Experimental investigation into the influence of ignition location on flame spread and heat release rates of polyurethane foam slabs

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Summary

This study presents the results from a set of 11 large-scale open fire tests performed on flexible polyurethane foam slabs/mattresses. The purpose of the study was to investigate the influence of the ignition location on the fire behaviour of the foam slabs and to generate data on a highly characterised material that could be used for modelling work in the future. A method for obtaining spatially resolved flame spread data for this type of material was presented using a gridded array of 5 × 10 thermocouples placed on the underside the foam slab and from this, flame spread was examined using three different approaches. The heat release rate (HRR) results showed clear shapes forming that were dependent on the ignition location, with two distinct behaviours being observed between the various different ignition locations, this was also observed in the calculated flame spread rate (FSR) data. Results within an individual test, showed the calculated range of FSRs over the geometry of the slab varied between approximately 1 and 8 mm/s depending on the ignition location. The average FSR values between tests varied between 3 and 7 mm/s and the maximum and minimum values were calculated to be approximately 11 and 2 mm/s respectively.

KEYWORDS

flame spread, flame spread rate, flexible polyurethane foam, heat release rate, ignition, ignition location, mattress

1 | INTRODUCTION

Understanding what may influence a fire scenario in real (large) scales is an important, though a complex task. In general, this may be done by performing large-scale experiments, unfortunately, these are commonly expensive and time consuming to perform. Due to this restraint, repeat tests, and investigating the influence of minor configuration changes may not be feasible in many cases. However, due to the inherent complexity of fire phenomena “minor” changes are also important to investigate when possible as they may bring new insights and can lead to a deeper understanding of fire behaviour.

Horizontal flame spread, for example, over mattress type products, is a much-studied area within fire science and there are many factors that can influence how a fire spreads horizontally over a material’s surface. The point-of-ignition is one such factor that is generally known to have an influence on flame spread and heat release rates (HRRs). Despite this, there are very few studies that attempt to investigate its influence systematically.

Mitler and Tu provided a brief study investigating the dependence of the burning behaviour of upholstered chairs on ignition location. As part of a series of full-scale chair burns at NIST, four identical chairs of one chair configuration (style C) were selected and four...
different ignition locations were tested: (a) centre chair seat cushion, (b) lower centre of chair front, (c) lower centre of chair side, (d) lower centre of chair back. Heat release, mass loss and smoke measurements were recorded, however, the ignition source was not discussed. The study concluded by stating that, based on the changes in HRR measurements recorded, ignition location can have a significant effect on the time to reach peak HRR, however, no further analysis is given.

In the book by Krasny et al.2—fire behaviour of upholstered furniture and mattress, the majority of the described work on ignition is about characterising different ignition sources and their effects. Section 4.6.0 mentions the fact the location will affect the results, however, the research quoted from NIST1 and the CBUF3 programme was on chairs.

Robson et al.4 and Ezinwa5 investigated the effects of thickness and ignition location on flame spread and HRRs over flexible polyurethane foam (FPUF) slabs. Tests performed as parts of these studies compared edge ignition (EI) and centre ignition (CI) locations on approximately square FPUF slabs. CI tests showed higher peak HRRs and faster flame area growth rates than the EI tests. The authors explain that the observed differences may be due to having a more pronounced pool fire with larger radiative feedback in the CI tests and that there may be higher convective heat losses associated with EI tests. However only two locations were chosen, without justification, and many of the tested samples were of different proportions making further comparisons and conclusions difficult as the differences in the geometry of the samples will also impact how the flame spreads across the surface of the slab and thus will convolute investigating the effect of ignition location.

Wang et al.6 investigated the effects of ignition condition (ie, location and type of ignition) on polymer melt flow flammability. Concluding that the ignition location “impacted considerably nearly all the important fire parameters, including peak HRR, time to peak HRR, smoke temperature, CO concentration and the extinction coefficient.” However, this was in a vertical flame spread context.

Söderbom et al.7 investigated the effects of changing the size and heat output of two types of propane burner ignition source (varying output from 1.7 to 40 kW), and concluded that there was little effect to the overall outcomes after their ignition criteria was met (a HRR of 50 kW), and that the ignition source only affected the ignition period (time to reach 50 kW criteria). However, they did not change the location of the ignition source in this case other than the change in physical dimensions and output of the burners used.

### 3 | MATERIALS

FPUF slabs were chosen as the test specimen as they could represent a semi-realistic scenario, in which the foam slabs act as a simplified proxy for bed mattresses. The FPUF investigated in this study was basic, commercially available, non-fire retarded polyether polyurethane, distributed by Sherlock Foams, UK. This particular foam has been used by Laboratoire national de métrologie et d’essais (LNE) as a reference material8 and in previous research studies by the authors.9,10 The choice was also made to provide data for modelling purposes. Basic properties are provided in Table 1 and readers are referred to previous research referenced above for more detailed properties on the tested material.

The slabs dimensions were 1200 × 600 mm with a thickness of 50 mm; this represents the standard-sized mattress dimensions of a child’s crib/bed. The foam was tested naked, that is, no textile covers or other materials were used as fuel in the study. Naked foam is used predominately to reduce the complexity of experiments and the data obtained, other work by the author9 investigated the same foam with fabric combinations at a bench-scale level.

### 4 | EXPERIMENTAL METHODOLOGY

#### 4.1 | Experimental setup

All experiments for this study can be characterised as free burning tests, performed under an open calorimeter at the Danish Institute of Fire and Security Technology (DBI). A total of 11 tests were performed for this specific study. Further tests were also carried out with this setup, however, additional metrics were added that were out of the scope of this study, thus they have been excluded. Before testing, slabs were conditioned for at least 24 hours at 23°C and 50% relative humidity.

A base frame to hold the samples was constructed from timber, on which a 12 mm calcium silicate board (CSB) was placed. Stone wool insulation was pressed in under the CSB between the frame supports to better protect the measurement equipment. The frame and board were fabricated to be slightly larger than the FPUF slabs and a small raised perimeter edge was added to the base frame so that any potential spillage from the fire tests would be prevented (refer Figure 1). The base frame CSBs and raised edge were covered in aluminium foil before each test so that any residue left could be removed before the next test was performed.

#### 4.2 | Measurement equipment

HRRs, mass loss and temperature measurements above and below the slab were performed for most tests. Video recording of each test was also undertaken.

HRR measurements were performed using an open calorimeter setup at DBI. The calorimeter setup is based on the ISO 24473
standard and measures HRR using oxygen consumption calorimetry. The combined expanded relative uncertainty of these measurements is considered to be between 7.1% and 10.6% based on the work from SP. Mass loss measurements were accomplished using a load cell (Sartorius M-177 with a sensitivity of 0.0001 kg) capable of holding the base frame and slabs. The load cell was protected from heat by the base frame and the insulation that was sandwiched in between the base frame supports, which did not touch the load cell.

Temperature measurements were performed using 0.5 mm diameter wire type-K thermocouples. Thermocouple (TC) arrays, set out in a grid of 5 by 10 (total of 50) were placed above and below the FPUF slabs for some tests, others were performed without the TC grid above the slab. The grid was positioned such that, spacing was 120 mm between each TC, and that the TCs on the sides were placed 60 mm in from the edge of the FPUF slabs as illustrated in Figure 1. Each TC location was identified based on its position in the grid, rows 1 to 5 were named A-E and columns were designated 1 to 10 as shown in Figure 2.

TCs placed below the slabs were done by drilling very small holes (approx. thickness of the TC wire) through the CSB, then pushing the TCs through each hole so that each TC stuck out approximately 3 mm from the surface of the CSB. TCs were then fastened from the backside of the board with aluminium tape and staples. During tests 6 to 8, a TC array was also placed above the slab and positioned in the same grid layout as the TCs below. TCs were suspended and attached 50 mm above the surface of the slabs using five steel wires (corresponding to positions A-E) tensioned between supports on either side of the slab configuration. Temperatures were logged at 2-second intervals using data loggers.

Measuring flame spread rates (FSRs) in this study employed the TC arrays embedded in the tray. This configuration was based on initial testing of the foam slabs in the cone calorimeter, where it was observed that temperature measurements on the underside of the
slabs had a distinct temperature rise. In addition, compared to temperature measurement performed above the slabs in the gas phase they were more robust and reliable, due to TC wire damage occurring in the gas-phase and the inherent turbulence within the flames above the slabs surface, making exact positioning of surface spread more difficult to obtain.

Due to the insulative properties of the foam slabs, it was observed that backside TC measurements stayed relatively low right up to the point of foam collapse, upon which a very sharp temperature increase could be observed in the time-dependent temperature readings, exemplified in Figure 3 (C4 or C5 refers to row and column designation). Assuming this was consistent throughout all the experiments, this gave a clear point at which the movement of the collapse could be monitored with relative certainty.

Structural collapse in these foams is a commonly observed phenomenon, with previous research outlining the mechanisms by which the foam decomposes into its component parts, allowing the release of the TDI component, leading to the collapse and subsequent pool fire for the polyol component to occur.8,14,15

4.3 | Ignition locations

This study aimed to investigate how changing the ignition location on a horizontal slab can affect commonly measured test outputs such as HRR and FSRs, five different ignition locations were chosen (refer to Figure 2). Tests were performed in an open calorimeter, and it was assumed that airflow around the slab was relatively symmetrical, thus flame spread behaviour could also be considered symmetrical (ie, behaviour would be similar igniting from either side of the slab when compared to its opposing side). Based on this assumption, the placement of ignition locations was confined to 1 quadrant of the slab, assuming symmetry in both planes as shown in Figure 2. However, it should be noted that no assessment of the symmetry was performed, thus the influence of, for example, drafts or other asymmetrical influences cannot be discounted.

Five locations were chosen within the quadrant, 1 in each of the quadrants 4 corners, and 1 in the centre of the quadrant, with the aim to spread the locations evenly over the space. Repeat tests were conducted on 4 of the 5 locations, with IL1 and IL3 being tested a total of 3 times, as these represented significant differences in spread mechanics from initial tests and a least 3 tests were required to get a basic measure of repeatability. Table 2 summaries the ignition locations for each test scenario. Tests 9, 10 and 11 were performed separately at a later date with differing environmental conditions.

4.4 | Test procedure

At the start of each test, aluminium foil was placed over the base tray and secured using aluminium tape. Each underside TC was checked to confirm that it had pierced the foil to reduce disruptions to the measurements from the foil. The FPUF slab was taken from the conditioning room and placed centrally in position on the base frame tray. When used, the above slab TC’s were then checked to confirm the position and the initial mass of the slab was recorded. HRR measurements, mass loss, TC logging systems and the video camera were then initiated in order to gather baseline data. After a 60s baseline recording, the slab was ignited. Ignition of the slab was performed using a small open flame diffusion gas burner, similar to the standard cigarette lighter,16 the ignitor was positioned in the chosen location and held there for 10s against the foam slab, it was then taken away. In all tests, slabs then continued to show a self-sustained burning and tests ran until the original foam fuel was fully consumed. Each test was

![Figure 2](https://wileyonlinelibrary.com) - TC ID layout and ignition locations (dashed lines indicate assumed symmetry lines) [Colour figure can be viewed at wileyonlinelibrary.com]

![Figure 3](https://wileyonlinelibrary.com) - Typical backside TC reading from two consecutive TCs showing sharp temperature increase and the time shift used to determine flame spread rates
allowed to run a short while after total flame extinction, to allow TCs on the slabs underside to drop in temperature.

4.5 | Data analysis

Data from multiple sources were analysed in this study, HRR measurements were calculated using oxygen consumption calorimetry\textsuperscript{12} principles, as per ISO 9705.\textsuperscript{17} Mass loss measurements from the load cell were converted from the analogue signal, to mass loss using a predefined conversion input in the data logging system. The calculation of FSRs based on the TC measurements was determined in a number of steps:

- The TC measurements were filtered/smoothed using a 10-point moving average to dampen any noise that may interfere with the calculations.
- The derivative of the TC curves was then calculated, and the maximum value was then found—due to the previous filtering step, the maximum value was always calculated to be on the initial temperature rise (as observed in Figure 3). This was taken to be the point in time at which fire spread had reached the TC.
- The time taken to reach this point was then determined.
- The distance between each TC position from the TC position closest to the ignition location (TCig) was also calculated for each scenario. Time \( t = 0 \) was when TCig reaches the stated maximum derivative, and distance to each point was calculated via Pythagoras’s theorem from TCig.
- The spread rate (in mm/s) between each TC location could then be determined by dividing the distance to TC from TCig by the time taken for the flame spread criterion to reach TC.

These values could then be averaged over the whole surface to determine the mean spread rate for that particular ignition scenario or could be used to interrogate flame-spread profiles further. The principle of these calculations assumes that horizontal spread rates over the surface of the slabs are equal to the horizontal spread rates at the underside of the slabs. There is an influence from the thermal properties of the CSB tray, a delay due to the thickness of the slabs, and there is some evidence to suggest that the collapse rates (ie, the vertical component) will change based on the heat flux received to the surface of the slab,\textsuperscript{15,18} thus the results from this study are likely to be a combination of both the horizontal and vertical spread rates due to the changing incident surface heat flux as the fire progresses. Hence, comparison with other spread rate studies may be misleading and should be considered when reading the results from this study. It was also observed that a distinct decrease occurred (although less pronounced than the observed increase) in backside TC temperature when burnout occurred at the TCs location, thus a burnout/extinction rate (ie, when the burning stops in each TC location) may also be calculated in the same manner.

5 | RESULTS

The set of results of interest for this study are the HRR and FSRs. Mass loss, total heat release, burn time, smoke production etc. were measured but are not discussed further in this paper.

5.1 | Heat release rates

HRR results are presented, based on their ignition location in Figure 4 with replicate tests when performed. HRR results are presented as time-dependent plots and in terms of peak HRR and time-to-peak HRR (Table 3).

For test 2—IL3, the HRR measurement malfunctioned and therefore no measurement was recorded, thus only two HRR results (test 5 and 9) from this ignition location scenario are presented, however, temperature measurements for test 2 were operational.

The HRR results show clear shapes forming that are dependent on the ignition location. However, if peak HRR is used as a measure of repeatability, considerable variation in these values was also observed for the repeat tests, which varied up to 70 kW in the most extreme case (IL2), this equates to an approximately 32% difference in peak HRR values for that case of repeated tests, for IL1 the

| Test number | Ignition location ID | Test ID | Location description |
|-------------|----------------------|--------|----------------------|
| 1           | IL1                  | Ee1    | East edge (long-side centre) |
| 2           | IL3                  | Ne1    | North edge (short-side centre) |
| 3           | IL2                  | C1     | Centre |
| 4           | IL4                  | NEc1   | North east quadrant corner |
| 5           | IL3                  | Ne2    | North edge (repeat) |
| 6           | IL1                  | Ee2    | East edge (repeat) |
| 7           | IL4                  | NEc2   | North east quadrant (repeat) |
| 8           | IL5                  | NEQc1  | North east quadrant centre |
| 9           | IL3                  | Ne3    | North edge (second repeat) |
| 10          | IL2                  | C2     | Centre (repeat) |
| 11          | IL1                  | Ee3    | East edge (second repeat) |
percentage difference is even higher at 36.5% for the largest variation in the repeated tests. Variation arising from the change in ignition location was higher, with peak values observed to double; rising from approximately 100 to 200 kW in some cases. To confirm that the changes in peak HRR between ignition locations are significantly different from the variation observed between repeat tests, a simple ANOVA test was performed between the different groups (ignition locations). The results of the ANOVA indicate that the differences between peak HRR values for the different ignition locations are statistically significant (assuming the measure of \( P < .05 \) for significance).
with a $P$-value of .046, although the limited data set means this conclusion is limited to being indicative.

However, this suggests that the peak HRR may not be an appropriate parameter to judge how the changes in ignition location impact on the overall test results due to the inherent variation observed in the repeat tests. Therefore, the correlation coefficient between both the replicate tests and the different ignition locations tests was calculated (Table 4). Note that test 8 (NEqC1) has been omitted as no repeats of this position were performed.

In general, Table 4 shows that a higher correlation coefficient values tend to be observed for the repeat tests and for the tests where similar behaviour in the HRR is observed (eg, c1-2 and Ee1-2-3).

It should also be noted that the cases of the greatest variation in results were for tests 9, 10 and 11 when compared to others performed. This is likely, in part, to be due to these tests being performed at a different time which may have resulted in slight differences in testing conditions.

### 5.2 Flame spread

Flame spread (in the context of this paper) is examined via three methods in the following section. Geometric flame spread visualisation—which simply maps the TC measurements on the geometry of the foam slab over time (see Figures 5 to 9). FSR maps—which visualise the calculated spread rate at each TC point using the methodology outlined in Section 4—data analysis (see Figures 10-14), and Global FSR values—in tabulated form; the mean, maximum, minimum and range of FSRs over the foam slab for each test (Table 5).

### 5.3 Visualisation of geometric flame spread

Using the TC method outlined in Section 4—data analysis, the geometric spread of temperature over the TC array (which is then equated with the flame spread in this study) was visualised by mapping each measurement at its geometric location under the foam slab and then tracking them over the time for each test period. Figures 5 to 9 highlight this TC mapping and the evolution of the temperatures over time, for each ignition location (IL).

Visualisation of the temperature spread shown in the figures below is a 2D representation of the TC plots highlighted in Figure 3 for all TCs positions under the foam slabs simultaneously. X and Y axes of Figures 5 to 9 are simply the length and width dimensions (ie, 600 mm x 1200 mm), while the colour bar is used to map the temperature gradient of the test period (in all cases this goes from 0°C to 500°C, with red approx. 100°C to 250°C yellow approx. 400 to 500°C). Data are visualised via contour plots in MATLAB that uses a basic linear interpolation to “smooth” data between points. Using the data obtained from the TC measurements provides a baseline, qualitative method of investigation for the scenarios; it exhibits how the fire spreads according to the ignition scenario, which can then be correlated visually with observations, HRR and other measurements. Time points chosen for Figures 5 to 9 are not identical and were simply chosen to illustrate different points in the evolution of the burning foam slabs. Quantitative investigation of this visualisation method is left for Section 6. Repeat tests are not included, for each ignition location as figures are only meant to be a visualisation aid, to observe the different spread evolutions.

### 5.4 Flame spread rate maps

Presented below are the FSR maps for each test, grouped in their prospective ignition location. The FSR maps represent the calculated FSR (in mm/s) at each TC location across the foam slab, from the TCig (point of ignition, that is, where flame spread = 0). Contour plots using the same form of linear interpolation to graduate the results were used in Figures 10 to 14. X and Y axes are the length and width of the foam slab, with whole numbers representing the TC locations and the colour bar on the right-hand side of the plots giving the FSRs in mm/s. Dark blue regions indicate ignition location (spread rate = 0). White sections that are visible on some of the plots in Figures 10 to 14, constitute a fault in that TC reading for that test, hence FSR to that point could not be calculated.

Table 5 shows that for ignition locations with higher FSRs for example, IL1, higher uncertainty in repeated test results is also
evident, with mean FSRs changing by up to 2.2 mm/s. Whereas, for ignition locations with lower spread rates the variation between repeated tests is reduced with a maximum of 1 mm/s in the case of IL3.

**FIGURE 5** Temperature evolution of backside TCs for IL1 (ID: Ee) mapped on the foam slabs geometric proportions over time (red in the top left sub-figure represents the point of ignition, time evolution goes left to right, and top to bottom) [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 6** Temperature evolution of backside TCs for IL2 (ID: C) mapped on the foam slabs geometric proportions over time (red in the top left sub-figure represents the point of ignition, time evolution goes left to right, and top to bottom) [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 7** Temperature evolution of backside TCs for IL3 (ID: Ne) mapped on the foam slabs geometric proportions over time (red in the top left sub-figure represents the point of ignition, time evolution goes left to right, and top to bottom) [Colour figure can be viewed at wileyonlinelibrary.com]

**DISCUSSION**

FSRs showed consistency over repeat tests, however, this consistency was reduced for repeat tests 9, 10 and 11 when compared to others.
performed, as was also true for the HRR results. This is likely, in part, to be due to these tests being performed at a different time which may have resulted in slight differences in testing conditions, unfortunately specific differences in environmental conditions at the test times were not recorded, thus further analysis as to why this occurred is not possible. The HRRs for the 11 tests showed clear differences among ignition locations even with the observed variation in repeat tests, with ignition locations 1 and 2 giving the highest peak values with the fastest rise. For ignition locations located on the short side of the slabs, these had a lower steadier burning phase (IL3, 4 and also 5 to some extent, although this result was more of a mix of the two types of behaviour). This can be observed both quantitatively from the HRR plots and also from the FSR calculations presented. Geometry of the tested slabs is a critical influence on this observed difference in behaviour. For IL3 and 4 the spread is limited to the width of the short side of the slab, and when the edges are reached spread can only occur in the one remaining direction, which explains the steady burning phase observed. In IL1 and 2, this limitation is not as pronounced, and the spread is “free” to move in multiple directions simultaneously which accounts for the higher HRR and FSRs observed.

Comparing the HRR results (with the delay of approximately 17 seconds travel time for the HRR measurement taken into consideration) and the backside TC measurements in Figures 15 and 16, it can also be observed that the “hot zone areas” (where the TC measurement has risen significantly) are similarly sized at the approximate time of peak HRR for IL1-2 and IL3-4. These are further indications highlighting the two different types of behaviour. These figures also suggest that within these two “classifications,” the ignition locations may be less important. This could lead to a decision for future testing that only one location from each behaviour class (eg, class 1: IL1-2 and class 2: IL3-4) may be sufficient to account for the potential effects of ignition locations on a fire scenario. This may be useful information for both fire scientist planning experiments and for fire safety engineers (FSEs) that may need to consider a fire scenario with a similar fuel source. In this case, FSEs may take a fire curve from each class to better cover the potential effects of that type of fuel source rather than picking one curve arbitrarily. However, it should be noted, that these results are only for one type of geometry, and much more remains to be studied, including the influence of “free vector space,” that is, “the allowable space for flames to

**FIGURE 8** Temperature evolution of backside TCs for IL4 (ID: NEc) mapped on the foam slabs geometric proportions over time (red in the top left sub-figure represents the point of ignition, time evolution goes left to right, and top to bottom) [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 9** Legend on next page.
spread/move into” on different geometries before anything more generalised can be suggested.

When compared with previous results, for example, Poulsen and Bwalya19 who tested foam slabs with the same x, y dimensions but thicker (200 mm). Peak HRR for the free burn was 498 kW which increased to 965 kW when placed in a mineral wool insulated room. FSRs for the free burning slabs were 8 mm/s (mean) and 12 mm/s in a room enclosure.

Pau20 tested 100 mm and 120 mm thick slabs with x-y dimensions of 1000 mm and 2000 mm. They were ignited only from one side location with a line burner. Peak HRRs were approximately 700 kW and 750 kW for the different thicknesses. A similar method to determine FSRs is used, however in Pau’s case, thermocouples were deployed on the top surface of the foam slabs and a given temperature (222°C) is chosen as the point that determines the arrival of the pyrolysis front. Thermocouples were laid out in four rows along
the top surface of the slab, hence, FSRs were only measured in one lateral direction (from the side of the ignitor to the opposite side of the foam slab). Pau's results show an exponential trend with increasing FSRs as it travelled over the surface of the foam slab. Maximum rates calculated were 12 and 26 mm/s for the 100 and 120 mm slabs. Mean rates were calculated to be 4 to 5 mm/s and 12 mm/s respectively. These are mostly higher than the values obtained in this study, however, one obvious difference (besides the material itself) that may account for part of this is the ignition source. Ignition in this study was performed by a small flame ignition (refer Section 4.4), whereas in Pau's case a burner the length of the foam slab side was used. This means much more of the foam is ignited in the beginning and thus the HRR and FSR will not have as long a ramp-up time and the flames only have one direction (along with the slab) to travel, both which may increase the spread rates.

Using the FSR maps (Figures 10-14), it can be observed that the highest FSRs tend to be observed not far removed from the point of ignition. This is different to, for example, Pau's outcomes that showed an increase over time. Part of this is likely explained by the differences in the ignition source and measurement methods, however for IL3—which is the test set that is closest to the work of Pau, this trend is not observed and a similar increase as in Pau's research is also observed, however less pronounced.

In Ezinwa’s doctoral thesis (and related publications) infrared cameras were used to determine the flame front for the rate calculations. For “edge ignition tests” an average of approximately 3.6 mm/s was calculated and for “centre ignition tests” this ranged from 2.9 to 4.0 mm/s. However, dimensions also differed for the various tests. Vertical spread, that is, collapse rate was calculated to be 1.76 mm/s, which is much higher than those determined by both Kramer et al and Livkiss et al who determined the rates to be dependent on heat flux/temperature but only within the range for 0 to 0.8 mm/s. However, using the correlation outlined in Livkiss et al., this collapse rate would equate to an exposure temperature of approximately 455°C which is well within the temperature ranges observed on the foam slab in the thermography images contained in the thesis. Interesting, this is also in the range of the observed maximum temperatures for the backside TCs in this study and 400°C to 450°C is the range at when the polyol component of the FPUF pyrolyses. This is the second stage reaction after the TDI has volatilised and the foam structure has collapsed. This suggests that a temperature of between 400°C and 500°C may be the maximum temperature any part of the “solid” foam slab can achieve before it is volatilised. Hence, any TC located in the foam, will not achieve a higher temperature unless it “sees” direct flame impingement.
As shown in the examples of previous studies, much variation can be observed between the different studies. With mean FSRs ranging from approximately 3.5 mm/s up to 12 mm/s. Results from the current study are somewhat in line with previous results, however, it is hard to compare results directly as the measurement methods, test conditions and the type of foam vary significantly. It should also be noted that using the mean FSR over the surface of the slab to compare studies is not ideal, as the information highlighted by the variation observed over the surface of the slab, can be lost by using a mean value. In this study's results, for IL1 and 2 a much higher variation can be observed, whereas IL3 and 4 the FSR is much more constant, however looking at the mean values hides much of these differences. Using mean and SD may also not be appropriate and this assumes a normal distribution of values over the surface of the slab, however, this is likely not a correct assumption. Differences may be better resolved by observing something like the range of values over the surface for each ignition location (i.e., the maximum value minus the minimum value for FSR over the surface), this is highlighted in
Table 6 which compares average values of the mean FSR vs the average values of FSR range for repeated tests. The FSR range shows a much clearer distinction between the two types of behaviour observed between IL1 and 2 and IL3 and 4.

The technique used for obtaining the FSRs, although seemingly quite reliable and robust, will likely only work for materials similar in nature to the FPUF used. As it relies on the material insulating well at the beginning and then having a type of failure that will allow of a sharp rise in temperature to be recorded. Typically for this type of material, that may be the structural collapse that is commonly observed in the study of FPUFs. The implications of using the back-side temperatures and equating it to surface FSR also needs to be considered in the use of this data, as the spread rate recorded in this study may more correctly be named the structural collapse spread rate, it is assumed that they can be considered as equal in this study for simplicity.

**FIGURE 13** Flame spread rates over the FPUF slab (in mm/s) for IL4 (two tests in total in order: NEC1, NEC2) [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 14** Flame spread rates over the FPUF slab (in mm/s) for IL5 (one test in total NEQc1) [Colour figure can be viewed at wileyonlinelibrary.com]
The total energy release for each test was consistent for all the tests giving values between 20 and 21 MJ. Mass loss rates, smoke production etc., although recorded are not discussed further. Thus, relationships with these parameters have not yet been examined.

### TABLE 5 Flame spread rate values for each scenario

| Test ID | Ignition location | Mean flame spread rate (FSR) (mm/s) | Max FSR (mm/s) | Min FSR (mm/s) | FSR range (mm/s) |
|---------|-------------------|-------------------------------------|----------------|----------------|------------------|
| Ee1     | 1                 | 6.4                                 | 10.0           | 3.5            | 6.5              |
| Ne1     | 3                 | 3.3                                 | 3.8            | 2.5            | 1.3              |
| C1      | 2                 | 4.1                                 | 6.7            | 2.5            | 4.8              |
| NEc1    | 4                 | 4.5                                 | 5.6            | 2.7            | 2.9              |
| Ne2     | 3                 | 3.7                                 | 4.3            | 2.5            | 1.8              |
| Ee2     | 1                 | 5.1                                 | 7.9            | 3.3            | 4.6              |
| NEc2    | 4                 | 4.8                                 | 6.1            | 3.3            | 2.8              |
| NEQc1   | 5                 | 4.5                                 | 8.6            | 3.2            | 5.3              |
| Ne3     | 3                 | 4.3                                 | 6.7\textsuperscript{a} | 2.0            | 4.7              |
| C2      | 2                 | 4.8                                 | 11.1\textsuperscript{a} | 2.5            | 8.7              |
| Ee3     | 1                 | 4.2                                 | 7.1            | 2.5            | 4.6              |

\textsuperscript{a}Possible outlier due to location.

### FIGURE 15 HRR + repeats (top) and backside TC measurements at approximate peak HRR (bottom) for ignition locations (IL) 1 and 2 [Colour figure can be viewed at wileyonlinelibrary.com]

7 | CONCLUSION

This study presented the results from a set of 11 large-scale open fire tests performed on FPUF slabs. The purpose of the study was to investigate the influence of the ignition location on the fire behaviour of the foam slabs, and to generate a set of large-scale test data on a highly characterised material that could be used for modelling work in the future, readers are referred to the authors other publications\textsuperscript{9,10} and especially the work of Bustamante\textsuperscript{8} on FPUF from the same supplier. These characterise the material at the level required for both thermal and pyrolysis models to be used. A method for obtaining spatially resolved flame spread data for this type of material was presented using a gridded array of 5 \times 10 thermocouples (50 in total) placed on the underside the foam slab.

The HRR results showed clear shapes forming that were dependent on the ignition location. With two distinct behaviours being observed between ignition locations IL1-2 and IL3-4, with IL5 appearing to be a combination of the two. This was also observed in the FSR data. Considerable variation in the peak HRR values was observed for the repeat tests, however, variation arising from the change in
The ignition location was more significant. Flame spread was examined using three different approaches: geometric flame spread visualisation—which simply mapped the TC measurements on the geometry of the foam slab over time, FSR maps—which visualised the spatially resolved calculated FSR at each TC point and global FSR values.

Results from the FSR calculations were somewhat in line with previous results, however, it is hard to compare results directly as the measurement methods and test conditions varied significantly, additionally, foam compositions were likely different. It was also noted that using the mean FSR over the surface of the slab to compare studies was not ideal, as information that can help to differentiate the burning behaviour of the samples can be lost. For IL1 and 2 a much higher variation was observed, whereas IL3 and 4 the FSR is more constant. Using the range of FSR values calculated over the surface of the slab showed a much clearer distinction between the two types of behaviour observed and is suggested as a better method to compare results.

The developed FSR measurement method in this study meant that FSRs could be easily visualised, and the results mapped to show significant variation in both the individual tests (FSRs changing throughout the fire development) and due to changes in ignition location. Within an individual test, the calculated range of FSRs at different positions over the slab varied between approximately 1 and 8 mm/s depending on the ignition location. The average FSR values (ie, averaged over the whole slab) varied between 3 and 7 mm/s depending on the ignition location. The maximum value was calculated to be approx. 11 mm/s and the minimum value approximately 2 mm/s over the whole test series. A relationship between peak HRR and FSR values was explored and shown to tentatively exist, however further data is required to confirm the results obtained herein.

Future work within this area of study could be to investigate the effects of different slab geometry, the impact the external environment, for example, walls, or enclosures, may have on the FSR mechanics and the effects of adding additional fabric material layers or fire retardants.

**TABLE 6** Mean FSR vs FSR range

| Ignition location | Mean FSR (mm/s) | FSR range (mm/s) |
|-------------------|----------------|-----------------|
| 1                 | 5.3<sup>c</sup> | 5.2<sup>c</sup> |
| 2                 | 4.5<sup>b</sup> | 6.4<sup>b</sup> |
| 3                 | 3.8<sup>c</sup> | 1.5<sup>c</sup> |
| 4                 | 4.6<sup>b</sup> | 2.8<sup>b</sup> |
| 5                 | 4.5<sup>a</sup> | 5.3<sup>a</sup> |

<sup>a</sup>Average of 1 value.
<sup>b</sup>Average of 2 values.
<sup>c</sup>Average of 3 values.

**FIGURE 16** HRR + repeats (top) and backside TC measurements at approximate peak HRR (bottom) for ignition locations (IL) 3 and 4 [Colour figure can be viewed at wileyonlinelibrary.com]
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