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Garnering understanding into complex firebrand generation processes from large outdoor fires using simplistic laboratory-scale experimental methodologies

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Abstract

A simple laboratory-scale experimental method was developed to study firebrand generation processes. As part of these experiments, Japanese wind facilities were used to elucidate the effect of wind speed on firebrand generation from structural materials. It was found that very simple experimental methodologies developed as part of this study for mock-ups of full-scale roofing assemblies yielded important understanding into firebrand generation processes for both real-scale structure combustion processes as well as available firebrand information from urban and wildland-urban interface (WUI) fires.

Keywords

wildland-urban interface (WUI) fires; urban fires; large outdoor fires and the built environment; firebrand; firebrand generation; structure firebrands

1. Introduction

Urban fires, wildland-urban interface (WUI) fires, wildland fires/wildfires, and informal settlement fires are examples of large outdoor fires omnipresent across the globe [1, 2]. WUI fires are frequently discussed in the international news media; however, these may be inappropriately labeled as wildland fires, as the name does not suggest the combustion of structures. WUI fires occur where structures and vegetation coincide and have resulted in significant losses, both in terms of life and property destruction [3]. In Northern California, a series of WUI fires happened in 2018 that made the public acutely aware of the extreme destructive power such fires possess. By the time these WUI fires were brought under control, in excess of 18,500 structures were gone and scores of people perished [4]. In many regions throughout the world, population centers are intensely populated. In such areas, the risk exists for large urban fires. In Asia, and especially in Japan, people desire to live in city centers, and this results in high population densities in these urban areas. For these reasons, the risk of potentially destructive urban fires is always present. There is a long history of

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such urban fires, such as the Meireki Fire in the 1600s up to the recent Itoigawa Fire in Niigata in 2016. The constant threat of earthquakes in Japan only adds to these risks [2]. In the developing world, there are many informal settlements, often referred to as shantytowns. In both South Africa and the Philippines, these informal settlement fires have resulted in vast destruction and left many homeless [1, 5, 6].

Urban fires and WUI fires may result in the destruction of hundreds to even thousands of structures [7]. To come up with effective solutions to reduce these losses requires an understanding of the underlying physical ignition mechanisms in these fires. In these fires, firebrands act to ignite structures and also carry fire spread processes [8-10].

Firebrand processes may be divided into 4 components; generation, transport, deposition, and ignition [11]. For a significant time, research programs related to firebrands have been centered on transport processes. Very few research programs have placed expenditures on firebrand generation and ignitions processes [12-25]. The recent invention of the firebrand generators has led to new knowledge about weak points structures possess to firebrand showers [12, 26]. Much effort is still required to determine how firebrands are produced during structure burning [27, 28]. Previous research focused on development of simple-laboratory experiments for firebrand generation from wall assemblies [27]. Better knowledge with respect to the physics of generation will provide new countermeasures to be able to lessen the amount of firebrands liberated from these combustion processes.

Experiments that employed mock-ups of full-scale roofing assemblies were undertaken in a quest for improved comprehension into firebrand generation processes as roofing assemblies also are considered to be a large source of firebrand generation. The important influences of wind speed on firebrand generation processes in these experiments was also considered. An exhaustive comparison with findings from the simple laboratory-scale experimental method developed in this study were made to available firebrand generation information from much more complex and realistic scale-studies, including experiments and post-fire investigations.

2. Experimental Description

All of the experiments that made use of mock-ups of full-scale roofing assemblies were undertaken at the National Research Institute of Fire and Disaster's (NRIFD) wind facility, located in Tokyo, Japan. A 400 cm diameter fan allows for wind generation. The generated wind field was quantified to be within $\pm 10\%$ (two standard deviations) over a cross-section of 200 cm by 200 cm. Experiments were performed within this cross-section.

Mock-ups used in this study were roofing assemblies constructed with plywood and wood studs, with the dimensions of 610 mm (W) x 610 mm (H). A series of experiments over various scales were conducted to determine the size of the mock-up roofing assembly, and it was decided to use half the width and the height of the full-scale assembly. The focus on the sheathing materials is important to discern if these would contribute to actual production of firebrands. The roofing angle was maintained constant and selected to match those commonly observed (25°). The sizes of the mock-up assemblies were determined based on extensive investigations by the authors into firebrand generation from structure combustion

processes over several years [27, 29-34]. The schematics of the mock-up roofing assembly and the full-scale roofing assembly are shown in Figure 1. The full-scale roofing assembly methodology has been described elsewhere but the data here is new, as the sheathing type is plywood as opposed to oriented strand board (OSB) [33]. The recent OSB experiments were conducted using a large-scale wind tunnel in Tsukuba, Japan operated by the Building Research Institute (BRI).

Experiments were operated with careful, well-defined procedures. Mock-up roofing assemblies were ignited with a burner (shown in Fig. 2; in the shape of the letter T) with heat release rate (HRR) of $32 \text{ kW} \pm 10 \%$ (two standard deviations) for 600 s. To provide repeatable experimental conditions and constant flame contact areas, all ignitions were initiated without wind.

Key knowledge garnered as part of the full-scale roofing assembly experiments were applied to develop the ignition methodology for the mock-up assemblies. The mock-up assemblies were exposed to the burner for 600 s. This was the same time used for the full-scale assemblies. If the burner was applied for less than 600 s, after the wind field was switched on, the roofing assembly would extinguish, providing insufficient firebrand collection from lack of actual combustion. If the ignition time of 600 s was exceeded, the roofing assembly was degraded significantly prior to wind application, making it unstable for firebrand collection as it lacked structural integrity to sustain combustion (collapsed).

Upon ignition, gas supply to the burner was terminated and the desired wind was applied. Experiments were terminated when the combustion of the assemblies was completed or the assemblies degraded structurally, compromising the ability to observe the generation processes.

Multiple water-filled trays were carefully placed downwind behind the assemblies to collect firebrands generated from the assembly combustion (Fig. 3). Water in the trays was required to cease the firebrand combustion processes. All the firebrands collected in the trays were considered to be burned and released from the assembly. After the experiments these water-filled trays were collected and a labor intensive process to remove the water from the collected firebrand commenced. The firebrands were dried to remove all the moisture. The masses of the dried firebrands were individually measured, and pictures were taken for further analysis.

The projected area of a firebrand was determined using image processing methods. Projected areas with the largest dimension and second largest dimension were determined. The ability of the image analysis method to calculate the projected area was ascertained by comparing to shapes of areas easily calculated from geometric equations. The uncertainty in determining the projected area was $\pm 10 \%$ (two standard deviations). The uncertainty in the firebrand mass was approximately $\pm 1 \%$ (two standard deviations). The collection method and image analysis used for this study are the same as our previous firebrand generation studies [27, 29 -34].

3. Results

Experiments with mock-up roofing assembly or full-scale roofing assembly were undertaken for two different wind speeds, 6 m/s and 8 m/s. To help understand these experiments better, pictures are shown in Figure 4.

Figure 5 displays images of firebrands collected from both the full-scale and mock-up roofing assemblies. These images are typical examples used to determine the projected area, as well as to compare characteristics of firebrands generated from the different assemblies. The images also show the characteristics of firebrands collected from the mock-up roofing assembly combustion and those from full-scale roofing assemblies. It is also useful to compare physical characteristics of the firebrands collected from roofing assembly combustion. Median mass, thickness, and projected area of firebrands collected under each condition are provided in Table 1. As seen in Fig. 5, firebrands collected from both the mock-up roofing assembly and full-scale roofing assembly possess typical characteristics of firebrands from wall assemblies constructed with plywood and studs [34].

The size and mass characteristics of firebrands are important to be able to not only conduct ignition studies but also be able to model the generation and subsequent transport and deposition processes of firebrands from burning structures. An important characteristic of firebrands is the relationship between mass and projected area [27]. The relationship between the projected area and mass can be described as follows;

$$m_{firebrand} = \rho_{firebrand} \times t_{ave, firebrand} \times PA_{firebrand} \quad (1)$$

Here $m_{firebrand}$ is firebrand mass, $\rho_{firebrand}$ is firebrand density, $t_{ave, firebrand}$ is the firebrand average thickness perpendicular to the projected area, and $PA_{firebrand}$ is the maximum projected area of a firebrand. Thus, firebrand data under each condition were also examined to be fitted into linear equations in the form of Eq. 1.

3.1 Mass and Projected Area

3.1.1 Repeatability of data—Figure 6 compares repeatability of the firebrands generated from two mock-up roofing assemblies using the ignition methodology that was described above. Two experiments were conducted for each of the wind speeds considered. As the mass versus projected area had a linear relationship (described in Eq. (1)), the repeatability of ignition methodology may be observed for both wind speeds shown in Figure 6. As the primary focus on this research is the relationship between the mass and the projected area of firebrands produced from mock-up assemblies, this relationship is shown in Figure 6.

3.1.2 Comparison with full-scale experiments—Figure 7 displays a comparison of mock-up roofing assembly experiments to those using full-scale roofing assemblies (15.8 mm thickness plywood sheathing). For the full-scale and mock-up roofing assemblies, the mass versus projected area had a linear relationship that varied with wind speed. Similar

trends were seen as wind increased to 8 m/s from 6 m/s. This is similar to our previous study with wall assemblies [27].

Figure 8 shows the relationship between the value of slope in Fig. 7, $\rho_{\text{firebrand}} \times t_{\text{ave, firebrand}}$ and the wind speeds, with mock-up roofing assembly and full-scale roofing assembly. [34]. The uncertainties were calculated based on R^2 given the uncertainties in measurements described above. While the value for full-scale roofing assembly was slightly larger than the ones for mock-up roofing assembly, the trend is well captured (see Fig. 8).

The force from wind to roofing assembly can be shown as

$$F_{\text{wind}} \propto v^2 \quad (2)$$

Here F_{wind} is the wind force applied to the assemblies and v is the wind speed towards the specimen. Wind force increases 1.7 times, as wind speed increases from 6 m/s to 8 m/s. In this case the value of the slope increased 1.4 times and 1.6 times for mock-up assembly and full-scale assembly, respectively, as the wind speed increased from 6 m/s to 8 m/s.

3.3 Comparison with post-fire investigation data

Firebrands generated in the current work were compared with firebrand data collected from actual urban fires. While there are greater uncertainties in post-fire investigations as compared to laboratory-scale experiments, findings from actual fire events are needed to provide validation to laboratory scale findings. Details are provided elsewhere, but important background information on these past fires are provided to help the understanding of readers. The Itoigawa-city Fire happened in 2016 and damaged one hundred and forty-seven structures, eventually destroying 82 % of these structures [10, 35]. During the fire, the average wind speed was 9 m/s with gusts up to three times this average. The fire was put out 30 hours after it started. Firebrands were scattered over a large part of the city and ignited ten structures, subsequently producing mass urban fire spread. The ignitions from the scattered firebrands overwhelmed available firefighting resources.

The burned area was approximately 40,000 m². Firebrands ignited wooden structures fitted with Japanese style tile roofing assemblies. This fire is the worst urban fire in Japan in the last 40 years. Firebrands were collected at many areas in the city (burned area) after the fire was brought under control. A total of 277 firebrands were collected, and one was provided by the local fire department. Care was taken to sample firebrands from areas where known firebrand ignitions had been reported. After the collection, firebrands were oven-dried until the mass of firebrands became constant before the measurement. The collection method was different from that used in this study (not possible to place water pans during actual urban fire) while the same analysis was performed on the collected firebrands.

Figure 9 displays a comparison of firebrands generated from mock-up roofing assemblies constructed from wood studs and plywood as compared to firebrands collected from the 2016 Itoigawa-City Fire. In order to focus on the relationship between the mass and the projected area of firebrands, mass up to 5 g and projected area up to 25 cm² is shown in Fig. 9; thus the biggest firebrand with mass of 114 g is not included in Fig. 9. The data have

similar trends, and firebrand data from Itoigawa-city fire was found to fit into Eq. (1). Thus, again, the slope of value in Fig. 9 is compared with current experimental data in Fig. 10. The value of slope, $\rho_{\text{firebrand}} \times t_{\text{ave, firebrand}}$ from Itoigawa-city fire was found to be in good agreement with the data from Fig. 7. The uncertainty is naturally larger than those from experiments in controlled conditions due to the unknown materials and occasional gusts of wind during the fire. Despite the unknown factors due to the actual fires, the current experimental methodology of mock-up roofing assembly combustion captures the trends quite well.

3.2 Thickness and Mass

In addition to the projected area, the thickness of each firebrand was measured with precision callipers. The information on average firebrand thickness is desirable given Eq. (1). However, as firebrands rarely have uniform thickness and it is difficult to define or measure average thickness, the maximum thickness of firebrands is offered here.

Figure 11 displays these data plotted as a function of firebrand mass. It is interesting to observe that similar firebrand thicknesses were also observed between the full-scale roofing assemblies as well as the mock-up roofing assemblies. While the observed relationship was weak, similar trend was confirmed via curve-fit. As the wind speed increases from 6 m/s to 8 m/s, the force applied to the combusting assemblies will also increase. For these reasons, the maximum thickness of generated firebrands becomes bigger, which is similar to the conclusion deduced from the mass versus projected area relationship discussed in 3.1.

Firebrand maximum thickness was rarely observed to be greater than 10 mm and none greater than 15 mm, regardless of whether full-scale or mock-up roofing assemblies were used. This was expected as the plywood thickness in this study was 15.8 mm, and it is unlikely that the thickness of firebrands could exceed the original thickness. While it is possible that plywood may expand during the initial combustion process, as it is fabricated from multiple layers of thin veneers glued together, the collected firebrands suggest that the ultimate thickness is reduced due to subsequent pyrolysis and enhanced combustion process during transport.

4. Conclusions

Large outdoor fires are becoming an increasing problem of global importance. An important aspect in the rapid spread of large outdoor fires are the production or generation of new, far smaller combustible pieces from the original fire source known as firebrands. Experiments that employed mock-ups of full-scale roofing assemblies were undertaken in a quest for improved comprehension into firebrand generation processes. The important influences of wind on firebrand generation processes in these experiments was also considered. An exhaustive comparison of the findings from the simple laboratory-scale experimental method developed in this study were made with available firebrand generation information from much more complex and realistic scale-studies, including experiments and post-fire investigations. It was found that the very simple experimental methodologies developed as part of this study for mock-ups of full-scale roofing assemblies yielded insights into

firebrand generation processes for both real-scale structure combustion processes as well as available firebrand information from urban fires.

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6. References

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Highlights:

- Simple laboratory-scale method developed to study firebrand generation processes
- Series of experiments performed igniting mock-up roofing assemblies
- Japanese facilities used to ascertain wind effect on firebrand generation processes
- Laboratory-scale experiment yielded understanding of firebrand generation processes

Figure 1.
Comparison of size of the mock-up roofing assembly (left) and the full-scale roofing assembly (right) in this experimental series.

Figure 2. Schematic of roofing assembly mock-ups. The location of T-burner and wind direction are shown.

Mock-up roofing assembly experiments

Full-scale roofing assembly experiments

Figure 3.
Placement of the water pan arrays both in mock-up roofing assembly experiments and full-scale roofing assembly experiments.

Figure 4.
Typical experimental images at the wind speed of 8 m/s. Mock-up roofing assembly (top)
and full-scale roofing assembly (bottom).

Figure 5. Examples of images used to determine the projected area of collected firebrands. Those collected from mock-up roofing assembly (left) and those collected from full-scale roofing assembly (right). The wind speed was 8 m/s.

- Firebrands from mock-up roofing assembly (6 m/s)
- Firebrands from mock-up roofing assembly (6 m/s) (repeat)

- Firebrands from mock-up roofing assembly (8 m/s)
- Firebrands from mock-up roofing assembly (8 m/s) (repeat)

Figure 6.
The repeatability of the methodology to generate firebrands from mock-up roofing assemblies constructed from wood studs and plywood.

Figure 7.
Comparison of full-scale roofing assembly experiments to those of mock-up roofing assembly intended to study firebrand generation processes.

Figure 8.
Relationship between the value of slope in Figure 7 and the wind speeds.

- Firebrand data from Itoigawa-city fire (ave. 9m/s)
- Firebrand data collected from mock-ups roofing assembly (8m/s)

Figure 9.
Comparison of firebrand generated from mock-up roofing assemblies with firebrands collected from the 2016 Itoigawa-city fire.

Figure 10.
Comparison with urban fire, mock-up roofing assembly, and full-scale roofing assembly

Figure 11.

Comparison of firebrand thickness generated from mock-up roofing assemblies as compared to full-scale roofing assemblies for two wind speeds (6 m/s and 8 m/s).

Table 1

Median of mass, thickness, and projected area of firebrands

wind speed (m/s)	Mock-up roofing assembly		
	mass (g)	thickness (mm)	projected area (cm ²)
6	0.042	2.8	0.71
8	0.074	4.3	1.1
	Full-scale roofing assembly		
6	0.035	2.5	0.60
8	0.057	3.6	0.83