Reconstruction of Grenfell Tower fire. Part 2: A numerical investigation of the fire propagation and behaviour from the initial apartment to the façade

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Summary
The dramatic event of the Grenfell Tower in 2017 reminds the importance of addressing fire issues as a whole and clearly highlighted one of the major roles played by the façade as fire propagation vector. To understand and analyse this disaster, numerical simulation allows particular phenomena to be evaluated more easily. The numerical model addressed for the fire behaviour of the façade system was developed using a multiscale approach and validated at different scales. In this paper, the fire behaviour of the façade and of its window frames is addressed. A computational fluid dynamics (CFD) model is used to investigate the fire spread from the initial apartment to the overall façade with different scenarios for the fire source and ventilation. Fire propagation through windows to the façade and to upper apartments is addressed. General curves representing the re-entry of flames into upper apartments are extracted from simulations. The numerical results are validated by comparison with observations from videos and pictures of the real fire. Numerical results show that whatever the initial fire location and ventilation conditions, even if the fire source is of hundreds kilowatts, it is enough to ignite the adjacent element early and to the appearance of external flames shortly after.

KEYWORDS
compartment fire, façade insulation, fire propagation, numerical simulation, ventilated façade

1 | INTRODUCTION

Increasing the energy performance of buildings is a crucial global sustainable development objective. However, building features and products (on their own or in combination) may have an impact on fire safety. In the case of externally insulated façade systems, the products used either for the render/cladding or the insulation may be combustible. Moreover, for ventilated façades, the air gap between insulation and cladding may be a vector of fire propagation via the chimney effect. Thus, both the materials taken independently and the system itself are potentially a source of propagation of the fire on a façade. The recent dramatic event of the Grenfell Tower in London1 in June 2017 reminds of the importance of addressing fire issues as a whole. One of the major roles played by the building’s façade as fire propagation vector was clearly highlighted.
Intermediate scale façade fire propagation tests according to the ISO 13785-1 standard, with additional heat release rate (HRR) and gas analysis, were previously performed by Guillaume et al. on nine different combinations of aluminium composite materials (ACM) and insulators. Numerical simulations, detailed in Dréan et al., were performed with the code Fire Dynamics Simulator (FDS) to reproduce three of these fire tests. Thermal characteristics of the system components were integrated into the model. The justification of the numerical model used for thermal degradation analysis was addressed. The first aim of that study was to validate the numerical model by comparing its output with the aforementioned experimental results, including details in terms of flows and thermal conditions at each location in the tested system. The second aim was to allow a better understanding of how the fire propagates on the overall system and on the insulation and cladding, of which the cladding system comprises. The fire behaviour of each component of the overall system was thus modelled numerically.

After the Grenfell disaster, the UK government commissioned seven large-scale BS 8414-1 fire tests. The objective was to determine the combinations of insulation and ACM cladding that could safely be used. In Dréan et al., the influence of scale on the fire behaviour of façade systems featuring ACM-based cladding was investigated numerically using the validated numerical model described in. Simulations were performed in order to reproduce three of the UK Government’s BS8414 fire tests, detailed in. Then, the numerical model was modified to use coarser numerical cells that are more commonly encountered in large-scale simulations and engineering studies. Using such a coarse grid was necessary because of the difficulties and time taken in modelling larger scales, such as a full-scale façade on a high-rise building. However, a numerical hypothesis must be fixed in order to apply the model developed using an accurate fine grid to a coarser grid. The main objective was to reproduce the thermal gradients in gas and solid phases achieved with the initial model. For example, in the coarser grid model, the air cavity has the same thickness as the cell size. The exchanges between the materials and the gas phase were also evaluated in a larger cell. The numerical simulations and the original BS8414 tests showed that the ACM cladding was the most important element driving the global fire behaviour of the façade systems considered. In particular, ACM-PE-based façade systems showed very strong fire propagation whatever the insulant. This series of simulations was a part of a larger study including several steps of increasing complexity. Once the numerical model for the fire behaviour of the façade system was validated at intermediate and large scales, building-scale façade systems were investigated numerically.

Several studies have shown the feasibility and usefulness of numerical simulation for high-rise building fires and for post incident analysis. Numerical simulations were used, after the World Trade Centre disaster in 2001, to provide deeper analysis of the fire propagation inside the structure. One of the most important features for assessing the fire behaviour of façade systems is to properly represent fire spread from the fire compartment of origin to the façade. External flames venting through an opening, such as a window aperture, expose the façade system to heat and can lead to ignition of façade components and fire spread to the façade. This, in turn, creates a significant risk of fire spread to adjacent floors or buildings. The performance of façades, when exposed to flames venting through a compartment opening, has been extensively studied, experimentally and numerically.

The Grenfell Tower is a 24-storey high-rise building. The tower was refurbished in the period 2012-2016. A new insulated ventilated façade system was installed on all of the building’s elevations, and new windows were fitted. The over-cladding was mounted on the existing reinforced concrete envelope. The Grenfell Tower disaster happened on 14 June 2017. The fire spread to the façade via a kitchen fire in an apartment located at the lower floor of the east façade of the tower, resulting in flames breaking out through the kitchen window. This has been extensively detailed in expert reports and is shown in video and photographic records of the real fire. These records have been used to provide an analysis of the postbreak-out vertical and horizontal fire propagation on the whole façade of the Grenfell Tower in Guillaume et al.

In this paper, the development of the initial internal kitchen fire at Grenfell Tower, its propagation through/around the kitchen window opening, over the façade and re-entry into subsequent compartments are investigated. Three-dimensional (3D) numerical simulations were performed with the computational fluid dynamics (CFD) code FDS. The Grenfell Tower façade is modelled to investigate fire behaviour at window frames and its spread through the façade. Fire propagation from the façade into additional apartments through window frames is also assessed. It includes validation by comparison with video and photographic observations of the real fire. The thermomechanical analysis performed in Koohkan et al. is used to validate proposed window failure criteria. The modelling of the Grenfell Tower façade is based on the numerical model previously validated against experimental results from large-scale BS 8414-1 tests. Guillaume et al. made a thorough analysis of observational data from the Grenfell Tower disaster and created an analysis of the vertical and horizontal fire propagation over the whole façade.

The initial fire, before spreading outside, was a localized fire close to the wall and window, in the south-east corner of the kitchen in flat 16, located on the fourth floor of the east façade of the Grenfell Tower. The CFD model was used to evaluate the spread of the initial kitchen fire, to the building’s façade through/around the kitchen window opening and the propagation of the fire over the façade. Re-entry of the fire into subsequent apartments through window openings is also assessed, and general fire evolutions representing the re-entry of the flames inside the apartment are extracted from the simulation for the kitchen, the living room, and the bedroom. The model was validated by comparing its output with video and photographic records of the real fire. Additional thermomechanical analysis was performed on the windows used in the tower refurbishment. Both open and closed windows were analysed, to determine whether they would fail by falling inwards or outwards. Thermal loads from apartment and façade fire simulations were considered as boundary conditions. Predicted time to first failure of the frame was around 4 to 5 minutes.

This paper presents the hypothesis selected and the results for each step of the study performed.
Regarding the uncertainties related to the initial fire source that has led to the Grenfell disaster, the main objective of the present study is to provide a better understanding of the possible fire scenarios that lead to the development of the fire along the façade. Due to the complexity of the investigation and the lack of information, numerical models are useful to provide elements or scenarios that can be discarded. More complex models can be proposed if more information are available, and several scenarios can be assessed numerically. However, in this work, a preliminary analysis of the probable fire development in the initial apartment is addressed, until the ignition of the façade system.

## 2 | DESCRIPTION OF THE FAÇADE SYSTEM AND OF THE INITIAL APARTMENT

The Grenfell Tower is a 24-storey high-rise building, refurbished in the period 2012-2016. A new insulated ventilated façade system was installed on all of the building’s elevations, and new windows were fitted. The over-cladding was mounted on the existing reinforced concrete envelope. This included a series of 14 octagonal columns around the building’s perimeter: five columns on the north and south façades of the building leading to four bays, and four columns for the east and west façades of the building leading to three bays (Figure 1).

From levels 4 to 23, all floors have a similar layout of six flats (four two-bedroom flats and two one-bedroom flats). Video and photographic records and other evidence show that the initial fire was located in the kitchen of flat 16 located on the 4th floor of the east façade of the Grenfell Tower, as indicated in fig. 10 of Prof Luke Bisby’s expert report to the Grenfell Inquiry. Flat 16 comprised two bedrooms, one living room, a bathroom with separate WC, and several small storage spaces; a linking corridor; and a kitchen partitioned from the living room with a set of timber sliding doors. A schematic of this flat and the approximate arrangement of the kitchen, where the fire started, are indicated in fig. 11 of Prof Luke Bisby’s expert report to the Grenfell Inquiry.

The façade system installed during the Grenfell Tower refurbishment consists of cassettes of 4 mm (ACM-PE) cladding and 160 mm (PIR) insulation (100 mm on the columns), with a 150-mm ventilated air gap between these elements (100 mm on the columns). The system was mounted directly onto the building’s 200 mm thick concrete spandrels and octagonal columns. Details of the façade system are shown in fig. 14 in page 36 and fig. 17 in page 40 of Professor Luke Bisby’s expert report. The façade system installed on Grenfell Tower was offset from the existing building envelope by about 320 mm, and about 250 mm for the columns. Sections of the façade between the windows were fitted with infill panels (figs. 8 and 9 of Professor Luke Bisby’s expert report). These panels comprised 25-mm extruded polystyrene insulation with 2-mm aluminium facing on either side.

The new window frames were mounted on continuous aluminium rails that were mechanically fixed into the existing concrete envelope at the top and bottom of the openings. After the refurbishment, the new windows were offset by approximately 180 mm towards the outside of the building compared with the existing windows. The window assemblies comprised an aluminium frame, fixed and openable double-glazed casements (Metal Technology window “Thermally Broken Tilt and Turn Window System 5-20”), and infill panels housing an extract fan unit. The addition of new internal window reveals was required, to fill the gap between the existing envelope and the new façade system. The reveals were installed over the top of the existing window frame and were made with 9.5-mm unplasticized (rigid) polyvinyl chloride (uPVC).

Horizontal and vertical mineral wool cavity barriers were installed, roughly in line with compartment walls and floors. They were fitted in the space between the existing concrete façade and the new external (ACM-PE) cladding to ensure compartmentation of that space. However, installation errors were evident: for example, the cavity barriers were cut such that continuity of cavity compartmentation was not ensured (fig. 26 of Professor Luke Bisby’s expert report). The frame of the façade system comprises horizontal and vertical aluminium rails. They are installed under every window frame (fig. 21 of Professor Luke Bisby’s expert report) and continuously over the full height of the building on the outer surfaces of the columns and at the corners where the windows/spandrels about the columns (fig. 18 of Professor Luke Bisby’s expert report).

## 3 | NUMERICAL SET-UP

In this study, a 3D CFD model is used to evaluate fire spread from the initial apartment (flat 16), located on the fourth floor of the east façade of the Grenfell Tower, to the façade through the kitchen window. The initial fire within the kitchen of flat 16 before spreading outside was a localized fire close to the kitchen’s wall and window. Interaction between the wall and the fire must be taken into account for a meaningful assessment of fire spread. Thermal action by the fire on the initial apartment’s walls, particularly on the wall corresponding to the façade, is not homogeneous. A strong gradient exists, including the window frame. A zone model will give an average temperature that may underestimate local temperatures, in particular, in this case, at the window end of the kitchen. 3D modelling assesses local effects and these can be compared with video and photographic observations.
The numerical simulations were performed with the CFD code FDS version 6.7.0. FDS is a computational code in fluid dynamics that incorporates a combustion model and a large-scale model (LES) for the description of turbulent flows. This tool allows 3D modelling of the computational domain. It considers heat transfer at walls, ventilation conditions for the removal of hot gases, and air intake. The Navier-Stokes equations are solved in the limit of low Mach number, thermally driven flow with an emphasis on smoke and heat transport from fires. The radiative heat transfer is included in the model through the solution of the radiative transport equation for a grey gas. Detailed information is provided in the FDS reference guide.\(^5\)

The default submodels of FDS were used for the gas phase radiation exchanges with 100 (default value) solid angles. The combustion model with primitive and lumped gas species definition to solve a transport equation for each species to be tracked was also investigated as well as the use of a single step reaction for CO production because of uncertainty in the occurrence of this phenomena and regarding well-ventilated conditions for the combustion observed experimentally and numerically. The fuel burnout in each solid numerical cell is accounted for by the specification of the combustible mass of the object through the bulk density parameter. Thus, when the mass contained in each solid cell is consumed and the solid disappears from the calculation cell by cell. This feature is used to consider for the destruction of the cladding as observed experimentally with ACM-PE experiments. The default Deardorff model is used for the LES subgrid modelling. The default near-wall model with a wall function for smooth wall is used. The heat transfer at walls is simulated with a subsequent heat of vaporization to account for the energy loss due to the vaporization of the solid fuel. The justification of the numerical model used for thermal degradation analysis is addressed in Dréan et al\(^4\) and validated at larger scale in the other study.\(^7\)

In the numerical model of the partial tower, it has been assumed that there is no fire propagation pathway between floors of the tower via ducts, heating, ventilation, and air conditioning (HVAC) systems, or holes in apartment ceilings or walls. The fire propagation from one apartment to another (horizontally or vertically) occurs only via the façade fire spread and window failure.

Video and photographic records and other evidence show that the initial fire was located in the kitchen of flat 16 located on the fourth floor of the east façade of the Grenfell Tower. In the first step, a numerical model of flat 16 has been created and comprised the kitchen and the adjacent living room (Figure 2). The total dimensions of the numerical model are 7300 \(\times\) 8800 \(\times\) 3000 mm (L \(\times\) w \(\times\) h), with open boundary conditions for pressure. Mesh size is taken as 50 \(\times\) 50 \(\times\) 50 mm for the apartment. The model comprises a total of 1.5 million cells.

For the second step, to investigate the fire development in the bedroom of flat 16, a numerical model has been developed for the bedroom and the building exterior. The dimensions of the numerical model are 2900 \(\times\) 5800 \(\times\) 3000 mm (L \(\times\) w \(\times\) h) with open boundary conditions for pressure. Mesh size are taken as 50 \(\times\) 50 \(\times\) 50 mm for the apartment. The model comprises a total of 0.4 million cells.

The window in the kitchen of flat 16 is modelled with dimensions of 1.2 \(\times\) 1.5 m\(^2\) (w \(\times\) h). The total floor surface area of the kitchen is 8.64 m\(^2\). In the living room, there were two windows in each external wall: two through the east façade and two through the north façade. The total floor surface area of the living room is 24.16 m\(^2\). The bedroom window of flat 16 is modelled with dimensions of 1.2 \(\times\) 1.5 m\(^2\) (w \(\times\) h). The total floor surface area of the bedroom is 11 m\(^2\).

The expression given in previous studies\(^{19,41,42}\) allows the evaluation of the maximum HRR of a fire that can burn in a compartment with a given ventilation rate. The maximum HRR that can be burnt inside the compartment is thus close to 3.3 MW for the kitchen and the bedroom and 6.6 MW for the living room. In the FDS reference guide\(^5\) and literature,\(^{43}\) a criterion for the quality of the mesh resolution is given for simulations involving buoyant plumes. It is assessed using the non-dimensional \(D^*/\Delta x\) ratio, where \(\Delta x\) is the size of the grid cells and \(D^*\) the characteristic fire diameter depending on the fire HRR. Following this expression, for the total HRR in the kitchen and bedroom (Q = 3.3 MW) and in the living room (Q = 6.6 MW), the adequate mesh size \(\Delta x\) to obtain reliable predictions of the radiative heat flux comprises between 0.09 and 0.38 m. Thus, the considered grid size is sufficiently fine to capture accurately the combustion and turbulence phenomena of the system.

The thermal characteristics of the system components are integrated into the numerical model from Dréan et al\(^7\) in terms of density, thermal conductivity, heat capacity, emissivity, heat of combustion, ignition temperature, mass loss rate, species release rates, and all the thermal and combustion properties considered for all materials of which the system comprises.

A close-up of the façade and of the windows model is shown in Figure 3. The locations of the horizontal and vertical cavity barriers, aluminium, and PVC frames as well as infill panels are highlighted. In the numerical model, the façade system consists in 4 mm (ACM-PE) cladding and 160 mm (PIR) insulant (100 mm for the columns), with a 150 mm ventilated air gap between these elements (100 mm for
The characteristics of the horizontal and vertical cavity barriers and vertical aluminium rails are matching those of the products used in the refurbishment. Local gaps in the cavity barriers have been represented in the model by cutting the solid obstacles at location designed in the expert’s reports, mainly near the column junction, as well as the continuity of the aluminium cladding rail along the columns and under window frame. The window infill panels have been included in the model, as have the new PVC reveal liners and the pieces of insulation that fill the gaps behind them, allowing local ignition of PVC and gases to pass from façade to column. The combustion of the façade cladding (ACM-PE) and insulant (PIR) follow the fire model developed in Dréan et al and subsequently validated in the other study with a coarse grid. It is assumed that the PVC window sill will ignite and disappear if its surface temperature reaches 160°C, representative of the melting and falling of the PVC.

The window failure mechanism implemented in the numerical model is linked to the partial failure of the lateral and upper aluminium frames of a window. Each part disappears if its surface temperature reaches 550°C. This temperature corresponds to the loss of the mechanical properties for the aluminium. Glazed elements, such as windows, generally fail due to frame distortion and the thermal gradient at their edges. Thus, the window glazing is divided numerically in six to nine pieces; each piece disappears if at least two adjacent window frames disappear.

The assumptions used for the location of the different furniture in the living room and the kitchen are shown in Figure 4. The fire contribution of the different items of furniture is detailed in the Supporting Information. The numerical approach is based on the fire development of each single furniture inside a room when a given ignition temperature is reached. The individual material properties and HRR evolution in function of time are indicated in the see Supporting Information.
Numerical Analysis of the Fire Development in the Initial Apartment

Based on the description of the apartment and the evidence of ignition of different items, fire development in the initial apartment (flat 16) was investigated. The fire in the kitchen of flat 16 must have provided sufficient heat to combustible materials in or around the window for them to reach their ignition temperature. Following the hypothesis of Torero, this could either be through direct flame impingement or as a result of sustained contact with smoke and/or heat accumulated in the kitchen at a remote location from the immediate fire plume. Uncertainty concerning the initial fire source exists, as discussed in Professor José Torero’s expert report. This study assumes that the first ignited item is located in the south-east corner of the kitchen, close to the window, as proposed in Professor Luke Bisby’s expert report. Regardless of fire source, the development of the fire will be controlled by ventilation and hence the flow rate of air through the kitchen’s window and doors. A fridge/freezer and a mini-fridge were reported as being present in the kitchen at a remote location from the immediate fire plume. Numerical modelling has been performed considering each fridge as the fire source. The smouldering of both fridges is represented by a slow increase in HRR over 5 minutes.

In scenario 1a, the fire source is the mini-fridge existing at the left of the kitchen’s window. The kitchen’s door is kept closed in this scenario, assuming the confinement of the fire by the owner and by the firefighters. In scenario 1b, the fire source is the same, but the effects of the door opening is investigated, representative of the firefighters entering several times in the kitchen. The scenario 2 investigates the change of the fire source, since the fridge/freezer is also designated as a potential source.

4.1 Scenario 1a: ignition of the mini-fridge with restricted ventilation

The development of the fire from the mini-fridge in the kitchen of flat 16 under restricted ventilation conditions is investigated. The sliding partition between the living room and the kitchen, and the doorway
from the corridor into the kitchen are closed. However, “closed” does not mean air-tight and slight air-leakage, typical of doors, was built into the model. Air-leakage due to the subsequent opening of doors during firefighter intervention was also built into the model. This air-leakage was represented by the addition of a gap on one side of booth doors. The size of this gap was 0.1 × 2.0 m (w × h), ie, 0.1 m for the whole height of the doors. Two numerical cells (2 × 0.05 m) are involved in calculating properly the mass flow through the openings. A fan unit mounting panel made of PVC is modelled on the left part of the window. Its dimensions are 0.4 × 0.5 m (w × h). An external and an internal view of the kitchen are indicated in Figure 5.

The smoke extinction coefficient under the ceiling of flat 16 was evaluated numerically at 2 and 3 minutes after ignition (Figure 6). Due to uncertainty about the type of smoke detector and its location in the kitchen, the value of 0.4 m\(^{-1}\) is considered when it is reached in a large area and is used for the smoke detection by a detector located at the kitchen ceiling. This value corresponds to a visibility of 7.5 m (no light condition), so that the entire kitchen length is still visible from the door. In Professor Luke Bisby’s expert report,\(^{31}\) it is recorded that the fire was first notified to emergency services in the 999 call by the occupant of flat 16, after detection of a fire in the kitchen. This call happened at 00:54:29 AM. The time of detection is based on the assumption of a maximum delay of 2 minutes between fire detection in the kitchen and the 999 call. This is assumed to be minimal given the size of the kitchen and given the type of materials present in the kitchen. Furthermore, regarding the short distance between the bedroom and the kitchen, this time delay for the owner to be alerted by the fire alarm, to see the fire in the kitchen and to call the 999 is realistic. This yields an assumed detection time of around 00:51:00 AM and 00:52:00 AM and thus ignition at around 00:49:00 AM. Thus, the hypothesis of fire detection occurring between 2 and 3 minutes after ignition in the kitchen seems coherent. When detection occurs, the fire is not fully developed and a maximum HRR of 150 kW is found numerically.

The fire development for this scenario is shown in Figure 7, starting after ignition. The adjacent PVC window surround ignites at 7 minutes 30 seconds. The fire spreads over the PVC elements of the window frame. Then, at 8 minutes 30 seconds, the fan unit mounting panel on the window ignites too. Adjacent kitchen furniture, firstly

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**FIGURE 5** View of the model of the kitchen wall of flat 16: (A) external and (B) internal with the mini-fridge (red volume) and the fan unit in the window [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 6** Smoke extinction coefficient under the ceiling of the flat 16—2 and 3 min after fire ignition—Scenario 1a [Colour figure can be viewed at wileyonlinelibrary.com]
the fridge, ignites at 9 minutes. The fan unit is partially absent after 12 minutes 30 seconds, and flames are visible from outside through the aperture of the window 2 minutes afterwards. The right part of the window fails after 18 minutes 30 seconds and the left part after 22 minutes, leading to longer external flames through the kitchen windows. The external cladding ignites at 20 minutes.

The HRR achieved from the simulation over time for this scenario is shown in Figure 8. The annotations in this figure refer to Table 2, which details the observation predicted by this model. A maximum total HRR value of 4 MW is observed 30 minutes after ignition and comprises heat from the kitchen fire and the external flames. Parts of the externally insulated façade system are already burning and contributing to the total HRR.

The times of observations during the real disaster are shown in Table 3. Figure 9 superimposes these observation times onto the modelled HRR curve to show the correlation between the observations and the numerical predictions. It should be noted that 26 minutes after the call for emergency, firefighters are intervening and start extinguishing the fire in the kitchen and the living. However, the external cladding is already burning. Thus, after 01:20:48 AM, the predicted HRR must be considered carefully.

Regarding gas temperature in the transverse plane of the kitchen between 7 min 30 s and 12 min 30 s after ignition, which could correspond to 00:57:30 to 01:02:30 AM, the hot layer temperature is under 200°C at the start of this period, before fire propagation to adjacent combustible elements immediately thereafter. This is coherent with the temperature values measured by the firefighters entering the flat 16 at 01:07:21 AM. Even when the fire has propagated and the fan unit has failed at 12 minutes 30 seconds after ignition, flashover is not reached inside the kitchen, and gas temperatures under ceiling...
are lower than 500°C to 600°C before firefighter’s intervention. However, these temperatures are high enough for adjacent combustible element to ignite and for the window surround to fail. The window frame is close to the flames, and the local temperatures reach 500°C to 600°C on the materials leading to its failure.

### 4.2 Scenario 1b: ignition of the mini-fridge with free ventilation

For scenario 1b, the same apartment configuration and furniture as in scenario 1a is assumed. The only difference is the sliding partition between the kitchen and the living room is kept open. This ensures ventilation sufficient for the fire to develop.

The smoke extinction coefficient under the ceiling of flat 16 at 3 minutes after ignition confirms the hypothesis made for the detection occurring between 2 and 3 minutes after the fire ignition in the kitchen. The timescale of the initial fire development is approximated by evaluating the possible detection of the smoke in the kitchen happening around 00:51:00 and 00:52:00 AM, with the hypothesis of a maximum delay of 2 minutes before the call to firefighters at 00:54:00. When detection occurs, the fire is not fully developed and a maximum HRR of 150 kW is found numerically.

### TABLE 2 Observations, predicted by the model, of fire development in the kitchen of flat 16 for scenario 1a

| Event |
|-------|
| Ignition of PVC window surround |
| Ignition of fan unit mounting panel |
| Ignition of adjacent furniture |
| Fan unit mounting panel partially absent |
| Failure of the first window frame—external flames |
| Ignition of the external cladding above the firth window |
| Failure of the second window frame—stronger external flames |

### TABLE 3 Observations of the real fire development in the kitchen of flat 16

| Time (AM) | Event |
|-----------|
| 00:54:29 | First notification of emergency call |
| 00:55:36 | Flames visible at the left of the window; fan unit appears to be absent (external observation) |
| 01:07:21 | Fire brigade enters flat 16 |
| 01:08:06 | Smoke and longer flames visible at window (external observation) |
| 01:09:00 | Observation of fire spread to the cladding |
| 01:14:16 | Fire brigade opened the kitchen door and captured video footage |
| 01:14:23 | First pulse by the fire brigade |
| 01:14:25 | Second pulse by the fire brigade |
| 01:14:33 | Fire brigade reopened the kitchen door and captured video footage |
| 01:15:33 | Fire brigade reopened the kitchen door and pulsed water spray |
| 01:20:48 | Fire brigade reopened the kitchen door and attempted to extinguish the fire from the room |

### FIGURE 9 Heat release rate (HRR) predicted by the model (blue line), for fire development in the kitchen of flat 16 for scenario 1a, overlaid by observation timings from Table 3—probable time of detection of the fire in the kitchen is highlighted with green lines. Simplified evolution of the HRR is highlighted by red line [Colour figure can be viewed at wileyonlinelibrary.com]
The fire behaviour inside the kitchen and the living room (Figure 10) shows that between 9 and 11 minutes, the fridge/freezer ignites. After 12 minutes, the two fridges are burning. The fire develops in the kitchen and propagates to the adjacent washing machine, the cooker, and the work surface. At this time, no external flames impinge on the external façade even if the flames might have been visible from outside the Tower. Flames are observed at the window between 15 and 16 minutes. Between 15 and 20 minutes, the fire enters in the living room through the door between the kitchen and the living. The window in the kitchen has partially failed and external flames occur after 14 minutes (01:03:00 AM). However, a delay of 9 minutes is observed to measure significant external flames (Figure 11), corresponding to 23 minutes after the fire ignition (01:12:00 AM). At windows, 18 minutes after ignition (01:07:00 AM), the surface temperature on the frame inside the apartment goes up to 300°C and locally even 660°C on the top of the frames. These temperatures are critical for PVC ignition and

The modelled HRR over time, for this scenario, is shown in Figure 11. The fridge begins to burn fully between 5 and 6 minutes after ignition. A maximum total HRR value of 4 MW is observed 30 minutes after ignition and comprises heat from the kitchen fire (almost 2.5 MW) and the external flames (1.5-2 MW). Parts of the externally insulated façade system are already burning and contributing to the total HRR. However, after 01:20:48 AM, the firefighters start extinguishing the fire inside the kitchen, so the predicted HRR must be considered carefully after this moment.

The window in the kitchen has partially failed and external flames occur after 14 minutes (01:03:00 AM). However, a delay of 9 minutes is observed to measure significant external flames, corresponding to 23 minutes after the fire ignition (01:12:00 AM). At windows, 18 minutes after ignition (01:07:00 AM), the surface temperature on the frame inside the apartment goes up to 300°C and locally even 660°C on the top of the frames. These temperatures are critical for PVC ignition and

**FIGURE 10** Fire development inside flat 16 for the first 25 minutes after ignition—Scenario 1b [Colour figure can be viewed at wileyonlinelibrary.com]
for the structural integrity of aluminium. Thus, the windows are consid-
ered as totally broken at this time and removed from the simulation. At
25 minutes (01:14:00 AM), the fire is developed in the kitchen, and weak
propagation in the living room is observed.

4.3 | Scenario 2: ignition of the fridge/freezer with
free ventilation

As it is unclear what the first ignited item in the kitchen was, except
that it was located in the corner of the kitchen close to the column
and the window corner, a second fire scenario was investigated.

In this case, the large fridge/freezer ignites first. The evolution of HRR
for this scenario is presented in Figure 12 and compared with the HRR
from scenarios 1a and 1b. A similar evolution of HRR is observed for both
locations of the fridge. The main difference between HRR behaviours in
scenarios 1b and 2 is that higher values of HRR are reached locally in sce-
nario 2, due to the proximity of the fridge/freezer to the other kitchen
contents. The window failure begins earlier, 12 minutes after ignition.

In Professor Luke Bisby’s expert report,[31] it is noticed that the first obser-
vation of fire having spread to the cladding is at 01:09:00 AM, corre-
sponding to 15 minutes after the first emergency call, and 19 to 20
minutes after the fire ignition. This is coherent with the numerical obser-
vations indicated in Figure 13, with a first cladding ignition around 19
minutes. Even if the fire starts being extinguished inside the apartment
at 01:20:00 AM, the propagation at the façade has begun.

4.4 | Preliminary synthesis

For the three fire scenarios investigated for the initial fire develop-
ment in the kitchen, whatever the fire location (fridge or mini-fridge,
scenario 1b vs 2) and ventilation level (scenario 1a vs 1b), the same
conclusions can be drawn.

- Even if the fire source is less than 300 kW, it is strong enough to
  ignite the adjacent PVC window surround early.
- The fire propagation quickly leads to the ignition of the fan unit
  mounting panel and to the appearance of external flames quickly.
- When surroundings elements are ignited, the window frame fails in
  a few minutes.
- Even if the fire starts being extinguished inside the apartment at
  01:20:48 AM, façade fire propagation has begun.
- Flashover in the kitchen is not reached in any scenario.

The synthesis of the times for first window failure and cladding
ignition is addressed in Table 4. For the three scenarios investigated,
the observation during the real fire and the numerical prediction cor-
relate. No evidence of flashover was observed in the kitchen of flat
16 (photograph 12 from [MET00007748] in Professor Luke Bisby’s
expert report[31]), but fire propagation to adjacent elements in the
kitchen is clearly visible. The window frame appears failed. Fire

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**FIGURE 11**  Heat release rate (HRR) predicted by the model, for fire development in the kitchen of flat 16 for scenario 1b showing the contributions from internal and external combustion—probable time of detection of the fire in the kitchen is highlighted with blue lines [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 12**  Heat release rate (HRR) evolution of the fire for scenarios 1a, 1b, and 2—beginning of window failure for each scenario is indicated with coloured dotted lines [Colour figure can be viewed at wileyonlinelibrary.com]
The initial burning apartment (flat 16) with the external fire venting through the kitchen window is the starting point. The window is considered to be partially broken 13 minutes after fire ignition, corresponding to 01:02:00 AM and totally broken after 15 minutes of fire exposure, corresponding to 01:04:00 AM. This is consistent with the observation from the real fire of the fan unit appearing to be absent and flames passing under the infill panel mounting board and out of the window below at 01:05:00 AM and the first known images of the fire captured. The fire venting through the kitchen window is shown from a front and a lateral position in Figure 14. The flame shape has dimensions close to 1.35 × 0.55 m (l × w). The flame width corresponds to the window frame width and the flame projection to almost one third of the window height. This is consistent with the flame width at windows given by the expressions in Delichatsios et al and Kawagoe.

The modelled external shape of the flames is used as the boundary condition for the external fire, to facilitate the modelling of fire propagation to an upper kitchen window as illustrated in Figure 15. It is assumed that the contents of the kitchen in the upper apartment, and their locations, are the same as in the flat 16. The flame dimensions of 1.35 × 0.55 m (l × w) are used as plume surface below the window of the kitchen, and the HRR of the fire is applied using a simplified representation. The simplified HRR is representative of the difference between the total HRR and the HRR inside of the initial apartment fire, showing a maximum value of 1.5 MW—a simplified representation of the HRR is used to avoid numerical oscillations that could lead to instabilities. The external fire decrease will be driven by the consumption of the combustible load of the façade system.
External flames are significant 23 minutes after the fire ignition (01:12:00 AM). The external temperature of the window frame of the upper kitchen reaches values up to 660°C after 4 minutes of exposure to the significant external flames. Thus, the partial or total loss of the window of the apartment above the fire (flat 26) can be assumed at this moment. This delay corresponds to 27 minutes (01:16:00 AM) after the fire ignition in flat 16. This time is coherent with observations evaluating a window failure of the kitchen of flat 26 around 01:18:00 AM.

The fire propagation from the façade to the upper apartment (Figure 16) shows that the kitchen’s window is removed after 4 minutes of exposure and the external fire enters the apartment after 4.5 minutes of exposure. The fire then propagates to the kitchen elements, firstly to the two fridges close to the window.

The evolution of the evaluated HRR in the kitchen is similar to that for the internal part of the kitchen fire in scenario 1b (Figure 17). Thus, the HRR evolution evaluated for flat 26 can be used for every kitchen scenario above flat 16, as part of the evaluation of the fire propagation over the east façade.

5.2 Propagation of the fire from the façade to the living room of an apartment above flat 16

Regarding the propagation of the fire from the façade to the living room of an apartment above flat 16, the fire can come either from the kitchen of the apartment or from the exterior (façade fire). When the fire source is a fire in the apartment kitchen, limited propagation of
the fire into the living room is observed. Partial ignition of the dining

table is evaluated around 13 minutes and of the sofa around 22

minutes after flame exposure in the kitchen (Figure 18). In the case

of flat 26, this corresponds to 40 (01:29:00 AM) and 49 minutes

(01:38:00 AM), respectively, after fire ignition in flat 16.

The numerically evaluated HRR for the living room is shown in

Figure 19. Its contribution is negligible. The first peak is due to the din-

ing table ignition, and the second peak is due to the partial ignition of

the sofa. Flashover is not reached.

When the fire source is coming from the exterior (façade fire) of

the apartment, the window in the living room close to the kitchen fails after

4 minutes of exposure, in a similar manner to the failure of the kitchen

window. The external fire enters the apartment 1 minute after the win-
dow failure and propagates to the living room furniture, firstly to the

dining table (Figure 20). The subsequent fire propagation to other furni-

ture in the living room (sofa, TV set, chairs, and carpet) is slow, and it

takes more than 15 minutes to observe significant propagation.

The numerically evaluated total HRR inside the living room (Figure 21)

shows a maximum HRR of 6 MW is reached at 32 minutes after the window

breakage and flashover is observed. Thus, when a window failure happens in

the living room, this HRR evolution is representative for every living room

fire scenario above flat 16, because the scenario of a fire starting in the kitchen leads to negligible propagation to the living. This result is comparable with those indicated in Hietaniemi and Mikkola47 for a living room fire.

5.3 | Propagation of the fire from the façade to the

bedroom of an upper apartment above flat 16

The propagation of the fire from the façade to the bedroom of an

apartment above flat 16 has been investigated. The fire comes from

the exterior (façade fire). Because the bedrooms are adjacent to a cor-

ridor, a scenario of a fire from the interior of the apartment was not
The bedroom furniture and its location are shown in Figure 22. The fire propagation over the bedroom façade is shown in Figure 23. The flames are drawn in black and white to provide a better visualization of the progressive disappearance of the cladding and of the appearance of the insulation (orange colour). Propagation to the external cladding of the lateral column is observed after 9 minutes of exposure and of façade after 14 minutes of exposure. The external cladding is burning for 10 minutes, until it is progressively consumed. The cladding is totally consumed after 30 minutes of exposure. The insulant is visible after 29 minutes of exposure and burns in well-ventilated conditions.

When the fire source is the façade fire, the window in the bedroom fails after 4 minutes of exposure in a similar manner to the failure of the kitchen and living room windows. Then, 4 minutes after window failure, the external fire enters the apartment and propagates through the cladding.
to the bedroom furniture, firstly to the bed mattress, 6 minutes 30 seconds after window failure (Figure 24). The fire propagates to the other furniture of the bedroom: nightstand n°1, wardrobe, nightstand n°2, respectively, 9 minutes, 12 minutes, and 14 minutes 30 seconds after the window failure. It takes more than 16 minutes to observe a significant propagation leading to a flashover. Then, residual combustion is observed until 35 minutes.

The numerically evaluated HRR inside the bedroom (Figure 25) shows a maximum value of 3 MW reached 15 minutes after the window failure and reflects the occurrence of flashover. Thus, when a window failure happens in the bedroom, this HRR evolution is representative for every bedroom fire scenario above flat 16. For the apartments vertically above flat 16 on the east façade, two bedrooms exist. However, it is assumed that these bedrooms are identically furnished and that the fire will develop in a similar way for each room. Thus, the fire HRR achieved is considered to be applicable to the two bedrooms in each apartment.

5.4 | Numerical evaluation of window failure

To verify the failure delay achieved during the CFD analysis, the thermal and thermomechanical performance of the window frames used in the Grenfell Tower refurbishment are addressed.

Post-disaster observations have shown different failure modes of the window frames, with for example, inward and outward fallout of windows. Thus, the relation between the initial position of the window during the disaster (close, open, and tilt) and its fallout mode need to be investigated. The time to failure depending on a given opening configuration needs to be addressed too. Opened or in-tilt opening configurations are probable because the Grenfell disaster happened during summer, and hot temperatures were recorded during the night of the disaster. The early windows failure may lead to the re-entrance of fire in flats. Thus, the numerical criterion for this failure is of main importance in the fire spread investigation, and more accurate thermal models than those of FDS are needed.

Window failure from external or internal fire was assessed numerically using the FEM code ANSYS, based on the prior analysis of the external fire that broke out from the kitchen of flat 16. This facilitated the evaluation of the heat fluxes imparted to the each part of the window frames, which comprised aluminium and polyamide thermal breaks.

Numerous different frame configurations and sizes were used in the refurbishment. However, this study focused on the window frame sized 1241 mm × 1285 mm. The window is glazed with 26-mm-thick double glazed units. The window glass is set inside a composite aluminium frame structure made up of two aluminium profiles separated by polyamide thermal breaks. The details of the geometry and cross section of the frame, modelled for thermal and mechanical performance, are given in previous studies.

The thermal analysis consisted of computing the material warming due the thermal actions obtained from a real fire scenario. Both frame and casement window sections were modelled. A part of glass, which participates as an interface between two walls of casement window, was also modelled. The thermal loads used in this modelling were taken from the CFD calculations detailed above of the external fire that broke out from the kitchen of flat 16.

The mechanical behaviour of the aluminium window, when subjected to thermal loads, was investigated. Two configurations were studied and consisted of a closed casement window and an in-tilt position window, respectively. Polyamide thermal bridge temperatures of
the of up to 80°C were observed after 3 minutes of fire exposure and up to 200°C after 5 minutes of exposure. The partial failure of the frame was thus expected between 4 and 5 minutes of exposure. Additional thermomechanical analyses were performed on windows that were initially opened or closed, to model whether the windows would fail by falling inwards or outwards. For each case, strong deformations of the frame appeared between 5 and 10 minutes of external fire exposure. The window was expected to partially fail during this time. These results are consistent with the criteria for window failure used in the fire models, i.e., the beginning of failure after 4 minutes of façade fire exposure, as shown in Figure 26. The window frame deformations lead to the outer failure of the external profile after 5 minutes of fire exposure (Figure 27).

6 | CONCLUSIONS

This study aimed to model and to understand the fire development and propagation inside the apartment of origin of the Grenfell Tower fire and the behaviour of the kitchen window of that apartment. The
fire propagation through the window to the external façade and later to upper apartments was also addressed.

A numerical model of the Grenfell Tower façade was constructed based on a model previously validated by comparison with experimental results from large-scale BS 8414-1 tests.

Based on literature data and expert's reports, the fire development due to the ignition of objects located at east end of the kitchen of the apartment of origin was investigated. Ventilation conditions and fire source location were also investigated through three different fire scenarios. Numerical results show that whatever the initial fire location (fridge or mini-fridge, scenario 1b vs 2) and ventilation conditions (opened or closed kitchen door, scenario 1a vs 1b), the same conclusions can be drawn. The fire detection occurred less than 3 minutes after the fire ignition, during the smouldering phase of combustion of the source. Even if the fire source is less than 300 kW, it is great enough to ignite the adjacent PVC window surround early. The fire propagation quickly leads to the ignition of the fan unit mounting panel and to the appearance of external flames shortly after. When surroundings elements are ignited, the window frame fails in a few minutes. Even if the fire starts being extinguished inside the apartment at 01:20:48 AM (31 minutes after the fire ignition), façade fire propagation has begun. Flashover in the kitchen is not reached in any scenario and was not needed for the fire to spread to the façade.

For the three scenarios investigated, observations from the night of the disaster and the numerical model correlate. No evidence of flashover was found in the initial apartment, but fire propagation within the kitchen was clearly visible. The window frame appeared to have failed.

The fire behaviour at window frames and its spread through the façade was investigated. The synthesis of the times for first window failure and cladding ignition was addressed for the three scenarios. Fire evolution for scenarios 1a and 1b were comparable; thus, the window failure seemed to be the main ventilation vector and the doors aperture appeared to have a reduced influence.

Fire propagation from the façade into upper apartments through windows was also assessed. External flames, venting from the window of the apartment of origin, as a result of the initial fire, were limited by internal ventilation and the window size. The heat release from the external plume was limited to 1.5 MW. General fire evolutions representing the re-entry of flames into the apartment above the flat of origin were extracted from the simulation, for the kitchen, living room, and bedroom. The model results were validated by comparison with observations from videos and pictures of the real fire. When exposed to significant external flames, the window failure happened in 4 minutes for each location investigated. This correlated with the additional thermomechanical analysis performed on both open and closed windows. Polyamide thermal bridge temperatures of the of up to 80°C were observed after 3 minutes of fire exposure and up to 200°C after 5 minutes of exposure. The failure of the frame was thus expected between 4 and 5 minutes of exposure. The full conclusions of this study will be addressed in future research.

Thus, the fire evolutions in terms of HRR curves evaluated for each room of an apartment above the initial fire apartment and the window failure criteria can be used to investigate the fire spread to the external façade and to the upper apartments in a larger numerical model of Grenfell Tower.

The main objective of the present study was to provide a better understanding of the possible fire scenarios that lead to the development of the fire along the façade. Due to the complexity of the investigation and the lack of information, more complex models can be proposed, and several scenarios can be assessed numerically. However, the difficulty of such investigation demands several scenarios and several hypotheses and assumptions. Years of investigations can be performing for only the apartment fire scenario. The ventilation impact on the initial fire development inside the apartment could be deeply investigated, with sequential opening and closure of the kitchen door. More accurate representation of the kitchen furniture, with detailed modelling of individual apparels, could also be a further investigation. Modification in the thermal properties of the materials and in the fuel definition will be evaluated in a later research. This work must be considered as a preliminary analysis of the probable fire development in the initial apartment, until the ignition of the façade system.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Guillaume E, Dréan V, Girardin B, Koohkan M, Fateh T. Reconstruction of Grenfell Tower fire. Part 2: A numerical investigation of the fire propagation and behaviour from the initial apartment to the façade. Fire and Materials. 2020;44:15–34. https://doi.org/10.1002/fam.2765