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Travel guide

A newly developed methodology, based on the concept of 'travelling fires' in large enclosures, will assist with structural fire analysis. **Jamie Stern-Gottfried, Guillermo Rein** and **José Torero** report

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CLOSE INSPECTION of real fires in large, open compartments reveals that they do not burn simultaneously throughout the whole compartment. Instead, these fires tend to move as flames spread, partitions or false ceilings break, and ventilation changes through glazing failure. These fires have been labelled 'travelling fires' and represent a new understanding of fire behaviour in modern building layouts.

Despite these observations, fire scenarios currently used for the structural fire design of modern buildings are based on traditional methods that come from the extrapolation of existing fire test data. Most of this data stems from tests performed in small compartments that are almost cubic in nature. This test geometry allows for good mixing of the fire gases and thus for a uniform temperature distribution throughout the compartment.

While this behaviour is different from that observed in real fires, it has generally been deemed a conservative, and therefore appropriate, approach for structural fire design in the absence of better and more relevant data. Although this approach might be considered acceptable for most design cases, the need for better optimisation of structural behaviour in fire will eventually require a more realistic definition of the fire.

Computational methods for determining structural behaviour have matured over the last decade and have enabled analysis of more complex structural systems. This has led to an understanding that many modern structures do not behave in the same manner as simpler, more traditional frame based systems. In order to address these differences, and continue to enable innovation in structural design, a more sophisticated characterisation of fire scenarios is required.

This article describes a new methodology to produce detailed fire scenarios accounting for travelling fires that are consistent with the requirements of analysis of modern structural systems and contemporary architectural features.

Traditional methods

It is important to understand the context of the current design methods to establish this new methodology. Traditionally, structural fire analysis has been based on one of two methods for characterising the fire environment:

- the standard temperature-time curve (as specified by various standards, such as BS 476: *Fire tests on building materials and structures*, ISO 834: *Fire resistance tests – Elements of building construction*, and ASTM E119: *Standard test methods for fire tests of building construction and materials*)

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Eurocode 1 design equations have limitations when it comes to the large floor plates and complicated architecture of modern buildings

- parametric temperature-time curves (such as that specified in EN 1991-1-2: 2002: *Eurocode 1. Actions on structures. Actions on structures exposed to fire*)

While both of these methods have great merits and represented breakthroughs in the discipline at their times of adoption, it is recognised that they have limitations.

The standard temperature-time curve, which is used as the basis for the fire rating system in most building codes and standards worldwide, was first published in 1917[1]. The standard fire 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, so that 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 period; never reduces in temperature due to fire decay; and is independent of building characteristics such as geometry, ventilation and fuel load.

Critical parameters

The next major landmark for structural fire analysis, in terms of design, was a guidance document produced in Sweden in 1976[2]. This work incorporated the current understanding of compartment fire dynamics based on tests conducted in small-scale enclosures. The guide presented the key factors of compartment fire temperatures as the fuel load, ventilation and the thermal properties of the wall linings. It gave design recommendations and a series of temperature-time curves for a wide range of critical parameters, accounting for the cooling period of the fire.

The Eurocode parametric temperature-time curve is based on the same fire science as the Swedish design guide. The Eurocode temperature-time curve was developed to collapse all of the curves given in the Swedish guidance document into a simplified mathematical form.

Eurocode 1 states that the design equations for the parametric temperature-time curve specified are only valid for compartments with floor areas up to 500m^2 and heights up to 4m. In addition, the enclosure must have no openings through the ceiling and the thermal properties of the compartment linings must be within a limited range. As a result, common features in modern construction, such as large enclosures, high ceilings, atria, large open spaces, multiple floors connected by voids, and glass façades, are excluded from its range of applicability. These limitations, which are largely associated with the physical size and geometric features of the experimental compartments on which the methods are based, ought to be carefully considered when the method is applied to an engineering design beyond the recommended ranges of applicability. This is particularly relevant given the large floor plates and complicated architecture of modern buildings.

It is noted that PD 6688-1-2:2007: *Background paper to the UK National Annex to BS EN 1991-1-2* suggests that designers can ignore the Eurocode 1 limitations on floor area and compartment height, and can expand the range of the compartment lining values. However, while this allows engineers to use the equations on more practical applications, it does not appear to address the observed travelling nature of real fires in large compartments.

Travelling fires

A travelling fire is when only a portion of a floor plate is fully involved in flames that then move to other areas of the floor as burnout occurs in locations of earlier burning. The fire travels as flames spread to unburned fuel, partitions or false ceilings break, and ventilation changes through glazing failure.

Over the last decade, there have been several real, large fires where fires were observed to travel across floor plates and between floors. These fires include those in the World Trade Center Towers 1, 2 and 7 in New York in September 2001; the Windsor Tower in Madrid, Spain in February 2005 *(pictured left)*; and the Faculty of Architecture building at TU Delft in the Netherlands in May 2008. All of these fires led to some form of structural failure.

This concept of travelling fires is in direct contrast to the basis of current design methods, which assume uniform conditions throughout the compartment for the entire duration of burning. A fire that burns uniformly within a large enclosure would generate high temperatures, but only for a relatively short duration. However, a fire that travels will still create elevated temperatures away from the fire (the far field), as well as flame temperatures in the near field *(see Figure 1 overpage)*. A travelling fire can therefore inflict the structure with elevated temperatures for longer durations.

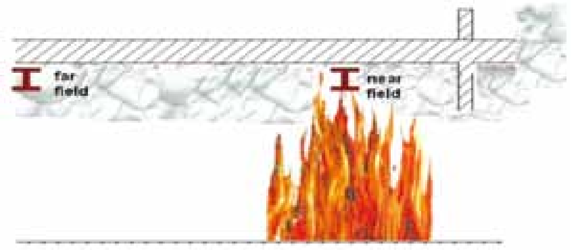

Figure 1: Illustration of the near and far fields in a large compartment fire[3]

Due to the discrepancy between fire behaviour in actual incidents and the assumed fire behaviour in traditional design methods, it is possible that current practices for structural design do not consider a potentially worst-case fire scenario. Non-uniform heating across a compartment floor could cause a failure mechanism in the structure, which may not occur if uniform temperatures were applied to the structure. For example, a cool, unheated bay in a multi-bay structure could produce high axial restraint forces, and that could result in failure of a heated element.

In most situations, however, traditional design methods may be overly conservative, compared to the impact of a real fire. Therefore, it is beneficial to have a methodology that can incorporate the actual dynamics of a travelling fire into structural analysis, to better enable structural and architectural design innovation.

There is currently no approved guidance to assist structural fire engineers in quantifying travelling fire behaviour for structural analyses.

New method

A new methodology is currently being developed at the University of Edinburgh[3,4] that allows for a wide range of possible fires, including both uniform burning and travelling fires, by considering the fire dynamics within a given building. This methodology has two unique characteristics when compared to the traditional methods:

- more than one fire is considered – that is, a full ‘family’ of fires is investigated, with each fire having a different area of burning
- the methodology divides the effect of a fire on structural elements into the near field and the far field

By considering a range of fires, instead of just one, and splitting the effect of a fire into the near and far field, instead of just one uniform field, this methodology allows the full range of possible fires to be considered. This is important because the exact nature of a fire that may challenge a structure cannot be known during the design phase of a building.

The family of fires can be selected by taking a range of fire sizes, expressed in terms of percentage of floor area burning. For example, a small fire might be 1% of the total floor area and the largest possible fire is 100% of the floor area. Because the burning rate of such large fires tends to be nearly uniform, the burning time for a fire in a given area is the same, regardless of the size of the area. This burning time is typically 15-20 minutes for typical office fuel loads[3,4]. For example, assuming a fuel load of 600MJ/m^2, a 1MW fire burning over 2m^2 would take 20 minutes to burn out. A 20MW fire burning over 40m^2 would also take 20 minutes to burn out. These burn out times are consistent with observations of the World Trade Center fires[5,6].

In a travelling fire, only a portion of a floor plate is fully involved in flames, which then move to other areas of the floor as burnout occurs

Due to this uniform burning, a fire that simultaneously covers 100% of the floor area would burn out in about 20 minutes, as it is area independent. A fire that involves 1% of the floor area would burn out locally in about 20 minutes, but then continue to burn as it travels throughout the compartment. Thus, this small fire would last more than 30 hours in a 2,000m^2 floor plate. Clearly, these are extreme values, but the various fire sizes between the two cover the full range of total fire durations physically possible.

Field characteristics

Once the full range of fire sizes has been identified, the characteristics of the near field and the far field of each fire can be determined. The near field is simply the floor area of the fire, and the far field is the remainder of the floor. The near field temperature is that of the flames, usually around 1,200°C. The far field temperature varies with distance from the fire and can be affected by specific building geometry, such as atria. The far field temperature distribution can be determined from various fire engineering tools, such as hand calculations[4] or computational fluid dynamics models[3].

Passing on the full temperature variation of the far field to a structural

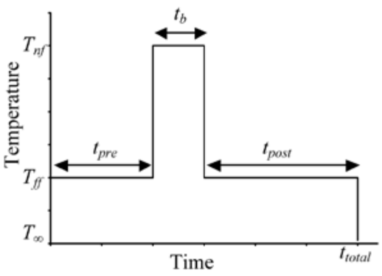

Figure 2: Temperature-time curve at a structural element in one area of a compartment during a travelling fire[4]

model could be prohibitively cumbersome. Therefore a single, averaged fire temperature is used in this methodology.

Once this procedure has been followed, the temperature-time curve for any given structural element can be determined. A generic example of this is given in Figure 2, where:

T_{nf} is the near field temperature
T_{ff} is the far field temperature
T_∞ is the ambient temperature
t_{pre} is the time after ignition but before the fire arrives
t_b is the time the fire burns locally at the element being examined
t_{post} is the time after the fire has travelled past the element

The growth and decay phases are assumed to be much faster than the burning time and thus are neglected from the curves. Note that, while the growth and decay phases are assumed to be fast in the gas phase, the resulting structural steel or concrete temperature-time curves will have noticeable periods of growth and decay, due to their thermal inertia.

Determining both t_{pre} and t_{post} is dependent on the path of the fire and the exact position of the structural element being examined. However, it is not possible or practical to establish a fire's path of travel *a priori* to a real incident; therefore assumptions must be made for worst-case conditions. Clearly, many paths of fire travel are possible, and the sensitivity of this parameter on the structural response is one aspect of the methodology to be explored and developed further.

An example of the resulting set of far field temperatures for a full family of fires is given in Figure 3. The results are for a single floor of a large building with a 2,000m^2 floor area and 3m floor to ceiling height. The façade of the building is completely glazed.

The temperatures shown in Figure 3 are for the far field only. Any one structural element subjected to a specific fire will experience a curve that includes both far field and near field temperatures, like that given in Figure 2. The curves for the standard fire and the Eurocode 1 parametric temperature-time curve do not make this distinction – their temperature-time curves are for a single, uniform temperature for the entire compartment. Note that the case of a fire covering 100% of the floor area is a uniform fire (the near field and the far field are the same).

The temperature-time curves generated by this new methodology can be used as inputs to structural analysis tools for areas of interest. The curves produced allow structural engineers to calculate structural steel or concrete temperatures and the resultant structural response with their current design tools. This new methodology also facilitates the collaboration between fire safety engineers and structural fire engineers, which is an identified need within the structural fire community[7], to jointly determine the most challenging fire scenarios for a structure and its subsequent behaviour.

Conclusions

The traditional design methods for thermal inputs for structural analysis are known to be valid for small enclosures. However, observations of real fires in large, open compartments indicate that fires tend to travel through a floor plate.

This new methodology, based on the concept of travelling fires in large enclosures, has already been applied to real buildings for initial case studies. While further development of the methodology is needed, progress is being made to better characterise the fire environment of large enclosures. In addition, by enabling fire safety engineers and structural fire engineers to work together to better understand the structural behaviour of a building due to fire, the methodology will help ensure more optimisation and innovation in structural and architectural design ■

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Figure 3: Far field temperatures for a range of fires and the traditional methods[4]