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Lai'an Fire Tests: Influence of Opening Condition on the Fire Dynamics of Real Urban Village Dwellings

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Abstract. As the most common informal settlement in the far east, urban villages are subject to very high fire risks due to relatively poor fire safety conditions and inefficient management. However, no experimental research has been conducted on the fire dynamics of Chinese urban village dwellings to date despite their own characteristics. In this work, two real-scale experiments with different opening conditions (both window and door open or closed) were performed in two urban village dwellings located in Lai'an County, with identical dimensions of 4.4 (length) × 3.3 (width) × 2.8 (height) m^3 and a fuel load of 407 MJ/m^2. The important parameters, in terms of inside gas temperatures, burning behavior, gas flow velocities at the opening, total heat release rate and flame behavior, were measured or estimated. It was found that the effect of the opening condition has a significant influence on the flashover occurrence, smoke movement and temperature distributions. In particular, with the window and door closed, the compartment fire self-extinguished, but the breakage and fallout of glass panels dramatically changed the fire dynamics from smouldering combustion to a post-flashover compartment fire. The interaction between enclosure fire dynamics and the fallout of window and door was then established. The experimental results would provide basic data and perception for further numerical or analytical analysis concerning the fire safety of urban village dwellings.

Keywords: Urban village, Informal settlement fire, Opening condition, Glass fallout

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1. Introduction

Urban villages, also called "villages in the city", are settlements that compose high density self-built or self-modified buildings, appearing on both outskirts and downtown segments of major cities due to rapid urbanization, which is normally considered the most common informal settlement in the far east [1]. With low living expenses and housing rent, a large number of domestic immigrants choose to live in urban villages, resulting in a redundant population that they can accommodate; in Shenzhen, one of the largest Chinese cities, there are still approximately 58% population living in urban villages in 2021 [2].

Similar to the informal settlement in other regions (Africa and South America) [3], a large number of UVDs (urban village dwellings) were constructed by rural residents decades ago and often reformed without the permission of the local government, which makes it very difficult to comply with current fire safety codes. In 2017, an urban village fire occurred in the Beijing Daxing district, causing 19 deaths [4] and another UVD fire in the same year in Changshu resulted in 22 deaths [5]. According to the fire statistics of 2021, the number of fires in self-built urban villages accounts for approximately 60.5% of the total number of residential building fires in China [6], indicating the serious fire safety situation of UVDs in the largest developing country.

In recent years, informal settlement fires have been extensively investigated in terms of large- or reduced-scale experiments, CFD (Computational Fluid Dynamics) simulations and GIS (Geographic Information System) analysis [7]. The dwellings with thermally-thin boundaries have been investigated experimentally to understand the fire dynamics of metal sheet wall compartments [8, 9]; FDS (Fire Dynamics Simulator) simulations have been performed to study the fire development and spread behaviour inside or between dwellings [10, 11]; and GIS methods for informal settlement fires have been developed to evaluate the critical separation distance between informal settlement dwellings [12] and propose a fire risk assessment methodology with LiDAR roof mapping [13]. However, to date, almost all informal settlement fire research has focused on the South African issue [7], where dwellings are normally constructed by single galvanized steel sheeting. Regarding the other most rapidly urbanizing region, Asia, little is known about its informal settlement fire characteristics, especially the most representative UVDs, despite its fire safety concern being highlighted approximately 10 years ago [14]. Different from the construction materials and structures of South African shacks, UVDs are usually built of bricks or concrete with multiple compartments and storeys. For security reasons, some shacks have no or very small windows [15], but the complexity of openings (ventilations) condition in UVDs will significantly change the stage of compartment fire and affect the spread of fire to surrounding dwellings. It was found that the vent size and geometry have a considerable impact on the vertical temperature and oxygen concentration profiles [16]. Large-scale compartment fire tests with unrestricted and restricted openings were conducted to analyze the ventilation effects on the thermal characteristics of fire spread modes and energy balance, and the results showed that compartments with large openings induced high momentum-driven flows and low gas phase temperature [17]. For urban village fires, the GIS method was used to analyze the fire hazard in Bandung City of Indonesia with four variables: population density, building density, building quality and road class [18]. To the authors' knowledge, to date, there have been no any full-scale experiments of the fire dynamics of the most common informal settlement, UVD, in China, which significantly hinders the development of renovation methodology and fire safety code development for UVD [19]. What is more, in prior compartment fire experiments, it was assumed that there are no glass windows and doors and that the sudden change in opening conditions caused by window or door fallout could not be well captured [7], which considerably differs from the real and complex ventilation conditions.

In this work, two full-scale experiments were conducted in real UVDs located in Lai'an County, Chuzhou City, China: in the first test, no door or window was installed, leaving the openings completely open; in the second test, both the glass window and door were initially closed tightly. All the room dimensions, construction materials and furniture were kept identical to make reasonable comparisons. The specific experimental conditions and results are introduced in detail in the following sections.

2. Experimental

As shown in Fig. 1, two UVDs, named Compartments 1 and 2, with identical internal dimensions of 4.4 m (L) × 3.3 m (W) × 2.8 m (H), were burnt on 23rd March 2021 in a real urban village building, as shown in the attached video. Both dwellings were built in the 1970s with brick walls covered by cement, which was considered a common type of UVD. New furniture, including a wooden bed (with 1 foam mattress, 4 cotton quilts and 2 pillows), foam sofa (with 6 throw pillows), wooden desk, wardrobe, nightstands and chairs, were placed in the dwelling based on the real situation suggested by Lai'an Fire Brigade. A synthetic curtain was installed at the window in each compartment. All the combustible furniture and their positions were strictly kept identical; the folding of the cotton quilt and the positions of pillows on the bed and sofa were the same as well. It should be noted that all the combustible materials have no fire retardant and were provided from furniture markets where local UVD residents normally bought them.

The detailed dimension and instrument layout are shown in Fig. 2a. In Compartment 1, no glass window or door was installed, thus two openings i.e. a window with an internal dimension of 2.8 m (L) × 1.6 m (H) and a door of 2.0 m (H) × 0.8 m (W) were kept open during the whole burning process. For Compartment 2, the layout of the furniture, measurement instruments, and fire ignition method were identical to those of Compartment 1. The only difference between the two dwellings is the opening situation: a wooden door and a window consisting of four float (non-tempered) glass panels ($1.6 \times 0.7 \times 0.002$ m^3) and a uPVC (also known as Unplasticised Polyvinyl Chloride, a low-maintenance building material that can be used as window frames) window frame were initially installed and closed tightly in Compartment 2. Assuming the heat combustion of wood, cotton and foam are respectively 17.5 MJ/kg [20, 21], 12.3 MJ/kg [22] and

(a) Compartment 1 (without window glass and door)

(b) Compartment 2 (with window and door closed)

Figure 1. Compartments before ignition.

23.0 MJ/kg [23], the fuel load in the compartments is estimated to be approximately 407 MJ/m^2, within the UVD fuel load range of 380–560 MJ/m^2 in a previous survey [24] and almost identical to the South Africa informal settlement average fuel load of 410 MJ/m^2 [8].

To monitor the gas-phase temperature variations in the compartment, a total of five thermocouple trees were fixed at the centre and four corners of the compartment, named T1-T5. On each tree, there were 5 K-type (nickel–chromium) sheathed thermocouples, named TC1-5, with a diameter of 1 mm, placed at distances of 500, 1200, 1750, 2250 and 2750 mm from the floor (TC1 is the lowest and TC5 is the highest). Another two thermocouple trees, T6 and T7, were fixed at the window and door to measure the flow gas temperature at the opening. It should be noted that in Test 2, there were an additional 8 sheet thermocouples (TP1-8) placed at the surface centre and frame-covered edge of the glass panels, as shown in Fig. 2c, which were fixed by high temperature glue and aluminum foil tape. The measurement ranges of the sheathed thermocouples and sheet thermocouples were 0–1100°C and 0–1000°C, respectively, and the measurement error of

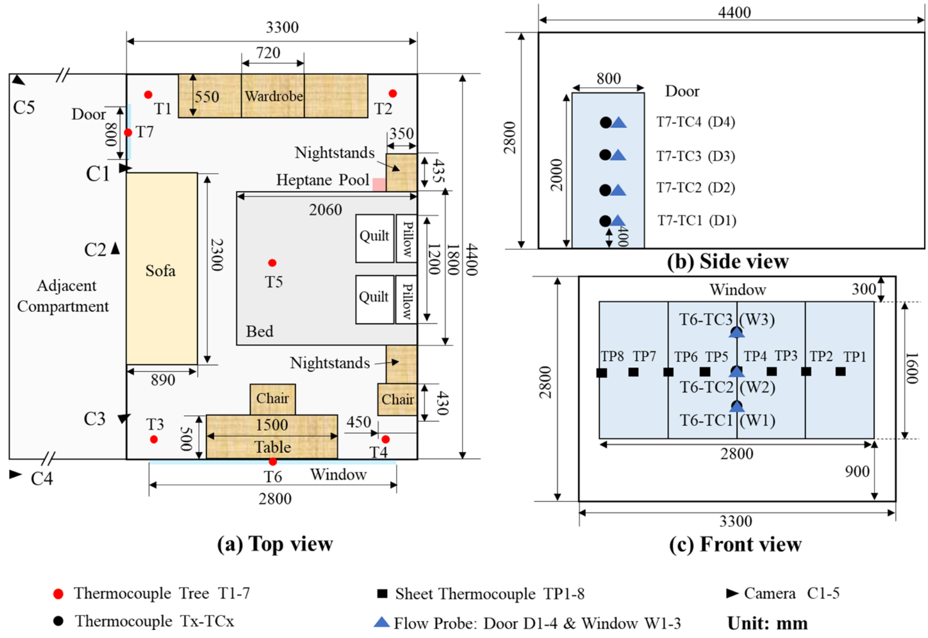


Figure 2. Layout of the furniture and instruments.

all thermocouples is ± 0.5% of the measured temperature. Therefore, the error of the thermocouple in the tests does not exceed ± 6°C. To obtain the gas velocity at the opening, a total of seven bi-directional flow probes with corresponding thermocouples were installed along the centerline of the window and door: three at the window and four at the door with 400 mm intervals, as shown in Fig. 2b and c. The flow probe consisted of a pressure gauge and S-type pitot tube, which measures the pressure difference (Δp) and converts it to the gas flow rate (v) with a conversion coefficient of 0.83, $v = 0.83\sqrt{2\Delta p/\rho}$. The indications of the pressure gauge were set zero to calibrate the gas flow velocity when ignition. A total of 5 real-time recording cameras with a resolution of 1920 × 1080 were installed in the separation wall or the adjacent room. In addition, a drone and a digital camera approximately 10 m away were employed to record the whole process. A fuel pane of 0.1 × 0.1 m^2 with 100 mL heptane, located in the corner of the nightstand and bed, was used as the ignition source (red square in Fig. 2a).

3. Experimental Results and Discussion

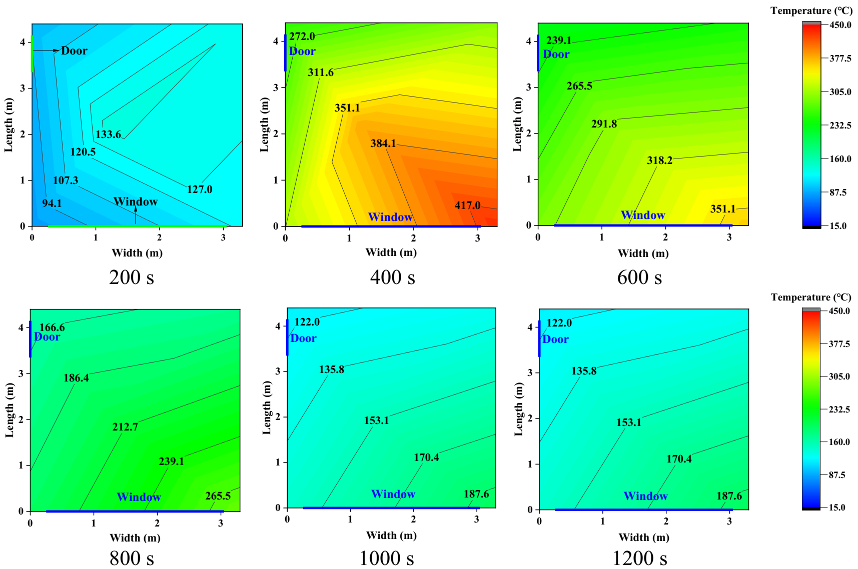
To explore the influence of opening size on the development of compartment fires, Test 1 (no door and window, i.e., door and window remained open) and Test 2 (with door and window initially closed, and opened or broken during the test) were carried out. The two tests were burnt on the same day of 23rd March 2021. The ambient temperatures of Test 1 and Test 2 were 15°C and 16°C, respectively.

The ambient wind speed was not recorded during the tests, but according to the weather forecast, the wind speed was less than 2 m/s, and the difference in ambient wind speed between the two tests was small. Therefore, the ambient conditions are assumed to be identical.

3.1. Description of Test 1

In Test 1, after the ignition of the fuel pan, the flame could directly contact the mattress and ignite it at 131 s, as shown in Fig. 3a. Approximately 10 s later, the cotton bedding was ignited. At 153 s, the flame ignited the pillow that was nearer

(a) The fire development, observed by C1.



(b) The temperature distributions close to the ceiling (Unit: °C).

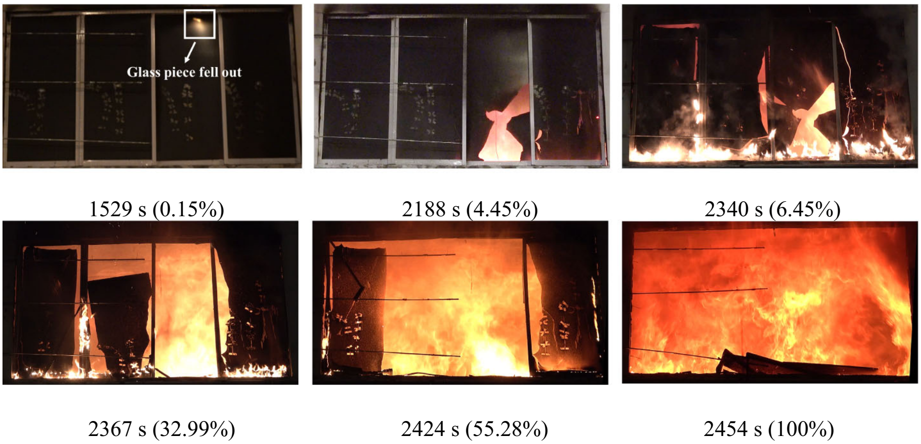
Figure 3. The fire development and temperature distributions of Test 1.

to the fuel pan; meanwhile, the smoke began to gather at the ceiling. With continuous burning, at 176 s, the folded quilt was ignited, and smoke began to emerge from the window. The smoke started to move outside from the other opening, the door, at 190 s. After the flame ignited the remaining quilt and pillow on the bed in the next 30 s, the fire spread considerably more rapidly. The maximum temperature of the upper gas in the compartment was 595°C at 348 s. At the same time, the velocities of upper gas (compartment gas flow out) at the door and window also reached the maximum values, approximately 2.5 m/s and 5.0 m/s respectively. At 256 s, the whole bed was immersed in the fire, as shown in Fig. 3a, and the smoke emerging from the window reached the maximum, which indicates the start of rapid growth. At 264 s, the smoke filled the whole compartment, and the indoor visibility became quite low, as observed by the camera. With the gradual accumulation of smoke, at 302 s, the smoke overflowing from the door reached the maximum. The chair near the window was ignited at 368 s, which was the last ignited furniture. Note that the wooden table near the open window had a large amount of cool air inflow (approximately 2 m/s) above it, and the radiation heat from the flame was not enough to reach the heat flux or temperature required for ignition, so it was not ignited throughout the test. After approximately 600 s, the fire began to decay. With the consumption of fuel, the flame decreased and went out at 1850 s. The temperature distribution close to the ceiling, extracted from the top thermocouple, i.e., TC5 in each tree with the unit °C, is shown in Fig. 3b, where the layout is the same as Fig. 2a. It can be seen that the variance in the temperature distribution was consistent with the above description. However, no visible flame was ejected from the window and door during the whole experiment.

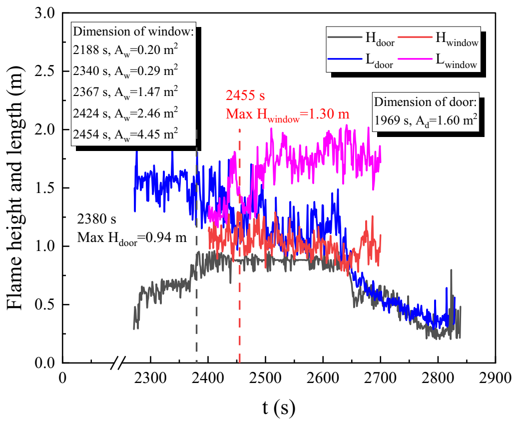
The maximum temperature of the upper gas in the compartment was 595°C at 348 s, which is slightly lower than the criteria of flashover (600°C) [21]. What is more, there was no visible flame ejected out and not all the combustible material surfaces were ignited (wood table). $A_T/A_v\sqrt{H_v}$ [A_v are the areas of openings, $A_v = A_1 + A_2(m^2)$; H_0 is the height of the opening and $H_v = (A_1H_1 + A_2H_2)/A_v(m)$; A_T is the boundary surface area (m^2).] is used to distinguish fuel-controlled fires (less than 8 to 10 $\mathrm{m}^{-1/2}$) and ventilation-controlled fires [21]. In Test 1, the value of $A_T/A_v\sqrt{H_v}$ is approximately 7.0, which is determined as a fuel-controlled fire [21]. Therefore, there was no flashover in Test 1, and a fully developed, ventilation-controlled fire was not achieved.

3.2. Description of Test 2

Almost identical to what occurred at 131 s in Test 1, in Test 2, the fire spread to the end of the bed and ignited the bedding at 128 s, which confirms the repeatability of the two full-scale tests at the early stage of the fire (fuel control). The smoke flowed out through the gap, the natural small space between the door and the frame, from 220 s. However, the fire started to weaken at 240 s, becoming smouldering combustion at approximately 950 s due to lack of oxygen. It should be noted that the crack initiated in the window glass at 1479 s, and with subsequent cracking, the first glass piece naturally fell out at 1529 s (shown in Fig. 4a and the video), suggesting that smouldering combustion could induce the non-



(a) The fracture behavior of glass windows and their fallout fractions.



(b) Flame height and length from door and window.

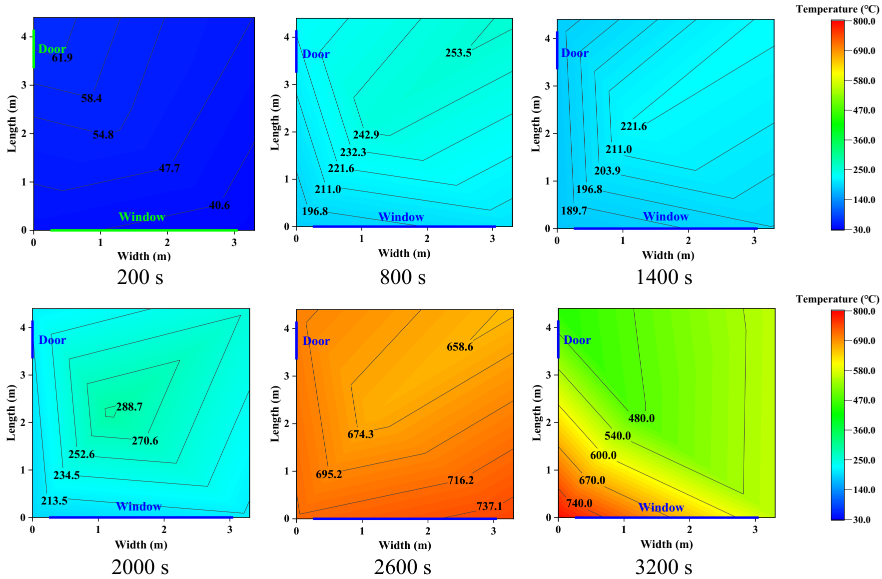
Figure 4. The burning behaviour of Test 2.

tempered window glass fallout, allowing fresh air entrance. After the glass fallout, the small flame at the small new opening became larger and brighter immediately, as shown in Fig. 4a, and it can be anticipated that the fire may grow back with more glazing breakage and fallout. Nevertheless, because of the spatial and temporal limitations of real fire experiments beside the busy road, to accelerate the fire, at 1585 s, another piece of glass fallout was formed by the conductor throwing a stone. This kind of interference is sometimes unavoidable in real-scale experiments, which also occurred in previous work [25, 26]. The glass fallout ensured that no backdraft would occur if the door was suddenly open, and then the equipped firefighter opened the door at 1969 s, as shown in the video. At 2515 s, the upper gas temperature reached a maximum of 1085°C. Afterwards, the float glass pane started to fall out gradually, and the uPVC started to burn and lose its structural stability, accelerating the fallout of the window frame: the window fell

2,270 s Started to eject from door | 2,270 s No flame ejected from window | 2,310 s Flame from door | 2,310 s Started to eject from window

2,380 s Maximum flame height from door | 2,380 s Flame from window | 2,455 s Flame from door | 2,455 s Maximum flame height from window

(c) The interactions between new openings and compartment fires.



(d) The temperature distributions extracted from the top TC at each tree (the same spatial location with Fig. 2(a)) (Unit: °C).

Figure 4. continued.

off completely at 2454 s, and the upper gas outflow velocity at the window reached its maximum value of about 4.5 m/s. The height (H) and length (L) of the spilling flame from the door and window were obtained through the OpenCV program. The flame spilled from the door and window at 2270 s and 2310 s, respectively. However, the spilling flame of the window from 2340 s to 2400 s is too small to be recognized, and only the flame height and length after 2400 s are shown in Fig. 4b. It should be noted that the two ejected flames from the door and window interacted with each other. According to mass conservation, more unburnt gas was "attracted" to flow out from the window opening, resulting in an increase in the length of the flame at the window and a decrease in the flame length at the door, while the variation of flame height at door and window was not obvious at 2400 s to 2630 s, as shown in Fig. 4b. Fig. 4c presents that the maximum length and width of the ejected flame from the door were 0.9 m and 1.8 m, respectively; the maximum length and width from window were 1.3 m and 2.1 m, respectively. After the fire, the door and window were both burnt out. Figure 4d demonstrates the temperature variance throughout the fire, and it can be found that during the smouldering combustion stage, the maximum gas temperature appeared at the ceiling, which was approximately 250 to 300°C, and with gradual fallout of glazing, the temperatures increased rapidly to above 900°C.

In Test 2, the compartment fire reached the ventilation-control stage, thus, the theoretically calculated maximum temperature can be obtained by Law's method [8] which is an analytical method to define gas temperature in ventilation-controlled fire [27–29]:

$$T_{\max} = \frac{6000(1 - e^{-0.1\Omega})}{\sqrt{\Omega}}$$

$$\Omega = \frac{A_T - A_v}{A_v\sqrt{H_v}}$$

where T_{max} is the maximum gas layer temperature and is calculated to be 1174°C. The calculated result agrees well with the experimental result of 1085°C at 2515 s with an error of less than 9%, which is similar to the error of Barnett's work on 142 tests to develop an empirical model for fire compartment temperatures (10%) [28]. In addition, regarding the glass surface temperatures (measured by sheet thermocouples), in Test 2, the third glass panel first cracked at 1479 s, at which the temperature difference between the fire exposed and covered areas was 50°C on the glass surface, which is reasonably smaller than 60 to 90°C for 6 mm-thick float glazing [30] as the smaller thickness of glazing may result in a smaller critical temperature difference for thermal breakage [31].

3.3. Discussion

3.3.1. Gas-Phase Temperature In Tests 1 and 2, the burning lasted for 33 min and 72 min, respectively (the during time of Test 2 includes all the time from flame due to ignition, smoldering, and flame caused by the appearance of new vents). In Test 1, fire development may be divided into several distinct stages like standard compartment fire, including the ignition, growth and decay period [21], while very

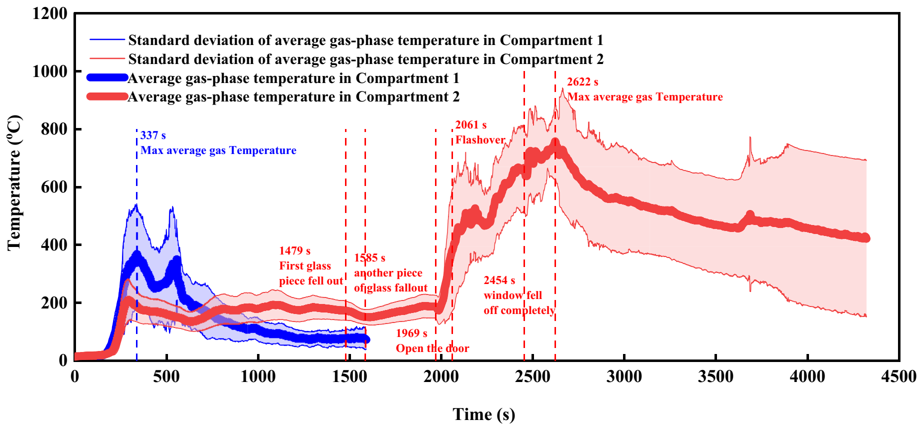


Figure 5. The average gas-phase temperatures in Tests 1 and 2.

different from Test 1, in Test 2, flaming combustion disappeared several minutes after ignition, and the smouldering maintained for more than 10 min, resulting in the accumulation of combustible gas. To illustrate fire development, the compartment average gas-phase temperature with standard deviation is demonstrated in Fig. 5. The upper and lower lines are the value of the average temperature plus or minus the standard deviation temperature, which indicates the degree of temperature heterogeneity throughout the compartment [25]. Note that the temperatures are the average of the whole compartments, which include both hot and cold layers. The maximum average gas temperatures in Test 1 and Test 2 were 365°C at 337 s and 758°C at 2622 s, respectively. In Test 2, the ventilation conditions affected the fire development process significantly. After the glass cracked for the first time (1479 s), the temperature of the gas in the compartment decreased slightly due to the outflow of hot gas. When the window was broken by the conductor, the temperature curves continue a slight downwards trend due to the outflow of hot gas and fresh air through the window. However, with an increase in oxygen concentration, the combustibles' smoldering and heat release increased, resulting in the temperature curves beginning to increase. The temperatures at this moment may not be high enough to cause backdraft even more ventilation would be induced [32]. When the door was opened at 1969 s, the fire changed from the smouldering to developing stage and reached the flashover stage at 2061 s.

3.3.2. HRR Estimation The heat release rates of Tests 1 and 2 are estimated by the gas-phase temperature in the compartment based on the MQH method, and the MQH method was verified to be in good agreement with the actual measured value when calculating the HRR in the compartment by Kweon et al. [33] (calculated results shown in Fig. 6):

$$\Delta T = 6.85\left(\frac{\dot{Q}^2}{A_v\sqrt{H_v}h_kA_T}\right)^{1/3}$$

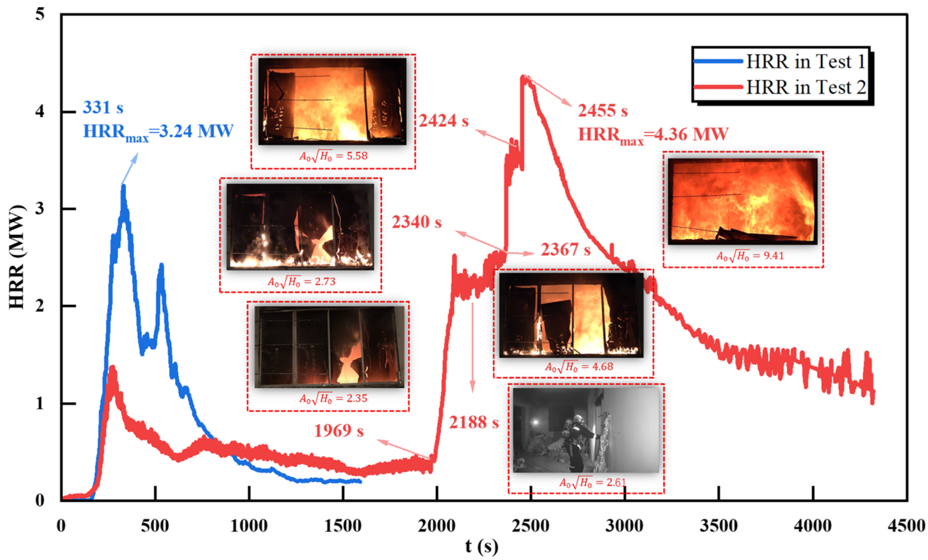


Figure 6. Estimation values for HRR of Test 1 and Test 2.

where ΔT is the temperature increase of the hot gas, $\Delta T = T_g - T_a(K)$, and h_k is the heat transfer coefficient, which can be approximated by:

$$h_k = \sqrt{\frac{k\rho c}{t}}$$

The thermal properties of brick are given as [21] $k = 0.69\,\mathrm{W/m\cdot K}$, $c_p = 0.84\,\mathrm{kJ/kg}$, $\rho = 1600\,\mathrm{kg/m^3}$, for the air in the environment, $\rho_a = 1.2\,\mathrm{kg/m^3}$, $T_a = 288\,\mathrm{K}$, $c = 1.05\,\mathrm{kJ/kg\cdot K}$.

Note that the ventilation condition in Test 1 was constant, while in Test 2, there was no vent until 1585 s. Thus, at 0 to 1585 s, the heat released by the fuel which is divided into the enthalpy to heat gases and the heat loss to the room surfaces was expressed as:

$$\dot{Q} = \rho_a V c \frac{\Delta T}{\Delta t} + h_k A_T (T_g - T_a)$$

where V is the volume of gas in the compartment. From 1585 s on, the ventilation factor $(A_v\sqrt{H_v})$ changed due to the breakage and fallout of the glass and the opening of the door, as shown in Fig. 6. The maximum heat release rate reached approximately 3.24 MW (331 s) and 4.36 MW (2455 s).

The difference in HRR between Tests 1 and 2 may be caused by different ventilation conditions and combustible gas concentrations. For the large ventilation factor in Test 1, the heat loss from the window and door was large; in Test 2, as the opening size gradually increased, the heat loss was slower than that in Test 1.

Table 1
Methods for Predicting the Flashover HRR

Methods	Equations
Babrauskas	$\dot{Q} = 750A_v\sqrt{H_v}$
Thomas	$\dot{Q} = 7.8A_T + 378A_v\sqrt{H_v}$
Hagglund	$\dot{Q} = 1050A_T\left(\frac{1.2A_v\sqrt{H_v}}{A_T} + 0.247\right)^3$

In addition, more combustible gas accumulated in the smoldering stage, and the heat release rate was greater than that in Test 1 when the oxygen concentration was sufficient. Moreover, combustibles such as wooden desk, wardrobe, nightstands and chairs were not completely ignited (only a small part of the furniture was burnt) in Test 1, while all combustibles were burned away in Test 2, which resulted in the total heat released in Test 1 being much less than that in Test 2.

3.3.3. Ventilation and Flashover In the tests, smouldering combustion occurred in the compartment with no opening or a small opening factor ($A_v\sqrt{H_v}/A_T < 0.002$, Test 2 with door and window initially closed, or with an opening about 0.023 m^2 at the window); for the compartment with a large opening ($A_v\sqrt{H_v}/A_T \approx 0.647$, Test 1 with door and window remained open), flashover did not occur, as the energy released by fuel through windows and doors would be lost to the environment by convection and radiation during Test 1; an appropriate opening factor ($A_v\sqrt{H_v}/A_T \approx 0.175$, after the door was opened in Test 2) could lead to flashover. Ventilation is an important factor affecting the development of compartment fires and the flashover-induced time [34, 35]. The methods for calculating the HRR required for flashover based on the ventilation factor are shown in Table 1 [35]. Table 2 shows the calculated results of each method and compares them with the experimental HRR at flashover which was estimated by the measured gas-phase temperature.

The calculated HRR required for flashover was larger than the experimental HRR in Test 1, thus, it was estimated that flashover cannot occur in Compartment 1. However, at approximately 2040 s to 2060 s, the experimental HRR exceeds the value required for flashover, which indicates that flashover could occur in Compartment 2.

4. Conclusions

In this work, two full-scale experiments were conducted in UVD with a fuel load of approximately 400 MJ/m^2, located in Lai'an, and the critical parameters, in terms of HRR, gas temperatures, opening gas velocities and glass surface temperatures, were measured. Two opposite opening conditions were designed to resemble the real situations of the residents' homes. It could be established that the opening conditions have considerable influence on the fire dynamics of the UVDs: with the window and door open, the compartment fire dynamics could be divided

Table 2
Comparison of Calculated HRR Required for Flashover and Experimental Result

	Test 1 (unit: MW)		Test 2 (unit: MW)	
Methods	HRR required for flashover	Experimental result (estimated from measured temperature	HRR required for flashover	Experimental result (estimated from measured temperature
Babrauskas	7.05	3.24 (maximum value, 331 s)	1.79	1.80 (value at flashover, 2061 s)
Thomas	4.07		1.45	
Hagglund	5.06		1.76	

into different 3 or 4 stages, as in previous laboratory research, while if the door and window glass were implemented, the development of compartment fire may go through a long smouldering combustion stage, during which window glass breakage and fallout would play a key role in fire development. The primary conclusions and critical data are summarized below:

(1) In Tests 1 and 2, the maximum upper gas temperatures were approximately 595°C and 1085°C, and the maximum heat released rates were 3.24 MW and 4.36 MW, respectively, which suggests that a significantly more severe post-flashover compartment fire may be reached under the Test 2 condition if the opening factor is increased gradually, and the opening factor could not result in flashover occurrence under the Test 1 condition.
(2) The opening factor has an important effect on the compartment fire stage. In this work, flashover cannot occur in Test 1 with the door and window remaining open ($A_v\sqrt{H_v}/A_T > 0.647$) due to the low gas-phase temperature caused by the heat loss to the environment through the openings; no opening or small opening formed by the conductor throwing a stone ($A_v\sqrt{H_v}/A_T < 0.002$) in Test 2 resulted in smouldering combustion because of insufficient ventilation; an appropriate opening factor, not only reducing the heat loss through the openings but also ensuring enough oxygen for combustion, could result in flashover.
(3) The thermal breakage and fallout of window glass may induce a dramatic change in a compartment fire from smouldering combustion (insufficient ventilation) to full development stages (ventilation control) and interact with the fire dynamics significantly. In particular, in UVD, thin float (non-tempered) glass panels and combustible window frames were extensively employed, so the fallout of both glass and frame may fall out easily, which needs to be noted in firefighting.
(4) With the window and door completely closed, the smouldering stage of the compartment lasted more than 10 min (under this experimental condition), which suggests that a rapidly developing fire and even flashover would occur if the door is opened. The smouldering fire in the compartment can also induce glass breakage and fallout that may result in a post-flashover compartment

fire. In addition, a small opening in the window created by the firefighters, leaving the compartment burning, may be an efficient way to avoid dangerous backdraft during the rescue.

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SUPPLEMENTARY INFORMATION

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