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The Performance of Wood and Tile Roofing Assemblies Exposed to Continuous Firebrand Assault

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Abstract

The performance of tile roofing assemblies as well as untreated cedar shake roofing assemblies exposed to continuous firebrand showers were compared. Specifically, experiments were conducted for two types of concrete tile roofing assemblies (flat and profiled), one type of terracotta tile roofing assembly (flat), and an untreated (without any fire retardant) cedar shake roofing assembly. The design of the roofing assemblies were based on construction guidelines in the USA. The duration of the firebrand flux was fixed at 20 minutes, and the wind speed was varied from 6 m/s to 9 m/s. These wind speeds were chosen to be able to compare roofing assembly performance to similar assemblies exposed to a batch-feed firebrand generator which had limited duration of firebrand exposure (6 min). The average firebrand mass flux that *arrived* at the surface of the roofing assemblies was 0.3 g/m²s. Results indicated that for the untreated cedar shake assemblies, ignition occurred easily from the firebrand assault, and this type of roofing assembly generated their own firebrands after ignition. To attempt to quantify the degree of penetration, the number of firebrands that penetrated the tile roofing assemblies, and deposited onto the underlayment/counter-batten system was counted as function of wind speed for each assembly. Firebrand penetration was observed, even for the flat tile assemblies. It is believed that these are the first-ever experiments described in the peer-reviewed literature to expose wood and tile roofing experiments to continuous wind-driven firebrand showers.

1.0 Introduction

Wildland-Urban Interface (WUI) fires have become a problem of great concern worldwide. There have been significant WUI fires in Australia, Chile, Greece, Portugal, Spain, and the USA over the past ten years [1–3]. The fires in Australia in 2009 claimed the lives of more than 150 people [2].

Japan does not have a specific problem of fires spreading from the wildlands to communities, such as the WUI fire problem in the USA and other countries [4]. Rather, Japan is located in one of the most earthquake prone areas of the world. After large earthquakes, many fires may simultaneously occur that can easily overwhelm fire-fighting

resources. Since most Japanese cities are densely populated, severe fire spread can occur within these urban areas [4].

The WUI fire problem can be viewed as a building ignition problem [1,5]. For years, post-fire studies have identified firebrands as a major source of ignition in both WUI and urban fires (see Ref. [6] for a review of many of these studies). Only until recently has an experimental capability been developed to begin to enable the quantification of structure component vulnerability to wind-driven firebrand showers. The interested reader is referred elsewhere to comprehensive reviews of this technology [7–9].

Post-fire investigations have identified a building ignition mechanism by which very small firebrands penetrate under a non-combustible tile roof covering to ignite a building [6]. Current standards (*e.g.* ASTM E108 [10]; UL 790 [11]) evaluate the ignition of roofing assemblies to fire by placing a burning brand (wood crib) on top of a section of a roof assembly under an air flow. The dynamic process of multiple wind-driven firebrands landing and then being transported through non-combustible tiles/gaps as a function of time was not considered. Manzello *et al.* [12] revealed the vulnerabilities of curved ceramic tile roofing (Spanish tile roofing) assemblies to ignition under a controlled wind-driven firebrand attack using the NIST Firebrand Generator.

Major bushfires in Australia led to the establishment of a Royal Commission to examine the suitability of building codes for the construction of houses in bushfire (or wildfire) prone areas [2]. With many wildland fires propagated by wind-driven firebrands, the resistance of building elements to wind-driven firebrands has become a topic of great interest worldwide [5,13].

As part of an industrial collaboration with NIST and the Tile Roofing Institute (TRI) in partnership with the Roofing Tile Institute of Australia (RTAA), concrete tile roofing assemblies (flat and profiled tile) as well as terracotta tile roofing assemblies (flat and profiled tile) commonly used in the USA, Australia, and elsewhere, were exposed to wind-driven firebrand showers [14]. The purpose of those experiments was to determine if firebrands were able to penetrate the tile assemblies and melt the sarking material (please see [14] for description of sarking material used). The results demonstrated that firebrands penetrated between the tile gaps and melted the sarking material for both types of concrete tile roofing assemblies (flat and profiled tile) and the profiled tile terracotta roofing assembly when exposed to wind-driven firebrands. The flat tile terracotta roofing assembly performed best, probably due to its interlocking design. For these tiles, the firebrands were observed to become trapped within the interlocking sections of the tiles and as a result, the firebrands were not transported past the tiles towards the sarking material. These experiments used the original NIST batch feed firebrand generator, and therefore the duration of the firebrand exposure was limited to around 6 min [14]. This original batch feed device was used because: (1) industry was interested in a direct comparison to the experiment protocols used for the Spanish tile roofing assemblies, (2) the batch-feed version of the Firebrand Generator was far less expensive to operate and provided a simple cost-effective tool to determine if further work was required (*i.e.* if firebrand penetration and melting of sarking occurred).

The objective of the present investigation was to evaluate the performance of tile roof assemblies as well as untreated (without any fire retardants) cedar shake roofing assemblies exposed to *continuous* firebrand showers. The duration of the firebrand flux was fixed at 20 minutes and the wind speed was varied from 6 m/s to 9 m/s. The wind speeds were chosen to be similar to legacy ASTM/UL [10–11] test methods (where a wind speed of 5.4 m/s was specified), as well as prior work [12, 14] to similar assemblies exposed to a batch-feed firebrand generator of limited firebrand exposure. In particular, a wind tunnel speed of 9 m/s was selected for these experiments, because this is near the upper limit of the Fire Research Wind Tunnel Facility (FRWTF) in Building Research Institute (BRI), Japan. The outcome of these experiments is expected to be of value to roofing manufacturers as well as fire authorities/code officials in countries where large outdoor fires are a problem.

2.0 Experimental Description

2.1 Details of firebrand generation

Figure 1 is a schematic of the full-scale Continuous Feed Firebrand Generator. The description differs from descriptions available elsewhere [15–16] since the feeding system was redesigned to be able to generate firebrand size and mass distribution using wood chips in an effort to be able to produce a wider range of exposure conditions; reasons for this are provided below. The device consisted of two parts: the main body and a continuous feeding component. In this work, the main body of the generator was the same as prior investigations (Dragon component); only the feeding system was modified. The feeding system was connected to the main body and was equipped with two gates to prevent fire spread (described in more detail below). Each gate was alternatively opened and closed. A blower was connected to the main body and the purpose of the blower is described below. All components of the full-scale Continuous Feed Firebrand Generator were constructed of stainless steel. A major challenge when constructing this device was designing a completely contained feeding system shielded from the wind tunnel air flow.

The feeding system consisted of a pneumatic cylinder coupled to a cylindrical container where wood pieces were stored (see Figure 1). Below the wood storage area, a plate was installed that allowed variation in the volume of wood to fall from the storage area to the first gate. This volume was set precisely to allow a specific mass of the wood chips to fall into this volume. When the air pressure was applied, the sliding rod of the pneumatic cylinder moved forward and separated the wood chips from the storage area to the first gate, where they were then dropped into the second gate that led to the Dragon where they were ignited (see Figure 1). Care was taken to select the pneumatic cylinder (15 cm bore with 17.8 cm stroke; maximum pressure of 1.7 MPa and maximum load of 12 kN; this is about 4 times more force than our previous device of 3.1 kN; see [15–16]); smaller sized pneumatic cylinders were observed to be unable to cut through the wood and would jam. The two-gate system was required to contain the fire from spreading from the Dragon to the feed system and each gate was driven by pneumatic cylinders as well.

For all tests, Japanese Cypress wood chips were used to produce firebrands (see Figure 2). These were provided from a supplier and upon arrival, these chips were filtered using a 1 cm mesh to remove very fine wood pieces. The wood chips were also oven dried, as they were

shipped wet moisture content (MC) greater than 70 % on a dry basis. These size wood pieces were selected to produce firebrands with larger projected area at a specific mass than our prior studies using continuous firebrand generation [15–16]. The length, width, and thickness of wood chips before combustion are 27.6 ± 7.5 mm, 18.2 ± 6.3 mm, and 3.3 ± 0.8 mm (average $\pm$ standard deviation), respectively. An important characteristic of our prior studies was that the firebrand size and mass produced using was tailored to those measured from full-scale tree burns, and actual WUI fires [15–16]. It is clear that more data is needed for firebrand size/mass distributions from various types of vegetation, structures, and actual WUI and urban fires [9]. The authors have begun to develop a database of firebrand production from burning structures/structure components [17–19]. This paper is the first attempt to expose building elements to firebrand showers with size and mass commensurate to distributions in this structure firebrand data set. Additional details are provided in the results section below.

An operational parameter that was varied was the blower speed. When the blower was set to provide an average velocity below 2 m/s measured at the exit of the Dragon when no wood pieces were loaded, insufficient air was supplied for combustion and this resulted in a great deal of smoke being generated in addition to firebrands. At blower velocities above 2 m/s, smoke production was mitigated, but many firebrands produced were in a state of flaming combustion as opposed to glowing combustion. It has been suggested that firebrands fall at or near their terminal settling velocity. As such, when firebrands contact ignitable fuel beds, they are most likely in a state of glowing combustion, not open flaming [20]. It is possible for firebrands to remain in a flaming state under an air flow and, it is reasonable to assume that some firebrands may still be in a state of flaming combustion upon impact. The purpose of this device was to simulate firebrand showers observed in long-range spotting, and therefore, glowing firebrands were desired. It is noteworthy to mention that the blower speed was lower than when Douglas- fir wood pieces were used and this is simply due to the fact the Japanese Cypress wood chips had larger projected area, making this type of geometry much easier to loft.

As in prior experiments using the NIST Dragon, the new experimental device was installed inside the test section of BRI's FRWTF (see **Figure 3**). The facility was equipped with a 4 m diameter fan to produce the wind field. The cross section of the FRWTF is 5 m wide by 4 m high.

2.2 Details of Roofing Assembly Construction

The roofing assemblies were placed at a distance of 2 m downstream from the full-scale Continuous Feed Firebrand Generator (see **Figure 3**). Assemblies located at this distance receive an intense flux of firebrands from the Dragon and allow for direct comparison of all prior roofing studies [7, 14]. A custom assembly was constructed to mount the roofing assemblies. In these experiments, USA construction details were followed. Specifically, for the cedar shake roofing assemblies, guidelines available in the Cedar Shake and Shingle Bureau [21] were followed. The Tile Roofing Institute [22] design manual was followed for all tile roofing assemblies; counter-battens were used for all tile roofing assemblies in this

study. An example of the construction details for the flat tile roofing assemblies is shown in **Figure 4**.

For the cedar shake roofing assemblies, the base frame was constructed of 2×6 joists. Plywood (C-D Exposure 1) was used as the sheathing material. Felt underlayment (No. 30 felt) was applied on top of the plywood sheathing (not oven dried; nominally 11 % MC) and the untreated cedar shakes were applied as the final layer. The length of each cedar shake was 457 mm with 255 mm exposure. A starter course of cedar shakes, 381 mm long, were used, per guidelines in [21]. The cedar shakes were oven dried prior to the experiments to represent a worst-case scenario. The dried shakes were then taken to wind tunnel test section, and the roofing assemblies were constructed. MC of cedar shakes were measured prior to testing and did not re-absorb significant moisture.

In the case of the tile roofing assemblies, the base frame was constructed of 2×6 joists, and was lined with oriented strand board (OSB) sheathing. The OSB was not oven dried; nominally 11 % MC. Felt underlayment (No. 30 felt) was applied on top of the OSB sheathing and the wood batten spacing was adjusted depending on the type of ceramic or terracotta tile roofing assembly being tested.

Figures 5–8 display the cedar shake roofing assembly as well as three types of tile roofing assemblies tested, including two concrete tile roofing assemblies (flat and profiled tiles) as well as one terracotta tile roofing assemblies (flat tiles). The differences between the flat and profiled tiles are obvious in the images. Roof angle was $A=25$ degrees (commonly found in practice) for all the roofing assemblies for direct comparison to prior work [12, 14]. Specifically, experiments conducted by NIST and the Tile Roofing Institute (TRI) in partnership with the Roofing Tile Institute of Australia (RTAA) [14] used the same roof angle.

The overall dimensions of each roof assembly were 1.2 m by 1.2 m. It is important to realize these dimensions are slightly different than what is used in current legacy roofing test methods [10–11]. This has been done intentionally for comparison to prior work [12, 14] where all roof assembly dimensions were 1.2 m by 1.2 m. Presently, the authors are generating a database of roofing assembly performance under various wind-driven firebrand exposures using these dimensions.

A typical experiment was conducted in the following manner. The roofing assembly was installed inside the test section of the FRWTF. The wind tunnel speed was set to the desired level (e.g. 6 m/s or 9 m/s). Wood pieces were first loaded into the cylinder storage container, and the air compressor needed to provide compressed air for the pneumatic cylinder and gate system was switched on (air compressor pressure was set to 0.7 MPa). The blower was set at 2 m/s, and two propane burners were ignited and inserted into the side of the device. The propane burners were operated continuously during the experiment. The pneumatic piston was then activated and the sliding rod was positioned to allow wood pieces to enter the volume in the metal sleeve. The sliding rod was moved to push the wood pieces (170 g) to the first gate. The gate was opened, closed, and the second gate was then opened, and the wood fell into the Dragon. The feeding rate was varied to determine the optimal conditions

for continuous firebrand showers. Based on prior work, a wood mass loading 150 g to 200 g every 15 s resulted in adequate firebrand generation [15–16]. As a result, in these experiments, $170 \text{ g} \pm 30 \text{ g}$, fed into the Dragon every 15 s provided an adequate firebrand generation rate to ignite building materials. A supply of 170 g corresponded to approximately 560 wood pieces deposited every 15 s. It is important to note that finer control, and therefore less uncertainty per each feed, was obtained when feeding with machined Douglas-fir pieces, as compared to the wood chips used here [15–16]. The reason for this is that the Douglas-fir pieces are all of uniform size, while chips vary to some extent.

The number flux (number of firebrands generated/ m^2s), at the exit of the device, was measured at a feeding rate of 170 g every 15 s (680 g/min). To determine the number flux, the number of firebrands was counted at every frame of the video recording, and summed every second. Based on the analysis, the number flux reached a steady value of $533/\text{m}^2\text{s}$ 150 s after feeding began. The first firebrands began to be generated $\sim 20 \text{ s}$ after feeding was commenced.

Mass flux data (mass of firebrands generated per square meters per second) were calculated by multiplying the number flux and the average mass of each firebrand at a feed rate of 170g every 15 s. To measure the firebrand mass, another set of experiments was conducted using a series of water pans placed downstream of the NIST full-scale Continuous Feed Firebrand Generator. Water pans were required in order to quench combustion of the firebrands. If the water pans were not used, the firebrands would continue to burn and by the time collection was completed; only ash would remain. After the experiment was finished, the pans were collected and the firebrands were filtered from the water, using a series of fine-mesh filters. Firebrands were dried in an oven, at 104°C , for 16 h. As in previous work, the mass versus drying time was monitored to determine the duration needed to completely dry the firebrands.

3.0 RESULTS AND DISCUSSION

Figure 9 (a) displays the projected area of the generated firebrands at 6 and 9 m/s. Image analysis software was used to determine the projected area of a firebrand by converting the pixel area using an appropriate scale factor. It was assumed that deposited firebrands would rest flat on the ground and the projected areas with the maximum dimension and the second maximum dimension of three dimensions were measured (for cylindrical and flat shaped firebrands respectively). Images of well-defined shapes (e.g. circular objects) were used to determine the ability of the image analysis method to calculate the projected area [17]. Based on repeat measurements of different areas, the standard uncertainty in determining the projected area was $\pm 10 \%$. The mass of each firebrand was measured by a precision balance with 0.001 g resolution. Repeat measurements of known calibration masses were measured by the balance which was used for the firebrand mass analysis. The standard uncertainty in the firebrand mass was approximately $\pm 1 \%$. The mean mass and standard deviation of each firebrand were obtained and determined to be $0.03 \text{ g} \pm 0.02 \text{ g}$. Therefore, the mass flux of generated firebrands was calculated to be $16 \text{ g}/\text{m}^2\text{s}$.

Figure 9 (b) shows the comparison of the size and mass distributions of firebrands from the full scale Dragon in this study and studies related to the experimental database of firebrand production from structure components [18, 19] under a 6 m/s wind. Firebrands generated in this study were commensurate to those measured from burning structure components. For reference, the average projected area of firebrands generated in this study tailored to burning structure components was $1.56 \text{ cm}^2 \pm 0.85 \text{ cm}^2$, as compared to $0.77 \text{ cm}^2 \pm 0.2 \text{ cm}^2$, in prior studies of continuous firebrand generation tailored to burning trees and data from an actual WUI fire, where Douglas-fir wood pieces were used to generate firebrands [15–16].

It is important to note that all the generated firebrands that depart the mouth of the Dragon do not land on the surface of the roofing assemblies. The average total firebrand mass flux arriving at the roofing assembly was estimated from video records to be $0.3 \text{ g/m}^2\text{s}$.

Approximately 35 % of the firebrand mass generated from the Dragon arrived at the roofing assembly surface. It is of interest to note that the arrival mass flux of firebrands to the roofing assemblies was the same with prior work using the batch-feed Dragon [14]. Even though the mass flux departing the Dragon's exit was higher than the previous batch-feed study ($16 \text{ g/m}^2\text{s}$ versus $10 \text{ g/m}^2\text{s}$ for the batch-feed device), less firebrands arrived at the roof surface due to the overall larger projected area of the firebrands; such counter-balance produced the same arrival mass flux at the roofing assembly for both studies.

3.1 Untreated (Without Any Fire Retardants) Cedar Shake Roofing Assemblies

Figure 10 displays images of the ignition process for the untreated cedar shake roofing assemblies under an applied wind speed of 6 m/s. Firebrands accumulated in the gaps between the cedar shakes. Eventually, smoldering ignition (SI) of the cedar shakes was observed evidenced by intense smoke generation. SI transited to flaming ignition (FI). The same behavior was observed under an applied wind speeds of 9 m/s. As wind speed was increased, the ignited cedar shake roofing assembly produced its own firebrand showers. A separate, intricate study was not conducted to collect the firebrand distribution generated from the burning cedar shake roofing assembly, but a picture of the types of firebrands produced is shown in Figure 11. In these experiments, no attempt was made to design the roofing support deck to be non-combustible, since it was believed that the cedar shakes themselves would produce firebrands once ignited. The results demonstrated that this was the case and the secondary firebrand showers produced by the burning cedar shakes is clearly not desirable in any WUI fire situation.

3.2 Tile Roofing Assemblies

For both types of concrete tiles (flat and profiled), as well as the terracotta (flat) roofing assembly, firebrands were observed to accumulate in the gaps of the tiles. The firebrands continued to burn until they were able to penetrate the tile gaps and pass onto the underlayment/counter-batten system. In all tiles that were experimented upon, the most severe penetration occurred in the field of the roofing assembly, not at the leading edge.

To attempt to quantify the degree of penetration, the number of firebrands that penetrated the tiles, and deposited onto the underlayment/counter-batten system was counted as function of wind speed for each tile roofing assembly. These results are shown in **Figure 12**. As can be

seen, the terracotta tiles (flat), resulted in the most firebrand penetration. Firebrand penetration resulted in smoldering ignition of the counter-batten system but a transition to flaming ignition was not observed. These SI may be observed in Figure 13a for the terracotta tiles (flat) and **Figure 13b**, for the concrete tiles exposed to firebrand showers at 6 m/s. It is important to note that the thickness of the firebrands that penetrated the tiles were measured. The thickness of the firebrands were on the order of 1 mm thickness (very thin firebrands).

The concrete tiles (profiled) were the most sensitive to the amount of penetration as a function of wind speed. At the lower wind speed of 6 m/s, more firebrands were able to accumulate at the tile gaps (see Figure 14), which led to more firebrands being able to penetrate the tile gaps. In general, firebrand accumulation on the top of the roof assemblies was observed to decrease as the wind speed was increased from 6 m/s and 9 m/s. Naturally, profiled tiles were the most sensitive to this behavior, due to the raised profile.

An important parameter that was varied was the alignment of the tiles. In the Tile Roofing Institute manual [22], it specifies that the field tiles are to be offset. In this work, most of the experiments were conducted with the tiles aligned (not offset), since it is easier to construct the assemblies. However, experiments were also conducted by offsetting the tiles. **Figure 15** displays the influence of tile offset for the concrete (flat) tile assembly. In the figure, the top panel displays the offset tiles. Firebrand penetration was not influenced by offsetting the tiles. The numbers of firebrands that penetrated the same type of concrete tiles (flat) at 6 m/s, was 92 firebrands (offset tiles) vs 94 for aligned tiles. In either case, the number of firebrands that were observed to penetrate the tiles were similar. The offsetting of the tiles also did not hinder firebrand penetration in previous studies using the batch-feed firebrand generator [14].

Regardless as to whether the tiles are aligned or offset, these experiments may be a best-case scenario because in realistic applications the gaps between tiles may change with time due to earthquakes, settling of the structure, aging of the roof, or other possible reasons such as tile cracking. Manzello *et al.* [12] simulated those effects and observed greatly reduced performance of roofing assemblies as compared to well-aligned Spanish tile roofing assemblies.

Finally, it is worthwhile to compare these results to the prior scoping study using tile roofing assemblies exposed to firebrand showers using the batch-feed Dragon [14]. Whether USA or Australian roofing construction details are observed, firebrands are capable of penetrating concrete and terracotta roofing assemblies. In the prior study by Manzello [14], batten ignition was not observed, due to the limited firebrand exposure. In addition, in the prior scoping study, the flat tile terracotta roofing assembly performed best probably due to its interlocking design. For these tiles, the firebrands were observed to become trapped within the interlocking sections of the tiles and as a result, the firebrands were not transported past the tiles towards the sarking material. In the present study, all the tile assemblies resulted in firebrand penetration under longer exposures (again 20 min versus 6 min in Manzello [14]).

4.0 Summary

The performance of tile roofing assemblies as well as untreated (without any fire retardants) cedar shake roofing assemblies exposed to continuous firebrand showers were compared. The duration of the firebrand exposure was fixed at 20 minutes and the wind speed was varied from 6 m/s to 9 m/s. Results indicated that for the untreated cedar shake assemblies, ignition occurred easily from the firebrand assault, and this type of roofing assembly generated their own firebrands after ignition. With respect to the tile roofing assemblies, firebrand penetration was observed, even for the flat tile assemblies. It is believed these are the first ever experiments in the peer-reviewed literature to systematically determine wood and tile roofing vulnerability exposed to continuous wind-driven firebrand showers. As a part of future work, experiments are ongoing to apply these experimental protocols to profiled tile roofing assembly designs used specifically in Japan.

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6.0 References

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Figure 1.
Schematic of the NIST Continuous-Feed Firebrand Generator (NIST Dragon).

Figure 2.
Picture of Japanese cypress wood chips used to generate firebrands.

Figure 3.
Schematic of BRI's Fire Research Wind Tunnel Facility (FRWTF).

Figure 4.

Construction edge details when using counter-battens, from Tile Roofing Institute Manual, for flat tile roofing assemblies [22]. A similar construction technique was followed for profile tile assemblies. As the use of a mesh screen was optional, a 1/8" mesh screen was used in all experiments.

Figure 5. Cedar shake roofing assembly exposed to wind-driven firebrand showers. The length of each shake was 457 mm with exposure of 255 mm. The height, from the wind tunnel floor to the front edge of roof deck, was 1210 mm.

Figure 6. Concrete tile (profiled) roofing assembly exposed to wind-driven firebrand showers. The dimensions of each tile were 440 mm long by 315 mm wide. The height, from the wind tunnel floor to the front edge of roof deck, was 1210 mm.

Figure 7. Concrete tile (flat) roofing assembly exposed to wind-driven firebrand showers. The dimensions of each tile were 430 mm long by 330 mm wide. The height, from the wind tunnel floor to the front edge of roof deck, was 1210 mm.

Figure 8. Terracotta tile (flat) roofing assembly exposed to wind-driven firebrand showers. The dimensions of each tile were 355 mm long by 229 mm wide. The height, from the wind tunnel floor to the front edge of roof deck, was 1210 mm.

(a)

(b)

Figure 9.

(a) Size and mass distribution of generated firebrands as a function of wind speed. (b) Comparison of size and mass distributions of firebrands generated in this study and in previous studies [18, 19]. In Figure 9b, the mass is shown up to 0.2 g, as most of the firebrands collected from the structure component experiments were less than 1 g, and 10 cm², respectively.

Figure 10.
Firebrand accumulation and subsequent flaming ignition of untreated cedar shake roofing assembly exposed to firebrand showers at 6 m/s.

Figure 11.
Picture of firebrands generated from ignited cedar shake roofing assembly at 9 m/s. For reference, the hole in of the bracket is 6.4 mm in diameter.

Figure 12.

The number of firebrands that penetrated the tile roofing assemblies as a function of applied wind speed.

Figure 13. Firebrand penetration resulted in smoldering ignition (SI) of the counter-batten system but a transition to flaming ignition was not observed. These SI may be observed in (a) terracotta tiles (flat) and (b) the concrete tiles (profiled) exposed to firebrand showers at 6 m/s.

Figure 14. Concrete (profiled) tiles exposed to firebrand showers at 6 m/s. Areas where firebrand accumulated are shown in the yellow circles. It was observed that these types of accumulations decreased as the wind speed was increased.

Field Tiles Offset **Field Tiles Aligned**

Figure 15.
Photos showing the influence of tile offset on tile roofing assembly construction.