Reconstruction of the Grenfell Tower fire – Part 4: Contribution to the understanding of fire propagation and behaviour during horizontal fire spread

Eric Guillaume1 | Virginie Dréan1 | Bertrand Girardin1 | Talal Fateh2

1Efectis France, Saint Aubin Cedex, France
2Efectis UK-Ireland, Newtownabbey, UK

Correspondence
Eric Guillaume, Efectis France, Route de l’Orme des Merisiers, Saint Aubin Cedex 91193, France.
Email: eric.guillaume@efectis.com

Summary
The tragic events at Grenfell Tower in 2017, involving a combustible façade system, have raised concerns regarding the fire risk that these systems pose. In this series of articles, so far published, fire development inside the initial apartment has been investigated using an appropriate computational fluid dynamics (CFD) model. Several scenarios including different fire sources and ventilation conditions were addressed. Fire propagation through the window to the external façade and to higher apartments was modelled. This model was validated by comparing the numerical results with the visual observations reported in the Grenfell Inquiry. A CFD model of the complete east face of the Grenfell Tower was then created. This paper details CFD modelling of the complete Grenfell Tower façade during the late horizontal phase of fire spread. As the physics of lateral flame spread is different from that for upward flame spread, it is important to assess the validity of the model, thus far developed, for this configuration. Fire propagation over the whole façade is modelled and compared with observations from the real disaster. This provides a better understanding of its fire behaviour and of the contribution of architectural details and their impact on fire spread.

KEYWORDS
CFD, façade fire, fire propagation, Grenfell Tower, numerical simulation, ventilated façade

1 INTRODUCTION

The Grenfell Tower is a 24-storey high-rise building located in London. It was refurbished in the period 2012-2016 with a new insulated ventilated façade system and new windows installed on all of the building’s elevations. The Grenfell Tower tragedy happened on 14 June, 2017. The fire spread to the façade via external flaming from an apartment located in a lower residential floor of the east face of the Tower. This has been extensively detailed in the Grenfell Inquiry Expert Witness reports and in video and photographic records of the real fire. These records were used to provide an analysis of the, post-break-out vertical and horizontal fire propagation over the whole façade of the Grenfell Tower in Reference 5.

In previous studies, a multi-scale numerical approach was used to assess the fire performance of the refurbished façade system used on the Grenfell Tower. This was underpinned by intermediate scale ISO 13785-1 and large-scale BS8414-1 reaction-to-fire tests and used the computational fluid dynamics (CFD) code fire dynamics simulator (FDS) version 6. The output of these simulations showed that the ACM cladding was the main product driving the overall fire behaviour of façade construction in this specific system. In particular, systems that featured ACM cladding made with a polyethylene core (ACM-PE) showed extensive fire propagation regardless of the insulant used.
Fire spread over facades is one of the fastest modes of fire spread in buildings. The excess of air, the verticality of the facade, especially when no deflectors are provided, and the inside/outside pressure difference are some of the main factors that facilitate fire spread, and it spread from compartment to compartment.  

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 Reference 22. Fire propagation over the facade and from the facade to apartments through windows was also explored. The overall heat release rate (HRR) for typical apartment rooms and window failure criteria were estimated roughly, based on assumed apartments contents prior to the fire. A complementary thermomechanical analysis of window failure was performed and reported in Reference 23.

The full height of the Grenfell facade was modelled numerically to determine its fire behaviour.  

The full height of the Grenfell facade was modelled numerically to determine its fire behaviour. A comparison between the numerical results and the video and photographic records of the real fire was used to validate the modelling of the vertical fire spread over the east face of the Tower. The results highlighted that the installed cavity barriers were effective in limiting fire propagation during the short time period of integrity of the cavity. This previous study, dedicated to the initial vertical fire spread on the east face of the Tower, as well as observations, showed limited horizontal propagation of the fire during this initial phase of 30 minutes.

After 01:29 AM during Grenfell disaster, when the fire had reached the top of the Tower, observations showed that strongly enhanced horizontal fire propagation occurred, especially via the Tower’s architectural crown. The fire spread across the four faces of the Tower from 01:29 AM up to 04:09 AM, due to the combustion of the insulated facade system and the apartment contents.

This work comprises the modelling of horizontal fire propagation for the whole Grenfell Tower considering both facade and apartments. The thermal and combustion characteristics used for the facade system were validated in References 6 and 7 at intermediate and large scales.

The HRR for the initial fire and the contribution of the apartment fires were estimated in Reference 22 and used in this study for each floor of the Tower. In addition, the window failure criteria assessed in Reference 23 were used for each apartment opening.

Therefore, depending on local window breakage, the numerical model takes into account the contributions of all the apartments’ contents. The architectural details of the refurbished facade, reported in Reference 16, were used in the current modelling.

This publication reflects the full-scale fires on the east, north, south and west faces of the Grenfell Tower, using the numerical models previously validated for the facade system, the initial apartment fires and window failure. Fire spread over the external facade and to higher apartments was validated by comparison with video and photographic records of the real fire. This provides a better understanding of fire behaviour and the role of architectural details in fire spread. Additionally, the numerical model allows further investigation into the effect of changing the insulant material used in the cladding system.

**Figure 1**

(A) Original schematic of the south/north and east/west faces of Grenfell Tower3 — B, Schematic of floor plan for the 4th to 23th floors of Grenfell Tower3 [Colour figure can be viewed at wileyonlinelibrary.com]
2 | NUMERICAL EVALUATION OF THE GRENFELL TOWER FIRE

2.1 | The Grenfell tower

Architectural details of the façade system and the Tower are indicated in references.2-4,22 The Tower perimeter included a series of 14 columns: five columns on the north and south faces of the building leading to four bays, and four columns for the east and west faces of the building, leading to three bays as shown in Figure 1. Hence, respectively, the north and south faces, and the east and west faces were identical. From levels 4 to 23, all floors had a similar layout of six flats (four two-bedroom flats and two one-bedroom flats) and a lobby, as indicated in Figure 1. These flats are called “X1” to “X6” in this paper. For example, “X6” flats referred to the apartments from 16 (4th floor) to 206 (23th floor), and “X1” flats referred to the apartments from 11 (4th floor) to 201 (23th floor).

2.2 | Numerical setup

The three-dimensional CFD model reported in Reference 16 was adapted to simulate horizontal fire spread over the east and later the north, south and west faces of the Tower following the initial vertical propagation.

In the numerical model of the Tower, it is assumed that there is no fire propagation pathway between floors inside the Tower via ducts, HVAC systems or holes in apartment ceilings or walls. Fire propagation from one apartment to another, horizontally or vertically, occurs only via the façade and depends on window failure. Wind was not considered in the model because the analysis described in Reference 5 showed that the horizontal fire propagation rate over the Tower was equal in both clockwise and counter-clockwise directions, at the level of the architectural crown and at different heights above the 19th floor, and was, thus, independent of the wind. Therefore, this work considers horizontal fire spread on the upper parts of each of the four faces of the Tower independently.

Because the east and west faces, and the north and south faces, respectively, are identical (Figure 1), two different numerical models were built to simulate fire propagation over the faces of the Tower (Figure 2). In Reference 16, the numerically modelled vertical fire spread over the east face of the Tower was validated by comparison with video and photographic records until the fire reached the top of the east face at 01:29 AM. The fire conditions at this time, in terms of burning surfaces, contributing flats and HRR, are thus known at every location on the façade and in the apartments and are used as boundary conditions (BCs) for each independent horizontal fire spread model including face and next corner.

The total dimensions of each numerical domain were four times 40 \times 20 \times 87 m (l \times w \times h), with open BCs for pressure. Mesh size was uniform and taken as 0.25 \times 0.25 \times 0.25 m. About 4.5 million cells were used per face, for a total close to 18 million cells. Each face model integrates the related flats; for example, the “X6,” “X1” and “X2” flats and associated façade elements comprise the model of the east face, while the “X2” and “X3” flats and associated façade elements comprise the model for the south face.

The numerical model used the thermal characteristics of the system components from6 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. Thermal properties for other materials used in the model are given below.

The thermal properties of concrete are extracted from the Eurocode 2.24 Namely, a density of 2300 kg/m³ has been used during the current study and the emissivity was taken as 0.8. The window glazing was assumed to be a sandwich comprising glass/air/glass, with thermal properties taken from the Efectis database for standard materials.
glazing and from Reference 25. Glass has a density of 2490 kg/m³. The emissivity is taken as 0.87. The window units incorporated metal-faced XPS cored sandwich panels. The thermal properties of XPS are taken from References 25-27. Namely, a density of 20 kg/m³ is used in this study. The heat capacity and thermal conductivity are, respectively, 1.13 J/g/K and 0.03 W/m/K and the emissivity is taken as 1. The ignition temperature of XPS protected by a metallic sheet can be estimated as around 500°C.25 XPS has a heat of combustion of 40 MJ/kg.26,27 The CO yield is 0.06 g/g26,27 and the soot yield is 0.2 g/g.26 The asymptotic mass loss rate is 0.032 kg/m²/s.26 Window reveals comprise rigid PVC. The thermal properties of PVC are taken from References 26-29. A density of 1380 kg/m³ is used in this study. The emissivity is taken as 0.95. The ignition temperature of PVC can be estimated as around 200°C. PVC has a heat of combustion of 16.4 MJ/kg.29 The CO yield is 0.063 g/g,26 the soot yield is 0.176 g/g,26 and the HCl yield is 0.27 g/g,26,30 The asymptotic mass loss rate is 0.016 kg/m²/s.28 The thermal properties for mineral wool are extracted from Efectis database and from product datasheet. It has a density of 360 kg/m³ and a specific heat of 1.0 J/g/K. The emissivity of the cavity barrier is taken as 1.

The actual architectural details related to window frames, aluminium rails and cavity barriers have been used. The window failure criteria assessed in references22,23 are used for each apartment opening throughout the façade, that is, partial window breakage when a surface temperature of the frame reaches 550°C31 (Figure 3).

The HRRs of the initial fire, as well as the apartment fire contributions, further detailed in Reference [22], are assumed for each floor of the Tower. The HRR of the individual furniture implemented in the apartment is indicated in Reference 22 and an overview is addressed in Figure 3. Individual pre-defined heat release curves are used for kitchens, living rooms and bedrooms. The same curves are used for all flats on all floors, in the absence of more specific detail. The total surfaces of these rooms are conserved in the numerical model. For the two bedroom apartments, “X2,” “X3” and “X5,” the HRR per unit area was the same as the “X6” flats because of their identical layout. For the one-bedroom flats, “X1” and “X4,” the HRR per unit area of the “X6” flats was kept. Thus, the HRR of each “X1,” and “X4” room varies according to its surface area. It was assumed that these compartment fires start 4 minutes after window breakage occurs, corresponding to the time needed for flames to enter into a compartment and ignite adjacent furniture, as validated in previous steps.

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. The default Deardorff model was used for the LES sub-grid modelling. The default near-wall model with a wall function for a smooth wall was used. The heat transfer at walls was simulated with a subsequent heat of vaporisation to account for the energy loss due to the vaporisation of the solid fuel. Detailed information is provided in References

![Figure 3](https://wileyonlineibrary.com)
FIGURE 4  Comparison of observations and the output of the numerical simulation of fire propagation over the east face — third phase of propagation (01:23 AM to 01:29 AM). Blue regions indicate areas where firefighting was efficient, not considered in the simulation. Red areas figure flame extension [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 5  Report of fire boundary conditions for the numerical simulation of fire propagation over the east face at the end of the vertical spread (01:29 AM) A, Observations and B, Heat release rate [Colour figure can be viewed at wileyonlinelibrary.com]
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 CO production, because of uncertainty in the occurrence of this phenomena and regarding the well-ventilated conditions for combustion observed experimentally and numerically.

**FIGURE 6** Numerical simulation of the fire propagation over the four faces of the Tower between 01:30 AM and 04:30 AM. Fire spread indicated every 30 minutes [Colour figure can be viewed at wileyonlinelibrary.com]
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, the solid disappears from the calculation cell by cell. This feature is used to take account of the destruction of the cladding as observed experimentally in the aforementioned medium- and large-scale fire tests. Reference 7 addresses the justification of the numerical model used for thermal degradation analysis.

2.3 | Summary of the numerical evaluation of the initial vertical fire propagation over the east face

The main objective of the simulation described herein is to evaluate and understand the horizontal propagation triggered when the fire reached the crown of the Tower, after the vertical fire propagation over the east face above the apartment of origin, and the influence of architectural details on the flame spread.

The modelling described in Reference 16 focused on the part of Grenfell Tower that suffered vertical fire spread in the early stages of the disaster from 1:08:00 AM to 1:29:00 AM.

During the third phase of vertical spread, observed from 01:22 AM to 01:29 AM, the rate of vertical fire propagation over the façade increased strongly until the fire reached the crown of the Tower at 01:29 AM. The furniture in the kitchens and living rooms of “X6” flats, above Flat 16, contributed to the fire and enhanced the external flames. Almost all the kitchen and adjacent (east face) living room windows of the “X6” flats have failed by 01:29 AM.
**FIGURE 7** Comparison of observations\(^2\)\(^-\)\(^5\) with the numerical simulation for the fire propagation over the east face from 01:36 AM to 03:20 AM — Fire is spreading horizontally in both a clockwise (from east face to south face) and an anticlockwise (from east to north face) direction [Colour figure can be viewed at wileyonlinelibrary.com]

| Time (am) | Real fire observations | Numerical model |
|-----------|------------------------|-----------------|
| 01:36 am  | ![Image of real fire observation] | ![Image of numerical simulation] |
| 01:56 am  | ![Image of real fire observation] | ![Image of numerical simulation] |
| 02:23 am  | ![Image of real fire observation] | ![Image of numerical simulation] |
A summary of the results is indicated in Figure 4 which shows a comparison between the observed and simulated fire propagation over the east face. The observed fire propagation is well reproduced by the numerical model. The fire spread keeps a vertical shape while ascending. Limited horizontal propagation was observed at this stage as it only begins when the crown is reached after 01:29 AM. The blue area in Figure 4 indicates the zone of action of firefighters trying to extinguish the fire after 01:24 AM from the exterior of the Tower, which is not included in the simulation.

3 | NUMERICAL EVALUATION OF HORIZONTAL PROPAGATION OVER THE EAST, NORTH, SOUTH AND WEST FACES

3.1 | Initial conditions for horizontal propagation over the east face

Observations and records from the fire show that horizontal flame spread over the east face of the Tower began after the fire reached the
FIGURE 8  Comparison of observations\textsuperscript{2–5} with the numerical simulation for the fire propagation over the north face from 01:36 AM to 03:20 AM — Fire is spreading horizontally in anticlockwise (from east to north face) direction [Colour figure can be viewed at wileyonlinelibrary.com]

| Time (am) | Real fire observations [2] [3] [4] [5] | Numerical model |
|-----------|----------------------------------------|-----------------|
| 01:36 am  | ![Image](image1.png) From East To West | ![Image](image2.png) |
| 02:10 am  | ![Image](image3.png) From East To West | ![Image](image4.png) |
| 02:34 am  | ![Image](image5.png) From East To West | ![Image](image6.png) |
crown at 01:29 AM.\textsuperscript{1-5} Previously published numerical modelling details the state of the fire, at this time, at each location on the façade and in each apartment.

As the time at which each flat ignited, or when each window failed, is known, it is possible to report the fire as BCs on the external façade of the Tower (see Figure 5). The applied
BC yields good reproduction of the vertical fire spread as evidenced by the flame shape over the east face and by the HRR. Thus, the third phase of the vertical fire spread described in Reference 16 is used as the starting point of the present calculation.

3.2 | Horizontal propagation over the whole tower

The fire spread over the four faces of the Tower was modelled from 01:29 to 04:30 AM. The progress of the numerical simulation, every 30 minutes, is shown in Figure 6.
3.3 COMPARISON WITH THE OBSERVATIONS

Results of the numerical simulation of horizontal fire spread along the east, north, south and, later, west faces are shown in Figures 7 to 10, respectively. The clockwise and anticlockwise directions of the fire propagation along each individual face of the Tower are indicated, and comparisons with observations from the real fire, from expert report's,2-4 are provided. The time intervals shown were determined by the availability of observational data.

After 01:29 AM, the fire spreads over the east face and onto the north face (see Figures 7 and 8). The observations of the real fire between 01:36 AM and 01:56 AM indicated that the flames seem to
extinguish locally at the centre of the east façade. This is due to a lack of fuel since the cladding has burned for more than 30 minutes. The flames are located close to the column between "X6" and "X1" flats. Later, the horizontal fire spread becomes significant and flames reach the upper "X1" flats. Two paths of fire spread emerge, and the fire is clearly now spreading horizontally past the vertical columns.

The numerical results closely match the observational record at 01:36 AM. The two paths of fire spread are detectable in the simulations and the north face starts to be involved (Figure 8). The upper "X6" living rooms, located at the corner between the east and north faces, are burning from the 20th to the 23th floors. The contribution of "X6" kitchens, initially burning during the vertical fire spread, is ending at this stage of the fire. The "X1" flats, living rooms, located close to the right column, are burning from the 15th to the 23th floors. The "X1" kitchens start contributing from the 17th to the top floors. At this time, no "X1" bedrooms are involved.

Around 01:56 AM, the horizontal spread reaches all "X1" flats above the 15th floor. The simulation overestimates the horizontal fire propagation over the east face between the 12th and 16th floors of the "X6" and the "X1" flats. However, between the 17th floor and the crown, the fire spread is reproduced well by the numerical model. Large parts of the façade are burnt and are represented by black surfaces in images from the numerical model. The "X1" bedrooms are now contributing from the 18th to the 23th floors. The downward fire spread for "X1" flats between the 17th and 19th floors seems marginally underestimated by the numerical model. This could be due to the dripping of flaming materials, such as polyethylene, from the external cladding. This effect was not considered in the numerical simulation for technical limitations, but it was observed during the real fire that this led to the ignition of the façade below the main fire and probably maintained fires in zones where droplets accumulated.

The fire propagates horizontally across the east and north faces of the Tower between 2:10 AM and 2:23 AM. Large burned and extinguished areas are visible on the east and on the north faces of the Tower (see Figures 7 and 8). Downward fire spread occurs near the column between "X1" and "X2" flats above the 12th floor. This phenomenon is well reproduced by the model above the fourth floor but underestimated at lower floors. The whole upper part of the east face is burning, from 18th to 23th floors, at this time. All the "X6" flats above the sixth floor are contributing to the fire. Moreover, all the "X6" living rooms are involved and lead to the fire spread enhancement visible on the north face. The "X6" bedrooms are now involved, from the seventh to the top floors. The horizontal fire spread across the north face is well predicted, except between the fourth and seventh floors where the action of firefighters is not taken into account.

Between 2:34 AM and 2:48 AM, the fire is clearly propagating in a V-shape. The south face is then involved in its upper part, with the contribution of the living rooms of "X2" flats ignited on the east face (Figure 9). Downward propagation along the vertical columns of the east face is still visible and is captured by the simulation.

The fire reaches the west face of the tower around 2:40 AM in the simulations. However, no observations are provided between 2:34 AM, where the fire reaches (approximately) the north/west corner, and 3:08 AM, where the fire has propagated to the west face (Figure 10). The four faces of the Tower are burning at 3:11 AM, although the fire is almost extinguished for the east and north faces. Residual apartment fires are observed in the simulations between the 11th and 15th floors for "X1" and "X2" flats (east face). The horizontal propagation for the south face is slightly underestimated numerically between the 21th and 23th floors. This can be related to flaming dripping materials, not simulated, that can ignite lower parts of the external cladding. The fire spread from north to west faces becomes significant after 3:11 AM. Thus, almost 30 minutes are needed for the fire to propagate across the corner column.
FIGURE 10  Comparison of observations²–⁵ with the numerical simulation for the fire propagation over the west face from 01:36 AM to 04:30 AM — Fire is spreading horizontally first in an anticlockwise (from east to north face) direction and then in a clockwise (from south to west) direction [Colour figure can be viewed at wileyonlinelibrary.com]

| Time (am) | Real fire observations [2] [3] [4] [5] | Numerical model |
|-----------|----------------------------------------|-----------------|
| 01:36 am  | ![Real fire observation](image1) From North To South | ![Numerical model](image2) |
| 03:11 am  | ![Real fire observation](image3) From North To South | ![Numerical model](image4) |
| 03:20 am  | ![Real fire observation](image5) From North To South | ![Numerical model](image6) |
Between 3:20 AM and 3:33 AM, the south and west faces are involved. The fires on the east and north faces are almost extinguished due to the lack of combustible materials. However, these two faces have burned for almost 3 and 2 hours, respectively. The contribution of apartment fires appears, therefore, to be important in explaining the long duration of these fires. Moreover, the calorific load of the façade alone is not sufficient to maintain the fire for such long times. These phenomena have been well reproduced by the simulations.

According to observations, the fire reached the south-west corner of the Tower around 3:48 AM. The numerical model predicts the ignition of the west corner column close to 3:53 AM. Thus, the horizontal propagation of the fire is slightly underestimated by the numerical model at this location. However,
regarding the global fire behaviour along the four faces of the Tower, the fire spread is well reproduced by the numerical model for each face.

At 3:53 AM, the fire continues to spread only on the west face. Residual apartment fires are observed in the north and south faces both in the simulations and the observations.

The clockwise and anticlockwise fire paths merge close to south-west corner at 4:09 AM. After this time, some parts of each façade remain unburnt. The boundaries of these unburnt parts may demonstrate the limit of external firefighting efforts. Their actions were not included in the simulations, leading to differences with the observations on the lower part of the Tower.

4 | ANALYSIS OF THE RESULTS

4.1 | Horizontal fire spread rate

The numerical model for horizontal fire spread across the whole Tower is validated by comparison with observations of the real fire and allows the analysis of the horizontal rate of flame spread for several floors of the Tower as done in Reference 5.

This analysis for the crown level is presented in Figure 11. As a first approach, uncertainty in time is estimated as ±5 minutes and uncertainty in distance as ±2 m. This analysis shows that the rate of flame spread at the crown is similar for both the clockwise (from east face to south face) and anticlockwise (from east face to north face) spread. An average flame spread rate was estimated at about 0.29 m/min. This value is consistent with that evaluated in Reference 5 and close to 0.3 m/min. The numerical prediction agrees with the observations of the real fire at each time recorded. Details of the clockwise and anticlockwise propagation are addressed in Figure 12 and in Figure 13, respectively. The numerical simulations show that the fire propagates to the north, south and west faces, respectively, at 1:36 AM, 2:30 AM and 2:37 AM.

Regarding the clockwise direction (Figure 12), the average horizontal rate is close to 0.28 m/min. For the anticlockwise direction (Figure 13), the average horizontal rate is close to 0.31 m/min.

Table 1 addresses the synthesis of the horizontal fire propagation at crown level in terms of spread rate at each location. Although the average spread rate for both clockwise and anticlockwise directions is similar,
the local values at specific flats or at columns are quite different. Indeed, the average spread rate at corner columns is 60% higher for the clockwise direction than for anticlockwise. However, the local effect of the columns included in the façade tends to decrease the average spread rate for the clockwise direction but to increase it for the anticlockwise one. However, the average horizontal spread rates for each face of the Tower, including the architectural details, is close to 0.3 m/min (Table 2) and to the values taken from observations and detailed in Reference 5.
4.2 | V-shape of the fire

During the horizontal spread across the east, north, south and west faces, after 01:30 AM, the fire is clearly propagating in a V-shape with an average angle close to 0.7°/min, as shown in Figure 14. This angle (\(\alpha\)) corresponds to the angle between the maximum extent of horizontal propagation at the crown level and the local origin of the V-shape, as indicated in Figure 14, considered in the east-north corner column at fourth floor. The average values are summarised in Table 3.

Numerically, the angle of the V-shape is higher for the east face and then decreases for north, south and west faces. Following observations, a similar angle is found for the east and north faces, while a lower value is evaluated for the south and west faces. The angle related to the establishment of the V-shape seems to decrease with the order of the faces involved in the fire (east then north, south and west) and thus follows the horizontal spread around the Tower. This can be related to the fire being more intense during its first phase (vertical spread and horizontal spread along the east face) mainly driven by the combustion of the cladding.

4.3 | HEAT FLUXES TO THE FACADE

Figure 15 shows the thermal load on window frames (in terms of gauge heat flux), during initial vertical fire development over the east face, as estimated numerically in Reference 23 from Reference 22. The maximum heat flux imparted to the window frames is about 120 kW/m² after 3 to 4 minutes of fire exposure, while the minimum heat fluxes evaluated for the lower and lateral parts of the window frames are between 30 and 70 kW/m². These ranges of values are comparable with the heat fluxes evaluated during the later horizontal fire spread over the Tower at characteristic times (Figure 16). Heat fluxes between 30 and 120 kW/m² are reached on the façade and at windows. Thus, the hypotheses for the window breakage used in the present study from Reference 22, are still valid for all the studied apartments.
Heat release rate

The total HRR estimated numerically during the fire spread over the four faces of the Tower is shown in Figure 17. The contributions of the façade system and of the apartment furniture are included.

The HRR is below 100 MW before 01:20 AM. After this time, the HRR increases quickly as the fire exhibits a rapid propagation, corresponding to the third phase of vertical spread over the east face. At 01:29 AM, the fire reaches the top of the Tower and a maximum value of 650 MW is achieved. Then, the external cladding of the east
FIGURE 15  Thermal heat fluxes imparted to the exposed face of the window during the vertical fire spread along the east face of Grenfell Tower. [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 16  Heat flux received on the façade at characteristic times of the fire propagation over the Tower [Colour figure can be viewed at wileyonlinelibrary.com]
face, corresponding to flats "X6," is consumed, and the HRR tends to decrease. After 01:36 AM, the horizontal fire spread begins in both directions. Apartment fires of the initial "X6" flats are involved while the external cladding is almost extinguished. The north face begins to contribute to the fire through the external cladding and the apartment furniture, and the HRR increases from 100 to 620 MW. This corresponds to the fully developed fire inside and outside the east and north faces and to the early contribution of the south face. The south face is involved after 02:23 AM and the west face after 02:37 AM.

During the horizontal fire spread, the local HRR observed for each face represents initially the contribution of the upper external cladding and apartment furniture at the flame spread front, then the remaining contribution from the apartments through the windows. This leads to an average total HRR, with the contribution of the cladding and the apartment furniture, between 150 and 250 MW for each face during horizontal propagation.

However, no data are neither used nor available to compare the HRR. It is essentially a result from the simulation.

5 | INVESTIGATION OF THE EFFECT OF A CHANGE IN THE INSULATION MATERIAL

The impact of using a non-combustible insulation material was investigated during the initial vertical fire spread, in Reference 16, using the numerical model. Similarly, the use of mineral wool [MW], instead of the PIR insulation, is investigated in this study, while the cladding remains the initial [ACM-PE].
A comparison between observations from the real fire and the modelled [ACM-PE + MW] fire propagation shows the same shape during the first and second linear phases from 01:08 AM to 01:22 AM. After 01:24 AM, the vertical fire spread was faster for the model with [ACM-PE + MW] than for the [ACM-PE + PIR] configuration. In References 6 and 7, the same slight differences in the fire behaviour of [ACM-PE + PIR] and [ACM-PE + MW] systems were observed at intermediate and large test scales, where the use of [MW] as the insulation tended to slightly increase the fire spread. This increase 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 is not related to the [PIR] combustion but to the heat of gasification and relative insulating properties of both products and probably highly dependent on heating scenario. Hildalgo has previously investigated similar effects for PIR at a small scale, and the trend is similar to that observed by our team in these façade systems at other scales.

The horizontal fire spread along the east face of the Tower after 01:29 AM was investigated numerically using the model from Reference 16. The comparison between numerical simulations of the fire with a [PIR] and [MW] insulation is shown in Figure 18 and in Figure 19. The horizontal and downward fire spread seem more significant when [MW] is used in the model. A delay of 3 to 5 minutes is observed in the vertical and horizontal fire spreads for the “X1” flats when [PIR] is used. Furthermore, the downward fire spread in the case of [MW] is higher: for example, at 01:52 AM, the fire reaches the bedroom of flat 111 while the bedroom of flat 151 just ignites at the same time for the [PIR] insulant (Figure 18). An average difference of four floors is evaluated in the downward fire spread at 01:56 AM.

![FIGURE 17](Evolution of total HRR for the fire propagation over the tower — A, total heat released, B-E, contribution of each face indicated, respectively, east, north, south and west [Colour figure can be viewed at wileyonlinelibrary.com])

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(A)  
(B)  
(C)  
(D)  
(E)  

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At crown level, the horizontal fire spread simulated with [MW] is close to the one evaluated for [PIR] insulant (Figure 19). The global HRR evaluated for the east face is comparable with that generated when [PIR] is used as insulation (Figure 20). Peaks in HRR look very similar for [PIR] and [MW] insulation for the first 30 minutes. However, the HRR is significantly higher for [MW] between 40 and 60 minutes and for [PIR] between 70 and 120 minutes.

**FIGURE 18** Comparison between numerical simulations of the fire with [PIR] and [MW] insulation — Horizontal fire propagation over the east face after 01:29 AM [Colour figure can be viewed at wileyonlinelibrary.com]
The main objective of the simulation described in this publication was to evaluate and understand the horizontal propagation triggered when the fire reached the crown of the Grenfell Tower and the influence of construction details, after the fast vertical fire spread over its east face.

This simulation of the façade, from the initial apartment, onto and over, each face of the Tower, used a numerical model for fire propagation that had been validated against multi-scale experimental observations. An initial scenario for vertical fire spread over of the east façade of Grenfell Tower considered the architectural details of the refurbished façade and contributions from the combustion of the contents of all the apartments, until the fire reached the top of the east face at 01:29 AM. The modelled vertical fire spread was validated by comparison with video and photographic observations of the real fire. This was the starting point for a deeper analysis of the later horizontal spread of the fire.

The full-scale fires along the east, north, south and west faces of the Grenfell Tower, the apartment fires and window failure are addressed in this paper. Because the east and west faces, and the north and south faces are identical, two different numerical models were built to simulate fire propagation along the four faces of the Tower. The fire conditions at the end of the vertical fire spread, in terms of HRR and heat of combustion, were known at every location in the façade and in the apartments and used as BCs for each independent horizontal fire spread model.

The numerically predicted horizontal fire propagation was consistent with observations of the real fire. The numerical model was able to reproduce complex phenomena such as downward propagation along the vertical columns and the descending V-shape of the fire. However, the external firefighting efforts as well as the effects of dripping materials were not included in the simulations, as well as dripping and movement of combustibles, leading to differences with the observations, especially on the lower part of the Tower at the later stages of the fire.

The numerical model allowed the analysis of the horizontal rate of flame spread at the crown of the Tower. This showed that the rate of flame spread at the crown was similar for both the clockwise (from east face to south face) and anticlockwise (from east face to north face) spread, with an average value estimated at 0.3 m/min. This value is consistent with that evaluated in Reference 5. However, although the average horizontal rates were comparable, the columns included along the faces seem to decrease slightly the local horizontal spread at crown level in the clockwise direction and to increase the spread rate in the anticlockwise direction, meaning that the fire propagation rate over the façade between columns was influenced by the direction. During the horizontal spread across the east and north faces, the simulation showed that the fire was clearly propagating in a V-shape and an average angle close to 0.7°/min was calculated for both faces. However, the angle related to the establishment of the V-shape seems to decrease with the order of the faces involved in the fire (east then north, south and west) and thus follows the horizontal spread around the Tower. This can be related to the fire being more intense during its first phase (vertical spread and horizontal spread along the

**CONCLUSIONS**

The main objective of the simulation described in this publication was to evaluate and understand the horizontal propagation triggered when the fire reached the crown of the Grenfell Tower and the influence of construction details, after the fast vertical fire spread over its east face.
east face) mainly driven by the combustion of the cladding leading to internal fires.

The horizontal fire spread over the east face of the Tower after 01:29 AM was investigated numerically with mineral wool [MW] replacing the [PIR] insulation that was used on Grenfell Tower, while the cladding remained as [ACM-PE]. The comparison between numerical simulations of the fire with a [PIR] and [MW] insulation showed that the horizontal and downward fire spread seemed slightly enhanced when using [MW].

Even if the numerical model addressed in this paper correlates well with observations during the Grenfell fire, several modelling assumptions were needed as detailed in previous studies in this series. The same considerations can be addressed for the present paper, in terms of numerical hypothesis considered for the model developed for the accurate fire grid to be applied to a coarser one as used, numerical criterion for the window failure and the geometrical model of the Tower since 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. External wind was not considered in the model.

The numerical model of Grenfell Tower, with fire spread validated both vertically and numerically, can be useful in understanding the tenability conditions inside the Tower, in terms of toxic effluents released or thermal ambiance. This will be the basis of further research, as will calculations of uncertainty and sensitivity.

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ORCID
Eric Guillaume https://orcid.org/0000-0002-3055-2741
Virginie Dréan https://orcid.org/0000-0002-3216-1808
Talal Fateh https://orcid.org/0000-0002-4204-0540

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