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Travelling Fires for Structural Design Part I: Literature Review

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Abstract

Close inspection of accidental fires in large, open-plan compartments reveals that they do not burn simultaneously throughout the whole enclosure. Instead, these fires tend to move across floor plates as flames spread, burning over a limited area at any one time. These fires have been labelled "travelling fires". Current structural fire design methods do not account for these types of fires. Despite these observations, fire scenarios most commonly used for the structural design of modern buildings are based on traditional methods that assume uniform burning and homogenous temperature conditions throughout a compartment, regardless of its size.

This paper is Part I of a two part article and is a literature review of travelling fire research. A brief background to the traditional methods that assume uniform fires is given along with critiques of that assumption, such as the heterogeneity of compartment temperatures and the observation of travelling fires in both accidental events and controlled tests. The research in travelling fires is reviewed, highlighting the pioneering work in the field to date. The main challenge in developing tools for incorporating travelling fires into design is the lack of large scale test data. Nonetheless, significant progress in the field has been made and a robust methodology using travelling fires to characterise the thermal environment for structural analysis has been developed. The research in quantifying the structural response to travelling fires is also reviewed.

Keywords: travelling fires, structures and fire, design fires, building fire safety

1.1 Introduction

Close inspection of accidental fires in large, open-plan compartments reveals that they do not burn simultaneously throughout the whole enclosure. Instead, these fires tend to move across floor plates as flames spread, burning over a limited area at any one time. These fires have been labelled "travelling fires".

Despite these observations, fire scenarios most commonly used for the structural design of modern buildings are based on traditional methods that assume uniform burning and homogenous temperature conditions throughout a compartment, regardless of its size. These two assumptions are at the root of many of the existing methods' limitations, as applied to large compartments, and have never been confirmed experimentally. Developing methods to enhance optimisation of structural fire design, by obtaining a more accurate characterisation of actual building performance, requires a more realistic definition of potential fire scenarios. Specifically, incorporation of travelling fires will be necessary to reflect the state-of-the-art knowledge of fire dynamics in large spaces.

This paper reviews research focused on travelling fires in structural analysis. It highlights the recent historical developments as well as current uses. The paper examines both the definition of the thermal environment as well as structural analyses based on travelling fires.

1.2 Traditional Design Methods

The earliest attempts of fire testing to understand structural performance in fire led to the standard temperature-time curve, first published in 1917 [1]. This curve and associated test methods given in standards, such as BS 476, ISO 834, and ASTM E119, have formed the basis for the fire rating systems in most building codes and standards worldwide. The curve came from collating various fire tests into one idealised curve. The tests that fed into the

development of the standard fire were intended to represent worst case fires in enclosures to determine if the structure could withstand burnout. However, these tests were conducted and the standard fire created prior to much scientific understanding of fire dynamics. Thus the standard fire, unlike a real fire, has a relatively slow growth rate, never reduces in temperature due to fire decay, and is independent of building characteristics such as geometry, ventilation and fuel load [1, 2, 3]. More recently Manzello et al. [4], have noted that the standard fire does not accurately reflect the nature of real fires that do not uniformly heating of building elements.

As fire science matured, models of post-flashover fire behaviour were developed to account for a better understanding of compartment fire dynamics based on tests conducted in small scale enclosures. Most of the theoretical models developed were based on the assumption of uniform compartment temperatures [5]. This is the case for both analytical models and zone models. Karlsson and Quintiere [6] note that this assumption, among others, is required for an analytical solution of the energy balance for the compartment. In particular they note that the methods of Magnusson and Thelandersson in 1970 [7] and Babrauskas and Williamson in 1978 [8] adopted this approach.

Pettersson et al. [9] developed a design guide, based on the work of Magnusson and Thelandersson [7], for specifying the thermal environment to be used for structural design. The guidance document provides a set of temperature-time curves for various compartment ventilation factors, fuel loads, and compartment linings. This work was further developed by Wickström [10] and became the basis for the Eurocode parametric temperature-time curve [11], which is a widely used method in structural fire engineering today.

While other methods exist [12, 13, 14, 15], they all assume homogeneous conditions, including uniform burning, throughout the fire compartment. Drysdale [2] notes that a justification of this assumption often used is that there is supposedly a small gradient in the vertical temperature distribution during a post-flashover fire and even smaller horizontal gradients. For example, a single test from 1975 is cited showing a nearly uniform vertical

temperature distribution at one moment at the onset of flashover. Section 1.3 of this paper presents critiques of this assumption.

While the traditional methods tend to look at full compartment involvement, other methods have been developed to look at localised fires [11, 16]. While only local in nature, these methods are relevant to travelling fires in that they characterise the conditions near the flames.

Eventhough this paper is predominately focused on travelling fires, it is important to note the relevant developments in the methods used to analyse the structure. Buchanan [17] and Law et al. [18] provide concise histories of this development. What is of relevance to this review is the move from solely analysing single elements to that of whole frame behaviour, which was largely driven by specific accidental fires and large scale testing at Cardington. Travelling fires, which provide highly non-uniform and transient heating in time over the full length of a large compartment, may have a considerable impact on whole frame structural behaviour.

1.3 Limitations of the Uniform Burning Assumption

As noted in Section 1.2, the traditional design methods for specifying the thermal environment for structural analysis are based on an assumption of uniform burning and temperature conditions. Stern-Gottfried et al. [19] have reviewed this assumption by analysis of existing experimental data from well-instrumented fire tests. Results show that dispersion from the spatial compartment average is significant and that the assumption of uniform temperature conditions does not hold well. While this review was conducted for relatively small enclosures, the findings are likely to be more relevant for large enclosures. Furthermore, Buchanan [3] notes that post-flashover fires in open plan offices are unlikely to burn throughout the whole space at once.

It is worth noting that the traditional methods assume that worst case conditions are caused by ventilation controlled fires. However, a recent review by Majdalani and Torero [20] of

early CIB tests and the resulting analyses of compartment fire behaviour done by Philip Thomas and others highlights that ventilation controlled fires are unlikely in large enclosures and that they are not necessarily more conservative for structural analysis than fuel bed controlled fires. Majdalani and Torero note that while the different burning behaviour between ventilation and fuel bed controlled fires was clearly stated in the original studies, ventilation controlled fires have nonetheless been assumed to be the most severe case for design.

Although limited experimental data exist on fire spread and homogeneity in large enclosures, examination of specific tests and the study of accidental fires can provide insight into the fire dynamics of larger enclosures.

1.3.1 Evidence from Experiments

Kirby et al. [21] ran a test series burning wood cribs in a long enclosure with approximate dimensions of 22.9m x 5.6m x 2.8m. All of the tests were ignited at the rear of the compartment, except one in which all wood cribs were ignited simultaneously. The results of all tests showed that the fire moved relatively quickly from the ignition location to the front of the compartment, where the vent was located. After the fuel in the front of the compartment burnt out, the fire progressively travelled back into the compartment and ultimately consumed all of the fuel and self-extinguished at the rear. Temperature results at the rear, middle and front of the compartment of Test 1 from this series are shown Figure 1.1.

Thomas and Bennetts [22] conducted a test series of ethanol pool fires in a small rectangular enclosure (1.5m x 0.6m x 0.6m) to determine the influences of ventilation size and location on burning rate. They found that there were significant differences in burning rates between having the opening on the short end (long enclosure) or the long side (wide enclosure). They observed temperature differences across multiple locations of up to 500°C, generally with greater temperatures nearer the vents, as this is where the flames resided more often. This work was continued further [23] with another experimental series of pool fires in a larger, long enclosure (8m x 2m x 0.6m), in which the opening size on the short end was varied. The

results obtained were similar to both their earlier work [22] and that of Kirby et al. [21]. They conclude that a structural element near the vent would be exposed to more severe conditions than one further inside the compartment.

The well instrumented tests conducted at Dalmarnock [24] and Cardington [25] were shown to have large standard deviations (in excess of 200°C at times) within the temperature field [19]. Additionally, peak local temperatures in these tests were found to vary from 23% to 75% above the compartment spatial averages, and local minimums ranged from 29% to 99% below the averages.

All of the tests mentioned here show, even in relatively small scales, that fires travel and do not burn uniformly throughout the whole test enclosure.

1.3.2 Evidence from Accidental Fires

Accidental, large fires that have led to structural failure, such as those in the World Trade Center Towers 1, 2 [26] and 7 [27] in September 2001, the Windsor Tower in Madrid, Spain in February 2005 [28] and the Faculty of Architecture building at TU Delft in the Netherlands in May 2008 [29] were all observed to travel across floor plates, and vertically between floors, rather than burn uniformly for their duration. Similar observations were made of the Interstate Bank fire in Los Angeles in 1988 [30] and the One Meridian Plaza fire in Philadelphia in 1991 [31]; although no structural failure is associated with these fires.

The travelling nature of the fire in Tower 2 at the World Trade Center is shown in Figure 1.2, which gives the recorded observations of the fire location and burning behaviour along the East Face [26]. It can be seen that the area of flaming shifts dramatically on the floors of fire involvement, both horizontally across floors as well as vertically between floors.

Other than the fires in Towers 1 and 2 of the World Trade Center, which ended at the time of building collapse, all of the incidents listed above lasted for many hours. The Interstate Bank fire was the shortest and lasted a little under four hours, at which point it was controlled by fire fighters. The One Meridian Plaza fire was the longest, which lasted for almost 19 hours

as it burnt from the 22nd to the 30th floor, where it was eventually controlled by a sprinkler system.

These fires, in addition to being visually observed as travelling, had durations that are well in excess of the time periods associated with the traditional design methods. This is primarily due to those methods assuming uniform burning on one floor only.

1.4 Pioneering Methods

To progress past the limitations of the traditional methods, it is necessary to develop engineering techniques that account for travelling fires. This section reviews the published methods utilising travelling fires.

1.4.1 Large Firecell Method – Hera New Zealand

As part of a long term research programme at HERA in New Zealand aimed at understanding the behaviour of complete steel frames exposed to fire, Clifton [32] produced a first of its kind report related to design using travelling fires. The report, entitled "Fire Models for Large Fire Cells" and referred to as the Large Firecell Method (LFM) in this paper, gave an approach to apply specific fire models to develop temperature-time relationships for travelling fires through a "firecell". By Clifton's definition, a firecell is essentially one compartment of a building. For example, an open plan office floor would be a single firecell.

Clifton acknowledged the challenges of developing this type of methodology. He stated that no such method existed before and that there was a "paucity of experimental data available", which required "a crude and simplistic approach to their development".

Therefore the model necessitated numerous assumptions regarding fire size, ventilation conditions, fire spread, fuel distribution and fuel type. Clifton applied two different fire models to generate temperature-time curves and created a set of rules on how these should be applied to "design areas" within the fire cell. Each design area of the firecell at any one

time could be classified as one of the following conditions: fire, preheat, smoke logged, or burned out. This is illustrated in Figure 1.3 at a fixed moment in time.

The temperature-time curves for the design areas were calculated by one of two models given, both for ventilation controlled fires. Temperatures for the preheat and delayed cooling (for after burnout) periods were taken to be between 200 and 675°C, depending on the type of construction used in the first version of the report and then subsequently modified to 400 to 800°C in the proposed changes to the document.

In the first version, Clifton set the size of each design area based on the fuel load density. He suggested 50m^2 for a fuel load under 500MJ/m^2, 100m^2 for fuel loads between 500 and 1000MJ/m^2, and 150m^2 for fuel loads greater than 1000MJ/m^2. This was modified to have the fire area be 50m^2 for all fuel loads in the proposed changes. Windows were assumed to break once the adjacent gas temperature reached 350°C. The rate of fire spread was based on the Kirby experiments [21] highlighted in Section 1.3.1 and was specified to be 1m/s for well ventilated conditions and 0.5m/s for less ventilation (as determined by the opening factor).

Combining all of the various inputs in the method gives temperature-time curves at any structural element. An example is shown in Figure 1.4.

Clifton noted that due to the assumptions needed, and the lack of experimental data, that the LFM should mostly function as a research tool and should only be used for single element checks in design.

Moss and Clifton [33] used the LFM in analysis of the large frame tests conducted at Cardington. However, they noted that this method, combined with detailed structural analyses led to results "that that appeared to be realistic," but "could not be related to any directly comparable experimental results". Further applications of this method are not readily apparent in the literature.

1.4.2 Travelling Fires Methodology – University of Edinburgh

The Travelling Fires Methodology (TFM), which has been developed independently from the LFM over the last few years, incorporates travelling fires for structural design. Full details of this method are given in Part II of this paper.

The TFM calculates the fire-induced thermal field such that it is physically-based, compatible with the subsequent structural analysis, and accounts for the fire dynamics relevant to the specific building being studied. In order to achieve this, a fire model is selected that provides the spatial and temporal evolution of the temperature field.

The fire-induced thermal field is divided in two regions: the near field and the far field. These regions are relative to the fire, which travels within the compartment, and therefore move with it. The near field is the burning region of the fire and where structural elements are exposed directly to flames and experience the most intense heating. The far field is the region remote from the flames where structural elements are exposed to hot combustion gases (the smoke layer) but experience less intense heating than from the flames. The near and far fields are illustrated in Figure 1.5.

Early work on the TFM by Rein et al. [34] used Computational Fluid Dynamics (CFD) to study both uniform and travelling fires in a multi-storey high rise building, with atria connecting groups of three floors into "villages". Later work by Stern-Gottfried et al. [35] simplified and refined the method for a single floor, utilising a ceiling jet correlation to generate far field temperatures. Jonsdottir et al. [36] took this updated version and examined resultant steel temperatures. Collaboration with structural fire engineers led to work [37] exploring the response of a generic concrete frame to travelling fires, including a detailed sensitivity study. Stern-Gottfried and Rein [Part II of this paper] then developed the methodology further by extending the examination of the concrete frame via simplified heat transfer and identified the critical parameters for applying the method to design.

The TFM does not assume a single, fixed fire scenario but rather accounts for a whole family of possible fires, ranging from small fires travelling across the floor plate for long durations with mostly low temperatures to large fires burning for short durations with high

temperatures. Using the family of fires enables the TFM to overcome the fact that the exact size of an accidental fire cannot be determined a priori. This range of fires allows identification of the most challenging heating scenarios for the structure to be used as input to the subsequent structural analysis.

Each fire in the family burns over a specific surface area, denoted as A_f, which is a percentage of the total floor area, A, of the building, ranging from 1% to 100%. Compared to this approach, the conventional methods only consider full size fires, which are analogous to the 100% fire size in the TFM. All other burning areas represent travelling fires of different sizes which are not considered in the conventional methods.

The TFM assumes that there is a uniform fuel load across the fire path and the fire will burn at a constant heat release per unit area typical of the building load under study. From this the total heat release rate can be calculated by Eq. (1.1).

$$\dot{Q} = A_f \dot{Q}'' \tag{1.1}$$

where $\dot{Q}$ is the total heat release of the fire (kW)

A_f is the floor area of the fire (m^2)

$\dot{Q}''$ is the heat release rate per unit area (MW/m^2)

Furthermore, the local burning time over the fire area can be calculated by Eq. (1.2).

$$t_b = \frac{q_f}{\dot{Q}''} \tag{1.2}$$

where t_b is the burning time (s)

q_f is the fuel load density (MJ/m^2)

Values typically used in the application of the TFM are $570MJ/m^2$ for the fuel load density and $500kW/m^2$ for the heat release rate per unit area. This leads to a characteristic burning time, t_b, of 19min. This time correlates well to the free-burning fire duration of domestic

furniture, which Walton and Thomas [38] note is about 20min. It is also in line with Harmathy's [39] observation that fully developed, well ventilated fires will normally last less than 30min.

Note that the burning time is independent of the burning area. Thus the 100% burning area and the 1% burning area will both consume all of the fuel over the specified area in the same time, t_b. However, a travelling fire moves from one burning area to the next so that the total burning duration across the floor plate is extended. This means that there is a longer total burning duration for smaller burning areas.

As noted above, the TFM splits the temperature field into two portions: the near field (flaming region) and the far field (hot gases away from the fire). In the case of the 100% burning area, all of the structure will experience near field (flame) conditions for the total burning duration (which is equal to the burning time, t_b). However, for the travelling fire cases, any one structural element will feel far field (smoke) conditions for the majority of the total burning duration and near field conditions for the burning time when the fire is local to the element. Therefore the TFM must quantify both the near field and far field temperatures.

The TFM assumes the near field is 1200°C to represent worst case conditions, as this is the upper bound of flame temperatures generally observed in compartment fires [2]. To calculate the far field temperatures in the TFM, an engineering tool must be selected and applied to each member of the family of fires developed. The TFM is modular in this aspect, as any calculation method that takes fire size and geometry as inputs and produces temperature as a function of distance from the fire may be used.

As stated above, the early work [34] used a CFD fire model to study the temperature field as a function of distance from the fire. As the case study for that work involved an atrium, a detailed three-dimensional model was needed. Indicative results from the case study are shown in Figure 1.6.

Later variations of the TFM [Part II, 35, 36, 37] focused on a simpler method to obtain far field temperatures by using a ceiling jet correlation developed by Alpert [40]. This correlation is given below in Eq. (1.3).

$$T_{max} - T_{\infty} = \frac{5.38\left(\dot{Q}/r\right)^{2/3}}{H} \tag{1.3}$$

where T_{max} is the maximum ceiling jet temperature (K)

T_{∞} is the ambient temperature (K)

r is the distance from the centre of the fire (m)

H is the floor to ceiling height (m)

Note that while Alpert gives a piecewise equation for maximum ceiling jet temperatures to describe the near field ($r/H \leq 0.18$) and far field ($r/H > 0.18$) temperatures, only the far field equation is used as the near field temperature is assumed to be the flame temperature in the TFM. Although it was acknowledged that the ceiling jet correlation does not fully characterise the fire dynamics of the scenarios selected, it provided sufficiently accurate results to progress the development of the TFM.

In order to limit the amount of information passed to the structural analysis, the first iteration of the TFM [34] only took a single far field temperature from a point away from the flaming region (see red lines showing indicative temperature in Figure 1.6). Later versions used a fourth power average of temperature for the far field in a bias towards radiative heat transfer [35, 36, 37]. However, in more recent work [Part II], this assumption has been relaxed and a spatially resolved temperature field that varies with distance from the fire is used. Instead, the compartment is divided into discreet nodes, each with their own temperature. Figure 1.7 shows the temperature-time curves developed at a single point for averaged and spatially resolved far field temperatures.

The TFM provides results of the full temperature field evolution over time, which can be used to examine particular structural elements or full frame behaviour. The fire travels at a velocity related to the size of the fire. These velocities vary from centimetres per minute for

small fires to metres per minute for large fires, which is a broader range than that used by Clifton in the LFM. While the TFM is not claiming to predict the flame spread rate, the range of fire sizes examined is deemed to cover the full extent of what is physically possible in an enclosure fire.

In the TFM when averaged far fields are used they can be plotted together and compared to examples of traditional methods. This is shown in Figure 1.8.

It can be seen from the results of the TFM that hotter far field temperatures last for less time than cooler ones. The standard fire and parametric fire curves are similar to the far field temperatures of travelling fires for sizes between 25% and 50% but do not account for the near field conditions like the TFM does. The results of the standard fire curve cannot be explained after one hour of burning in terms of the possible fire dynamics in large enclosures.

While a simple plot cannot be shown with single far field temperatures for the TFM with a resolved far field, the results can nevertheless be used for heat transfer and structural analysis. Their results are better compared to the traditional methods via the resulting structural performance, as shown for a single member of the family of fires in Figure 1.9.

The temperature fields generated from the TFM have been applied to both concrete and steel structures by means of heat transfer analyses [Part II, 36]. These analyses have looked at the temperature of either steel rebar within concrete or steel beams as a loose surrogate for structural performance. The results showed that travelling fires have a significant impact on the performance the structures examined and that conventional design approaches cannot automatically be assumed to be conservative. Medium sized fires between 10% and 25% of the floor area were found to be the most onerous for the structure. This is due to a balance of burning duration and far field temperatures.

Detailed sensitivity analyses of the input parameters of TFM have also been conducted [Part II, 37], showing that the structural design and fuel load have a larger impact on the

structural behaviour than any numerical or physical parameter required for the methodology.

1.5 Structural Response

In his plenary lecture at the IAFSS Symposium in 2008, Buchanan [17] stated:

> *The two disciplines of combustion science and structural engineering are miles apart, so two groups of experts will always be needed. For this reason it would be very foolish to rush towards coupling of fire models with structural models. Any such coupling would lead to a "black box" mentality with a major decrease in our ability to make accurate predictions of structural fire behaviour.*
>
> *Fire engineers and structural engineers need to talk to each other much more than they do now, and each group needs to learn as much as possible of the other discipline. These two topics are too big and too different for us to educate combined specialists in both disciplines.*

The comments made by Buchanan, and reinforced by Law et al. [18] highlight the need for close collaboration between the two disciplines. The TFM has been developed with such collaboration in mind [Part II, 34, 35, 36, 37].

This section reviews research involving detailed structural analysis of travelling fires.

1.5.1 Steel Frame

The first detailed analysis of structural behaviour in response to travelling fires was conducted by Bailey et al. [41]. This work, which was notably conducted prior to publication of Clifton's LFM and twelve years before Buchanan's call for multi-disciplinary collaboration, was pioneering in its recognition for the need to consider the structural impact of a more realistic fire environment than the conventional methods by examining travelling fires.

Bailey et al. extended use of a Finite Element Model (FEM) from previous research involving uniform fires to study a two-dimensional frame exposed to a spreading fire. The work began with a focus on the effect of the cooling phase of a fire on the structure. The authors then

note that incorporating the cooling phase allows consideration of "fires which spread progressively from an ignition point in a single compartment (or a zone within an open-plan area) to adjacent areas of the building". They go on to state:

> *The effect of a spreading fire is that both cooling and heating are taking place simultaneously in different zones. This is arguably a more typical condition than the assumption that the temperature changes uniformly throughout the fire-affected zone, and in view of the effects of restraint observed during cooling is one which requires investigation.*

The study compares the response of a two-dimensional bare steel frame exposed to a spreading fire with that of a uniform fire, over both three and five structural bays. The uniform fire was defined by a temperature-time curve representing a "natural" fire. The travelling fire was represented by the same natural fire curve, but offset in time for the bays of secondary fire involvement. Once the temperature-time curve in the first bay reached its peak, the fire was assumed to begin in the adjacent bays. Similarly, the bays of tertiary fire involvement were assumed to ignite when the temperature-time curve reached its peak in the secondary bays. The temperature-time curves used are shown in Figure 1.10.

While this method replicates the movement of elevated temperatures associated with travelling fires, the use of a temperature-time curve reproduced with a delay does not capture the actual fire dynamics of a travelling fire, as can be seen by the relevant details discussed in Sections 1.3 and 1.4 of this paper. The temperature-time curve used represents a ventilation controlled fire. However, a fire burning in only one bay of a structure nine bays wide is unlikely to be ventilation limited, especially in the early durations of the fire, as the air available from the rest of the structure will provide sufficient oxygen to keep it well ventilated. Additionally, local exposure to flame temperatures (near field conditions), and not just compartment average temperatures associated with the calculation methods of ventilation limited fires, are likely.

Furthermore, this method does not account for elevated smoke temperatures away from the fire. The temperature in a bay adjacent to the first one exposed remains ambient until its curve begins at 36min. Given that the bays are 8m in dimension, it is much more likely that temperatures in the adjacent bay would be well above ambient. This behaviour could be

explained if each bay were a fully enclosed, fire rated compartment that fails 36min into the fire, however this is not the scenario described by the authors.

Bailey et al. went on to examine the vertical displacements and axial forces in the beams of the structure. They found that higher beam displacements occur for the spreading fire cases than the uniform ones. The authors noted that these conclusions cannot be readily generalised and further study is required with different temperature-time curves and offset times.

1.5.2 Concrete Frame

Recently, Ellobody and Bailey [42] have conducted a study of the impact of horizontally travelling fires on a post-tensioned concrete floor. While this study utilises sophisticated structural analysis, including a three-dimensional FEM, the fire definition is very similar to that of Bailey et al. [41]. Specifically, a base temperature-time curve is applied to the first bay of heating and is shifted in time to provide the heating of bays that become subsequently involved in the fire. In this study, the base temperature-time curve was taken from Eurocode 1. Two time delays were examined; one of 64min and the other 30min.

The structural response was viewed in terms of tendon temperatures, deflections and axial displacements. These parameters were examined at several critical locations over time as well as in terms of their final residual values. Ellobody and Bailey noticed that the "change in heating/cooling scenarios between zones resulted in cyclic deflection patterns at some locations". They also found that the time delay used for shifting the temperature-time curve had an impact on the structural response and the worst case could result from a uniform heating or travelling fire case. The authors recommended that engineers consider a range of travelling fires for use in structural design to ensure the most onerous case is found.

Given a very similar method for thermal definition was used in this paper as Bailey et al. the same critiques of the that method apply; namely the inherent assumption of a ventilation limited fire in an open space and the lack of consideration of hot smoke away from the fire. In fact, the cyclic deflection patterns observed by Ellobody and Bailey may have resulted

from the lack of elevated far field temperatures. This is because in their analysis some elements would be exposed to ambient gas phase conditions while others to peak temperatures, when in reality the ambient exposure would more likely have been that of smoke temperatures on the order of several hundred degrees Celsius. A detailed investigation of the structure, following the same method as Ellobody and Bailey but with elevated far field temperatures, would need to be performed to determine if the cyclic deflection patterns are an actual phenomenon or not.

The work of Law et al. [37], a collaborative research project between the fire engineers Stern-Gottfried and Rein and structural engineers Law and Gillie, applied the TFM to a generic concrete frame. The temperature field was generated as explained in Section 1.4.2 and then applied to a FEM of the concrete frame.

The structural modelling results were examined in terms of rebar temperature, sagging tensile strain, hogging tensile strain, and deflections. The results for rebar temperature showed that fire sizes between 10% and 25% of the floor area produced the most onerous results for the structure. All of the more detailed structural metrics showed that the 25% fire size was most challenging for the structure. In all four metrics the travelling fires proved to be a worse case for the structure than the Eurocode parametric temperature-time curves. A detailed sensitivity study showed that variations in the far field definition and differing fire shapes and paths of travel had little impact on the results.

In his PhD thesis [43], Law further examined the structural behaviour resulting from travelling fires, using sectional and utilisation analyses. Generally he obtained similar results, but did notice that 5% to 10% fire areas gave the worst case results for the structure when using a utilisation analysis of all columns. The strength of the methods applied by Law is that data from numerous fires can be viewed cumulatively to get a better understanding of the behaviour of each column. This is well suited to analyse results from the TFM, which produces a family of fires.

1.5.3 Vertically Travelling Fires

Noting that large, accidental fires tend to involve multiple floors, Röben et al. [44] examined the impact of vertically travelling fires on a multi-storey structure. The building they examined was used in previous work by the authors to understand the effect of the cooling phase on structural performance and had a concrete core and a steel-concrete composite floor system.

The study assumed three floors were on fire. Although Röben et al. noted that "horizontally travelling fires would give a more realistic representation of the fire spread through a compartment", the authors assumed horizontally uniform fires for their study, stating that it is "a common assumption in structural fire design". The heating pattern used was similar to the horizontal studies by Bailey et al. and Ellobody and Bailey, i.e. the same temperature-time curve was applied to each floor but with a time delay between floors. The heating curve used was a generalised exponential curve given by Flint [45]. Röben et al. noted that this curve was selected because analysis by Flint "showed it to be a better approximation for large compartments than the more commonly used "natural fire" curves given, for example, in the Eurocodes", however no theoretical background or physical justification of the method is given. The cooling phase was assumed to be linear between the maximum and ambient temperatures over a period of 1400s.

Three fire scenarios were used; uniform heating on all three floors, a time delay of 500s between each floor, and a time delay of 1500s between each floor. The authors noted that many factors influence the vertical spread rate. The values used in the study were to roughly capture the range of eyewitness accounts of vertical flame spread of between 6 and 30min in the Windsor Tower fire.

The results, primarily examined in terms of horizontal displacements of columns and total axial forces of floors, showed that the vertically travelling fire with a short time delay induced a similar structural response to that of the uniform heating case. However, the primary difference observed was a "cyclic pattern induced in columns" for the travelling fire. This pattern was also observed for the long delay travelling fire, but with longer time

intervals. The authors note that this cyclic deflection pattern has not been examined before and has a significant impact on the structure and, therefore, should be considered in design.

The observation of a cyclic pattern is similar to that of Ellobody and Bailey. However, this finding perhaps has more relevance for vertically travelling fires because compartment floors will likely limit the spread of hot gases that may preheat the upper floors prior to full fire involvement. Notwithstanding this argument, the nature of the column deflections may be affected by consideration of horizontally travelling fires as well. However, no studies to date have examined this.

1.6 Practical Applications

The works highlighted so far in this paper have pioneered or developed the concept of travelling fires and the subsequent structural analyses. This concept is beginning to grow within the fire engineering community. This section reviews recent developments in the use of travelling fires.

The TFM has been applied to case studies in the two real buildings shown in Figure 1.11. Stern-Gottfried et al. [35] generated the temperature-time curves for the Mumbai C70 building in the early stages of its design. Jonsdottir et al. [36] calculated the resultant steel temperatures from a temperature field generated by the TFM for the Informatics Forum at The University of Edinburgh. It was found that the TFM method resulted in higher peak steel beam temperatures than the traditional methods for medium sized fires of 10% to 25% area.

Sandström et al. [46] developed a pre-processing tool to rapidly apply travelling fires to a CFD model. They examined a 20m x 40m x 10m high, open plan building with natural ventilation in the roof and on all four sides for their case study, but do not explain what type of building this would represent. They developed a design fire based on Eurocode 1 [11] guidance, which ramps up at a “medium” t-squared rate, to a peak of 95MW, then linearly

decays. The developed heat release rate curve was then applied to two different uniform fire arrangements and six different travelling fires.

The uniform fires were applied over two different areas. One was 100% of the floor area and the other 12.5% of the floor area, each with a different value of heat release rate per unit area to obtain the same total design fire curve. The travelling fires were 0.125%, 0.5%, and 2% of the floor area. These were each examined initiating in both the centre of the compartment, as well as in the corner. It is not clear if the fires were actually travelling or were merely growing in physical size with sequentially igniting "burners" of fixed sizes. No descriptions of the travelling nature, velocity, or burnout characteristics were given. As with the uniform fires, the total heat release rate curves of these so called travelling fires were set to produce the total design fire curve.

Sandström et al. reported their results as average smoke layer temperature-time curves. They also included the results of a simulation using the two-zone model OZone [15]. The authors then focussed on the steady period of the design fire and compared temperatures of the different input methods. All methods, including OZone, produced similar results with steady temperatures in the peak period ranging between approximately 800 and 900°C. The lone exception was the case with the 12.5% area fixed size fire, which produced temperatures that increased from approximately 1050 to 1150°C over the peak period. The authors did not explain the reasons for this.

By reporting the averaged smoke layer results instead of some variation of temperature with distance from the fire, the analysis more closely resembles the traditional design methods that assume uniform conditions than the travelling fire methods already cited. Sandström et al. did not report on the degree of variation in the temperature field. However, given the height of the structure examined, it is noted that flames would likely not be present at the ceiling, meaning the temperature field may have been more uniform than those previously discussed. The peak period temperature data across the multiple definitions of fire were then examined statistically using a Gumbel Type I distribution. Sandström et al. explained

this was done to obtain some level of statistical certainty that a specific temperature would not be exceeded.

The authors concluded by stating that CFD could be used for more complex geometries and the next stages of the research would be to examine temperatures for specific structural elements in various locations. Although the inputs may include travelling, or growing, fires it is not clear from this study if the authors intend for this structural analysis to result from the averaged smoke layer temperatures or if they will examine spatially varying temperature conditions.

In a poster presented at Interflam in 2010, Shestopal et al. [47] provide a review of two case studies where travelling fires were used. The authors state that the worst case scenarios resulted from a spreading fire. They used CFD modelling of travelling fires to justify the reduction of fire resistance levels against those nominally required by the local building code. The case studies presented were for a supermarket and an office building.

The supermarket case study used a CFD model to predict flame spread. The authors examined various ventilation conditions and the impact on the final heat release rate. They recommended that shutters be used on detection to minimise the impact of the fire and direct it towards the vent, thereby assisting fire fighting.

The office building case study had a user prescribed heat release rate for a small base unit, taken from fire test data. Multiple base units were ignited in succession, with delays between 45 and 90s, to create the full heat release rate over time. The modelling assumed glazing failure based on an elevated temperature criterion.

It is noted that only high level details of this work were presented, as they are all that is possible with a poster. However, from the limited information presented, it appears the analyses may have extended beyond the capabilities of current CFD models, in particular for the supermarket case study, by predicting flame spread, which is a challenging physical process to accurately model [24, 48]. However, the spirit of this work, which examined

spatially varying far field temperatures, is in line with the ethos of the travelling fires methods.

1.7 Conclusions

The concept of travelling fires suggests a paradigm shift in structural fire engineering. The dynamics of travelling fires are central to better understanding the true structural performance of buildings exposed to real fires, and therefore the potential to enable architectural innovation and structural optimisation.

However, given the importance of travelling fires, there has been only a limited amount of research to date on the topic and more is needed. The earliest research by Clifton and Bailey et al. established the need for robust methods to account for travelling fires. The development and use of the TFM offers such an engineering technique. However, refinements to the TFM for horizontally travelling fires are needed to make it more robust. Additionally, fundamental work is needed to examine vertically travelling fires. As opposed to horizontally travelling fires, no framework exists to explore the dynamics of vertically travelling fires, which is currently hindering their application to structural analysis, despite the numerous incidents of vertically travelling accidental fires.

Of particular importance in the development and application of travelling fire methodologies is the close collaboration between fire engineers to define to the thermal environment and structural engineers to determine the subsequent structural behaviour.

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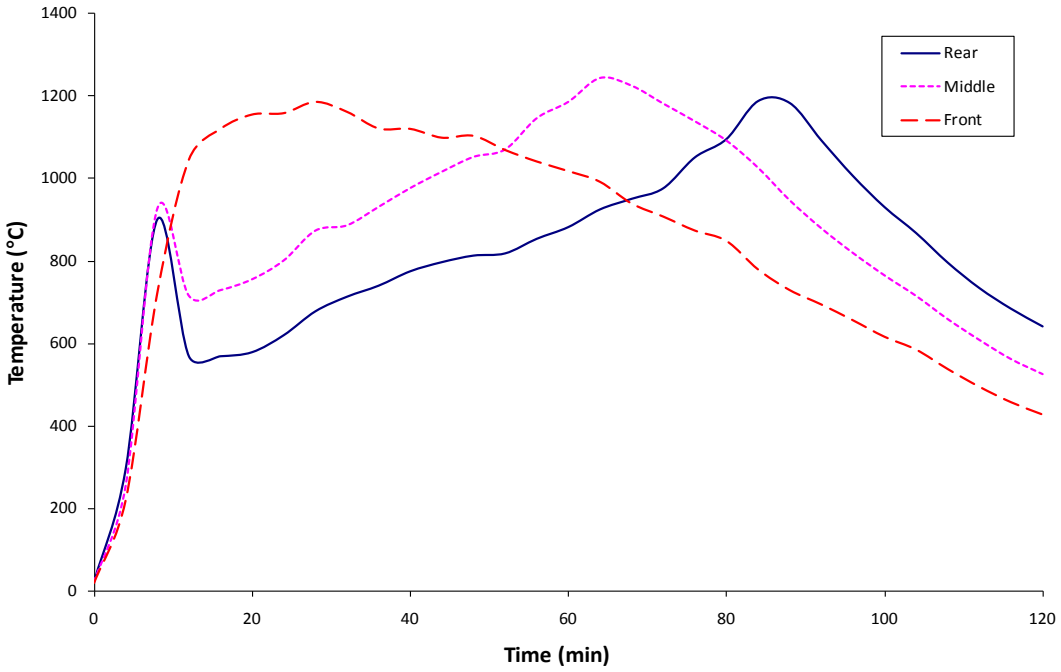


Figure 1.1: Comparison of temperature measurements over time at three different locations from the rear to the front of the compartment, illustrating non-uniform burning of the wood cribs during the tests of Kirby et al. [21].

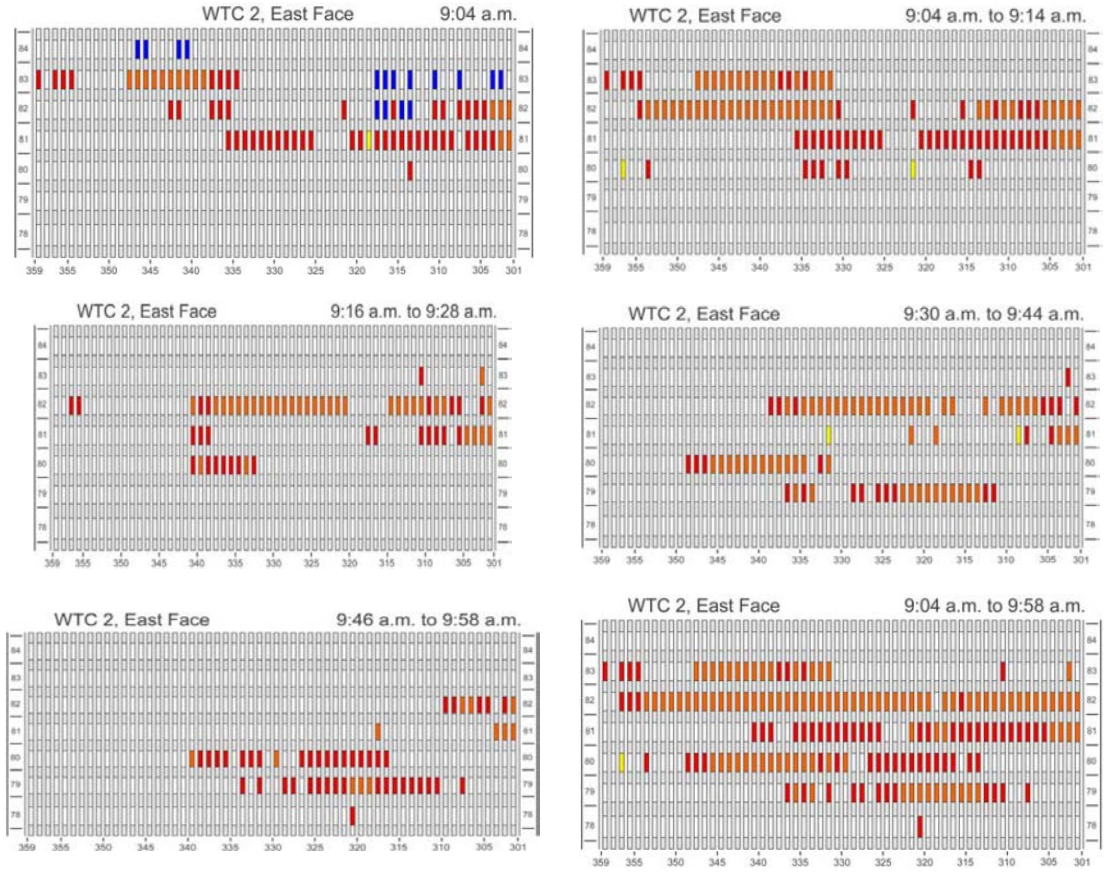


Figure 1.2: Observed fire locations over different time periods on the East Face of WTC Tower 2 [26]. Blue = observation not possible, White = no fire, Yellow = spot fire, Red = fire visible inside, Orange = external flaming.

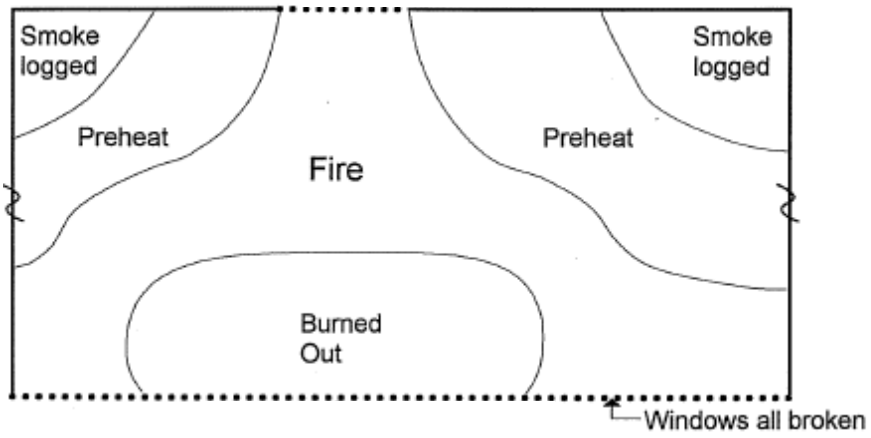


Figure 1.3: Representation of a spreading fire in the LFM [32]. Reproduced with permission from the author.

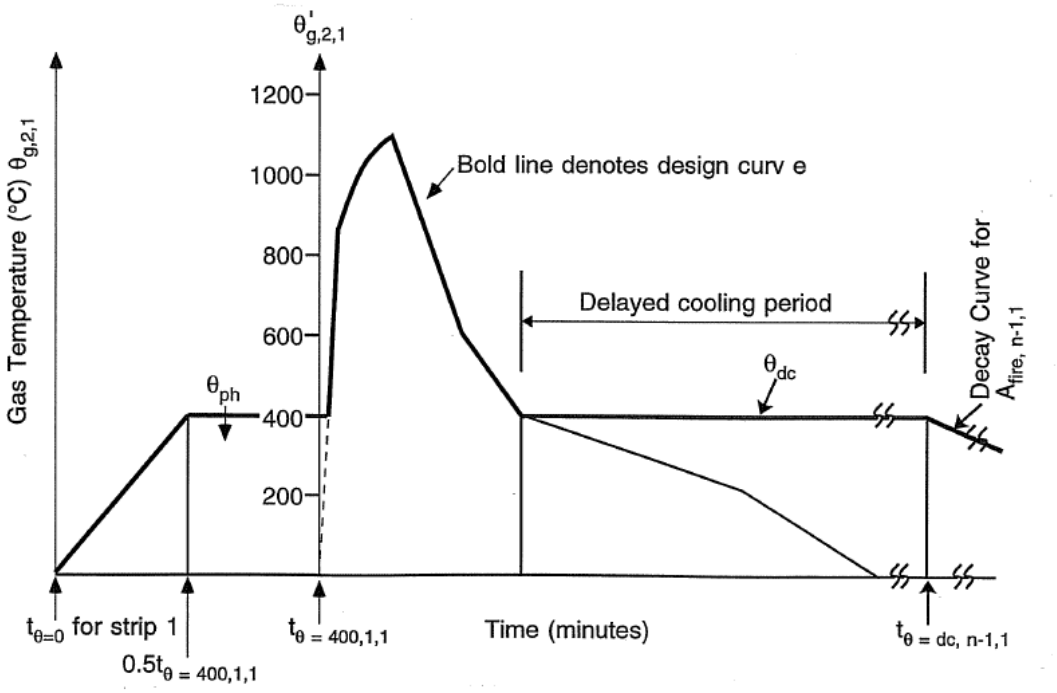


Figure 1.4: Temperature-time curve of one design area in the LFM [32]. Reproduced with permission from the author.

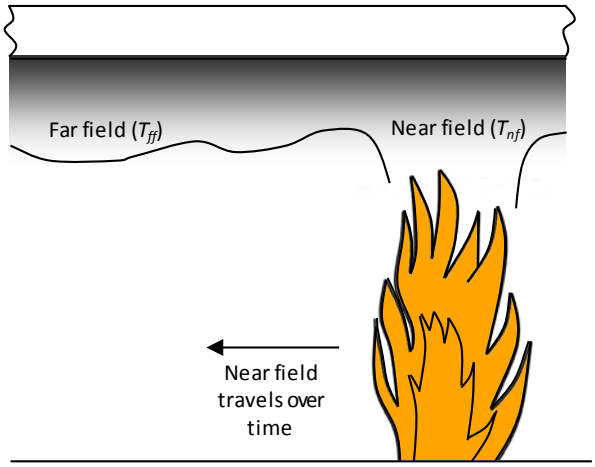
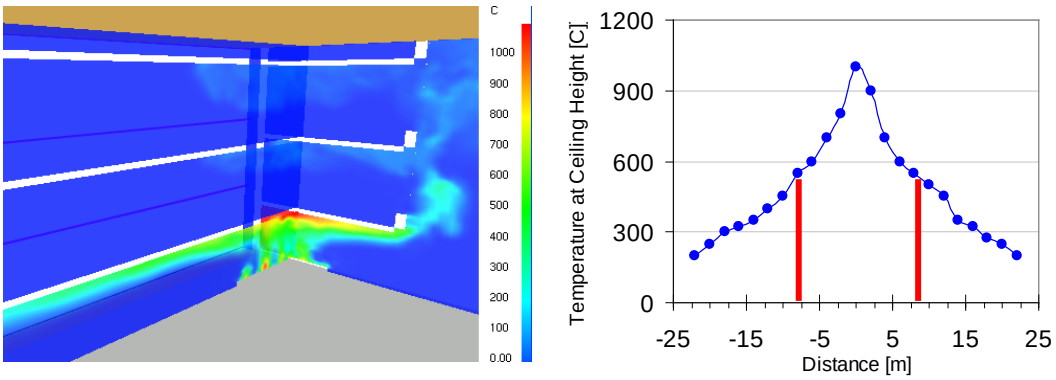


Figure 1.5: Illustration of near and far fields in the TFM.



(a) **(b)**

Figure 1.6: **(a)** Use of CFD with the TFM in a case study with an atrium; **(b)** Calculated far field temperatures for the same case study [34].

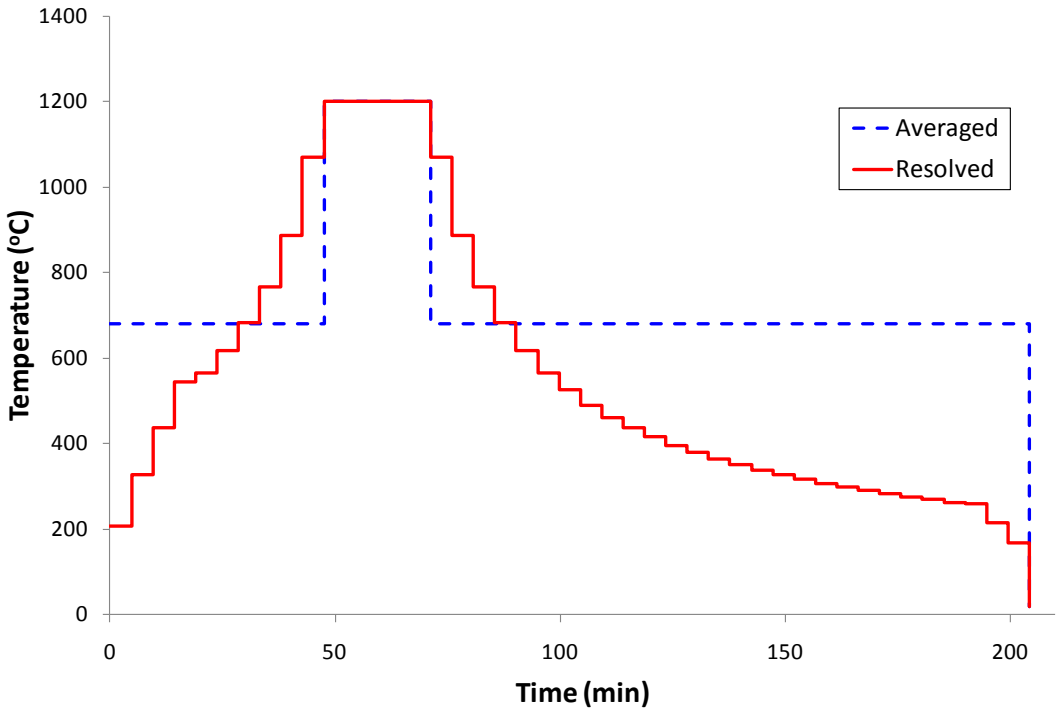


Figure 1.7: Temperature-time curves at a single location in the TFM, showing averaged and resolved far field temperatures.

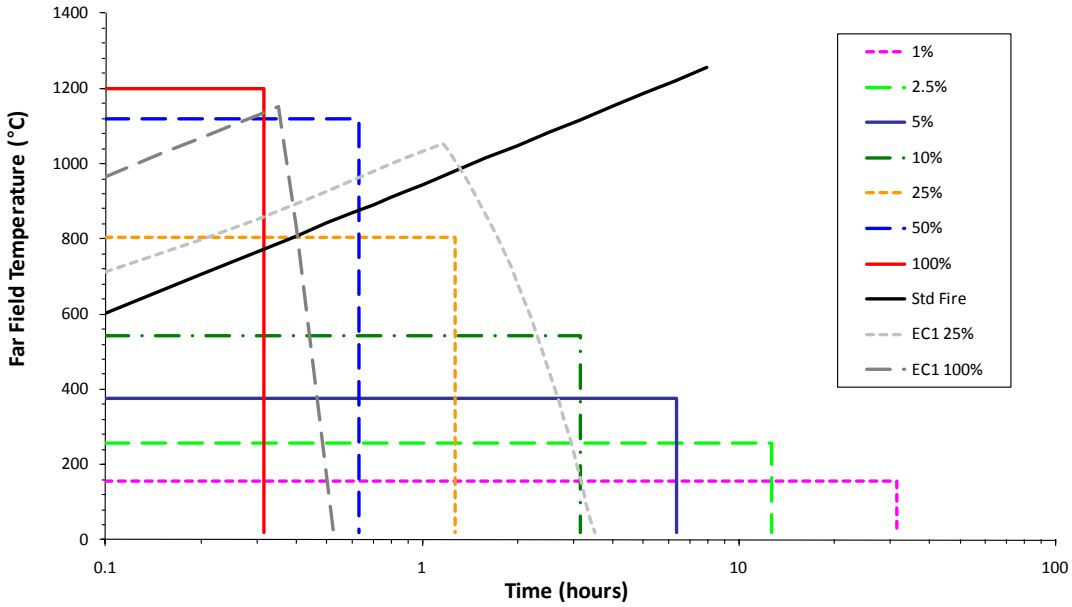


Figure 1.8: Averaged far field temperatures for a family of fires in the TFM and traditional methods as applied to a generic concrete frame 42m x 28m x 3.6m per floor [37].

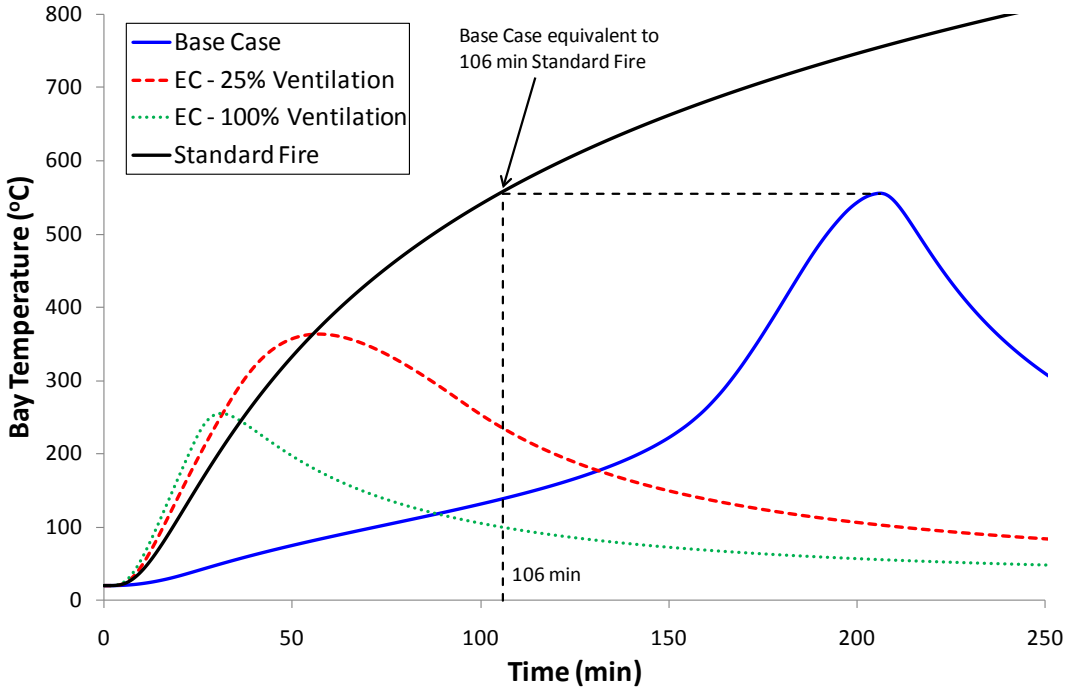


Figure 1.9: Comparison of rebar temperatures calculated using one fire size from the TFM (labelled base case), the standard fire, and two Eurocode parametric temperature-time curves in a similar generic concrete frame as shown in Figure 1.8 [Part II of this paper].

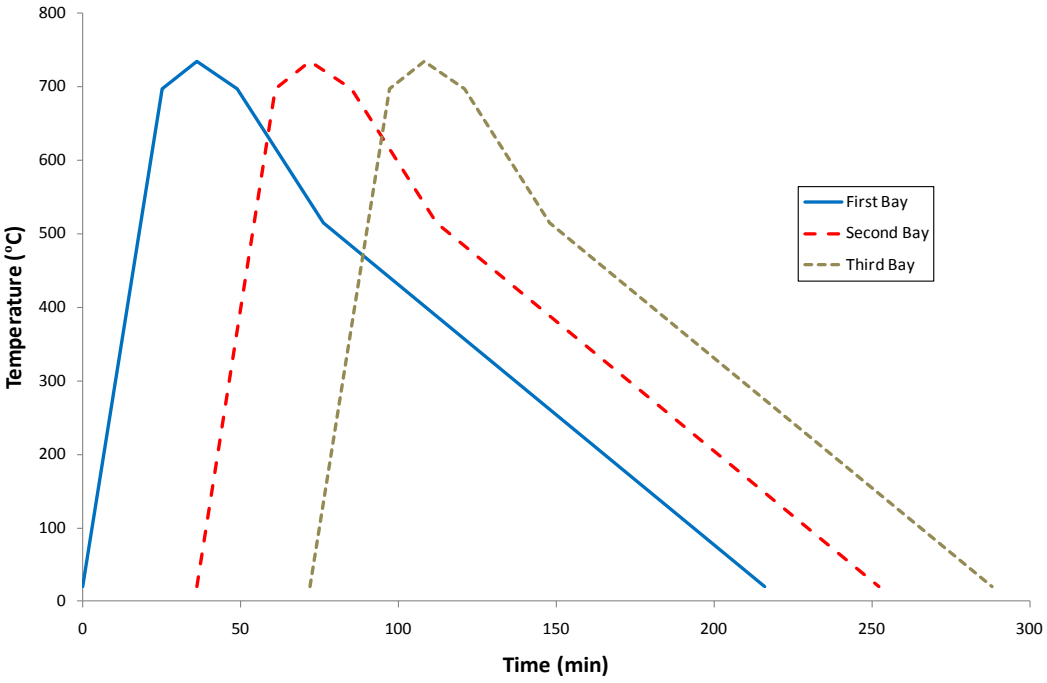


Figure 1.10: Temperature-time curves used by Bailey et al. (adapted from [41]).



(a) **(b)**

Figure 1.11: **(a)** Mumbai C70 by James Law Cybertecture [35]; **(b)** Informatics Forum at The University of Edinburgh [36].