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Introducing an Active Opening Strategy to Mitigate Large Open-plan Compartment Fire Development

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Highlights:

- 'Active opening' can effectively mitigate fire development in large compartments.
- Activation temperature of opening glass window is critical to the mitigation effect.
- A higher window for 'active opening' improves the mitigation efficiency.

Abstract:

'Traveling fire' behaviour was found in large compartment fire tests with initial window openings, which exhibits slow fire development benefiting fire safety design and firefighting. Since much faster fire spread is found in the same compartment with glass panels, this paper attempts to explore an 'active opening' strategy to open the glass panels to regain the ventilation assumptions. The proposed strategy uses an activation temperature to control the opening and it has been now implemented in the CFD fire models. Two extreme situations, i.e., initial opening without glass and windows initially closed with glass, are investigated. A striking difference of fire behaviour is found as flashover is observed in the latter scenario compared to the localized burning in the former case. While implementing active opening, the influences of activation temperature and window height on the performance of mitigating fire development are investigated. It is found that a lower activation temperature allows faster removal of hot smoke and thus avoids spontaneous ignition. Furthermore, the effect of window height is demonstrated as higher opening reduces the thickness of hot smoke, which effectively enables lower floor radiation and thus mitigates fast fire spread.

Keywords: compartment fires; travelling fires; CFD; performance-based design; fire dynamics

1. Introduction

A 'compartment fire' conventionally refers to a fire in enclosed space, e.g., a room, which exchanges the heat and mass though openings and enclosing boundaries. The 'compartment fire' framework has been well established for fire safety design [1–5], which signifies the factor of ventilation to the fire development in compartments, especially for the compartments of cubic shapes and small sizes. At the pre-flashover stage, hot smoke accumulates and the room temperature increases, which may later trigger spontaneous ignition of available fuel and enters post-flashover stage. If the fuel supply is sufficient, the size of openings becomes a dominating factor on the mass exchange and oxygen supply, and the peak gas phase temperature inside the enclosure. Thomas et al. [2] described the ventilation of a given compartment using the term 'opening factor', thereby experimentally obtaining the relationship between equilibrium temperature and ventilation in the compartment. Two regimes were categorized [3] with respect to the ventilation condition. Fires are observed to be ventilation-controlled (Regime I) when the opening sizes are small, in which case the fire intensity increases along with a higher opening size. In the case where the ventilation exceeds the demand for burning, fires are then fuel-controlled (Regime II), where enlarging the opening facilitates the escape of heat and thus reduces the heat release rate. Harmathy [4,5] reported similar views on the ventilation effects, and proposed that fire risk can be effectively minimized by enhancing ventilation capacity to ensure that the fire falls in fuel-controlled regime [6]. However, for the fire safety design of small compartments with limited ventilation, it is recommended to take the ventilation-controlled regime as the design strategy rather than providing excessive air supply through openings [7]. In most of fire accidents of small compartments, such opening is gained or suddenly increased after the glass breakage of windows, which occurs shortly after ignition due to the heating of accumulated hot smoke [8].

The 'large compartment fire', of a large floor area (e.g., around 100 m^2 as used in the full-scale tests), exhibits completely different behaviour compared to the fires in small cubic compartments. While sufficient ventilation is enabled through longitudinal space and large area of window openings, fire spread was found in a slow travelling manner as the burning front of intense burning region moves along with the burn-out front. This non-uniform fire behavior was commonly referred as a 'traveling fire' [9,10]. In these fire scenarios, oxygen supply is sufficient and smoke accumulation is less severe than small compartment fires. Hence, the fire is primarily controlled by fuel distribution, whereas the ventilation condition can affect the travelling behaviour. To ensure the premise of sufficient ventilation, most of travelling fire tests [11–14] adopted initial window openings without glass panels based on the assumption that glass breakage occurred at early stage. The recent work by authors has found that including glass panels may completely change the fire behavior as the localized burning at early stage cannot effectively trigger glass breakage for ventilation. In this paper, the numerically simulated results of large compartment fires with assumed initial opening and with glass panels are briefly discussed. Based on this finding and the travelling fire research, an 'active opening' strategy is proposed to regain the ventilation and to mitigate fast fire spread in large compartments. A series of case studies are conducted to demonstrate this strategy while introducing ceiling temperature-controlled flip of glass panels in CFD fire models. A much slower fire spread, and travelling behavior could be observed after implementing active opening. Moreover, the effect of activation temperatures and window locations are investigated, which suggests an appropriate triggering temperature and height of active opening are needed.

2. Effects of window ventilation to large compartment fire

In this section, the Kirby large compartment fire test [8] and the latest travelling fire tests are briefly discussed regarding the effect of ventilation through window openings. The Kirby test was conducted in a long compartment with ventilation at one end, which exhibited fast fire spread over the fuel bed from the igniting end to the other. In the recent large compartment fire tests [11–14], large and long windows were usually placed along the longitudinal wall and assumed as initial openings. With these window openings providing sufficient ventilation, a relatively slow 'travelling fire' behavior was observed, which differs from the fast fire spread as observed in Kirby test and maintains localized burning for a long fire duration. Based on those experimental observations, a slow 'travelling fire' is considered to be of more benefit to structural fire resistance and firefighting, as the heat release rate is much lower and the heating area is much smaller. This paper attempts to explore a strategy of ensuring such fire behavior in a long compartment with window glass panels, and this as explained later was denoted as an 'active opening' strategy.

2.1 Long compartment fire test - Kirby Fire test

The large-scale fire test (Test 2) by the British Steel Technology and Fire Research Station (BST/FRS) [8] presented a long compartment fire test with ventilation at only one side, which was different from the recent large compartment fire tests [12–15] focusing on 'travelling fire' behavior. The latter category of tests usually assumed initial window opening along longitudinal wall, which provided sufficient ventilation to the fire and the fire can maintain localized for a long duration.

As shown in Fig. 1, a total of 33 wood cribs were evenly spaced in the compartment, forming a matrix of 3 rows and 11 columns with 0.9 m row spacing and 1 m column spacing. The tested compartment was 22.8 m long, 5.6 m wide and 2.8 m high, with one end kept completely open. Its sidewalls along the longitudinal direction were made of 215 mm thick lightweight concrete, while the ceiling used a 200 mm thick reinforced concrete slab. The floor was filled with 125 mm deep sand and the other inner surfaces of the compartment were lined with 50 mm thick ceramic fiber blankets.

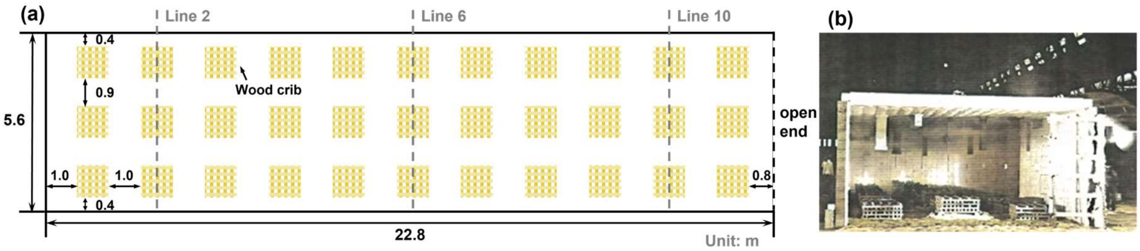

Fig. 1 Layout of the tested compartment.

2.2 Large compartment fire tests exhibiting 'travelling fire behavior'.

The aforementioned 'travelling fire' behavior refers to that a fire in large open-plan compartment exhibits localized burning and the intense burning region (near field) moves across the compartment floor area. This phenomenon has been observed in large compartment fire tests, where ventilation was provided through window openings on façade walls. Particularly, the travelling speed (a fast-travelling fire or a slow travelling fire) is dependent on the fuel load, compartment geometry, and ventilation conditions. As an example of fast travelling fire, the Veselí Travelling Fire Test [13] swept across a floor area of 13.4 × 10.4 m in 300 s (10 m^2 window opening). In the Malveira Fire Test [15], much slower fire spread was found in 237 minutes after ignition, which demonstrated a small localized fire in a long compartment (21m × 4.7m × 2.85 m) with large window openings (161.2m^2 in total). Similar travelling behavior has been found in the Tisová Fire Test [12] and other fire tests as briefly reviewed in the other paper of authors [16]. One common assumption of these tests is that all the windows were treated as initial openings without glass panels, which therefore ensured sufficient ventilation to the near field and the far field.

Fig. 2 Typical photos of travelling fires: (a) Veselí Fire Test [13] and (b) Malveira Fire Test [15].

2.3 Fire development in large compartments with glass panels

In reality, the windows of modern buildings are made of glass panels and they are usually closed for the sake of energy saving. The existence of glass would change the ventilation conditions, and then affects the fire behaviour in terms of the spread rate of fire flames. Regarding the glass breakage behavior in fires, Shield et al. [17,18] investigated the fall-out of the glass pane and proposed the following criteria of predicting breakage of float glass in fire: (a) the surface temperature of the glass pane exceeds 447°C, or (b) the heat flux received by the exposed surface of glazing reaches 35 kW/m^2.

While applying these criteria in numerical simulation of large compartment fires, it was found that the window glass did not break at early stage and the localized fire could develop to a fully-developed fire due to the existence of glass panels. As shown in Fig. 3, in the case without glass pane (initial opening as assumed in travelling fire tests), the fire development after ignition was very slow and localised burning was observed from 0s to 1800 s, which was similarly found in the existing travelling fire tests. However, in the case with glass panels, the failure of glass pane (progressive removal enabled in CFD fire models following the breakage criteria) did not occur at early stage but sequentially occurred alongside the spread of fire flames over the wood crib. At 900s and 1800s, a larger area of spontaneous ignition was found in the simulation as the floor radiation was high. The effect of glass panes to the large compartment fire development has been discussed in a parallel paper by the authors [19], which develops a glass breakage model with validation and implements it in simulating the different fire behaviour in large compartments with or without window glass. In this paper, the two cases are only briefly compared to demonstrate a key finding that including glass panels in large compartment fire models can change the slow travelling fire behavior to a very fast travelling fire even a fully-developed fire with flashover.

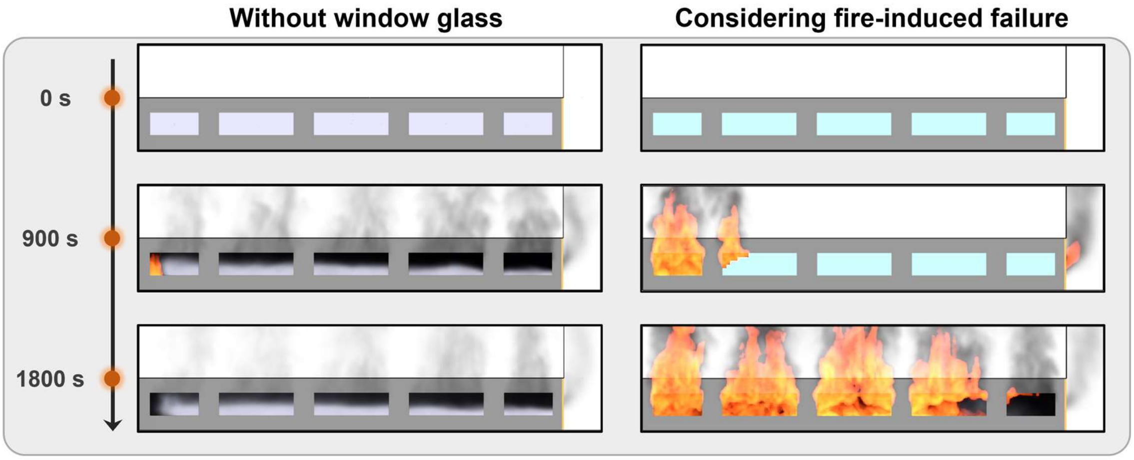

Fig. 3 Timeline of large compartment fire development with and without glass panes (side view).

2.4 A hypothesis of active window opening for ventilation

Based on the above presented discussion, this paper aims to explore a fire control strategy of actively providing ventilation through windows in a large compartment, which is to ensure the slow travelling fire behavior and to prevent a large fully-developed fire. In order to achieve a similar level of efficiency of ventilating hot air and smoke as the travelling fire tests without window glass, it is potentially feasible to actively open the glass windows while detecting a fire through heat detectors. It thereafter becomes a very explorative attempt on this new fire mitigation strategy by providing ventilation rather than limiting the ventilation to a large compartment fire.

Unlike the fast breakage of window glass pane in small compartments due to accumulated hot smoke, the fire impact may be not high enough to cause glass breakage at early stage of a large compartment fire [20]. Hence, the present work intends to link the activation of opening of glass windows with a control logic based on ceiling gas phase temperature. As illustrated in Fig. 4, an array of equally spaced temperature sensors is virtually installed in the CFD fire model, which are underneath the ceiling monitoring the gas-phase temperature and responsible to trigger the movement of glass panels from a closed window to an opened window. The activation occurs when the monitored temperature exceeds the specified 'activation temperature', and the whole response flow has been developed in the CFD fire simulation model. In this model, the control logic assumes activation at the point of detecting at least two sensors reaching the threshold temperature. Particularly, the active opening is realized through the flipping movement of glass panels, which rotates about the upper edge of the panels and serves as horizontal spandrel to deflect the released hot smoke. It should be clarified that this paper is aimed on preliminary research of 'active opening' for exploration and demonstration. More complex control logic, such as sequential opening from the nearest window to the adjacent ones, stepwise openings, and partial opening of window glass, will be further investigated using numerical and validated through experimental studies. Moreover, the heating impact to the external wall and the flipping window panels should be further studied to ensure the ultimate fire safety of implementing active opening strategy.

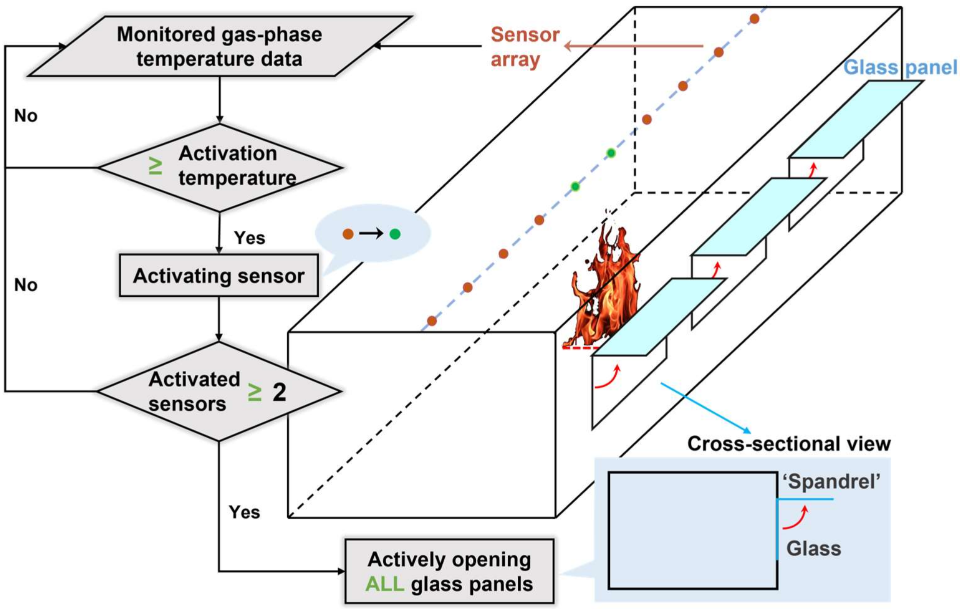

Fig. 4 Illustration of the control logic for opening windows mechanically.

3. Numerical Simulation for demonstrations of active window opening

3.1 Description of CFD fire models

The Fire Dynamics Simulator (FDS version 6.7.7) is employed to perform numerical investigations. The aforementioned Kirby test was used as the prototype model, while Table 1 presents the model configurations based on the information from the technical report [8].

Wood crib was used in Kirby test as shown in Fig.1. The original setup (Fig. 5a) adopted wood crib consisting of 7 layers of wood sticks with 10 sticks per layer. Each stick was 1 m long and of a 0.05 × 0.05 m cross section. The weight of each stick was roughly 1 kg, and the moisture content was about 10%. While the crib model of true sizes as shown in Fig. 5b requires a fine mesh, which will pose extremely high computational cost. Janardhan and Hostikka [21] suggested to use equivalent wood crib model (Fig.5c) to simulate the fire behavior. The setup of wood crib was modified to 4 layers with 4 wood sticks in each layer, where the cross-section of sticks was set as 0.1 × 0.1 m.

Table 1 Properties of materials used for the tested compartment.

Properties	Density [kg/m^3]	Specific heat [J/kg·K]	Thermal conductivity [W/m·K]	Emissivity
Lightweight concrete	1375	753	0.42	0.9
Reinforced concrete	450	1050	0.16	0.9
Fluid sand	1750	800	1.0	0.8
Ceramic fiber	128	1130	0.02	0.9

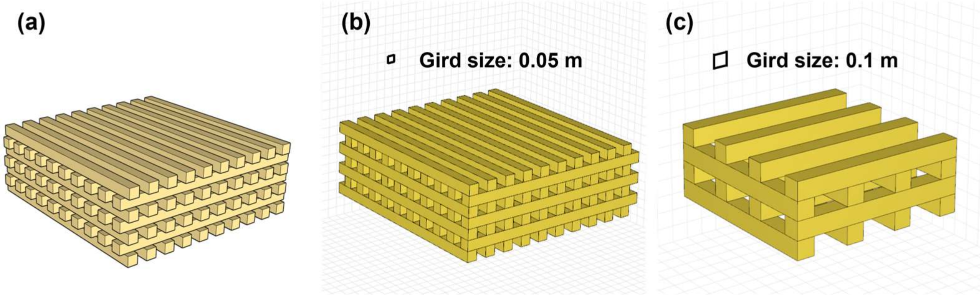

Fig. 5 Setup of the wood crib: (a) in real life, (b) in FDS model, and (c) in modified FDS model.

This equivalent model will cause the decrease of exposed area of wood crib in the FDS model, which in turn reduces the mass loss rate of the burning wood sticks. To consider this effect, the parameter AREA_MULTIPLIER is applied, which is calculated as:

$$\text{AM} = A_{real}/A_{FDS} \tag{1}$$

where A_{real} and A_{FDS} are the effective exposed areas of wood crib in real and FDS models, respectively. Moreover, the parameter BULK_DENSITY is correspondingly defined to ensure the designated fuel density. The choice of BULK_DENSITY [22] can be specified as:

$$BD = \frac{FLD \cdot A_{floor}}{V_{FDS} \cdot \Delta H_c \cdot (1-y_{char}) \cdot (1-y_{mois}) \cdot AM \cdot n_{crib}} \tag{2}$$

where FLD is the designed fire load density of the compartment with floor area of A_{floor}, and V_{FDS} is the effective volume of wood per crib in the FDS model. ΔH_c denotes the heat of combustion of wood, which was reported as 19.5 MJ/kg [8]. y_{char} and y_{mois} are the char yield and moisture content of the wood stick, which are specified as 0.195 and 0.1 in the FDS model, respectively. n_{crib} represents the number of wood cribs within the compartment. Thus, two essential parameters, AREA_MULTIPLIER and BULK_DENSITY were determined as 2.135 and 306.6, respectively.

The ignition of the wood cribs of the first column was controlled by the ignition temperature (320 °C). The energy required for ignition was provided by three identical burners of an area of 0.3×1.0 m^2, and each burner was placed under the center of the wood crib. Considering that the properties of the burner were not mentioned in Kirby's test report, after trial tests the HRRPUA of each burner was finally assumed to be a linear increase from 0 to 500 kW/ m^2 in 60 s, maintaining constant for 220 s, which is followed by a linear drop to 0 at 300 s. For the rest of wood cribs, the onset of ignition was governed by the pyrolysis reaction model on the basis of the Arrhenius equation. The pyrolysis process of wood cribs was resolved by a single-step pyrolysis model [22] including two parallel reactions:

$$pine \longrightarrow (1 - y_{char}) fuel\ vapor + y_{char} char \tag{3}$$

$$moisture \longrightarrow water\ vapor \tag{4}$$

The thermal and kinetic properties involved in this model are listed in the Table 2 and Table 3, respectively. Besides, the critical flame temperature was set as 1427 °C and the soot yield was assumed as 0.01 kg/kg. To ignite the wood crib, three 0.3 m^2 burners are placed on the floor. The HRRPUA of each burner increases from 0 to 500 kW/m^2 in 60 s, which remains constant for 220 s, and reaching burn-out at 300 s. The FDS models all adopt the same configuration. The Very

Large Eddy Simulation (VLES) mode was used to model the turbulence, and the radiative fraction of fuel vapor was defined as 0.35 by default [23]. The near-wall region was treated by means of the Smagorinsky form with the Van Driest damping function [24]. The grey-gas model was applied to estimate the radiative heat transfer, and its number of solid angles was increased from the default setting 100 to 200 to improve precision.

Table 2 Thermal properties of pine, char and moisture according to [8,25].

Properties	**Density [kg/m3]**	**Specific heat [J/kg·K]**	**Thermal conductivity [W/m·K]**	**Emissivity**
Pine	450	1350	0.15	0.9
Char	135	1080	0.13	0.98
Moisture	1000	4180	0.1	-

Table 3 Kinetic properties of pine and moisture according to [22].

Properties	**Order of reaction**	**Heat of reaction [kJ/kg]**	**Pre-exponential factor [1/s]**	**Activation energy [kJ/mol]**
Pine	1.69	250	1.41×10^{5}	8.97×10^{4}
Moisture	3.31	2500	9.57×10^{22}	1.36×10^{5}

3.2 Validation of the CFD fire model

In Kirby test, three thermocouple lines were located above the crib columns 2, 6 and 10, which are indicated as Line 2, 6 and 10 in Fig. 1. Fifteen thermocouples were installed on each line to record the horizontal temperature profile over the entire width of the compartment. The temperature variations after smoothing have been provided in the reference report [8], which enables the validation of the present FDS model. The simulated temperatures (dash line) against the reported temperatures (solid line) are shown in Fig. 6.

In general, the fire model well predicts the temperature development in the first hour, where errors are mostly within 6.3%. Whereas there are large discrepancies (more than 50 %) in the cooling phase (shaded in light gray). While the focus is cast on the fire development and flame spread regarding the consideration of glass panels, the fire model is validated and ready to use for further investigation.

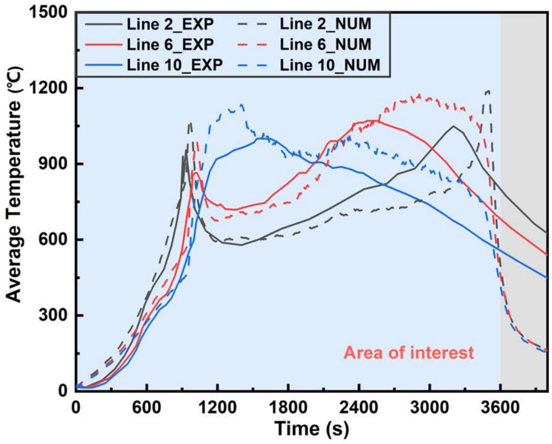

Fig. 6 Validation of the FDS model against Kirby test.

3.3 Implementation of active opening in CFD fire models

To enable the modelling of active opening at window glass panels, virtual thermocouples in the FDS model are employed to represent the sensor to monitor gas-phase temperature, which use a parameter SETPOINT to define the activation temperature for activation. The bead diameter of thermocouple was defined as 0.003 m, and its density and specific heat were set as 8655 kg/m³ and 0.44 kJ/kg·K, respectively. Each thermocouple is associated with a control device (denoted as AT_LEAST) that can be activated once its reading exceeds the prescribed temperature. In this paper, the value of the control device AT_LEAST is set to 2, which indicates that it will trigger the opening action of glass modules when it receives at least two signals from those monitoring thermocouples.

Based on the FDS model of Kirby test, a collection of case studies is conducted to examine the feasibility of active opening strategy and to investigate the opening control factors on fire development. As shown in Fig. 7a, five window panes were installed on the front wall of the validated model, similar to the setup of the Malveira Fire Test [15]. Following the proposed control methodology, the opening of those windows was controlled by an array of virtual thermocouples attached to the ceiling with a spacing of 1.2 m. Besides, the fully open sidewall in Fig. 1 was replaced with a typical small opening (see Fig. 7b), similar to Malveira test compartment.

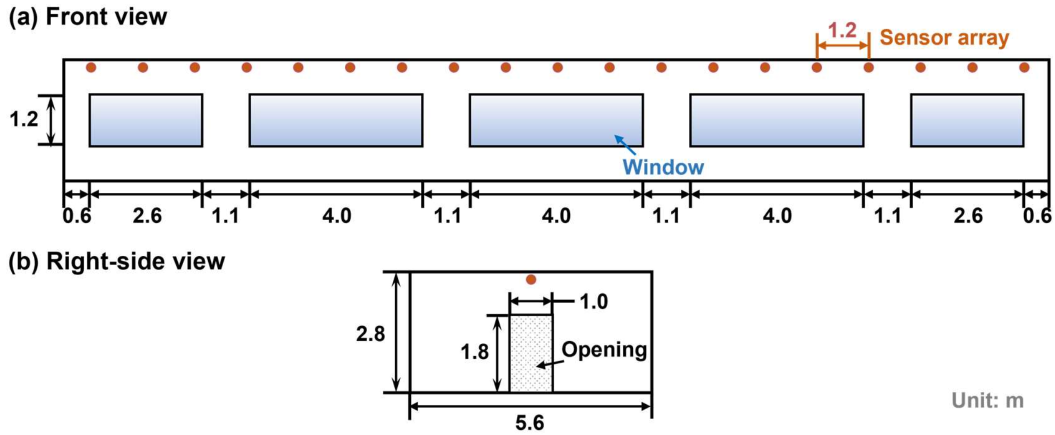

Fig. 7 Fire simulation model for case studies on active opening strategy.

A total of 10 cases are divided into 3 groups, while the key difference is summarized in Table 4. As the distance from window to ceiling affects the remaining smoke layer height, it was assumed as 0.8 m in Group A and Group B, whilst a 0.6 m height is adopted in Group C. The two cases of A1 and A2 represent two special scenarios as lower bound and upper bound of activation temperatures, i.e., initially opened windows (Case A1) and windows of no active opening (Case A2). In Group B models, the critical temperature for active opening is altered as 70ºC, 100ºC, 150ºC, 250ºC, which will reveal the sensitivity of activation temperature to the fire development while adopting active opening. Moreover, the thickness of smoke layer has been proved to contribute significantly to spontaneous ignition and flame propagation in large compartments [26]. Group C accounts for higher openings to allow for thinner smoke layers during the fires. The windows of Group C are placed at 0.6 m below the ceiling, whereas the activation temperature of each case is identical to that in Group B. The HRR of the fire, the smoke layer heights, the average smoke layer temperatures, and the heat fluxes received at the surface of each crib column are captured in these models, which are analyzed in Section 4.

Table 4 Summary of the setup of extrapolation cases.

Case No.	**Distance from the top rim of windows to the ceiling H_w[m]**	**Activation temperature T_{act} [ºC]**
A1	0.8	20 (initial opening)
A2	0.8	- (no active opening)
B1	0.8	70
B2	0.8	100
B3	0.8	150
B4	0.8	250
C1	0.6	70
C2	0.6	100
C3	0.6	150

C4	0.6	250

4. Discussions on active opening strategy for large compartment fires

4.1 Lower and upper bounds of active opening

When comparing the simulated fire behavior in Case A1 and A2, it can be seen that the smoke and flames accumulate rapidly in the compartment of A2, whereas a smaller fire is found in A1. The flame in Case A2 quickly spread over almost the entire wood cribs within 600 s, and a fully-developed fire is observed. On the contrary, the smoke has been effectively ventilated in Case A1 through the initially opened windows and the fire development is much slower. As shown in Fig.8, the flames remain localized at the initially ignited wood crib enabling a sustained small localized fire. Besides, the opened glass panels can deflect the upward flow of hot smoke, and the smoke temperature is significantly reduced owing to a smaller fire.

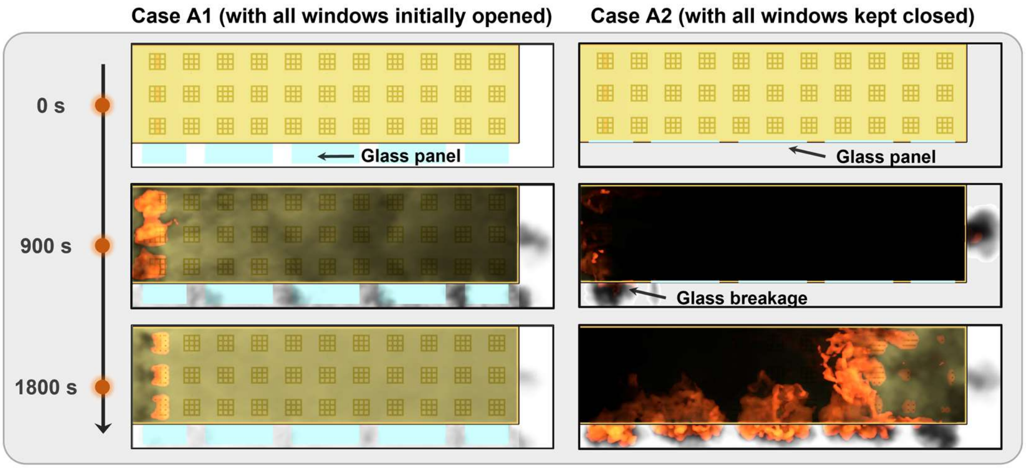

Fig. 8 Timeline of fire development for Case A1 and A2 (top view).

Fig. 9a demonstrates the different HRR histories while opening all windows at initial stage (A1)and adopting no active openings (A2). The upper section of Fig.9a illustrates the variations of total HRR in the both cases. With glass panels and no flip opening, the HRR of Case A2 is similar in the first 900 s to that in Case A1, which is followed by a higher fire intensity (peak HRR of over 50 MW) in A1 as more fuel surfaces are heated and ignited. As shown in the lower section of Fig.9a, a large portion of gas burning occurs at the opening (EXT) of Case A2.

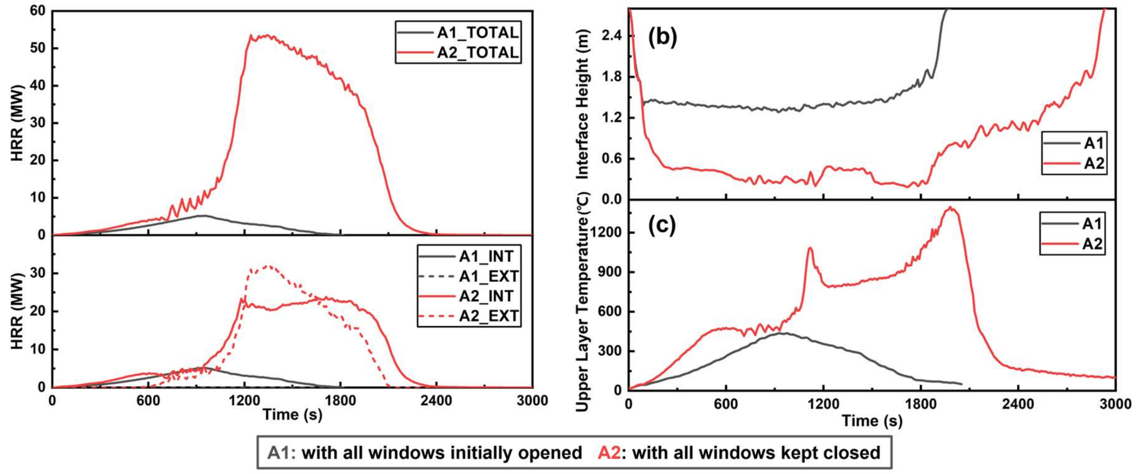

Fig. 9 Differences due to large opening strategy in: (a) HRRs, (b) interface height, and (c) upper layer temperature.

The differences in smoke layer heights of the two cases are clearly observed in Fig. 9b. The height of the smoke layer in both cases decreased rapidly at the beginning. Due to the early opening in A1, most of the smoke is ventilated in time to maintain the smoke layer height at around 1.4 m instead of almost engulfing the wood cribs, as seen in Case A2. As indicated in Fig. 9c, the average temperature of the smoke layer of Case A2 developed faster than that of Case A1, reaching its peak of about 500°C before 600 s. On the contrary, the peak average temperature of Case A1 was almost only 30% of that of Case A2, which was the result of the heat generated not being effectively diluted. Furthermore, the duration of Case A2 was significantly greater than that of Case A1, leaving the structural elements exposed to elevated temperature for a longer time.

4.2 Effects of activation temperature for active opening

The setting of the activation temperature largely determines the sensitivity of the active window opening system. The simulated cases show various responses by using different activation temperatures. Case B1 (T_{act} =70°C) successfully avoided fast fire propagation very similar to the initial opening as Case A1 (T_{act} =20°C). However, as illustrated in Fig. 10, the activation of window openings in other cases of Group B failed to prevent fire spread, and a large fire is found as shown in Fig. 10a. Fig. 10b compares the time points of key events in the fire evolution, including active opening of windows, remote ignition of adjacent cribs, and full development of fire. Their timelines indicated the delays in active window opening could shorten the onset of catastrophic fire, and even a delay of only about 50 s in opening windows between Case B1 and B2 would result in two distinct situations, as the initial conditions for the subsequent development might be significantly influenced.

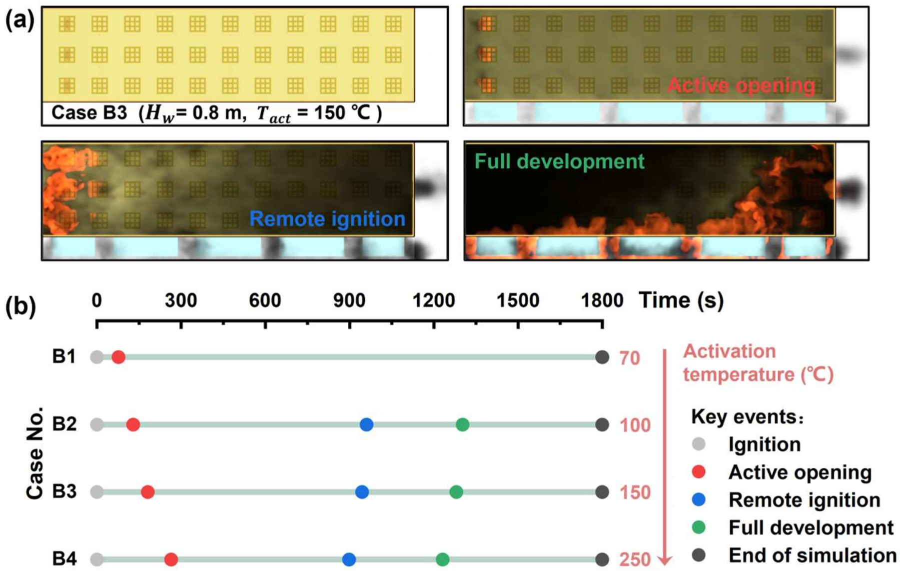

Fig. 10 Timelines of fire development after active opening: (a) representative fire development in Case B3 (top view) and (b) timelines of key events in Group B.

In Fig. 11, the effects of activation temperature on the height and average temperature of hot smoke layer as well as the average heat flux received by the adjacent wood cribs are illustrated. At the early stage, the smoke layer temperature histories are almost identical in all cases, which gradually increase as the fire develops. After triggering the action of opening windows in Case B1, its temperature rise rate dropped, showing a clearly different trend from the other cases, as shown in Fig. 11a. Similarly, as the windows were actively opened, the temperature rise curves of Case B2, B3 and B4 sequentially deviated from the extreme Case A2. This deviation indicated that the active opening of windows can effectively mitigate the accumulation of heat within the compartment, as the smoke is rapidly evacuated from the window openings. Case B1 brought the smoke layer back up to a level comparable to extreme Case A2 within 20s after the window opening. Moreover, the smoke layer temperatures in B2~B4 rise up to a level even higher than that of Case A2 without active opening, and then stabilized as shown in Fig. 11b. Nevertheless, their smoke layer was relatively thicker than that of the extreme Case A2 because of the late opening of the window, where Case B4 showed the largest gap of around 0.2 m. Due to this smallest distance to the floor as well as the highest temperature, Case B4 transferred the most heat to the wood crib surface below, which assisted the localized burning to induce the earliest remote ignition. Nevertheless, this measure of opening windows somewhat delayed the occurrence of remote ignition compared to Case A2, as indicated in Fig. 11c. Notably, Case B1 imposed a slightly enhanced heat flux at about 950 s in an attempt to ignite the wood surface below, but was promptly curbed by the favorable heat dissipation conditions. The levels of heat flux exerted on the adjacent wood surface by Case B2 and B3 were both comparable to that of Case B1, but their accumulation over a long period of time still triggered the remote ignition.

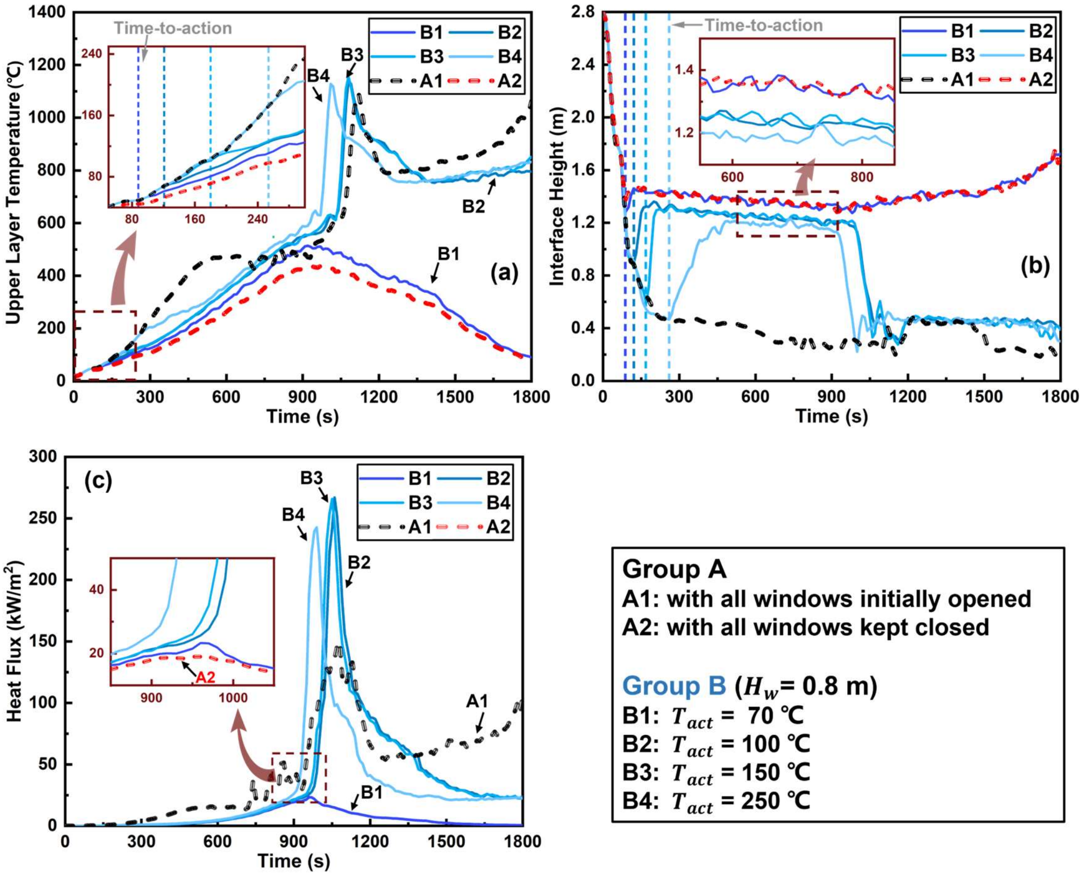

Fig. 11 Effects of activation temperature on: (a) upper layer temperature, (b) interface height, and (c) heat flux received by the second column of wood cribs.

In general, the use of active window opening strategy can mitigate the progress of large open-plan compartment fires, mainly by reducing the upper layer temperature, raising the height of the smoke layer, and weakening the thermal impact exerted on the adjacent wood surfaces. However, the mitigation brought by an untimely response is temporary, which is likely to be followed by a catastrophic fire due to adequate oxygen supply. Therefore, a proper setting of the activation temperature needs to be found to meet the needs of performance-based design for this type of modern buildings.

4.3 Effects of window opening height

The accumulation of the smoke layer dominates the fire development in large compartments, which has been presented in the cases of Group B. A thick smoke layer of high temperature can lead to higher floor radiation and faster flame spread. Group C was thus designed to counteract the accumulation of the hot smoke layer within the compartment by lifting the top edge of the windows. This alteration of the window arrangement proved to be effective in controlling the deposition of hot layer compared to the Group B case, which is illustrated in Fig. 12. Raising the height of the windows effectively elevated the opening height at which smoke was released after the implementation of the active window opening strategy. This subtle change successfully resulted in Case C3 that prevented fire spread at a high activation temperature of 150℃. Besides, the other cases in Group C by lifting up the windows all led to the effective mitigation of fire spread.

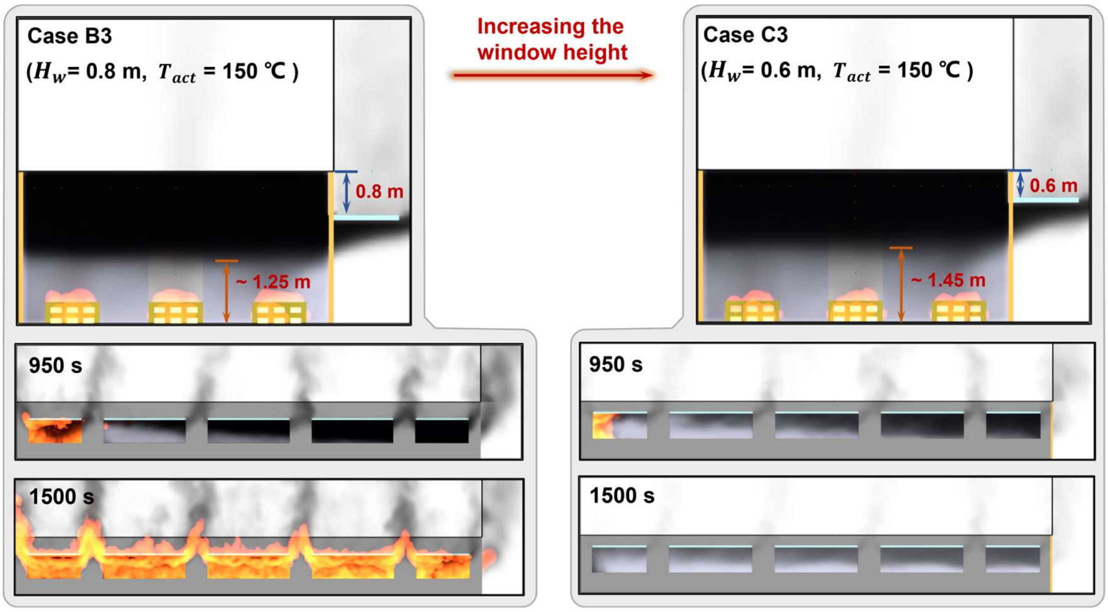

Fig. 12 Two distinct outcomes by elevating the window height.

The Case B1 of the best performance in Group B is used to compare with the cases of Group C to demonstrate the effect of window height. As shown in Fig. 13a, the smoke in all cases both accumulated and sank rapidly in the compartments at the beginning of the fire. The smoke was released after the window opening action being triggered, and then stabilized at variant heights. Similarly, the temperature of the smoke layer in each case developed slowly at the early stage, whereas the rate of temperature rise declined significantly as the windows were actively opened, as displayed in Fig. 13b. It can be seen that the earlier the active opening was triggered, the higher the smoke layer height were shown and the lower the smoke layer temperature being obtained at steady state, which underlines the importance of the activation temperature setting for mitigating fire development. Moreover, the smoke layer heights of all Cases in Group C were higher than that of Case B1, alongside lower smoke layer temperatures than B1 in all cases except Case C4, indicating that increasing the window height can improve the performance of smoke venting and heat removal, and thus enhance the effectiveness of the active opening system. Notably, despite its thinner smoke layer, Case C4 with slightly higher temperature transiently yielded a heat flux that exceeded that of Case B1 to adjacent wood crib, which came close to a catastrophic fast spread fire, as presented in Fig. 13c. This observation implies that the active opening strategy might become invalid if the activation temperature is raised too high, which highlights the need of early stage activation similar to sprinkler systems.

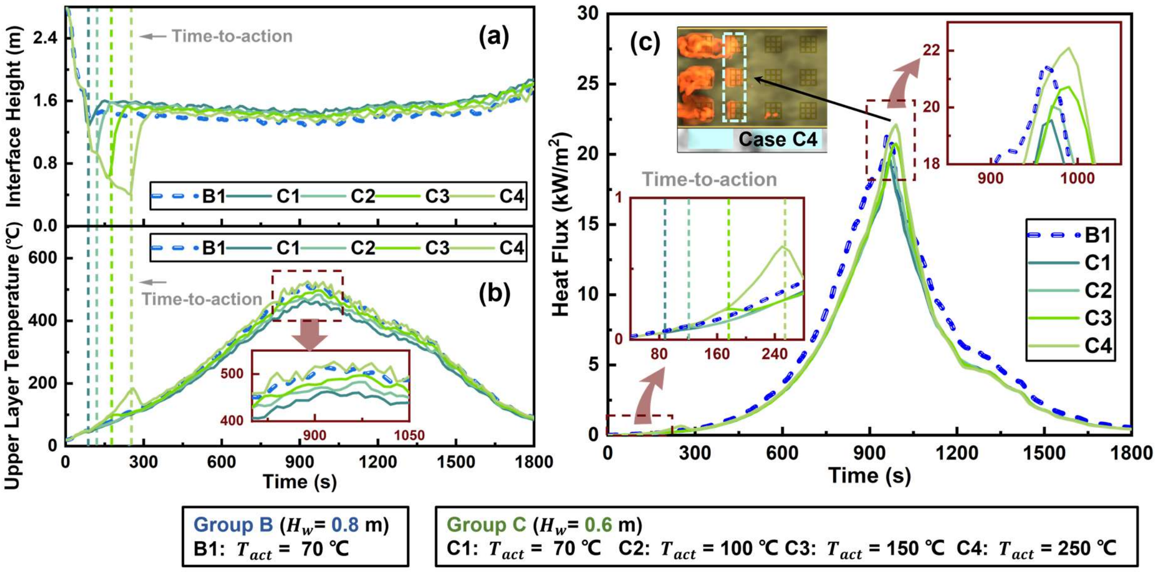

Fig. 13 Comparison of all the cases in Group C with Case B1 on: (a) interface height, (b) upper layer temperature, and (c) heat flux received by the second column of wood cribs.

In short, the demonstrations of Group C suggest that elevating the window heights during the design of modern buildings can be a wise solution to enhance the robustness of active opening strategy using.

5. Conclusions

This paper attempts to use an active opening strategy on façade windows to mitigate the fire development in large open-plan compartments. This strategy monitors the ceiling sensor temperature to trigger the active opening, and the whole action flow has been implemented in the CFD fire models for pioneering investigations. Two extreme situations, i.e., initially opening the windows and no active opening, are simulated to showcase the effect of considering window glass. It is observed that the hot smoke accumulated rapidly in the compartment with glass considered and exerted high levels of heat flux on the combustibles below, which will induce fast fire spread and even flashover in the compartment. On the other hand, initial opening of the windows as assumed in the travelling fire research exhibits localized burning and maintains relatively thinner smoke layer, which significantly reduces the heat release rate and benefits the potential firefighting.

This paper then investigates the key parameters that affect the performance of the active opening strategy. It is found that setting a lower activation temperature allows for the timely venting of hot smoke from the compartment, which can successfully avoid spontaneous ignition on remote items. While a higher activation temperature is in use, the active opening becomes invalid in suppressing the fire development. The effect of window height is studied and discussed, which shows that the top rim of windows fundamentally controls the residual height of hot smoke after active opening, which can effectively reduce smoke and ensure valid mitigation even at high activation temperatures.

It should be admitted that there are several assumptions as well as limitations in the present work. This paper considers no active fire suppression systems as the worst scenario of discussion, which is same to the discussion of travelling fire research. In future applications, the sprinkler systems may be simultaneously triggered to further suppress the fire development. As mentioned before, this strategy may cause fire spread to the upper floors of tall buildings or adjacent constructions. These side effects will be investigated in our upcoming work. Regarding the fuel arrangement, the simulated wood cribs are discrete and uniformly distributed, whereas a non-uniformly distributed fuel bed may cause other challenges to the active opening approach. In addition, the density of sensors in the proposed control logic can also affect the response time of the system, which should be taken into further account. Nevertheless, the application of active opening strategy in modern buildings opens up new thinking of fire safety measures, which supplies ventilation through windows at early stage rather than controlling ventilation. However, applying it in real buildings certainly requires more detailed research and experimental validations.

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Figure captions

Fig. 1 Layout of the tested compartment.

Fig. 2 Typical photos of travelling fires: (a) Veselí Fire Test [13] and (b) Malveira Fire Test [15].

Fig. 3 Timeline of large compartment fire development with and without glass panes (side view).

Fig. 4 Illustration of the control logic for opening windows mechanically.

Fig. 5 Setup of the wood crib: (a) in real life, (b) in FDS model, and (c) in modified FDS model.

Fig. 6 Validation of the FDS model against Kirby test.

Fig. 7 Fire simulation model for case studies on active opening strategy.

Fig. 8 Timeline of fire development for Case A1 and A2 (top view).

Fig. 9 Differences due to large opening strategy in: (a) HRRs, (b) interface height, and (c) upper layer temperature.

Fig. 10 Timelines of fire development after active opening: (a) representative fire development in Case B3 (top view) and (b) timelines of key events in Group B.

Fig. 11 Effects of activation temperature on: (a) upper layer temperature, (b) interface height, and (c) heat flux received by the second column of wood cribs.

Fig. 12 Two distinct outcomes by elevating the window height.

Fig. 13 Comparison of all the cases in Group C with Case B1 on: (a) interface height, (b) upper layer temperature, and (c) heat flux received by the second column of wood cribs.