Reconstruction of Grenfell Tower fire. Part 1: Lessons from observations and determination of work hypotheses

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Summary
The Grenfell Tower fire occurred on 14 June 2017, killing 72 people. The pattern and speed of vertical and horizontal fire spread characterize this catastrophic event. Plentiful video and photographic data of the fire spread available has been carefully verified and concatenated into a database. The verified data have been superimposed on a projection of the Grenfell Tower in order to track the development of the fire. The surface that is unburnt, burning, or extinguished, as well as the presence of internal fire at any given location, is thus recorded for the duration of the fire. An analysis of the results showed that the initial vertical propagation can be divided into three phases. After the façade ignited at the fourth floor, vertical propagation over time is linear, with a vertical fire spread rate of around 3.5 m/min until the fire reached the sixth floor. Then fire propagation decelerated. Finally, fire spread accelerated with a power four dependence. The maximum vertical fire spread rate was around 8 m/min as the fire reached the crown at the top of the building. Horizontal spread proved to be greatest at the level of the crown (0.293 ± 0.005 m/min). There is a linear relationship between speed of horizontal fire spread and height. These correlations and observations yield important conclusions, and eight different hypotheses capable of explaining the global behaviour of the fire are suggested.

KEYWORDS
expertise, façade fire, fire reconstruction, horizontal flame spread, vertical flame spread

1 | INTRODUCTION

The recent Grenfell Tower disaster in London¹ on 14 June 2017 highlighted the importance of building fire safety and shone a spotlight on the major role that façades can play as a fire propagation vector. Grenfell Tower fire was one of the major fires of the last few decades,¹ with 72 fatalities. The severity of the Grenfell Tower fire and its tragic consequences are in large part due to (a) the rapid propagation of the fire vertically over the east façade of the tower before spreading horizontally around the tower in both clockwise and anticlockwise directions and (b) the penetration of the fire through windows into apartments. The Grenfell Tower is a 24-storey high-rise building. All floors, from 4 to 23, have a similar layout consisting in six flats (four two-bedroom flats and two one-bedroom flats).

The tower was refurbished in the period 2012-2016. A new externally insulated façade system and new windows were installed on the whole building. The over-cladding was mounted on the existing reinforced concrete envelope. This included a series of 14 columns was present 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.

Video and photographic evidence demonstrates that the fire spread to the façade by penetrating the kitchen window of an apartment located on the fourth floor of the east façade of the tower. This has been extensively detailed in expert reports. This publication presents an analysis of the publicly available photographic, video, and documentary evidence from the fire, to help quantify the characteristics of the Grenfell Tower fire, as a first step in the creation of a numerically modelled reconstruction. It summarizes the available evidence and draws several hypotheses. It supplements and follows the experimental and numerical work performed by authors on materials and products of such façades.

2 | METHODOLOGY

2.1 | Principle

Due to its location in London and strong media interest, there is a large number of publicly available photographs and videos of the Grenfell Tower fire. Many of these photographs and videos are presented in the Grenfell Inquiry phase 1 reports from Bisby and Lane as well as from all the publically available material. This large dataset has been screened, based on availability of accurate “time-of-capture” records and on image quality. The timeline selected for the analysis is taken from these two references. Only events with a sufficient certainty in time have been kept.

In order to perform a quantitative analysis of all of this data, a physical 3D model of Grenfell Tower was built, based on a detailed database of information, including precise input data for each individual element of the tower’s construction and contents. Views of database contents are found in the Supporting Information. The model allowed each face of the tower to be flattened, to analyse the transition of the fire at corners and hence carry out various calculations of vertical and horizontal flame spread rates. The model facilitated analysis of floors 4 to 23 of Grenfell Tower and of the tower’s architectural crown. It enabled each façade of the tower to be divided into the individual elements of which it comprised. In total, the model of the tower is divided into approximately 3300 façade elements. Each individual element can be overlaid with a particular colour code to show whether, at a particular time on 14 June 2017, based on the available evidence, it was (a) unburnt (no overlay colour coding applied), (b) on fire (red), or (c) burnt residue (black). There is a fourth colour code of yellow for windows to demonstrate where there is fire within the flats. This model is based on evidence, eg, time-stamped pictures and videos, which allows confident assumptions as to the state of the component parts of the tower at specific times during the fire on 14 June 2017.

2.2 | Floors design and elevation

The model tower’s floors are all identical, from fourth to 23rd. Each floor comprises six apartments. Two of the apartments are only exposed to one side of the tower (the east and west face, respectively), whereas the remaining four apartments are corner apartments meaning that they are exposed to fire on two faces of the tower.

3 | INITIAL VERTICAL PROPAGATION

3.1 | Observations

The available evidence tends to suppose that the fire started in the kitchen, close to the window, of apartment 16, on the fourth floor of Grenfell Tower. The fire burned within apartment 16 for more than 10 minutes before breaking out onto the external façade of the tower. The fire was notified to the emergency services at 0:54:29 AM.

Fire is visible at the kitchen window of apartment 16, from approximately 1:05:36 AM. It is unclear what items within the kitchen of apartment 16 were burning at this point but the evidence from Bisby suggests that a fridge or fridge/freezer is burning close to the kitchen window. Fire is clearly visible on the external façade of the tower at apartment 16 by 1:08:06 AM. It is reasonable to assume that this is when the fire on the façade of the tower began.

The fire is mostly localized around the window lintel of apartment 16 between 1:08:06 AM and 1:14:53 AM, and so there is no evidence of vertical fire spread. Then the fire clearly spreads from floors 4 to 6 between 1:14:53 AM and 1:16:00 AM. There is no evidence showing the behaviour of the fire between 1:16:00 and 1:21:37, ie, there is no picture or video evidence between these times. During this period, propagation spread rate reduced—this is deduced from the position of fire at 1:21:37, from which time pictures are again available. It is clear from the evidence that after 1:21:37 AM, the fire propagates with an accelerated rate, reaching the crown of the tower by 1:29:00 AM.

The photographic and video evidence between the beginnings of the façade fire (approximately 1:08:06 AM) and the fire reaching the crown (approximately 1:29:00 AM) shows that the fire was contained between two vertical columns on the east façade. Table 1 summarizes these data.

| Local Time (AM) | Event |
|----------------|-------|
| 00:54:29       | First notification of fire to emergency services, by occupant of flat 16 |
| 1:05:36        | Flame visible at initial window (L4) |
| 1:08:06        | Flame around initial window, first evidence of external fire |
| 1:14:53        | Flames at midlevel between L4 and L5 |
| 1:15:37        | Flames at midlevel between L5 and L6 |
| 1:16:00        | Flames at midlevel between L7 and L8 |
| 1:21:37        | Flames at midlevel between L9 and L10 |
| 1:22:22        | Flames at midlevel between L10 and L11 |
| 1:23:09        | Flames at level up to L12 |
| 1:25:36        | Flames at level up to L20 |
| 1:29:00        | Flames reach crown, over L23 |
3.2 Data processing

The observations set out were plotted onto a graph (Figure 1) in order to understand the pattern of fire spread at Grenfell Tower. The graph’s y axis represents the vertical distance between the farthest reach of the fire and the lintel of apartment 16’s kitchen window on the fourth floor. The graph’s x axis represents the time on 14 June 2017. “0” on the x axis (time) represents 1:08:06 AM, being the first obvious sign of fire on the external façade of the tower following breaking out from apartment 16. Uncertainties have been estimated for time as ±15 seconds and for vertical distance as ±1 m.

Figure 1 shows that, initially, the fire does not spread 1:08:06 AM and 1:14:53 AM, i.e., there is no evidence of flame spread during these 6 minutes (phase 0). This phase corresponds with the time that is likely to be needed for the façade materials to reach ignition conditions. A detailed explanation of this phase needs further investigation that is not included in this paper. Then the first phase of vertical propagation (phase 1a) is observed between 1:14:53 AM and 1:16:00 AM. During this phase (just over 1 minute), the fire propagates to floor 5 and reaches window of floor 6. At this stage, the fire is still limited to a vertical line above the kitchen window of apartment 16. The plotting of this phase is based on three time-stamped photographs of the external fire, which are included in the database. These photographs show that the trend of the fire propagation during this phase is linear.

Between 1:16:00 AM and 1:21:37 AM (phase 1b), there are no timed photographs or videos (Figure 2). Although there is no evidence from between these times, the photographic and video evidence of the fire at the end of phase 1a and start phase 2 (the phases directly before and after phase 1b) means that the phenomenon driving vertical propagation during phase 1b can be investigated. The plots of phase 1a and phase 2 do not join together to form a steadily increasing curve; therefore, it is clear that the rate of flame spread significantly decelerates during phase 1b (from 3.6 m/min to an average value of 1.7 m/min).

Between 1:21:37 AM and 1:29:00 AM, the vertical flame spread accelerates (Phase 2). The fire reaches the architectural crown of
Grenfell Tower at 1:29:00 AM. The final rate of fire spread as plotted on Figure 3 is approximately 8 m/min. Still, at this time, the fire is constrained between the two vertical columns either side of apartment 16 on the east face of the tower. The data regression shows vertical fire spread with a power 4. The spread rate is similar to that measured in several other tall building fires, detailed in Bisby2 and Torero.4 Figure 4 reproduces data from Torero,4 supplemented by the results from this analysis.

3.3 Hypotheses

The observations described above have yielded several hypotheses from authors, to be studied in details in future research. These hypotheses and the particular observations on which they are based are summarized below.

Observation 1: The fire does not noticeably spread between 1:08:06 AM and 1:14:53 AM.

**Hypothesis 1.** This period of inactivity, almost stability, between when fire was first visible on the external façade and when the fire clearly started to spread vertically, is due to the time required to bring the ACM-PE cassette, which sat over the lintel of the kitchen of apartment 16, to ignition temperature.

Observation 2: The flame spread is linear between 1:14:53 AM and 1:16:00 AM, during which time the fire spreads from floor 4 to floor 6.

**Hypothesis 2.** The initial flame spread is driven by convection, which is driven by linear modes.

Observation 3: The flame spread significantly slows down between 1:16:00 AM and 1:21:37 AM.

**Hypothesis 3.** Between 1:16:00 AM and 1:21:37 AM, the fire enters apartments 26 and 36 on floors 5 and 6, respectively. The deceleration in the rate of spread is linked to the time it took for the fire to move into these apartments and to reach flashover before the additional energy from these internal fires burst back out to the external façade of the tower and restarted the vertical spread but at a higher rate.

Observation 4: The rate of flame spread accelerates to the power four between 1:21:00 AM and 1:29:00 AM.

**Hypothesis 4.** As the power four relationship is characteristic of the Stefan-Boltzmann Law, describing radiative heating, the fire spread is driven by radiation from the fire plume from 1:21:00 AM onwards.

Observation 5: Throughout the initial vertical spread of the fire from apartment 16 (which took more than 20 minutes), the fire is contained between two vertical columns.

**Hypothesis 5.** The construction of the vertical columns, which included cavity barriers and aluminium mounting and fixing profiles, played an important role in limiting horizontal flame spread, and this channels the vertical propagation during this period, i.e., before the fire reached the architectural crown of the tower.

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**FIGURE 3** Vertical flame spread—Phase 2 [Colour figure can be viewed at wileyonlinelibrary.com]
4 | HORIZONTAL PROPAGATION

4.1 | Observations

After 1:29:00 AM, when the fire reached the crown, it started to propagate horizontally. Fire propagated in two directions: clockwise and anticlockwise around the tower. Observations of this phase of the fire are summarized in the Table 2.

4.2 | Data processing

The observations set out in Table 2 have been plotted in Figure 5 in order to represent the spread of the fire once it reached the Grenfell Tower crown. The graph’s y axis represents the horizontal flame spread distance from the first part of the crown reached by the fire (ie, the top of the east face between the two vertical columns that bound apartment 16). The graph’s x axis represents the elapsed time form the time at which the initial vertical spread of fire reached the crown. Uncertainty in time is estimated as ±5 minutes and uncertainty in distance as ±1 m.

The plot is very linear, and there is no visible difference between the clockwise and anticlockwise rates of flame spread. The anticlockwise and clockwise routes of fire spread join together at the point on the west façade which is directly opposite to the point at which they began on the east façade of the tower. The horizontal average rate of flame spread is approximately constant to (0.293 ± 0.005) m/min at the crown of the tower.

The horizontal rate of flame spread was then analyzed for several floors of the tower. This analysis is plotted in Figure 6. Uncertainty in time is estimated as ±5 minutes and uncertainty in distance as ±2 m.

This analysis shows a progressive reduction in the speed of flame spread, the lower the floor. This is what caused the V-shape of flame spread observed on the tower. Regression accuracy is also reduced, the lower the floor, as external influences such as firefighting, columns, windows are more and more important. External firefighting efforts also probably reduced the rate of fire spread across the lower levels of the tower. A further analysis of the relationship between rate of horizontal fire spread and floor level is shown in Figure 7. This graph shows that flame spread is not influenced by external factors at heights between 50 and 65 me from the base of the tower—there is a linear relationship between rate flame spread and height at these elevations. Whereas external factors appear to have a much bigger influence on rate of flame spread under 45 metres.

Authors figured in the last row of Table 2 the effect of firefighting on the final observed degradations. Several regions in west façade and more in south and east façade are exempt from damages, confirming the efficiency of firefighting by the outside in these regions. Due to accessibility constraints and extinguishing means available with time, firefighting has been much more efficient on south and east façade, up to levels 10-11. This is coherent with many provisions around the world on the limit of efficiency of firefighting by the outside. All these observations are similar to those of Lane,3 sections 5, 7, 13, and more precisely section 17: firefighting by the outside with hose streams and ladders are detailed in Lane,3 sections 17.3. A comparison of heights is also available in section 17.5, pages 31 to 33, and fig. 17.29. A summary of these observations is stated in Table 3. Lane confirms there appears to be a correlation between the levels to which external water was applied and the lack of external damage on these levels (paragraph 17.5.7, page 32). Without this external firefighting, it is probable that fire will propagate downward more, eventually to ground level.

4.3 | Hypotheses

Observation 6: The rate of flame spread at the crown of the tower is the same for both the clockwise and anticlockwise spread and is estimated at about 0.3 m/min.
TABLE 2  Time sequence for horizontal flame spread

| Data processed | Observations |
|----------------|--------------|
|                | At 1:29:00 AM, the fire is constrained between two vertical columns and has reached the crown—the fire is shown in red. Propagation starts along the north-east corner column. |
| At 1:36:00 AM, two paths of fire spread emerge, and the fire is clearly now spreading horizontally past the vertical columns. Some surfaces are already burnt and seem to extinguish because of lack of fuel—these are shown in black (the external façade fire started 28 min before) |
| Between 2:10:00 AM and 2:23:00 AM, horizontal propagation occurs across the east and north faces of the tower separately. This propagation is mainly driven from the crown. Large burnt and extinguished areas are visible on the east and north faces of the tower. The north façade fire started 34 minutes before |

(Continues)
Between 2:34:00 AM and 2:48:00 AM, the fire is clearly propagating in a V-shape down the tower. The fire also reaches the south face of the tower. There is evidence of downward propagation along vertical columns of the east face of the tower that remain intact, i.e., the fire has been successfully constrained between two vertical columns.

Between 3:08:00 AM and 3:11:00 AM, the fire reaches the west face of the tower. Propagation continues at the same rate, especially at crown.

At 3:20:00 AM the south and west faces are alight. The east and north faces have finished burning.

At 3:33:00 AM, the fire continues to propagate on the south and west faces.
At 3:48:00 AM, the fire reaches the south-west corner of the tower.

At 3:53:00 AM, the fire continues to spread on the west face.
Hypothesis 6. Wind did not influence the fire at crown level and during horizontal propagation phase.

Observation 7: There are no significant irregularities in the horizontal propagation across all floors analysed.

Hypothesis 7a. Individual elements of the crown, such as columns or corners, had no effect on horizontal flame spread.

Hypothesis 7b. The position of apartment windows, e.g., whether they were tilted open or closed, had no influence on horizontal flame spread.

5 EFFECTS OF DETAILS

5.1 Window failures

The windows in place on the Grenfell Tower, from fourth floor upwards, were changed in 2016. The new windows were fixed on preframes composed of an upper aluminium profile and a lower L-shaped aluminium profile, which were both fixed to the original concrete opening. The preframe aluminium profile moves the window away from the concrete opening and adds a momentum to their mechanical behaviour. The window frames comprised outer and inner aluminium profiles connected by polyamide thermal breaks. Similarly, the window opening casements, supporting double glazing units, comprised two aluminium profiles connected by polyamide thermal breaks. The smaller windows, in the kitchens, could open inwards, hinged on a vertical edge. The larger ones were able to tilt open inwards and turn. These observations can be summarized as below.

- Post fire, many windows frames were still in place or partially in place with only their upper parts were melted.
- The outer and inner parts of the window frame and casement frame were split, meaning that the thermal break had been destroyed, leading to a loss of integrity in the window.
**TABLE 3** Collection of observations from firefighting by the outside

| Observation                              | Reference         |
|------------------------------------------|-------------------|
| Water jet on west façade up to level 7   | Lane 17.3.8       |
| Hose stream applied on south façade up to levels 9 and 10 | Lane 17.3.26     |
| Localization, time, and mean heights of extinction | Lane 17.26 (figs. 13.15 and 13.17) |
| Summary of water means                   | Lane 17.17 (fig. 13.17) |
| Comparison of heights reached by firefighting activities | Lane 17.26 (fig. 17.29) |

**FIGURE 3** Measurement of horizontal propagation at crown [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 6** Horizontal flame spread as function of tower level [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 7** Horizontal flame spread rate as function of height [Colour figure can be viewed at wileyonlinelibrary.com]
A large part of the upper preframes were melted. The lower preframes were protected by the insulant and so were often in better condition than the upper profiles.

A lot of windows had fallen into the apartments—if windows were tilted open at the time of the fire, they may have had the moment to fall in an inwards direction.

Some windows were still fixed to the lower pre-frame.

It can be difficult to determine whether the state of the windows is due to early failure or prolonged exposure to fire.

**Hypothesis 8a.** There were several different window failure behaviours depending on their position during the fire, eg, tilted open or closed—the mounting and fixing of the windows played an important role as well as their internal structure (featuring polyamide thermal breaks).

**Hypothesis 8b.** Different window positions led to a similar rapid (within a few minutes) failure of the windows and penetration of fire from the outside to the inside of the Tower.

### 5.2 Cavity barriers

Both vertical and horizontal intumescent cavity barriers were installed as part of the new façade. These cavity barriers are theoretically designed to close a 25-mm air gap during fires. From the evidence, there is no obvious conclusion regarding the performance of these cavity barriers during the fire. The only available evidence that provides some indication as to how the cavity barriers behaved during the fire is

- the limited horizontal flame spread at the early stage of the fire, ie, the fire was constrained between two vertical columns (Hypothesis 5) and
- the comparable rates of horizontal flame spread in both anticlockwise and clockwise directions.

Exact position and continuity of intumescent cavity barriers, as well as the size of air gap to close, are not fully certain and subject to discussions.

### TABLE 4 Summary of the evidence and wok hypotheses

| Evidence | Hypotheses |
|----------|-------------|
| Observation 1: The fire does not noticeably spread between 1:08:06 AM and 1:14:53 AM. | Hypothesis 1: The period of inactivity/stability at the beginning of the façade fire is due to the time required to bring the ACM-PE cassette, which sat over the lintel of the kitchen of apartment 16, to ignition temperature. |
| Observation 2: The flame spread is linear between 1:14:53 AM and 1:16:00 AM, during which time the fire spreads from floor 4 to floor 6. | Hypothesis 2: The initial flame spread is driven by convection. |
| Observation 3: The flame spread significantly slows down between 1:16:00 AM and 1:21:37 AM. | Hypothesis 3: During this period, the fire enters apartments 26 and 36 on floors 5 and 6, respectively. The deceleration in the rate of spread is linked to the time it took for the fire to move into these apartments and to reach flashover. The additional energy from these internal fires burst back out to the external façade of the tower and restarted the vertical spread but at a higher rate. |
| Observation 4: The rate of flame spread accelerates to the power four between 1:21:00 AM and 1:29:00 AM. | Hypothesis 4: The fire spread is driven by radiation from the fire plume from 1:21:00 AM. |
| Observation 5: Throughout the initial vertical spread of the fire from apartment 16 (which took more than 20 minutes), the fire is contained between two vertical columns. | Hypothesis 5: The construction of the vertical columns, which included cavity barriers and aluminium mounting and fixing profiles, played an important role in limiting horizontal flame spread, and this channels the vertical propagation during this period, ie, before the fire reached the architectural crown of the tower. |
| Observation 6: The rate of flame spread at the crown of the tower is the same for both the clockwise and anticlockwise spread. | Hypothesis 6: Wind did not influence the fire at crown level and during horizontal propagation phase. |
| Observation 7: There are no significant irregularities in the horizontal propagation across all floors analysed. | Hypothesis 7a: Individual elements of the crown, such as columns or corners, had no effect on horizontal flame spread. |
| Hypothesis 7b: The position of apartment windows, eg, whether they were tilted open or closed, had no influence on horizontal flame spread. |
| Observation 8: Windows failure behaviour | Hypothesis 8a: There were several different windows failure behaviours depending on their position during the fire, eg, tilted open or closed—the mounting and fixing of the windows played an important role as well as their internal structure (featuring polyamide thermal breaks). |
| Hypothesis 8b: Different window positions led to a similar rapid (within a few minutes) failure of the windows and penetration of fire from the outside to the inside of the tower. |
It is obvious that the integrity of the cavities were compromised when the ACM-PE external cladding had burnt away, irrespective of the integrity of the cavity barriers. The behaviour of the cavity barriers needs further experimental analysis.

5.3 Mounting and fixing details

The mounting and fixing brackets for the aluminium cassettes (in conjunction with the cavity barriers), appears to have played a role in limiting initial lateral fire propagation (Hypothesis 5). Nevertheless, these elements were mainly made of aluminium and melted. Further investigations will be performed experimentally and numerically to understand their behaviour during the fire.

6 CONCLUSIONS

In the aftermath of the Grenfell Tower fire, numerous studies have and will be produced trying to explain and/or to model the observed fire behaviour. In order to validate modelling of such fire, visual observations and quantitative data are of prime importance. This study draws together the numerous available data of the Grenfell Tower fire and presents their analysis and the additional observations that can consequently be made.

The initial vertical fire spread can be split into three phases: first, a linear phase is followed by a stagnation phase. The first phase is characterized by a constant spread rate of about 3.6 m/min. The stagnation phase is unusual and need to be explained. Then, before reaching the crown, power four behaviour is observed with a maximum vertical spread rate of 8 m/min when reaching crown.

Horizontal fire spread is quickest at the crown (0.293 ± 0.005 m/min). A linear correlation between the rate of horizontal fire spread and height is also obtained. This variation explains the rate of formation of V-shape induced by the propagation.

Construction details of the façade seem of prime importance for reconstruction and need to be studied further through modelling and testing. This includes windows failures, as well as cavity barriers, and mounting and fixing details.

Based on these and other observations, several hypotheses are proposed (see Table 4). These hypotheses will be the basis of reconstruction work performed by the authors.

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

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