind speed exposed to flaming firebrands (10 % flaming firebrands and 90 % glowing firebrands) were also performed. During the experiments, it was difficult to observe smoke production under the tiles. As discussed in the previous section, firebrands penetrated under tiles, which resulted in smoldering ignition of the debris. This eventually melted the underlayment and burned through the OSB sheathing around the battens (shown in Figure 13). The locations of burns were near battens as the ignition started with debris. Transition to flaming ignitions was not observed at 6 m/s. 10 % of flaming firebrands made a difference of the ignition events within the debris. Previous studies on ignition of pine-needles or fir-needles also showed flaming firebrands ignited debris more easily than glowing firebrands [16-18]. With limited firebrand exposure time, flaming firebrands had enough energy to sustain smoldering ignition (SI) to produce ignition on OSB sheathing.

For experiments at 9 m/s wind, flames were observed to be protruding from gaps between tiles. This indicated glowing firebrands penetrated under tiles, ignited combustibles (needles) and caused flaming. Once ignited, there was not enough oxygen under tiles, thus flames protrude from under the tiles due to lack of oxygen, which was observed for a certain time (shown in Figure 14), but eventually disappeared. This was observed with repeated experiments with a different time.

It is important to understand that flaming ignition is not required to burn thorough sheathing materials. Considering the difficulty to find roof ignitions by firebrands, it is safe to assume initial combustion state is smoldering. At some condition, sustained smoldering would transition to flaming, and eventually a flame can be observed from outside. It is expected oxygen under roof tiles would be consumed for debris combustion and once transition from smoldering combustion to flaming combustion occur, flame protrudes due to the oxygen limited condition in a space under roof tiles [19].

Summary

Japanese-style roof tile assemblies were exposed to firebrand showers using a firebrand generator placed inside a full-scale wind tunnel. The number of firebrands that penetrated under the Japanese-style roof tile assemblies was compared with those in the literature that used similar experimental protocols with roofing assemblies common outside Japan. Due to the profiled nature of the tiles, it was found that Japanese-style roof tile assemblies were the most vulnerable among roof tile assemblies for applied wind speed of 6 m/s wind speed. The size and mass of firebrands that penetrated under Japanese-style roof tile assemblies was compared, and it was found the firebrands were thicker than those sampled from non-Japanese roof assemblies. The experiments with debris revealed that glowing firebrands for a 9 m/s wind speed could cause flaming ignition under roof tiles with flame stretching out from roof tiles while under a 6 m/s wind speed, flame was not observed, but smoldering ignition was observed, which resulted in OSB sheathing being burned through.

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Figure 1.
Picture of Japanese-style roof tile. Roof tiles used for experiments are disaster-prevention style, which has joints to secure tiles in the case of earthquake or under strong winds.

Figure 2.
Schematic image of roof construction for Japanese-style roof tiles [15]

Figure 3. Characteristics of firebrands for these experiments. Flaming firebrands mean 10 % of firebrands were flaming and 90 % of firebrands were glowing.

Figure 4.
Measurement of dimensions of tiles for this study

Figure 5.
Placement of debris (upper: pine needle down: fir needle)

Figure 6.
Experimental image (6 m/s)

Figure 7.
Number of firebrands penetrated under tiles depending on wind speeds and roof tiles

Figure 8.
Penetration ratio depending on wind speeds and roof tiles

Figure 9.

(a) Comparison of Penetration ratio vs thickness of roof tiles **(b)** Comparison of Penetration ratio vs height of profile of roof tiles

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Figure 10.

(a) Comparison of the ratio of the penetration ratio at 9 m/s/ the penetration ratio at 6 m/s vs thickness of roof tiles

(b) Comparison of the ratio of the penetration ratio at 9 m/s/ the penetration ratio at 6 m/s vs height of profile of roof tiles

Figure 11. Characteristics of firebrands collected under different roof tiles under a 6 m/s wind speed.

Figure 12. Characteristics of firebrands collected under Japanese roof tiles under different experimental conditions.

Figure 13.
Images of flaming firebrands igniting debris then OSB sheathing. Yellow circles indicate same places. (upper: smoldering ignition in debris down: ignition on OSB sheathing)

Figure 14.
Images of flaming ignition under roof tiles.

Table 1

Characteristics of roof tiles

	Size (length (mm) and width (mm))	End-cap	Thickness (mm)	Height (mm)
Japanese-style roof tiles	305 x 305	Roof tile for edge was used	15	43
Concrete profile	440 x 315	None	29	27
Concrete flat	430 x 330	None	31	0
Terracotta flat	355 x 229	None	21	0

Table 2

Experimental conditions

Experiments without debris			
Wind speed (m/s)	6		9
Combustion state of firebrands	Glowing		
Firebrand arriving flux (/m ² s)	10.3		9.3
Experimental duration (min)	20		
Experiments with debris			
Wind speed (m/s)	6		9
Combustion state of firebrands	Glowing	Flaming	Glowing
Firebrand arriving flux (/m ² s)	10.3		9.3
Experimental duration (min)	15		Until flame was observed