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Structural fire engineering: realistic 'travelling fires' in large office compartments

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The speed a fire develops in large open-plan office compartments >150m2 is reasonably well understood by experienced firefighters. Such fires will not conform to typical flashover fire spread rates commonly observed in smaller compartments, but will be seen to travel at a far slower pace across open-plan office floors. It has recently been suggested that this reduced rate of fire spread may have some alternative impacts on structural heat transfer to those provided in the Eurocode and as such, is now beginning to have greater influence on modern design parameters. We already have some very tall buildings on our skylines where fire resistance provisions have been analysed in a way to account for travelling fire methodology, but it is perhaps both prudent and relevant that previous real fire experience is also researched more closely by design engineers in order to establish some wider validation and provide more confidence in such an approach.

Under the expert guidance of Professor Guillermo Rein and Dr Adam Sadowski (Imperial College) and guest speaker Dr Panos Kotsovinos (Arup), I was fortunate enough to take part in the 2018 MSc Module on Structural Fire Engineering based at Imperial College London, where serving fire safety and senior operational officers are more than encouraged to gain some invaluable experience.

The nine-week module begins with an introduction to fire dynamics and fire spread followed by an investigation into the heat transfer mechanisms of conduction, convection and radiation. The mechanical and thermal properties of steel and concrete at elevated temperatures are described, as are the effect of thermal strains on simple structural systems. The MSc module introduces students to both prescriptive and performance-based design according to the Eurocode, concluding with an advanced computational design project using ABAQUS.

The relevance of this teaching is to develop a greater awareness and understanding amongst structural engineers in how fire may spread horizontally in various ways throughout enclosures and by vertical extension to involve multi-floor levels. Then, most importantly, detailing how heat transfer analyses into key structural elements are undertaken across the building frame so that buildings involved in fire can be most effectively protected from disproportionate collapse whilst under fire attack. That is protected for a reasonable period of time to enable occupants to escape and/or firefighters to undertake effective firefighting intervention and rescue. This creates a speciality role for the structural fire engineer, where prescriptive design codes might be considered inapplicable for the design of large, complex or tall structures.

As an introductory 'taster' session to the MSc module, Professor Rein introduced some of the most recent academic research undertaken by Rein and his students[1] (based on their earlier research published in 2011[2]) describing travelling fire spread in large open-plan office buildings. Other research into travelling fires undertaken by the University of Edinburgh has also been recently published[3]. It has long been known by the fire service, but more recently acknowledged by academics, that fires in large office compartments (>150 m^2) take a much longer period of time than an instantaneous fully developed flashover fire before flaming combustion reaches the furthest wall or area. In effect the fire 'travels' across the surfaces of the fuel load at a specific rate of spread, determined by various fuel configurations, compartment geometry/layout and ventilation factors. This specific form of fire development has been noted by Rein's students to form two distinct zones:

(a) the near field and, (b) the far field. The far field model represents smoke temperatures, which decrease with distance from the near field (steady-state fire zone) due to mixing with air. Most importantly from a structural engineer's viewpoint, this has quantitative impacts on the amount and duration of heat transfer taking place in the structural elements that may alter the current knowledge base concerning structural stability in fire. Not only is there likely to be direct heat transfer into the structural frame as the fire burns at its peak of intensity, but additional heat transfer will occur in the far field zones for extended periods of time. This combination of pre-heating (far field), maximum heat transfer (near field) and cooling phase (far field) is something that does not appear to have been effectively addressed in structural fire design until most recently. Current design standards (e.g. Eurocodes) do not account for such fires. The standard fire and parametric time – temperature curves – are based on small scale tests (<100m^2) and assume uniform burning of fire and homogeneous temperature distributions in the compartment. As a result, many structural fire engineers are now incorporating the travelling fire methodology into their design of large open-plan office buildings where it may have greater impacts on the structural frame and the firefighting operation itself. This new travelling fire methodology has already found its way into the design of some very tall buildings in the centre of London.

Fire Spread Rates

The transitional event of flashover may be defined in various ways, but in general: ‘In a compartment fire there may come a stage where the total thermal radiation from the fire plume, hot gases and hot compartment boundaries (ceilings and walls) causes the radiative ignition of all exposed combustible surfaces within the compartment. Where the compartment is adequately ventilated, this sudden and sustained transition of a growing fire to a fully developed fire is known as a flashover’[4]. Such fires generally proceed to burn in a ventilation-controlled steady state, with flaming combustion occurring outside the vent opening (window) and to some varying extent, within the compartment itself.

Typically, the concept of ‘flashover’ cannot occur in its most traditional sense in fire compartments greater than approximately 150 m^2 floor area. In real terms, any determination made of ceiling temperatures >500°C in large compartments, using Alpert’s method of calculating ceiling jet flows[5] (for example), are only ever a measure of temperature in the hot gas layer and the event of flashover cannot ever be assumed to have occurred under such circumstances. Hot gas layers >500°C in residential sized compartments (<150m^2) are known to travel across the ceiling at speeds of 2 – 6 m/s dependent on ventilation configurations[6], whereas flaming combustion during flashover travels at a greater rate exceeding 8 m/s. In the Cherry Road (USA) fire simulation[7], after a basement sliding glass door was opened, leading to a ventilation induced flashover, the temperatures within the stairway exceeded 820°C with a gas velocity of approximately 8 m/s (18 mph).

The three firefighters badly burned in this fire were positioned on the upper level in the living room in front of the open doorway of the stairway to the basement. The temperatures in the hot gas flow-path in the upper half of the room remained at approximately 820°C as it exited the basement stairs. In the lower half of the living room, the temperatures ranged from approximately 180 to 580°C. In this case temperatures near the ceiling are far greater than 500°C. There have been several research studies undertaken around the world involving fire tests in large compartments, where it was demonstrated by fire engineers how fires are likely to travel at a predictable rate of spread that is somewhat slower than the sudden and sustained burning of a flashover occurring throughout the entire compartment at once. However, ‘real fires’ have been observed to travel across office floor space at varying rates, but the existing published test data appears to underestimate known realistic spread rates. It is therefore important that research test results are effectively compared or validated by real fire spread estimations as observed using CCTV, live video footage and by compiling firefighters’ statements at the time of these fires.

In the fire at the Interstate Bank in Los Angeles in 1988 the hot gas/smoke layer (not flaming combustion) travelled at an average speed of 475 mm/s (0.475 m/s) across the ceiling[8], as it eventually actuated all the smoke detectors on the 12th floor within 300 seconds. At the same incident the author’s research suggested that actual fire spread through the 1,625 m^2 compartment was travelling at an estimated rate of 36mm/s, in comparison. This is far short of the calculated flashover speed of 8,000 mm/s at the Cherry Road fire (mentioned above). In fact, to achieve typical ‘flashover’ gas layer velocities, the fire at the Interstate Bank would need to have travelled across and around the entire 12th floor-plate within less than 18 seconds. This fire actually took 66 minutes to ‘wrap’ around and fully involve the 1,625 m^2 office space at the 12th floor.

The author has attended the post-fire scenes of several referenced incidents in both the UK and USA during the period 1979 – 2004 and interviewed firefighters, fire commanders and relevant witnesses who were able to offer testimony as to how the fires spread to involve entire floor spaces over established periods of time. A privileged review of fire service-related documents, on-scene video/cctv and timed command reports enabled a clear picture of how quickly such fires spread and the times taken to reach specific parts of the floor space in each case. What became clear was that open-plan office fires were generally spreading to a point beyond the fire service's ability to intervene quickly enough and intervention times of 12-15 minutes (time to water on fire from point of first detection) were not quick enough to take control of the true rate of fire spread. In each case, the fires eventually spread vertically to involve several floors above the point of origin.

Typical travelling fire spread rates (mm/second) currently reported in the referenced literature:

- 2 mm/s (wood cribs in the open);
- 1.5 – 19.3 mm/s (research test fires);
- 2.5 – 16.7 mm/s (reconstruction of World Trade Center fires);
- 7.5 – 13mm/s (St. Lawrence Burns tests 1958)
- 14.5mm/s Interstate Bank fire Los Angeles 1988 noted by Clifton.
- 8.3 to 16.6mm/s assumed by Clifton for slow and fast fire spread fires respectively, based on the results of full-scale fire tests;
- 1.6 – 15 mm/s in SiFBuilder, computer model used by University of Edinburgh researchers.

Therefore, typical maximum fire spread rates for fires in enclosures of just 19.3 mm/s have so far been recommended for use in traveling fire design models.

When we talk of 'real fire' spread rates we must acknowledge that the lack of scientific data from compartment thermocouples and measured energy release rates means we are only able to estimate within a reasonable level of accuracy, just how quickly any fire spreads across space. It is clear though that realistic fire spread does not always follow a straight-line pattern of burn across the floor, but rather spreads according to venting configurations in heading towards windows as they fail and then heading back deeper into the compartment. This can create 'zig zag' or multi-directional cell-based patterns of fire spread. Therefore, from a firefighting perspective in particular, when estimating optimum firefighting intervention times and establishing minimum firefighting water requirements, it may seem more appropriate to measure the rate of spread according to an area based m^2/min. However, from a structural engineering perspective the fire spread rate along a direct path or route can still be approached using the mm/s measure.

The author's own travelling fire research and on-scene interviews included large open-plan office fires

Estimated Building Fire Spread Rates (Grimwood)
According to on-scene command reports, videos, CCTV and fire timed messages

Interstate Bank fire Los Angeles 1988 12th floor 1,625 m^2 surrounding a 511 m^2 central core 100 per cent fire involvement Fire spread to involve four more upper floors	24.6 m^2/min	36 mm/s Fire took 66 minutes to travel 142.4 metres (average length of fire zone around a central core) Note: if using the external wall of the compartment the spread rate would be close to 48 mm/s, but the average (central line of measure) is taken as above	This rate of fire spread would reach the limits of suppressive capability of a 550 L/min hose-line within 4-5 minutes; or a 750 L/min hose-line within 7-8 minutes of beginning a fire growth-curve.
CCAB 67 West Washington fire Chicago 2004 12th floor – 264 m^2 (230 m^2 fire area) 24 x 11m 87 per cent fire involvement (two end rooms not damaged)	15.3 m^2/min Slower area-based fire spread in comparison, caused by a cellular non-FR office on one side of open-plan area	27 mm/s Fire took 15 minutes to travel 24 metres	This rate of fire spread would reach the limits of suppressive capability of a 550 L/min hose-line within 7-8 minutes; or a 750 L/min hose-line within 10-11 minutes of beginning a fire growth-curve.
Telstar House fire London 2004 7th floor 80 x 14m 1,120 m^2 100 per cent fire involvement Fire spread to involve four more upper floors	24.3 m2/min	29 mm/s Fire took 46 minutes to travel 80 metres	This rate of fire spread would reach the limits of suppressive capability of a 550 L/min hose-line within 4-5 minutes; or a 750 L/min hose-line within 7-8 minutes of beginning a fire growth-curve.
Churchill Plaza fire Basingstoke 1991 8th Floor 1,673 m^2 100 per cent fire involvement Fire spread to involve two more upper floors	Undetermined - Fire was under-ventilated for over an hour prior to self-venting and subsequently being heavily wind driven under a fuel controlled burning regime	Undetermined - Fire was under-ventilated for over an hour prior to self-venting and subsequently being heavily wind driven under a fuel controlled burning regime	N/A

Table 1: Firefighting intervention times and adequate firefighting water estimations for travelling fires in offices

such as the Interstate Bank fire in Los Angeles in 1988, where fire spread through five floors of a 62-storey steel framed building; Telstar House in London where fire spread through five floors of a 12-storey building; Churchill Plaza (Basingstoke UK) in 1991 where floors 8-10 of a 12-storey steel framed building, constructed in 1988, were badly damaged by fire. In 2003, a fire occurred in a Chicago office tower where six people died. The author's direct involvement as a fire investigator on this fire enabled further research into the travelling fire concept, where the fire was known to spread through a 230 m^2 open-plan office area, taking 15 minutes to travel the 24 metres to the furthest wall from an original point of origin.

The fire spread rates (opposite) in open-plan office fires demonstrate that once a fire reaches the beginning of its growth curve, generally acknowledged as the point when flaming combustion has reached one metre in height, the potential for an effective firefighting intervention relies on several factors. These include;

- The existence of active fire suppression systems
- Effective compartmentation and quality in construction to prevent hidden fire spread;
- Rapid response and deployment of firefighters with good access to the fire compartment;
- Adequate firefighting water available in the rising mains and at the nozzle to counter the energy being released from the involved fuel load at the time of first water (on fire)

Experience has shown that once a ventilated fire reaches an intensity level of 20-30 MW in the rate of heat release (around 100 – 200 m^2 of office floor area), the fire will enter a travelling fire mode and controlling any further fire spread will likely be beyond the capability of a single hose-line flowing 500 - 750 L/min. In real terms, this means that travelling fire spread rates of 15 – 20 m2/min may be beyond the suppressive capacity for a single hose-line within around seven to ten minutes from point of detection/start of fire growth curve. Combine this with typical fire service response and deployment times and it is clear that firefighters are likely to be playing catch-up with the fire as it continues to escalate faster than additional hose-lines can be laid in, particularly if the heavy stream from an external water tower is not a viable or immediate option.

Travelling Fire - Firefighting Intervention and Adequate Firefighting Water

How much water is considered 'adequate'? In general, firefighters will apply firefighting water into an enclosed fire compartment using a combination of spray and solid stream in direct attack at the fuel base. According to Grimwood[9] (Eq.1), the heat absorption of firefighting water applied at 1 Litre/second = 2.46 MW per L/s – (0.407 L/s/per MW at peak HRR) or; 24.42 L/min per MW of Qmax (the point of peak heat release) is required to achieve control and suppression of building fires, which closely correlates with Barnett's calculation of 23 L/min/MW. Further correlations are seen with the author's PhD research into the practical need for adequate firefighting water at 5,401 working building fires in the UK, 2009-2012.

MW (heat absorption of a hose-line)
$= (W_{gas}\ E_{gas}\ 3.3\ \dot{f}\ 0.15)+(W_{fuel}\ E_{fuel}\ \dot{f}\ 0.35)$ Eq.1

Where

W_{gas} = Percentage of water applied into the gas phase (36%) based on live tests

W_{fuel} = Percentage of water applied into the fuel phase (64%) based on live tests

E_{fuel} = An energy input of 2.6 MJ/kg is required to vaporise 1 kg of water at 100°C when applied onto the fuel-phase

E_{gas} = An energy input of 3.6 MJ/kg is required to transform 1 kg of water at 100°C to steam at 600°C when applied into the gas-phase – If water were applied into a 3000C gas layer as opposed to 600°C, according to the above calculations a lesser energy input of 3.4 MJ is needed. The heat absorption capacity would then be just 3.4 MW.

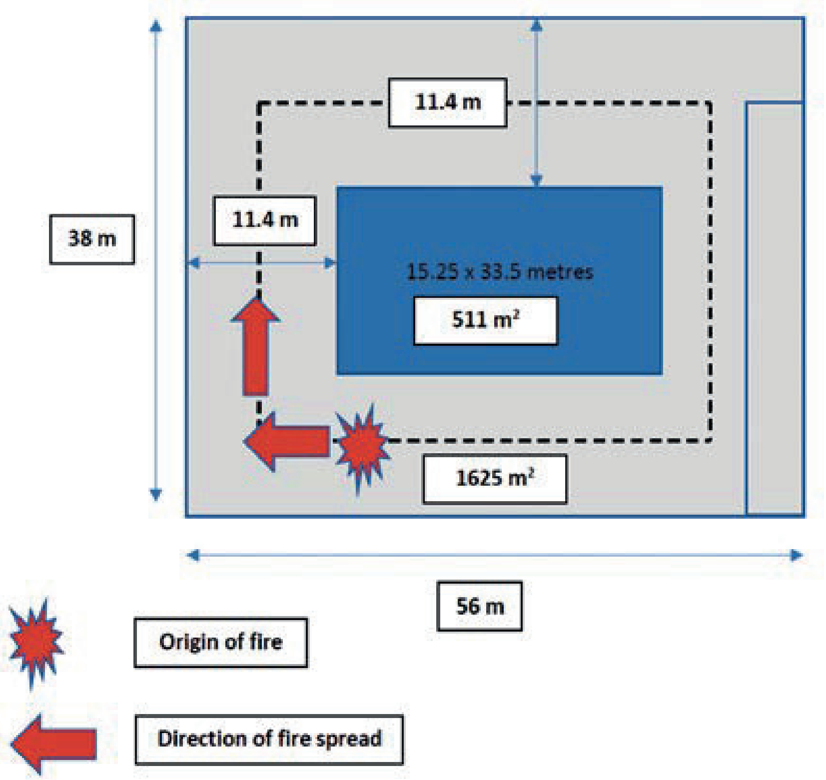
3.3 = An efficiency factor based on the Rasbash 'fire-point' theory

0.15 = The practical efficiency factor of water applied in the gas phase
0.35 = The practical efficiency factor of water applied in the fuel phase
} 50% Total efficiency[10]

∫ = The quantity of water applied into the fuel or gas phase in Litres/sec.

Equation 1 is calculated as follows:
Flame Suppression
(36%[11]) 0.36 x 3.6 x 3.3 x 1 x 0.15 = 0.64 MW
Fuel Base Cooling
(64%[12]) 0.64 x 2.6 x 1 x 0.35 = 0.58 MW
Total = 1.22 MW
Qs = 1.22 / 0.5(kF)
= 2.44 MW per L/s
= 1 / 2.44
= 0.41 L/s/MW

Note: Qs = the heat absorption capacity (MW) of the water used directly on the fire
Kf = the combustion efficiency taken as 0.5 (50 percent efficiency)



The 12th Floor – Interstate Bank Fire Los Angeles 1988

Example One:
19mm HP Hose-reel tubing x 54m applying water at 1.83 L/s (110 L/min)
Flame suppression 0.36% x 3.6 MJ/kg x 3.3 x 1.83 L/s x 0.15 = 1.17 MW
Fuel base cooling 0.64% x 2.6 MJ/kg x 1.83 L/s x 0.35 = 1.07 MW
Total = 2.24 MW
Qs = 2.24/0.5(k_F)

Maximum heat absorption capacity = 4.48 MW

Example Two:
Smooth-bore 22mm nozzle applying water at 9.16 L/s
Flame suppression 0.36% x 3.6 MJ/kg x 3.3 x 9.16 L/s x 0.15 = 5.9 MW
Fuel base cooling 0.64% x 2.6 MJ/kg x 9.16 L/s x 0.35 = 5.33 MW
Total = 11.23 MW
Qs = 11.23/0.5(k_F)

Maximum heat absorption capacity = 22.5 MW

So, 2.44 MW per L/s suggests that for each 60 Litres/minute applied, 2.46 MW of energy release may be absorbed but, where the firefighter's water application efficiency is only 50% (this is an expected average based on test data) then only 1.23 MW is realistically cooled for the same flow. Similarly, where an involved fire load is releasing 20 MW of heat energy, a minimum water flow-rate of 20 x 0.41 x 60 = 492 L/min is needed to achieve effective cooling.

In a travelling fire situation, the fire spread rate that might be applied to open-plan offices > 150m^2 with ceiling heights to 3.5m FFL (2.5 - 3m suspended) should perhaps, more realistically, be 30mm/s (structural fire engineering) or 25m^2/min (firefighting intervention). This rate of fire spread is reflective of the ability for firefighters to deploy an adequate amount of water onto a growing (travelling) fire in a large office space in a timed intervention. This will enable the fire service and fire engineers to estimate with some greater accuracy, at what point in time following the start of a fire growth curve an effective firefighting/rescue intervention is likely to become over powered by travelling fire development. A more accurate estimate for heat transfer into structural elements in the near field and far field may also be considered by structural fire engineers.

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