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Firebrands Generated in Shurijo Castle Fire on October 30th, 2019

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Abstract. A fire started in Shurijo Seiden, or the main hall of Shurijo Castle, Naha-city, Okinawa, Japan on the morning of October 30th, 2019. The fire resulted in loss of 8 structures and many important Okinawan cultural assets. The original Shurijo Castle was destroyed many years ago and a replica was constructed and rebuilt to be as close as possible to the original building. The replica was fabricated mainly from wood (*Chamaecyparis taiwanensis*). Firebrands were reported during the fire. In this study, firebrands from Shurijo Castle was collected and analyzed. The data was compared with those from other investigation as well as experimental data.

Keywords: Investigation, Cultural heritage, Firebrands

1. Introduction

Increasing number of large outdoor fires, including urban fires, informal settlement fires, wildland-urban fires and wildland fires, has an impact upon people's lives [1]. One of drivers for quick fire spread in outdoor fire settings are known to be firebrands. Firebrands are produced from vegetation or structures, and travel far from the incipient fire, and cause ignition [2, 3]. The danger of firebrands has been pointed out for some time in post fire investigation [4, 5], yet the lack of reliable data from actual outdoor fire events makes it difficult to evaluate.

Only a few studies have been conducted to investigate the actual size of firebrands produced in the real fire events [6–10] coupled with experimental approaches [11–15]. For wildland-urban interface (WUI) fires, Manzello and Foote studied the trampoline showered by firebrands in the 2007 Angora fire in California, USA [7]. Firebrands burned through the trampoline, and made holes. Their analysis on burn patterns showed the more than 95% of firebrands have less than 1.0 cm^2 projected area. In the 2011 Bastrop County Complex Fire in Texas, USA, a similar method was applied and found that 90% of firebrands have less than 0.5 cm^2 projected area [8]. For urban fires, firebrands were collected in the 2010 Beppu city fire, and in the 2016 Itoigawa city fire both in Japan [9, 10]. Both investigations concluded the size of firebrands were small, mostly less than 10 cm^2

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projected area, and less than 1 g. Experimental approach varies from burning a whole structure [11, 12] to smaller components [13–15] with different collection methods. Despite difference, small firebrands with less than 1 cm^2 dominate the production.

In the Shurijo Castle fire in 2019, a large number of firebrands were observed, which prompted fire department to issue the evacuation recommendation [16]. Presently, this paper examines firebrand production from the Shurijo Castle fire, and comparison is made with firebrand data from literature.

2. About the Fire

On the morning of October 30th,2019, a fire started in Shurijo Seiden, Shurijo Castle, located in Naha-city, Okinawa, Japan. Figure 1 shows Shurijo Castle, before the fire. The exact time of the start of the fire is unknown. The heat was detected by a sensor at 2:34 AM on the 1st floor of Shurijo Seiden. Security guards saw smoke already filled around 2:35–2:37 AM. The fire was notified to Naha-city Fire Department at 2:41 AM and firefighters arrived at 2:48 AM. When they arrived, the fire was already observed ejecting the flame from Shirijo Seiden [17]. The fire spread quickly and overwhelmed firefighters, which resulted in the loss of 8 buildings (6 of them were totally destroyed, 1 was half destroyed, and 1 was partially destroyed) (see Fig. 2) [16]. In total, around 4,800 m^2 was burned.

Figure 1. Image of Shurijo Castle (Seiden) (before the 2019 fire) where a fire started. The height of Shurijo Seiden is 18 m.

Figure 2. Map of Shurijo Castle. Burned buildings and firebrand collection sites are indicated.

The cause of the fire is unknown [18]. The fire was controlled 11:AM, and extinguished 1:30 PM.

On the day of disaster, the weather was clear and wind speeds during the fire was around 5 m/s to 6 m/s from NNE (22.5 degree), then increased to 8 m/s with wind from ENE (67.5 degree) then East later that day, shown in Fig. 3 (a) [19]. As shown in Fig. 3 (b), the temperature was constantly around 24 °C until 7 AM, then increased during the day and the relative humidity was around 70% until 7 AM and decreased to 64% afterwards. The location of weather observatory is shown in Fig. 4.

The fires were intense; firefighters felt intense radiative heat from the fires, and it was impossible for them to keep working at the site at some point. Shurijo Castle itself is not the original building, having burned down 4 times before this incident. Nonetheless efforts were made to recreate the original building as much as possible during 30 years of construction which finished just 2019. The replica was fabricated mainly from wood (mainly *Podocarpus macrophyllus, Chamaecyparis taiwanensis, Quercus miyagii, Thujopsis dolabrata, Chamaecyparis obtusa)*. The total floor area of Shurijo Seiden was 1199.24 m^2 (3 floor) and height was 18 m [20]. Roof was constructed as hon-kawara-buki style—round tiles, and flatter (still has profile) tiles are placed alternately. Due to the large fire, large amounts of fire-

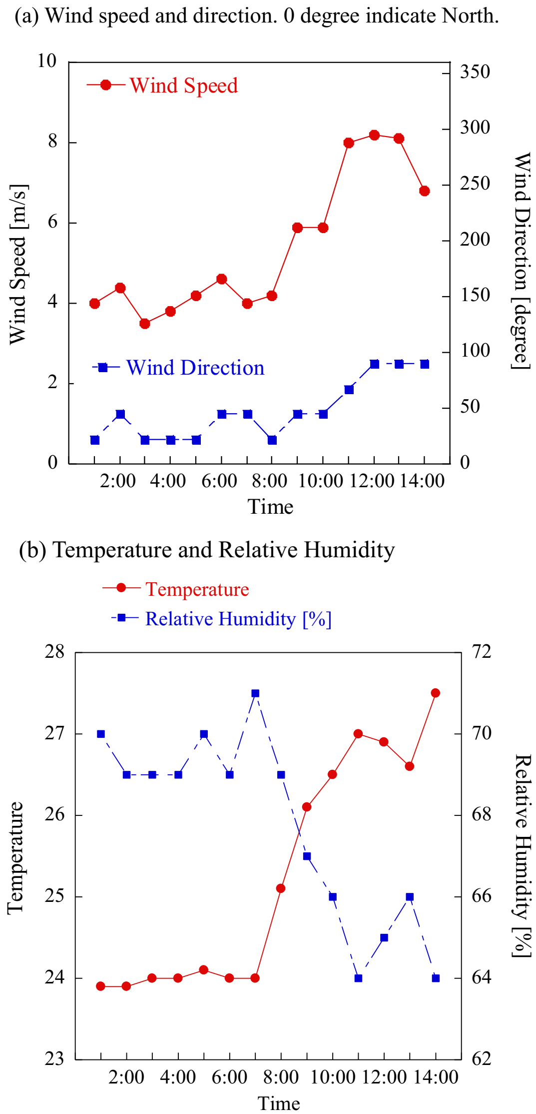

Figure 3. Weather information during the fire. a Wind speed and direction. 0 degree indicate North. b Temperature and Relative Humidity.

brands were produced, and Naha-city fire department issued the evacuation recommendation and opened three temporary shelters [16].

After the fire, investigation was undertaken and firebrands were collected in Shurijo Castle Park on November 4th, 2019 and November 5th, 2019. Figure 5 shows the situation after the fire disaster. Plastic from some of exhibit (approxi-

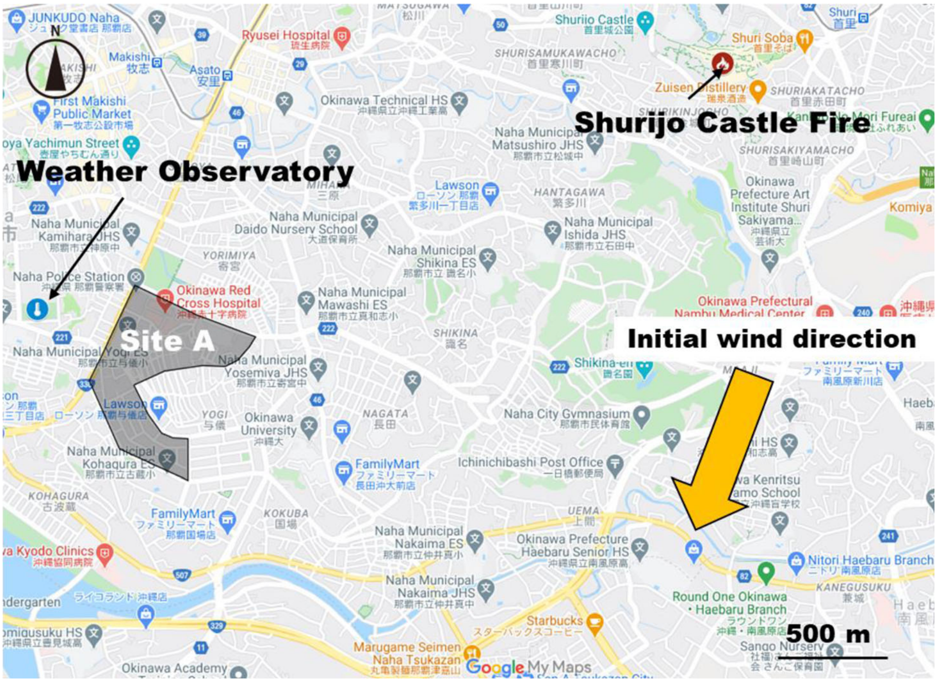

Figure 4. Location of Shurijo Castle and Weather Observatory in Naha-city, Okinawa, Japan. Site A indicates an area where firebrands were provided.

mately 30 m upwind from Seiden, or main hall) was melted. Trees were half burned, clearly only the side of the fire (near the location 6 in Fig. 2).

3. Firebrand Collection and Analysis

Firebrands were collected within the Shurijo Castle park on the locations shown in Fig. 2. Firebrands collected were deposited on grass as it is thought difficult for firebrands to move after landing. As the term "firebrands" means a burning air-borne object which may have the capability of starting the spot fires, the attention was paid to make sure those collected firebrands has not been extinguished before landing [3]. This was confirmed as some firebrands clearly charred grass upon landing, as seen in Fig. 6a, although there was no fire spread. Firebrands also landed on and charred tree leaves (Fig. 6b). Between the fire and the investigation, no rain was reported. Weather information is important as deposited firebrands may be broken or moved especially by rain. In this study, it was possible to collect firebrands on grass which is harder to move, while in other cases, it is important to collect firebrands from the places where external disturbance such as firefighting activity, weather, were less expected. The weather and location considered, collected firebrands were assumed to stay same place as deposited. Interest-

(a) Melted stamp rally board

(b) Half burned trees

Figure 5. Images shown for impacts of fires. a Melted stamp rally board b Half burned trees.

ingly, there was areas where no firebrands or burn patterns were found. It is possible firebrands burned out before landing or simply no firebrand deposited certain directions. Shurijo Castle was built on top of a hill and had a very

(a) A firebrand on leaves

(b) Charred marks by firebrand(s)

Figure 6. Pictures of collected firebrands. a A firebrand on leaves b Charred marks by firebrand(s).

complicated wall and gate structure, which also are expected to play a role in firebrand deposition.

In addition to the collected firebrands, four firebrands were provided by member of Naha-city Fire Department (the location is shown in Fig. 4 as Site A). Firefighter collected firebrands to simply show how far firebrands fly (approximately 2 km from the fire). 307 firebrands were collected. In total 311 firebrands were analyzed. Firebrands were carefully transported to National Research Institute of Fire and Disaster after the collection, and the analysis was performed there. Collected firebrands were dried in an oven of 104 °C. The temporal variation of mass loss was determined as function of time to determine the drying time to remove moisture. Based on this analysis, 24 h were sufficient to remove moisture from the collected firebrands. The mass of each firebrand was measured with a scale; a picture was taken with a scale and thickness was measured with calipers. The projected area was decided based on this method was used in our previous studies such as [10, 13] but describe here in summary. The projected area was determined assuming the deposited firebrands would rest flat on the ground. The projected area was calculated by image analysis software by using an appropriate scale factor (pixels/cm).

4. Results and Discussion

Figure 7 shows the mass and the projected area of firebrands collected. The number in Fig. 7 corresponds to the number in Fig. 2. Figure 7 is shown in log–log scale to show the size difference. The location 1, at the upwind location of the fire,

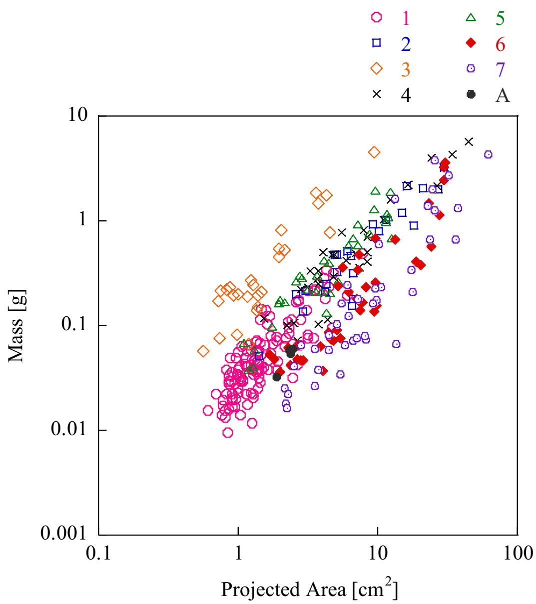

Figure 7. Size and Mass of firebrands collected from Shurijo Castle fire. Numbers and A indicate the collection site.

had the largest number of smaller firebrands compared to other locations. Firebrands collected at location 3 showed heavier trends than those from other locations. Location 3 is within the forest, and firebrands were collected on the ground. It is possible only heavier firebrands landed on the ground as firebrands would land on tree first then drop (land) on the ground.

One important ongoing question related to firebrand research is to correlate the distance from the source to the characteristics of firebrands. The Tachikawa number, used to characterize wind-blown debris [21], has been used for these types of analysis [8, 9]. The Tachikawa number has linear relationship with flying distance as well as $\frac{A}{m_{firebrand}}$. In short,

$$Ta \propto \frac{A}{m_{firebrand}}$$

$$Ta \propto D$$

Thus, $\frac{A}{m_{firebrand}} \propto D$

Here A is the projected area of a firebrand, $m_{firebrand}$ is the mass of a firebrand, and D is the flying distance. Given the liner relationship between the mass and the projected area of firebrands, $\frac{A}{m_{firebrand}}$ was calculated and plotted in Fig. 8 along with distance from a) center of the buildings, and b) the closest burned building. The distance and $\frac{A}{m_{firebrand}}$ shows the positive relationship except for location 3 in Fig. 2.

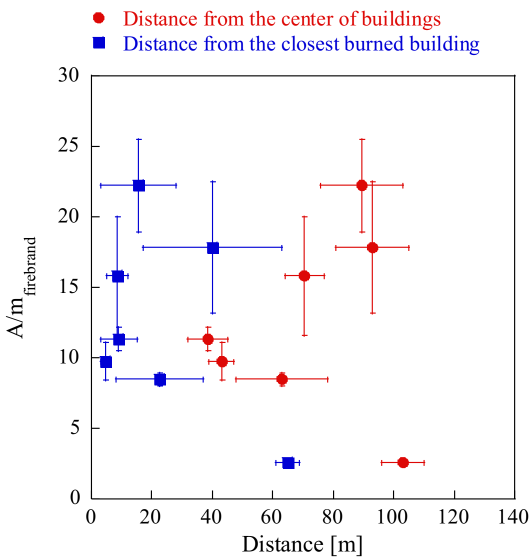

Figure 8. The relationship between the ratio of projected area and mass of firebrands vs distance from the source.

As discussed before, firebrands collected location 3 are heavier than those from other locations and have an impact on Fig. 8. Figure 9 shows the results of internet survey taken from [22]. This internet survey was done through the company (macromill). Three hundred twenty-one people in Naha-city joined this survey at the begging of February 2020. Questions were related to the location at the time of the fire, whether or not they saw the fire or firebrands, and what size of firebrands they observed. The location was identified based on the local area name

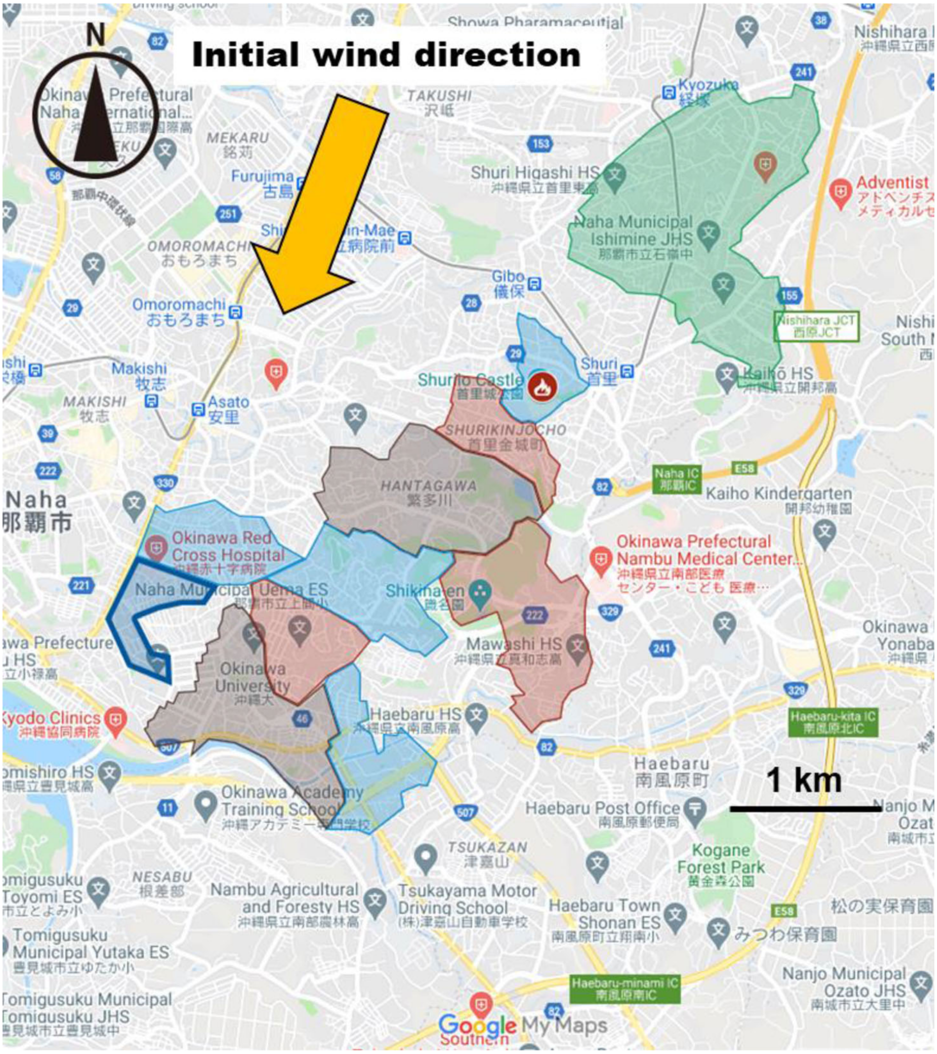

Figure 9. Firebrands transport distance based on online survey. Gray: firebrand size is small like powder, Green: firebrand size less than 1 cm, Blue: firebrand size between 1 and 5 cm, Red: firebrand bigger than 5 cm.

and witness information was cooperated with the location. Based on the survey, firebrands from Shurijo Castle fires were observed upwind and at least 6 km downwind from the fire. It is useful to understand a big picture of firebrand travel distance from the fire without going to the site and talking with witness while more detailed data and more attempt will be needed in the future. While this enabled to see the firebrand distribution from the source in larger area, it shows firebrand distribution may not be as simple as it can be assumed based on *Ta* number.

Figure 10 shows the thickness and the mass of firebrands collected. This relationship is more diverse than previous experimental data [13–15]. A variety of thicknesses were seen in firebrands collected, especially from location 1, 6 and 7 for given mass.

Figure 11 shows the comparison with firebrands collected in different investigations in Japan, namely, the 2010 Beppu-city fire [9], and the 2016 Itoigawa-city fire [10]. Wind speeds during the fires are different from those from the Shurijo Castle fire. Yet, since actual firebrand data from actual fires is limited, it is important to compare results, nonetheless. The wind speeds of Beppu-city fire and the Itoigawa fire were around 10 m/s with an average 9 m/s, respectively. Figure 9 shows all firebrands follow a single relationship, despite vast difference in the fires and the fuel sources of the firebrands.

The Itoigawa-city fire contained larger number of smaller firebrands than the other fires compared here. One firebrand with a mass of more than 100 g is inclu-

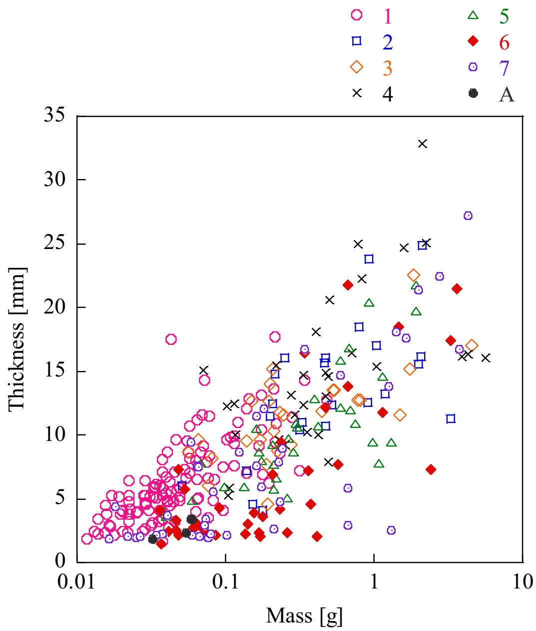

Figure 10. Thickness and Mass of firebrands collected from Shurijo Castle fire.

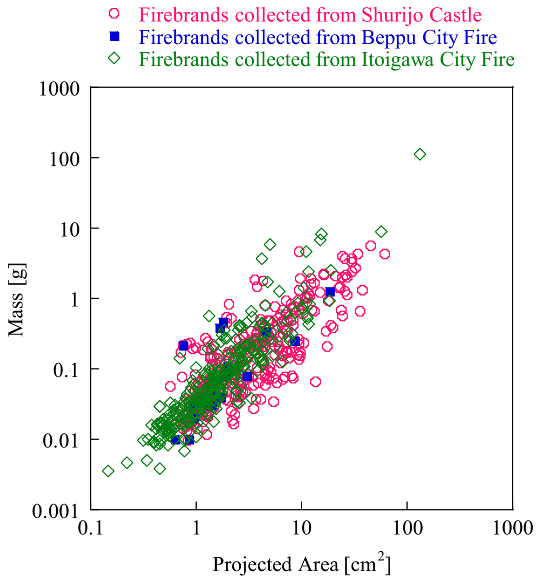

Figure 11. Comparison from previous investigation in Japan, Beppu city fire and Itoigawa city fire.

ded in Fig. 11, which makes it appear the Itoigawa-city fire produced a larger number of large firebrands, which in fact is not the case. Compared to the firebrand collection sites in the Itoigawa-city fire, which were mainly on roads or on roof tops, in the case of Shurijo Castle fire, firebrands were collected on the grass. For these reasons, it was difficult to find or collect smaller firebrands, as these could have landed under the grass itself, making it hard to see.

Figure 12 shows a comparison of firebrands generated in two previous experiments with a similar wind speed (4 m/s). One data set is that from the reduced-scale firebrand generator, which is adjusted to produce "structure firebrands" [23]. The other data set was that from reduced-scale firebrand generation experiments, specifically a corner assembly with a size of 61 cm × 122 cm × 2 and made from oriented stand board [24]. It is important to note that firebrand collection methods for experiments was using water pans, which is different from the investigation. Based on comparison, Shurijo-castle fire produced larger firebrands compared with those from the from experiments. As discussed above, firebrand collection location (on grass) may contribute to larger-sized firebrands. Nonetheless, the data provided here yields interesting insights from actual fire sources.

Despite the large number of firebrands that were observed, and evacuation was encouraged, no spot fires outside the Shurijo Castle park was reported to fire department during or after the Shurijo Castle fire. As residents were under evacuation orders, no resident interventions to put out spot fires were reported. One clear feature in this region of Japan is buildings are subject to many typhoons, therefore houses and buildings are built to resist high wind loads. Roof tiles are secured carefully with stucco (thus no space between roof tiles where firebrands

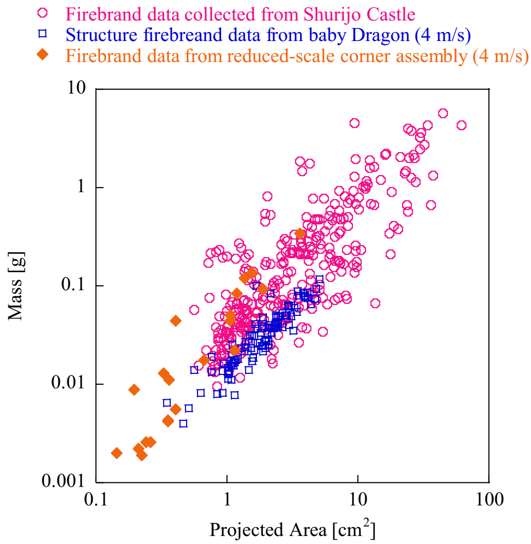

Figure 12. Comparison from other experiments under a similar wind speed.

may penetration) and main structural components are usually concrete. While these features do not prevent the possibility of spot fire ignitions, it appears to reduce the possibly, as no resident intervention measures were documented, and no spot fire ignition of structures were reported. In addition, the relative humidity (RH) was high, around 64% to 71%. While firebrands ignited grass and leaves, the fire never spread, as shown in Fig. 6.

5. Summary

A fire started on 30th October 2019 and resulted in 8 buildings lost after 14 h of firefighting. Due to the large fire, firebrands were observed everywhere. In this study, firebrands were collected in and around the surrounding area and compared with existing data. There is little available understanding from actual fire scenarios regarding firebrand production. To be able to better understand firebrand production processes, it is useful to try to collect information from actual fires. It is quite important to be able to link any research on firebrands in the laboratory to what has been actually observed in real fire situations. The procedures in this paper may also be used by other researchers to collect needed information from actual fire situations. The results show some promise understating the firebrand generation from historical buildings, especially when compared to laboratory studies.

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