Reconstruction of Grenfell Tower fire. Part 3—Numerical simulation of the Grenfell Tower disaster: Contribution to the understanding of the fire propagation and behaviour during the vertical fire spread

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Summary
The dramatic event of the Grenfell Tower (June 2017), involving a combustible façade system, has raised concerns regarding the fire risk that these systems address. Indeed, as façades are complex systems, it is not straightforward to assess which part of the system is involved in the global fire behaviour. Understanding such façade fires is thus very complex as it depends on a combination of various products and system characteristics, including window frames or air gap or cavity barriers. Fire development inside the initial apartment was investigated using an appropriate CFD model with different scenarios for the fire source and ventilation conditions in a previous study. Fire propagation through the window to the external façade and to higher apartments was modelled and validated against visual observations. This paper describes CFD modelling of the complete Grenfell tower façade, and investigates vertical fire spread behaviour over the full height façade from the initial apartment. Contributions from the combustion of all the apartments’ furniture, depending on window failure, and architectural details of the refurbished façade are considered in the numerical model. The modelling results are validated by comparison with photographic and video observations of the real fire.

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

1 | INTRODUCTION

The Grenfell Tower is a 24-storey high-rise building located in London, and refurbished in the period 2012 to 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 fire happened on June 14, 2017.1 The fire spread to the façade via external flaming from an apartment located at the fourth floor of the east face of the Tower. This has been extensively...
detailed in expert reports⁵-⁷ and is shown in video and photographic records of the real fire. These records have been used to provide an analysis of the post-breachout vertical and horizontal fire propagation on the whole façade of the Grenfell Tower in Guillaume et al.⁵ This reference proposes several hypotheses for further investigation.

After the Grenfell event, the UK government commissioned seven large scale BS 8414-1 fire tests.⁶-⁷ The objective was to determine the combinations of insulation and aluminium composite material (ACM) cladding that could be safely used. However, the BS 8414-1 test method requires that a test is stopped if flames are observed higher than the test rig or, here, when criterion⁸ of BR135 has failed. Therefore, this BS 8414-1 test campaign does not provide a tool to examine all façade fire scenarios. Numerical simulation is, thus, a useful tool to investigate, understand, and analyse such fires, and, of particular use, specific phenomena can be isolated and evaluated more easily. Several studies have shown the feasibility and usefulness of numerical simulation for high-rise buildings fires⁹-¹¹ and for post incident analysis.¹²-¹⁵ Numerical simulations, using the CFD code FDS (fire dynamics simulator),¹⁶-¹⁹ were used after the World Trade Center disaster in 2001 to provide deeper analysis of the fire propagation inside the structure.¹²

In Dréan,²⁰ the influence of scale on the fire behaviour of ACM-cladding façade systems was investigated. Numerical simulations were performed to reproduce the fire tests commissioned and detailed in previous reports.²¹-²³ The façade systems were simulated using a validated model.²⁴,²⁵ The results of the simulations closely matched the experimental fire test results and showed that the ACM cladding was the main element driving the overall fire behaviour of façade constructions. In particular, systems that featured ACM cladding made with a polyethylene core (ACM-PE) showed very extensive fire propagation regardless of the insulation used.

At a real scale, the model, using the CFD code FDS, was then used to assess the fire performance of the façade system used on the Grenfell Tower in Guillaume et al.²⁶ One of the most important factors in properly assessing the fire behaviour of a façade system is to accurately represent fire spread from the compartment of origin to the façade. Flames venting through an opening, such as a window aperture, expose the façade system to heat and leads to ignition of, and fire spread to, the façade.²⁷ This then poses a significant risk of fire spread to adjacent floors or buildings. Fire exposure, resulting from flames venting through a compartment opening, has been extensively studied experimentally and numerically at different scales.²⁸,²⁹

The development of the fire, inside the kitchen of the apartment of origin at Grenfell, and its behaviour at the kitchen window were investigated in Guillaume et al.²⁶ Fire spread over the façade and at the cavity barrier locations were also explored, as was fire propagation from the façade, through the windows, and into higher apartments. A thermomechanical analysis of window failure was performed.³⁰ The overall heat release rate (HRR) for typical apartment rooms and window failure criteria were evaluated. The results can be used to investigate fire breakout to the external façade and to higher apartments in a larger numerical model of the Grenfell Tower. For the scenario investigated in the previous study,²⁶ observations from the real event correlate with the results of the numerical modelling. There was no evidence of flashover in the initial apartment kitchen, but fire propagation within the kitchen was clearly visible. The window frame appeared to have failed. However, this study was only dedicated to fire spread over a small part of the façade, two floors high. Fire spread over the whole tower façade, including the impact of burning contents, was not addressed. Thus, the results generated can only be used as individual boundary conditions in a larger scale analysis.

In the current work, the full height of the Grenfell Tower façade is addressed, using a numerical tool, to determine its fire behaviour. A three-dimensional CFD model is used to evaluate fire spread to and vertically over the whole east face of the Tower. This fire breaks out from the apartment of origin (Flat 16), located on the fourth floor of the east face of the Grenfell Tower, through its kitchen window, as investigated in Guillaume et al.²⁶ The thermal and combustion characteristics used for the façade system are those validated in Dréan et al.²⁰ The heat release rate for this initial fire and the apartment fire contributions detailed in Guillaume et al.²⁶ are used for each floor of the Tower. The failure criteria for the windows, assessed in Guillaume et al²⁶ and Koohkan,³⁰ were used for each apartment opening. Thus, depending on local window breakage, contributions of all the apartments’ contents are considered in the numerical model. Architectural details of the refurbished façade are used. It is assumed that there is no pathway for fire to breach the compartment floors of the Tower via ducts, HVAC systems, or holes in ceilings or walls, and that fire propagation from one apartment to another (horizontally or vertically) can only occur via the façade and window failure.

Wind was not considered in the model because the analysis detailed in Guillaume et al.²⁶ showed that the horizontal fire propagation rate over the Tower was the same in both clockwise and anticlockwise directions and was, thus, independent of wind.

Modelling of the vertical fire spread over the east face of the Tower is described herein. It is validated by comparison with video and photographic records of the real fire.³ The impact of different façade components on vertical fire propagation is investigated by modelling the different façade system build-ups. The influence of cavity barriers on fire propagation is shown as well as the fire performance of windows.

This paper presents the hypothesis selected, the methodology applied, and the results for each step of the study performed.

2 | METHODOLOGY

2.1 | General methodology of the study

This study is the extension of the series of simulations addressed in Dréan et al.²⁰,²⁴ and Guillaume et al.²⁶ including several steps of increasing complexity. Guillaume et al.²⁶ made a thorough analysis of observational data from the Grenfell Tower event and created an analysis of the vertical and horizontal fire propagation over the whole façade. The vertical and horizontal propagation rates of the fire were calculated for the different faces of the Tower. It was shown that the external wind had negligible influence on propagation rate, at least at crown level.
The work described in Guillaume et al.\textsuperscript{26} investigated the development of the fire inside the kitchen of the apartment of origin in the Grenfell Tower and, in particular, its behaviour at the window end of the kitchen. The Grenfell Tower façade was modelled to investigate fire behaviour at window frames and its spread through the façade. The validated façade model described in Dréan et al.\textsuperscript{20} was used in terms of thermal properties and combustion behaviour. The fire propagation from the façade into additional apartments through window frames was also assessed. The work was validated by comparison with video and photographic observations of the real fire. This allowed the evaluation of heat release rate for typical apartment rooms and window failure criteria. The work performed in Kookhan et al.\textsuperscript{30} describes additional thermomechanical analysis of window failure using thermal loads from the apartment and façade fire simulations as boundary conditions. The results were consistent with the criteria for window failure used in the numerical model of the Tower.

This paper considers the full scale fire on the east face of Grenfell Tower, using the numerical model validated for the façade system, the initial apartment fires, and windows failure. Fire spread over the external façade and to higher apartments is addressed.

### 2.2 Numerical set-up

A three-dimensional CFD model is used to simulate vertical fire spread over the east face of Grenfell Tower. This fire is initiated at the kitchen window of the apartment of origin (Flat 16), as investigated in Guillaume et al.\textsuperscript{26}. The thermal and combustion characteristics of the materials of which the façade system is comprised are those validated in Dréan et al.\textsuperscript{20}. The heat release rate of the initial fire, as well as the apartment fire contributions detailed in Guillaume et al.\textsuperscript{5} are assumed for each floor of the Tower. The window failure criteria assessed in the previous studies\textsuperscript{24,30} are used for each apartment opening.

In the numerical model of the Tower, it has been assumed that there is no fire propagation pathway between floors of the Tower via ducts, 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. Wind was not considered in the model because the analysis detailed in Guillaume et al.\textsuperscript{5} showed that the horizontal fire propagation rate over the Tower was the same in both clockwise and counterclockwise directions, at crown and at different floors, and was, thus, independent.

The numerical simulations are performed with the computational fluid dynamics (CFD) code fire dynamics simulator (FDS) version 6.7.0. FDS is a computational code in fluid dynamics, which 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 McGrattan et al.\textsuperscript{16} The default sub-models 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 the 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 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, then 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 justification of the numerical model used for thermal degradation analysis is addressed in Dréan et al.\textsuperscript{24}

The default Deardorff model is used for the LES sub-grid 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.

### 3 BRIEF DESCRIPTION OF THE GRENFELL TOWER

#### 3.1 The Grenfell Tower

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. This included a series of 14 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. Views of the Grenfell Tower before and after the fire are available in previous studies.\textsuperscript{2,3,31} From levels 4 to 23, all floors have a similar layout of six flats (four two-bedroom flats and two one-bedroom flats, see Figure 1). Video and photographic records and other evidence show that the initial fire was located in the kitchen of Flat 16 of the east façade of the Grenfell tower (green part in top right corner of Figure 1).

#### 3.2 Façade system and constructive details

In this paper, the description ACM-PE refers to Reynobond PE,\textsuperscript{32} PE-foiled ACM cladding panels, and the description PIR refers to Celotex polyisocyanurate insulation boards.\textsuperscript{33}

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. 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 figure 14, p 36, and figure 17, p 40, in Bisby. The façade system installed on the Grenfell Tower was offset from the existing building envelope by about 320 mm. A description of the façade system and design details is provided in Guillaume et al.

The frame of the façade system comprises horizontal and vertical aluminium rails. They are installed under and over the window frames and continuously over the full height of the building on the outer surfaces of the columns and at the corners between the windows/spandrels and the columns. Details are provided in figure 18, p 41; figure 21, p 44; figure 22, p 45; and figure 24, p 47 of Bisby.

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 (figure 26, p 50, and figure 28, p 52, of Bisby).

Sections of the façade between the windows were fitted with infill panels (figures 8 and 9, p 28, of Bisby). These panels comprised 25 mm extruded polystyrene insulation with 2 mm aluminium facing on both sides.

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 uPVC (unplasticized [rigid] polyvinyl chloride). Details are provided in Koohkan et al. A schematic of the external wall refurbishment, including the cladding and the mounting details is addressed in Figure 2, from Lane.

4. NUMERICAL ANALYSIS OF THE GRENFELL TOWER FIRE: FIRE PROPAGATION

4.1 Description of the numerical model and hypothesis

The main objective of the simulation described herein is to evaluate the vertical fire propagation over the east face of the Grenfell Tower, above the apartment of origin and the horizontal propagation triggered when the fire reached the crown of the Tower.

First, partial numerical models of the east face of the Tower are addressed. They consist in parts of the Tower representing the two, and then six first floors, and allow local numerical investigations before the implementation of the full scale tower. Local mounting details can thus be deeply evaluated in terms of cavity barriers or aluminium rails along the Tower, which can be missed in a larger model.

Then, a quarter of the Tower’s surface area is modelled for this analysis of initial vertical propagation. This area comprises Flat 16—the apartment of origin on the fourth floor of the Tower, the stack of apartments directly above Flat 16, and the adjacent apartments on the east face of the Tower.

Apartments directly above Flat 16 (first floor of residential occupancy, but fourth overall floor in the Tower) are named Flat 26 (second floor of residential occupancy), Flat 36, until Flat 206 (20th floor of residential occupancy). The “X6” flats (X being the number of the floor of residential occupancy above Flat 16) comprised a kitchen, a living room, and two bedrooms with windows through the east face.

The flats located in the centre of the east face comprised a kitchen, a living room, and one bedroom with windows through the east face. These flats are designated as “X1” flats (Flat 11 to Flat 201).

The layout of a reference floor of the Tower is indicated in Figure 3, along with the limits of the numerical model addressed in this paper.

The thermal characteristics of the system components are integrated in the numerical model from Dréan et al. 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. Additional thermal properties for materials used in the model are given below. The thermal properties of concrete are extracted from the Eurocode 2.\textsuperscript{36,37} Namely, a density of 2300 kg/m\textsuperscript{3} is used in this study. The heat capacity and thermal conductivity are extracted from previous studies.\textsuperscript{36,37} The emissivity of concrete is taken at 0.8.

The window glasses are considered as a sandwich constituted with glass/air/glass. Their thermal properties are extracted from Efectis databases for standard glazing and from Mikkola et al.\textsuperscript{38} It has a density of 2490 kg/m\textsuperscript{3}. The emissivity is taken at 0.87.

The thermal properties of XPS are taken from previous studies,\textsuperscript{38-40} namely, a density of 20 kg/m\textsuperscript{3} is used in this study; the heat capacity and thermal conductivity are 1.13 J/g/K and 0.03 W/m/K, respectively; and the emissivity is taken at 1. The ignition temperature of XPS protected by a metallic sheet can be estimated around 500°C.\textsuperscript{38} XPS has a heat of combustion of 40 MJ/kg.\textsuperscript{39,40} The CO yield is of 0.06 g/g\textsuperscript{39,40} and the soot yield is 0.2 g/g.\textsuperscript{39} The asymptotic mass loss rate is 0.032 kg/m\textsuperscript{2}/s.\textsuperscript{39}

The thermal properties of PVC are taken from previous studies,\textsuperscript{39-42} namely, a density of 1380 kg/m\textsuperscript{3} is used in this study. The emissivity is taken at 0.95. The ignition temperature of PVC can be estimated around 200°C.\textsuperscript{40} PVC has a heat of combustion of 16.4 MJ/kg.\textsuperscript{40,41} The CO yield is of 0.063 g/g,\textsuperscript{39,41} the soot yield is 0.176 g/g,\textsuperscript{39} and the HCl yield is 0.27 g/g.\textsuperscript{39,43} The asymptotic mass loss rate is 0.016 kg/m\textsuperscript{2}/s.\textsuperscript{39}

The thermal properties for mineral wool are extracted from the Efectis databases and from the product datasheet.\textsuperscript{34} It has a density
of 360 kg/m$^3$ and a specific heat of 1.0 J/g/K. The emissivity of the cavity barrier is taken at 1.

For the architectural details related to window frames, aluminium rails and cavity barriers were used. The windows failure criteria assessed in Guillaume et al$^{26}$ and Koohkan et al$^{30}$ are used for each opening through the façade, i.e., partial window breakage when a surface temperature of the frame reaches 550°C. Numerically modelled heat release rates (HRR) from Guillaume et al$^{26}$ are used for the kitchen, living room, and bedroom of each flat. The total surfaces of these rooms are conserved in the numerical model. For the "X1" flats, the HRR per unit area of the "X6" flats was used. Thus, the HRR of each "X1" room varies according to its surface area. It was assumed that these compartments, fire starts at 3 minutes after window breakage, corresponding to the time taken for flames to enter a compartment and ignite furniture.

### 4.2 Numerical modelling of the east façade

As can be seen in Figure 3, the modelling described in this paper focuses on the part of the Grenfell Tower that suffered vertical fire spread in the first phase of the event from 1:08 AM to 1:29 AM. A close-up view of the Tower model is shown in Figure 4. The flats from the fourth floor to the 23rd floor are included. The apartment of origin, Flat 16, is highlighted in yellow. Half a floor is considered to represent the crown of the Tower. The internal layout (identical for each floor) of the parts of the Tower included in the model is provided in Figure 5. In each room, fire is applied as a boundary condition on its whole surface using the HRR evolution

![Figure 4](wileyonlinelibrary.com)

**FIGURE 4** View of the numerical model of the Grenfell Tower—east face with "X6" and "X1" flats—part of the north face with the living room of flats "X6." Flat 16 is highlighted in yellow [Colour figure can be viewed at wileyonlinelibrary.com]

![Figure 5](wileyonlinelibrary.com)

**FIGURE 5** View of the numerical model inside the Grenfell Tower—east face with "X6" and "X1" flats—part of the north face with the living room of flats "X6." [Colour figure can be viewed at wileyonlinelibrary.com]
estimated in Guillaume et al.\textsuperscript{26} for kitchens, living rooms, and bedrooms. The ignition of each apartment (other than the apartment of origin) is triggered by window failure in each room. Horizontal and vertical mineral wool cavity barriers and aluminium rails break the insulation layer, roughly in line with compartment walls and floors.\textsuperscript{2,3} Schematics of the façade are shown in Figure 8. The upper and lower parts of the aluminium window’s frames are apparent in black on the view of the numerical model. The lateral part of the window’s frames are considered to be adjacent to the cladding, and thus not visible. PVC window sills line the concrete wall inside the apartment. The window glazing breaks when the temperatures of both the exposed upper and lower parts of the aluminium frames reach 550°C.\textsuperscript{30,44}

### 4.2.1 Partial models

Two partial numerical models were investigated before addressing the full-scale tower, for which local mounting details can be evaluated using a finer grid.

The main characteristics of the addressed numerical models are indicated in Table 1 below.

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**FIGURE 6** Close view of the numerical model of the Grenfell Tower façade without the ACM-PE cladding—location of the cavity barriers (red), aluminium frame (green), infill panels (white), and PIR insulation (orange) [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 7** Details of the numerical model for the column of the façade. (Left) Full-scale model. (Right) Partial model [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 8** Close up schematic of the façade; sectional view (A) and front view (B) [Colour figure can be viewed at wileyonlinelibrary.com]
4.2.2 Full scale model for the east facade

The total dimensions of the numerical domain are $20 \times 30 \times 102$ m ($l \times w \times h$), with open boundary conditions for pressure. Mesh size is uniform and taken as $0.25 \times 0.25 \times 0.25$ m for the Tower. About 4 million cells were used.

In the FDS reference guide and literature, 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 representative length of the grid cells and $D*$ is the characteristic fire diameter calculated with the following relation:

$$D* = \left( \frac{Q}{\rho_\infty C_p T_\infty g} \right)^{1/5},$$

where $Q$ is the fire HRR, $\rho_\infty$, $C_p$, $T_\infty$, and $g$ are the ambient gas density (approximately 1.2 kg/m$^3$), gas specific heat (approximately 1 kJ/kg/K), gas temperature (20°C), and gravitation acceleration (9.81 m/s$^2$), respectively. Following this expression, the 0.25-m grid size considered is sufficiently fine to capture accurately the combustion and turbulence phenomena of the system for heat release rates up to 1 MW.

4.3 Numerical evaluation of the initial fire propagation from Flat 16 to Flat 26

Video and photographic records and other evidence, extensively detailed in expert reports, show that the initial fire was located in the kitchen of Flat 16, on the fourth floor of the east face of the Grenfell Tower, and that the fire spread to the façade via external flaming. Using the results of numerical modelling of the initial kitchen fire and additional fires from flame re-entry into the kitchens, living rooms, and bedrooms of higher apartments, a numerical model of the eastern face of the Grenfell Tower has been developed.

The development of the fire in its early stages (between Flat 16 and Flat 26 or floors 4 and 5, respectively) is illustrated in Figure 9. Observations cited in the Grenfell inquiry expert’s reports show that the flames were visible at the kitchen window of Flat 16 at 01:08 AM. The first observations of burning of the external cladding around the window were made between 01:09 AM and 01:10 AM. The same observations were made during the simulation, but, in addition,

- between 01:11 AM and 01:15 AM, the simulation shows that more and more ACM-PE cladding becomes involved in the fire;

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**TABLE 1** Numerical characteristics of the partial models

| Partial Model | Grid Size, m | Domain Dimensions, m | Total Cells, million |
|---------------|--------------|----------------------|---------------------|
| Two floors    | 0.1 x 0.1 x 0.1 | 12 x 15.2 x 7         | 1.28                |
| Six floors    | 0.1 x 0.1 x 0.1 | 12 x 15.2 x 20        | 3.6                 |

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**FIGURE 9** Illustration at different times of the simulated fire propagation over the cladding from Flat 16 to Flat 26—east face [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 10** Illustration at different times of the simulated fire propagation over the cladding (left) and the insulation (right) from Flat 16 to Flat 26—east face [Colour figure can be viewed at wileyonlinelibrary.com]
• at 01:14 AM the PIR insulation begins to contribute to the fire (Figure 10); the blue and red colours in Figure 10 are used to illustrate the burning rate of the insulation (when cladding is removed). Blue means no burning while red represents the local burning.
• After 01:15 AM the flames quickly propagate along the façade and over the cavity barrier; and
• at 01:18 AM the kitchen window of Flat 26 breaks.

CCTV footage shows flames covering the window at this time and window breakage is thus plausible. This is consistent with the observation, in Torero⁴, of the kitchen window of Flat 26 failing at around 01:18 AM. In the simulation, the Flat 26 kitchen window fails at 01:18 AM and the living room window (window adjacent to the kitchen window) at 01:22 AM. This validates the numerically predicted fire propagation at this point. Between 01:18 AM and 01:20 AM, the situation between Flat 16 and Flat 26 is stable, with intense burning of the cladding and increasing combustion of the insulation. After 01:18 AM, the cladding starts to burn away and holes in the ACM-PE occur.

4.4 | Numerical evaluation of the fire propagation from Flat 16 to Flat 66 (six storeys model)

A larger numerical model of the east face is addressed and concerns flats from the fourth to the ninth floor, located directly above the flat of origin. Thus, these flats will suffer directly the initial vertical fire spread. Such partial models are useful to investigate the influence of mounting details of the façade elements on the fire propagation with a reasonable calculation cost than a full scale model.

A close-up view of the partial tower model is shown in Figure 11. The flats from the fourth floor to the ninth floor are included. The apartment of origin, Flat 16, is highlighted in yellow. In each room, fire is applied as boundary condition on its whole surface using the HRR evolution estimated in Guillaume et al.²⁵ for kitchens, living rooms, and bedrooms. The ignition of each apartment (other than the apartment of origin) is triggered by window failure in each room.

Three scenarios were investigated using this partial model. They consist in the analysis of the vertical fire spread (a) with the known cavity barriers default of the façade (local cuts as indicated in Figure 12), (b) with no default of the cavity barrier (no cuts), and (c) with no continuity of the aluminium rails between windows and at edges of the columns (indicated in Figure 2).

The development of the fire in its early stages (between Flat 16 and Flat 66 or floors 4 and 9, respectively) is illustrated in Figure 13 for the scenario A. The blue and red colours are used to illustrate the burning rate of the cladding. Blue means no burning while red represents the local burning.

Observations cited in the Grenfell inquiry expert’s reports²³ show that the first flames were visible at the kitchen window of Flat 16 at 01:05 AM, and visible around this window around 01:08 AM. The first observations of burning of the external cladding around the window were made between 01:09 AM and 01:10 AM. The same observations were made during the simulation, but, in addition,

• at 01:14 AM, the fire has spread to the cladding between the fourth and fifth floors;
• after 01:16 AM, the flames quickly propagate along the façade and over the cavity barrier; partial failure of the kitchen window of Flat 26 is observed; and
• at 01:18 AM the kitchen window of Flat 26 breaks and the fire has spread to the cladding until the eighth floor;
• after 01:21 AM, the fire has spread to the cladding of the column, and infill combustion is observed; the fire has reached the ninth floor.

The development of the fire in its early stages is illustrated in Figure 14 for scenario B, where no defaults of the cavity barriers are implemented in the numerical model. The numerical fire spread is compared with the results from scenario A, with local defaults.

The observations indicate that the default of the cavity barriers have a negligible effect on the vertical fire spread of the fire. This is explained by the quick combustion and, thus, removal of the cladding, leading to the inefficiency of the cavity barrier even if local cuts exist.
The last scenario investigated using the partial model consists in the analysis of the vertical fire spread with no modelling of the continuity of the aluminium rails between windows and at edges of the columns.

The development of the fire in its early stages is illustrated in Figure 15 for scenario C. The numerical fire spread is compared with the results from scenario A.

The effect of the implementation of continuous aluminium rails appear to be large. Once the holes appear in the cladding after 01:18 AM, flames can penetrate inside the insulation between the horizontal cavity barriers where they are trapped. A quick horizontal propagation is then observed after 01:20 AM. The fire reached the X1 flats in 2 minutes.

4.5 | Numerical evaluation of the fire propagation: Vertical propagation over the east face

A comparison between the observed and the simulated fire propagation over the east face of the Tower is shown in Figures 16–18.

From 01:08 AM to 01:16 AM (approximately), fire propagation over the façade was slow (Figure 16). The vertical propagation of the fire is reproduced well by the model. Moreover, the modelled fire had the same shape as the real fire. For example, at 01:16 AM, the window of Flat 36 (sixth floor) was covered by external flames and the model predicts the same. During this phase, flames exit Flat 16 at 01:14:53 AM, following the kitchen window failure. Failure of the kitchen’s windows in
higher apartments is observed at 01:18 AM, but the contribution of apartment furniture to the fire is negligible at this time.

During the second phase of vertical spread, from 01:16 AM to 01:22 AM (approximately), the rate of vertical fire propagation over the façade increased (Figure 17), and is reproduced well by the numerical model. The fire spread maintains a vertical shape while ascending. During this phase, the furniture in the kitchens above Flat 16 contributes to the fire and enhances the external flames. Failure of kitchen
windows continues for higher apartments, and failure of the adjacent living room windows begins. Between 01:21 AM and 01:22 AM, the fire has spread up to the 10th floor.

The third phase of vertical spread is observed from 01:22 AM to 01:29 AM. The rate of vertical fire propagation over the façade increases strongly until the fire reaches the crown of the Tower at 01:29 AM (Figure 18). During this phase, the furniture in the kitchens and living rooms above Flat 16 contributes to the fire and enhances the external flames. Almost all the kitchen and adjacent living room windows have failed by 01:29 AM. The vertical fire propagation is

**FIGURE 17** Comparison of observations and the output of the numerical simulation of fire propagation over the east face—second phase of propagation (01:16 to 01:22 AM) [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 18** Comparison of observations and the output of the numerical simulation of fire propagation over the east face—third phase of propagation (01:23 to 01:29 AM) [Colour figure can be viewed at wileyonlinelibrary.com]
reproduced well by the numerical model. The fire spread keeps a vertical shape while ascending, and horizontal propagation begins. However, after 01:24 AM, firefighter intervention, which was not included in the simulation, lead to differences in horizontal propagation for floors 4 to 8. The area of action of firefighters trying to extinguish the fire from the exterior of the Tower is indicated by the blue area in Figure 18.

Using the numerical model, the gap in video and photographic evidence from the real fire, for the 5 minutes between 01:16 AM and 01:22 AM, can be filled. Outputs of the numerical modelling from this time period are shown in Figure 19.

The development of vertical fire propagation over the east face is shown in Table 2. There is a good correlation between observations from the real fire and the output of the numerical model. The difference in time for the fire to reach the top of the Tower is only 18 seconds.

The position of the flame front as a function of fire time is shown in Figure 20. The fire development can be split in three parts as indicated in Guillaume et al.5 For the first 3 minutes after the fire has ignited the external façade (from 01:08 AM to 01:16 AM), the fire spreads linearly with a rate in the range of 3 to 4 m/minute. Then, there is no video or photographic evidence from the real fire for 5 minutes (between 01:16 AM and 01:21 AM). During that phase, the numerical modelling shows a slowdown of the propagation rate. However, the propagation rate remains linear. After that point, from 01:22 AM to 01:29 AM, propagation accelerates and is proportional to \( t^4 \), until the fire reaches the top of the Tower (see Figure 18). The \( t^4 \) relationship is associated with radiative control of propagation. When the fire reached the crown of the Tower, the rate of vertical fire spread decreased. It can be seen that there is good agreement between the outputs of the numerical simulation and observations from the real fire for both the initial linear phases and the final \( t^4 \) phase.

During the three phases of vertical fire propagation that have been identified, the vertical velocity can be compared with past fire events. In Torero,4 the vertical fire spread rate is shown for previous fires in high rise buildings (some with combustible cladding). Figure 21 shows a comparison between this historic data and the outputs of the numerical model of the Grenfell fire. During the linear

![FIGURE 19](https://example.com/figure19)  
**Output of the numerical simulation of fire propagation over the east face during the period from 01:16 to 01:21 AM, during which there is no video or photographic evidence [Colour figure can be viewed at wileyonlinelibrary.com]**

| Local Time, AM | Propagation Based on Observation | Propagation Based on Numerical Results | Event/Observation |
|---------------|----------------------------------|--------------------------------------|-------------------|
| 01:08:06      | 0                                | 0                                    | Flame around initial window. |
| 01:14:53      | +6 min 47 s                      | +6 min 20 s                         | Flames at midlevel between L0 and L1. |
| 01:15:37      | +44 s                            | +1 min 05 s                         | Flames at midlevel between L1 and L2. |
| 01:16:00      | +23 s                            | +50 s                               | Flames at L2 window. |
| 01:21:37      | +5 min 21 s                      | +4 min 50 s                         | Flames at midlevel between L5 and L6. |
| 01:22:22      | +45 s                            | +40 s                               | Flames at midlevel between L6 and L7. |
| 01:23:09      | +47 s                            | +50 s                               | Flames at L8 window. |
| 01:23:36      | + 27 s                           | + 1 min                             | Flames at midlevel between L9 and L10. |
| 01:24:06      | + 30 s                           | + 35 s                              | Flames at midlevel between L12 and L13. |
| 01:25:36      | + 1 min 30 s                     | + 1 min 30 s                        | Flames at midlevel between L15 and L16. |
| 01:26:37      | + 1 min 01 s                     | + 45 s                              | Flames at midlevel between L17 and L18. |
| 01:29:00      | + 2 min 23 s                     | + 2 min 30 s                        | Flames reach the top of the Tower. |
|               | 20 min 37 s                      | 20 min 55 s                         | Total time |

**TABLE 2** Time delay between observations and total time for observations of the real fire and for the numerical simulation of fire propagation over the east face.
first phase of the Grenfell Tower fire, the fire spread rate seems comparable with the Joelma fire, with rates less than 5 m/minute. Then, for the second linear phase, it seems comparable with the Andraus and Lacrosse fires, with rates close to 5 m/minute. The third phase with a $t^4$ dependency gives a spread rate comparable with the Grozny and Mandarin Oriental fires, with rates close to 10 m/second. However, although the Grenfell fires spread up the complete height of the east face in less than 21 minutes, many historic fires have higher vertical spread rates of 10 to 25 m/seconds.

However, a pass in a BS 8414-1-2 test according to BR135 means that vertical flame spread is not more than 5 m above the combustion chamber with in the first 15 minutes of the test. Thus, a vertical fire spread of only 0.3 m/minute is tolerated. It appears that, even if the vertical flame spread during the first phase of the Grenfell fire is lower than other historic fires, it was more than 10 times higher than the maximum tolerable spread.

The numerically modelled east face kitchen and adjacent living room window failure times are indicated in Figure 22. At 01:14:53...
AM, flames broke out of the kitchen window of Flat 16, following failure of the window. The first failures of kitchen windows, for apartments above Flat 16, are observed from 01:18 to 01:23 AM. Then, the failure of the adjacent living room windows begins and propagates slowly from 01:23 to 01:26 AM. After that, from 01:26 to 01:29 AM, the failure of windows in kitchens and living rooms appears coincident. This is consistent with the observations provided in Torero\(^4\) where internal fires ignited at the fifth (Flat 26, just above the initial fire apartment), 12th (Flat 96, middle height of the Tower), and 22nd floor (Flat 196, at the top of the Tower) at 01:18, 01:25, and 01:28 AM, respectively. These observations are synthetized in Table 3.

The total HRR estimated numerically during the vertical propagation of the fire over the east face is shown in Figure 23. The contribution of the façade system and of the apartment furniture is included. Strong propagation of the fire is observed after 01:22 AM, corresponding to the third phase of vertical spread identified in Figure 16. At 01:29 AM, the fire reaches the top of the Tower and a maximum value of 375 MW is achieved.

### 5 | INVESTIGATION OF THE IMPACT OF MODIFICATION OF THE FAÇADE SYSTEM ON VERTICAL FIRE PROPAGATION

The impact of modifications in the insulation and the ACM cladding on vertical fire propagation over the east face of the Tower is investigated using the numerical model. The influence of apartment furniture and that of cavity barriers is also investigated.

#### 5.1 | Investigation into changing the insulation material

The impact of using a non-combustible insulation is investigated using the numerical model: mineral wool (MW) is considered instead of the PIR insulation that was used on the Grenfell Tower. The cladding

**TABLE 3** Observed and predicted window failure times during vertical fire propagation over the east face

| Floor/Flat | Observation from Torero\(^4\) | Observation from Simulation |
|------------|-----------------------------|-----------------------------|
| Floor 5/Flat 26 | 01:18 AM | 01:18:13 AM |
| Floor 12/Flat 96 | 01:25 AM | 01:25:38 AM |
| Floor 22/Flat 196 | 01:28 AM | 01:28:58 AM |

**FIGURE 22** Evolution of window failure times over the east face of the Tower for kitchen and adjacent living room windows (“X6” flats)

**FIGURE 23** Evolution of total heat release rate (HRR) for vertical fire propagation over the east face
remains the initial ACM-PE. A comparison between observations from the real fire and the modelled MW fire propagation is shown in Figures 24 and 25. The modelled fire with an MW insulation shows the same shape as the observations made during the Grenfell event, during the first and second linear phases from 01:08 to 01:22 AM (Figure 24). After 01:24 AM, the fire spread is faster for the model with MW than for the PIR insulation configuration (Figure 25).

Observations for vertical fire propagation correlate with the numerical evaluation of the total HRR and the position of the flame front on the façade as a function of fire time. HRR evolution, with PIR and MW insulations, is shown in Figure 26. Similar propagation is observed for both models, although the fire seems to propagate faster and to have a greater HRR in case of the MW insulation after 01:25 AM. A difference of 50 MW is observed after this time.

The position of the flame front as a function of elapsed time is shown in Figure 27. As for the PIR insulation configuration, the fire development for MW can be split in three parts. For the first 3 minutes after the fire has ignited the external façade, the fire spreads linearly with a rate close to 3 to 4 m/minute (from 01:08 to 01:16 AM). Then, a slowdown is observed, but the propagation stays linear (from 01:16 to 01:22 AM). After that point, a speed up proportional to time $t^4$ is observed until the fire reaches the top of the Tower at 01:29 AM.

In Dréan et al., same slight differences for the fire behaviour of ACM-PE + PIR and ACM-PE + MW systems were observed at intermediate and large test scale, where the use of MW as insulation tended to slightly increase the fire spread. This delay was related to the quicker start of combustion in the MW system, and to the energy absorbed by the PIR for charring, thermal cracking, and pyrolysis, leading to a competition between thermal and thermochemical effects. This effect was not related to the PIR combustion, but to the insulating properties of this material. The PIR shows better insulating performance than MW, and the heat is thus kept away from the insulant. In the case of the MW, the heat is absorbed by the insulant and can be released later. This energy is then available for the cladding combustion.

### 5.2 Investigation into changing the cladding material

The impact of using an inert ACM cladding, ACM-A2 instead of the ACM-PE cladding which was used on the Grenfell Tower, is
investigated using the numerical model. The insulation remains the initial PIR. No fire propagation over the façade is observed when the ACM‐A2 cladding is used together with the PIR insulation. The HRR evolution, with ACM‐A2 cladding is very close to that of the initial apartment fire (Flat 16). Thus, the fire propagation onto the façade is very limited and mostly because of the contribution of the PVC window frame and PIR insulation around the window reveal.

5.3 Investigation into the contribution of apartment contents

The contribution of the combustion of apartment contents to the rate of fire propagation on the Grenfell Tower can be modelled by assuming no contribution from the contents of the apartments above Flat 16 (fourth floor). This can be done by assuming that the windows have 30 minutes fire resistance. Thus, the fire cannot propagate from the façade to the interior of the Tower via apartment windows.

A comparison between the observed (real fire) and the modelled (fire rated window frames) fire propagation over the east face of the Tower is addressed. The modelled fire shows the same shape as the observation made during the real fire during the first and second linear phases from 01:08 to 01:22 AM. After 01:23 AM, the fire spread is slower for the model when there is no contribution from the contents of apartments above Flat 16 (Figure 28).

The evolution of the modelled HRR for the vertical fire propagation over the east face is indicated in Figure 29 for the cases where the contents of upper apartments do contribute and do not. It can be seen that apartment contents make a significant contribution to fire development. It reminds of the importance of the fire performance of windows. At 01:29 AM, a difference of 175 MW exists.
5.4 | Investigation of the influence of cavity barriers

To test the impact of cavity barriers, the numerical model is adjusted such that the horizontal and vertical cavity barriers between the insulation and the cladding are removed. The rest of the model remains the same as in the initial configuration.

A comparison between observations of the real fire, and that predicted by the adjusted numerical model, are shown in Figures 30 and 31. As soon as the fire ignites, the cladding above the initial fourth floor, the modelled fire (with no cavity barriers) shows a faster vertical propagation than the real fire. Even at early stages, from 01:08 to 01:15 AM, the fire reaches twice the vertical distance of the real fire. The top of the Tower is reached at 01:25 AM, 4 minutes before the real fire and the original model. The modelled evolution of HRR for the fire on the East face is indicated in Figure 32 for situations where there are and are no cavity barriers. The fire appears to propagate faster and seems to have a greater HRR without cavity barriers after 01:25 AM. The position of the flame front as a function of elapsed time is presented in Figure 33. As for the initial configuration, the development of the fire can be split into three parts. For the first 9 minutes, from 01:08 to 01:17 AM, as soon as the fire has ignited the external façade, the fire spreads linearly with a rate of around 1.4 m/minute. This rate is lower than for the initial configuration (3.6 m/min) but begins at early time; thus, the vertical distance reached by the fire is twice those reached during the initial fire for a given time. Then, the vertical propagation rate increases with a value around 3 m/minute, while a slowdown is observed for the initial configuration (1 m/min). After that point, from 01:21 to 01:24 AM, the fire propagation speeds up and has either linear progression with a rate around 9.6 m/minute or its progression is proportional to $t^4$, until the fire reaches the top of the Tower at 01:25 AM.

The cavity barriers seem to have an effect on the vertical spread by reducing it. The cladding releases flames inside the air gap upon burning. These flames are then trapped by the barriers. However, as the

![FIGURE 28](Image) Comparison between observations of the real fire and numerical simulation (with fire resistant windows) of fire propagation over the east face. Third phase of propagation (01:23 to 01:29 AM) [Colour figure can be viewed at wileyonlinelibrary.com]

![FIGURE 29](Image) Evolution of the heat release rate (HRR) for vertical fire propagation over the east face with and without the contents of apartments above Flat 16 contributing to fire development
cladding is quickly consumed, the cavity barriers are becoming inefficient. The flame can then spread to the upper level because the air gap does not exist anymore. However, the time delay for the cladding to be consumed and for the cavity barrier to be inefficient lead to the differences observed in the fire behaviour when no cavity barriers are implemented.

5.5 Investigation into the PIR insulation contribution to fire spread

The numerical model was adjusted by removing the cladding system and the cavity barriers. Thus, the external façade is now only made of the PIR insulation, representing, for example, a phase of construction without any cladding.

The predictions of the numerical model show that the fire propagation is restricted to the area of insulation between the initial fourth floor and the fifth floor. This area corresponds with the area covered by the external fire plume from the kitchen of Flat 16. The fire self-extinguishes after 01:24 AM.

5.6 Synthesis

A comparison between the simulated vertical propagation over the east face as a function of time for the different façade configurations investigated is shown in Figure 34.
CONCLUSIONS

This study aimed to model and understand the vertical fire development and propagation during the Grenfell Tower fire, using multiscale experimental and numerical validation before application to end-use scenarios. Fire modelling of the Grenfell Tower façade was conducted in order to investigate the development of the fire from the initial apartment, onto and over, the east face of the Tower. A previously validated numerical model, for the ACM-PE + PIR system that was installed on the Tower, was used. The numerical model considered the architectural details of the refurbished façade and contributions from the combustion of the contents of all the apartments (linked to the timing of local window failure). The modelled vertical fire spread over the east face of the Tower was validated by comparison with video and photographic observations of the real fire. The vertical fire propagation predicted numerically is consistent with the observations of the real fire. Fire growth on the east face of the Grenfell Tower consisted of three phases until the fire reaches the top of the Tower and vertical spread ceases.
Further investigation of the vertical fire spread was carried out for different façade system configurations. The influence of the insulation and cladding on fire development over the east face was investigated by substituting these materials in the model for a non-combustible insulation and cladding in turn. The influence of the cavity barriers and of fire resistant windows was also modelled numerically. Similar fire propagation is observed when ACM insulation is substituted by ACM-A2 cladding is used. In this case, the fire stays localized in the initial apartment. Thus, the numerical modelling suggests that the ACM-PE cladding was the main significant factor in the rapid upward spread of the fire. When fire resistant windows are used, the upper apartments are assumed to not contribute to the façade fire. A slower fire development is observed. When no cavity barriers are implemented, the vertical and horizontal fire propagation over the east face is faster.

Even if the numerical model addressed in this paper correlates well with the observations during the Grenfell event, several modelling assumptions were needed.

As discussed in Dréan et al., numerical hypothesis must be considered for the model developed for the accurate fine grid in another study to be applied to a coarser one as used in the present model. The main objective is to reproduce the thermal gradients achieved with the initial model in the gas phase because exchange between the solid and gas phases will be evaluated in a larger cell. Thus, to reproduce the numerical results that were validated against the test data using a fine grid, the computed ignition temperature for the insulant and the ACM cladding were adapted so the predicted behaviour remains similar to the experimental one and the numerical one at a smaller scale. This parameter has both a physical and numerical fitting meaning when modelling flame spread in a finite volume model such as FDS. It is then affected by simplifications to fluid and 1D heat transfer in solid submodels. Decreasing artificially the computed ignition temperature of the materials allows maintenance of a correct thermal gradient for the exchange between solid and the gas phases when large cells are used. Thus, the main hypothesis consisted in the modification of the computed ignition temperatures for insulant and ACM cladding established for the fine grid model, so that the coarser grid model reproduces the output of the fine grid model.

For the geometrical model of the Tower, it has been assumed that there is no fire propagation pathway between floors of the Tower via ducts, 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. External wind was not considered in the model. Additionally, further researches could address extended investigation in terms of numerical modelling with finest grid in cavities to observe the impact of more resolved mesh or 3D thermal transfer for solid materials. In the present model, the thermal transfer calculated with FDS is only 1D in materials. This can have non-negligible effects, especially for the horizontal fire spread. The window breakage criterion was also considered as a thermal load on the frame. This could be better investigated in further researches.

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