Fire Safety Journal 96 (2018) 105–114

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

# A field experiment on fire spread within a group of model houses

Keisuke Himoto [a,*], Masahiko Shinohara [b], Ai Sekizawa [c], Ken-ichi Takanashi [b], Hitomu Saiki [b]

[a] National Institute for Land and Infrastructure Management, MLIT, Tachihara 1, Tsukuba, Ibaraki 305-0802, Japan
[b] National Research Institute of Fire and Disaster, MIC, Jindaiji-higashi 4-35-3, Chofu, Tokyo 182-8508, Japan
[c] Graduate School of Global Fire Science and Technology, Tokyo University of Science, Kagurazaka 1-3, Shinjuku, Tokyo 162-0825, Japan

ARTICLE INFO

*Keywords:*
Urban fire
Conflagration
Field experiment
Fire spread
Flame height
Heat release rate

ABSTRACT

In this paper, we report on our investigations into the behavior of successive fire spread between multiple houses in an urban area. More specifically, to acquire data necessary for the validation of our computational models, we conducted a fire spread experiment with nineteen 1/3-scale model houses aligned in a former quarry at Iwafune Mt. in Tochigi Prefecture, Japan. Most previous experiments used wood cribs or gas burners as fire sources to investigate the behavior of a fully-developed urban fire, but gave less attention to its formation due to successive occurrence of fire spread between houses. Successive fire spread between houses cannot be adequately simulated as discrete fuel elements in urban areas without replicating the exterior geometry, including openings allocated in each wall; however, this factor, which affects the intensity of heat transfer between houses, has not yet been considered in previous experiments except those that used disused houses. The experiment comprised two tests. In test 1, fire spread between model houses did not occur as was originally expected because of the short duration of the fully developed fire phase at the fire origin model house. The average mass loss rate in the fully developed fire phase was 1.33 kg/s with the maximum flame height of 7.8 m. In test 2, ceilings and roofs of model houses that were left unburnt in test 1 were reinforced so as to enhance their compartmentation, which in turn extends the duration of fire at each model house and the heating period of the adjacent model houses. As a result, fifteen out of eighteen model houses were burnt due to successive fire spread that lasted for about 50 min. The estimated maximum heat release rate of the group fire was about 100 MW with the maximum flame height of 11.0 m. The flame height after roof burn-through was modeled by introducing a conversion factor into one of the standard flame height model considering fresh air supply through openings due to the pressure difference between inside and outside of a model house. Although the quantitative agreement was not satisfactory, the overall change in flame height over time was adequately captured with the present model.

## 1. Introduction

Urban fire is a low-frequency, high-consequence event involving successive spread of fire between houses, especially in a dense urban area where houses are located with small separations between each other [1, 2]. There are several notable cases of urban fire: Chicago Fire (1871) destroyed over 17,000 buildings and caused 300 fatalities; San Francisco Earthquake Fire (1906) burnt city area of 1,200,000 $m^2$ and caused 700 fatalities; Kanto-Earthquake Fire (1923) directly caused 92,000 deaths (out of approximately 105,000 fatalities in total) and destroyed approximately 212,000 houses (out of 373,000 ruined houses); Sakata Fire (1976) destroyed 1700 buildings in spite of considerable effort made by fire fighters; and Hanshin-Awaji Earthquake Fire (1995), which involved concurrent ignitions at multiple locations in Kobe city, destroyed 7000 buildings and caused 500 fatalities. Although such devastating conflagrations occur infrequently, relatively smaller fires that involve tens of buildings are not uncommon; a recent example is the fire that burnt about 150 buildings in Itoigawa in 2016 [3].

Attempts have been made to investigate dynamics of urban fire, or of mass fire in general, to elucidate its threat and ensure safety of the society. The researcher Countryman conducted field experiments using woodland fuels such as juniper and pinon trees in ordered piles simulating built-up residential areas. Although this is one of the few examples of full-scale mass fire experiments, the experiment focused mostly on the measurement of flow behavior in and around the prescribed fire [4]. Thomas correlated the size of flames with rates of burning in the open field by formulae derived from a dimensional analysis [5]. NRIFD conducted a series of fire spread experiments using large-scale wood cribs

* Corresponding author.
*E-mail address:* himoto-k92ta@mlit.go.jp (K. Himoto).

https://doi.org/10.1016/j.firesaf.2018.01.003
Received 11 May 2017; Received in revised form 29 October 2017; Accepted 7 January 2018

**Nomenclature**

| | |
|---|---|
| $A$ | Area of opening ($m^2$) |
| $c_p$ | Specific heat (kJ/kgK) |
| $D$ | Reference length (m) |
| $g$ | Acceleration due to gravity ($m/s^2$) |
| $H$ | Height (m) |
| $\Delta H$ | Heat of combustion (kJ/g) |
| $M$ | Mass (kg) |
| $\dot{m}$ | Mass loss rate (MLR) (kg/s) |
| $\dot{m}_e$ | Mass entrainment rate (kg/s) |
| $\dot{Q}$ | Heat release rate (HRR) (MW, kW) |
| $\Delta T$ | Temperature elevation (K) |
| $t$ | Time (s) |
| $z_{fl}$ | Flame height (m) |
| $\rho$ | Density ($kg/m^3$) |

*Suffix*

| | |
|---|---|
| $C$ | Collapse of walls |
| $F$ | Fuel |
| $FO$ | Flame ejection from window |
| $k$ | Opening |
| $R1$ | Burn-through of roof |
| $R2$ | Collapse of roof |
| $S$ | Spill of smoke |
| $\infty$ | Ambient gas |

and disused houses. Fires were started from each disused house in the latter experiment to investigate into behavior of a fully-developed phase of group fire rather than its formation phase [6,7]. Williams summarized basic aspects of urban and wildland fire as a phenomena [8]. Baum et al. performed a theoretical study representing large fires as ensembles of individual fires of differing strengths distributed over sites within the burning area [9]. Heskestad examined the flame breakup hypothesis of mass fires with a low flame height relative to flame base size [10]. Quintiere summarized an instrumented experiment of a prescribed burn of forest debris to simulate conditions of a mass fire. The objective of this experiment related to the need to improve the ability to estimate the atmospheric smoke obscuration at high altitude, in addition to predict the damage due to fire growth [11]. Sugawa et al. and Kamikawa et al. investigated merging behavior of flames from multiple fire sources, which could be observed in urban fires [12,13]. Kuwana et al. and Himoto et al. experimentally investigated behavior of fire whirl around an L-shaped fire source observed in 1923 Kanto Earthquake in a wind tunnel [14,15]. As an alternate of experimental approach, Rehm et al. extended the NIST computational model known as FDS to study community-scale fire spread [16]. Himoto et al. and Lee et al. analyzed behavior of fire spread in an urban area using a physics-based model, which simulates fire behaviors of individual buildings under thermal influence of other buildings [17–19]. Thomas et al. and Zhao introduced a cellular-automata approach determining the rate and extent of fire spread in an urban area [20,21].

Unfortunately, the behavior of fire spread between houses in an urban conflagration has not yet been thoroughly investigated. One of the major difficulties of urban fire research is that urban fires are low-frequency, high-consequence events for which only a limited amount of information is available from records of actual fires. As an alternative, laboratory or field experiments have served as an opportunity to fill this gap. However, most previous experiments generally used wood cribs or gas burners as fire sources to investigate the behavior of a fully-developed urban fire, but gave less attention to its formation due to successive occurrence of fire spread between houses as discrete fuel elements. Fire spread between houses cannot be adequately simulated as discrete fuel elements in urban areas without replicating the exterior geometry, including openings allocated in each wall; however, this factor, which affects the intensity of heat transfer between houses, has not yet been considered in previous experiments except for those using disused houses [7].

In this study, a fire spread experiment has been conducted with nineteen 1/3-scale model houses aligned in a former quarry at Iwafune Mt., Tochigi prefecture, Japan, so as to investigate behavior of successive fire spread between multiple houses in an urban area and to acquire data necessary for the validation of computational models. The model houses were mock two-story wooden houses with openings allocated in each wall and they were left open. In addition to the overall behavior of a group fire, the present report focuses on the effect of flame ejection from a burn-through vent in the roof, which is often observed when a wooden house is involved in fire. A flame ejected from a burn-through vent is considered as a major cause of fire spread in an urban conflagration, as such flames merge into a larger flame magnifying the radiation intensity on adjacent houses [1,12,13].

## 2. Outline of the experiment

A fire was started at one of the nineteen model houses and the behavior of fire spread between the nineteen model houses was studied. A photograph showing the arrangement of the model houses is shown in Fig. 1. The experiment comprised two tests, whose outlines are summarized in Table 1. In the first part of the experiment, test 1, fire spread between model houses did not occur as originally expected because of the short duration of the fully developed fire phase at the model house of fire origin B. Thus, in the second part of the experiment, test 2, ceilings and roofs of model houses that were left unburnt in test 1 were reinforced so as to enhance their compartmentation, which in turn, extends the duration of fire at each model house and the heating period of the adjacent model houses. In test 2, fire was started from the model house N. As a result of reinforcement, fifteen out of eighteen model houses were burnt due to successive fire spread that lasted for about 50 min. A snapshot of the second test is shown in Fig. 2.

## 3. Test 1

### 3.1. Experimental condition

The model houses were mock two-story wooden houses, which often comprise dense urban areas in Japan, built at 1/3 scale with a square footprint of 3.6 m by 3.6 m. The square footprint was selected so as to arrange each façade faces in front of one of the adjacent model houses and to simplify heat transfer calculation between the model houses. However, note that the scale was a geometrical scale and the similarity of fire behavior to full scale was not considered. The exterior walls and


**Fig. 1.** A photograph showing the arrangement of model houses.