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Quantifying Wind-Driven Firebrand Production from Roofing Assembly Combustion

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Abstract

Large outdoor fires present a risk to the built environment. Examples often in the international media reports are wildfires that spread into communities, referred to as Wildland-Urban Interface (WUI) fires. Other examples are large urban fires including those that have occurred after earthquakes. Firebrands are a key mechanism on how rapidly fires spread in urban fires and WUI fires. An experimental protocol has been developed to ignite full-scale roofing assemblies and quantify the degree of firebrand production during the combustion process. As wind is an important factor in firebrand generation, the experiments were conducted under a range of wind speeds at the Building Research Institute's (BRI) Fire Research Wind Tunnel Facility (FRWTF). A further unique aspect of this work is the experimental results are compared to firebrand size and mass distributions collected from an *actual* large-scale urban fire in Japan. Results of these experiments demonstrate that when only oriented strand board (OSB) is applied as sheathing, a significant number of firebrands collected from roofing assemblies were less than 1 g and 10 cm². It was also observed that experiments on individual building component firebrand generation provided useful insights into actual urban fire firebrand generation.

Keywords

Firebrands; Generation; Large Outdoor Fires; WUI Fires; Urban Fires

1. Introduction

Large outdoor fires are becoming an important research area across the world [1]. In many countries, wildland fires that spread into communities, termed wildland-urban interface (WUI) fires, are frequently seen in media reports and have resulted in loss of life and property damage. There have been several WUI fires all over the world. Recent examples include fires near the Great Smoky Mountains National Park in Tennessee in 2016 that claimed the lives of 14 people and destroyed more than two thousand commercial and residential structures. During October 2017, multiple WUI fires in California destroyed

more than five thousand structures and resulted in more than 40 deaths. In 2017, more than 60 people perished in WUI fires in Portugal.

In Japan, many cities are densely populated and there exists the potential for large-scale urban fires, even without the presence of earthquakes. The most recent of these urban fires occurred in Itoigawa City, Japan on December 2016. In this fire, 147 structures were damaged by fire, with 120 of 147 destroyed. The Great Hanshin earthquake in Kobe, Japan, in 1995 had urban fires that occurred after a strong earthquake. More than 285 fires were reported that burned more than 7,000 structures.

Firebrands are an important structure ignition mechanism in both WUI and urban fires. Hardly any data exist for firebrand size distributions from actual structures or large outdoor fires, such as WUI and urban fires [2–4]. In WUI fires, the structures themselves are a large source of firebrands, in addition to the vegetation [5]. It is important for the reader to grasp that WUI fires are more complex than wildland fires due to combined structure and vegetative fuel combustion processes. In the case of urban fires in Japan, structures are responsible for firebrand production, but as in the case of WUI fires, little is known about firebrand size/mass distributions produced.

In this paper, efforts to investigate firebrand production from full-scale roofing assemblies are presented. An experimental protocol has been developed to ignite full-scale roofing assemblies and quantify the degree of firebrand production during the combustion process. As wind is an important factor in firebrand generation, the experiments were conducted under a range of wind speeds. These results are being incorporated into a comprehensive database the authors are developing related to firebrand production from structures. A further unique aspect of this work is that the experimental results are compared to firebrand size and mass distributions collected from an actual large-scale urban fire in Japan to determine if individual building component experiments may be used to provide insights into actual urban fires.

2. Experimental Description

Experiments were performed in the Building Research Institute's (BRI) Fire Research Wind Tunnel Facility (FRWTF) by varying the wind speed. As part of the database development, wall assemblies and re-entrant corner assemblies were used in experiments; here roofing assemblies have been considered.

The roofing assemblies used in the experiments were 1.2 m by 1.2 m in dimension. Wood joists (2×6) were used as framing, and oriented strand board (OSB thickness - 11 mm) was used as the base sheathing material (see Fig. 1). As a first-step, specific roofing coverings, such as roof tiles, were not applied. OSB was selected as it is a common construction material used in USA and Japan. The assemblies were installed inside the test section of the FRWTF at BRI (see Fig. 2). A custom frame was used to support the roofing assemblies and roof angle was fixed at 25° . This roofing angle was selected is between a 5:12 and 6:12 roof pitch, within the range of those found in practice.

The FRWTF was fitted with a 4.0 m diameter axial fan to produce a wind field up to a 10 m/s ($\pm 10\%$). The wind velocity distribution was verified using a hot wire anemometer array. The wind speed was measured upstream of the roofing assembly at several vertical points off the ground (e.g. 1.0 m height). To track the evolution of the size and mass distribution of firebrands, a series of water pans was placed downstream of the assemblies. Water pans were placed side-by-side with no space between. The water pan array width was greater than the roofing assembly width.

The ignition method used in this study was developed based on lessons learned from igniting wall assemblies for firebrand collection [6]. This method provided repeatable conditions to collect firebrands during combustion of the assemblies. It is not simple to simulate the conditions of an actual WUI or urban fire in a controlled laboratory setting. The effect of wind speed on firebrand size and mass distribution generated from a given roofing assembly configuration is an important parameter to study, as large-scale disastrous WUI and urban fires occur under elevated wind conditions. For this study, each roofing assembly was ignited using a propane gas T-shaped burner with a heat release rate of 26 kW positioned adjacent to the assemblies for 10 min under conditions of no wind. T-shaped burners were superior to point ignition methods such as a single propane torch. The T-shaped burner was placed on the outside of the roofing assemblies, at the leading edge, since the purpose of this study was to simulate ignition from an outside fire. If the burner was applied with wind (e.g., 6 m/s), flaming combustion of the assembly was difficult to achieve due to convective heat loss from the applied wind flow. Another advantage of ignition without wind (with the burner applied for the same duration for each assembly) was that it provided more repeatable initial conditions for the experiments. Specifically, the width exposed to direct flame contact (60 cm) was similar for a given assembly. If igniting with wind, in addition to large convective heat loss, the contact area of the flame onto the OSB surface of the assembly became unsteady.

The total ignition time of 10 min was very important and carefully selected during ignition under no wind field. If an ignition time less than 10 min was applied, once the wind field was added, the roofing assembly would self-extinguish, and little or no firebrand collection was possible due to lack of combustion. If an ignition time longer than 10 min was applied, the roofing assembly was observed to be consumed a great deal before the application of wind, thus rendering it unstable for firebrand collection (i.e. large holes were formed due to long ignition combustion process compromising the structural integrity).

With the application of the T-shaped burner to the assembly under no wind for 10 min duration, flaming combustion was observed on the exterior of roofing assembly. Once the burner was switched off, the wind tunnel was switched on (stable wind in 1 min). Firebrands were collected until the assemblies were consumed to such a degree that they could no longer support themselves (loss of structural integrity). Fig. 3 displays an image after the ignition of roofing assembly, with a 6 m/s wind applied. Firebrands were collected using multiple water pans placed behind the roofing assembly. Water was necessary to stop the combustion of the generated firebrands. After deposition into the water pans, firebrands were filtered from the water using a series of fine mesh screens. Firebrands were dried in an oven at 104 °C for 24 h (to remove moisture prior to measuring mass and surface area).

3. Results and Discussions

Experiments were conducted for wind speeds of 6 m/s and 8 m/s. Pictures of typical firebrands collected from roofing assembly combustion are shown in Fig. 4. Image analysis software (numerous commercially available packages exist; these are not identified since no endorsement by BRI/NRIFD/NIST is desired) was used to determine the projected area of a firebrand by converting the pixel area using an appropriate scale factor. The projected areas with the maximum dimension and the second maximum dimension of three dimensions were measured. The easiest method to visualize this is to imagine a sheet paper, as firebrands are often of very thin thickness, so the largest projected area is of interest. Images of specific shapes that have known areas (e.g. circles) were used to determine the ability of the image analysis method to calculate the projected area [4]. The standard uncertainty in determining the projected area was $\pm 10\%$. 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 $\pm 1\%$.

Fig. 5 displays a comparison of the collected firebrand size and mass distribution collected from these experiments. To more clearly show the results, the graph is plotted using a log-log scale. Of the more than 250 firebrands collected, only two firebrands were larger than 2.5 g. Both OSB and wood stud combustion resulted in firebrand production.

It is of interest to compare these roofing assembly data to other experiments, conducted previously that considered re-entrant corner assemblies as the firebrand ignition source [6]. In those experiments, re-entrant corners (walls) were constructed using wood studs (2×4), with OSB sheathing applied (11 mm thickness). Specifically, the wall dimensions were 1.2 m wide one each side, with a height of 2.44 m. The wood studs were spaced 40 cm on center (common spacing in US construction) [6] and the same wind speeds were applied (6 m/s and 8 m/s; see [6] for more details).

Similar to the roofing assembly results, Fig. 6 is plotted using a log-log scale. A direct comparison of the different building components may be seen. Fig. 7 provides a histogram to better show the various firebrand sizes grouped in distinct size classes.

There are often few opportunities to compare laboratory experimental data to that collected from an actual large-scale urban fire. A unique aspect of this paper is that such a comparison is provided. Due to deployment of rapid investigative teams by the National Research Institute of Fire and Disaster (NRIFD) [4], firebrands were hand collected from rooftops of buildings and other areas that were protected from firefighting suppression efforts. It is important for the reader to grasp that water pans were not placed during an actual fire but the collected firebrands were wetted from the suppression efforts. All the collected firebrands were analyzed for projected area and mass determination using the same methods described as part of the experimental work (oven dried as above). The fire started in a Chinese restaurant in Itoigawa-city, Niigata, Japan, around 10:20 am on December 22nd 2016. 147 structures were damaged by fire, with 120 of 147 destroyed. An average wind speed on that day was around 9 m/s with gusts up to 27 m/s. Wind data was available from the Japan Meteorological Agency [7]. The fire was extinguished by 4:30 pm on December 23rd 2016.

Many firebrands were seen flying and were observed to ignite 10 near-by structures [7]. Of these 10 structures, 3 were damaged and 7 were destroyed. The exact mechanism on the onset of structure ignition remains under investigation. Fig. 8 displays a comparison of firebrands collected from individual building components to those collected from the Itoigawa Fire. Here, the comparisons were conducted under similar wind speeds and it is interesting to observe that individual building component experiments may be used to gain valuable insights into complex, actual urban fires. Table 1 displays statistical data.

The only known detailed analysis of a firebrand size distribution from an actual WUI fire was conducted from burn pattern analysis of a trampoline exposed to firebrand showers during Angora Fire in California [3]. Image processing of 1800 holes revealed that the largest burned area was 10.25 cm²; more than 95 % of all burned holes were less than 1.0 cm². It is probable that some burn patterns were larger in area than the firebrands due to progressive combustion or melting, but it was assumed that the overall size distributions of burn pattern areas were representative of actual firebrand sizes. This assumption was investigated by exposing sections of materials collected (trampoline) in the Angora fire to continuous wind driven firebrands generated in the laboratory using the unique NIST Dragon's lofting and ignition research (LAIR) facility [3]. Since there was no mass data available, a direct comparison to Fig. 8 is not possible but the trampoline burned areas indicate firebrands in the same size classes.

4. Summary

Large outdoor fires are becoming an important research area across the world. Firebrands are a key mechanism on how rapidly fires spread in urban fires and WUI fires. Efforts to investigate firebrand production from full-scale roofing assemblies were presented. An experimental protocol was developed to ignite full-scale roofing assemblies and quantify the degree of firebrand production during the combustion process. Each roofing assembly was ignited using a propane gas T-shaped burner positioned adjacent to the assemblies. As wind is an important factor in firebrand generation, the experiments were conducted under a range of wind speeds at the Building Research Institute's (BRI) Fire Research Wind Tunnel Facility (FRWTF). These roofing assembly data were compared to other experiments conducted previously that considered re-entrant corner assemblies as the firebrand ignition source.

As a simplification to a very complex problem, roofing assemblies were constructed using only OSB as a sheathing material. When only OSB is applied as sheathing, a significant number of firebrands collected from re-entrant corner assemblies and roofing assemblies were less than 1 g and 10 cm². These experiments show that building component firebrand generation can provide useful insight into actual large outdoor fire firebrand generation. The experimental protocols presented in this paper may be used to begin to unravel the complex process of firebrand production from structure combustion. As part of future work, it is of interest to determine the influence of various roof coverings on firebrand production.

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6. References

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Figure 1.
Schematic of roofing assemblies used for the experiments. A top view is shown.

Figure 2.
Top view of BRI's FRWTF; the location of roofing assemblies and water pan array is shown.

Figure 3. Roofing assembly combustion exposed to an applied wind speed of 6 m/s. The T-shaped burner is shown (gas supply terminated since 10 min ignition period has passed).

Figure 4.

Images of typical firebrands collected for the image analysis. In these images, firebrands were collected at 6 m/s from roofing assembly combustion.

Figure 5. Size and mass distribution of collected firebrands from roofing assembly combustion. The roofing assembly was constructed from 2×6 joists lined with OSB as sheathing.

Figure 6.

Size and mass distribution of collected firebrands from re-entrant corner assembly combustion [6] directly compared to roofing assembly data in Fig 5. The wall dimensions were 1.2 m wide one each side, with a height of 2.44 m.

Figure 7.
Comparison of size distribution for roofing assembly combustion to re-entrant corner assembly combustion [6].

Figure 8.

Comparison of firebrands collected from individual building components to those measured from an actual urban fire.

Table 1

Comparison of average firebrand size and projected area collected from individual building components to those measured from an actual urban fire.

Conditions	Average Firebrand Mass (g)	Average Firebrand Projected Area (cm ²)
Roofing Assembly (8 m/s)	0.1	1.5
Itoigawa Fire (9 m/s)	0.7	3.2
Re-entrant Corner (8 m./s) [6]	0.6	4.5