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Some Considerations for the Fire Safe Design of Tall Buildings

Adam Cowlard[1], Adam Bittern[1,3], Cecilia Abecassis-Empis[1], and José L. Torero[1,2†]

[1]BRE Centre for Fire Safety Engineering, University of Edinburgh, Edinburgh, EH16 3JL, UK
[2]School of Civil Engineering, University of Queensland, Queensland, 4072, Australia
[3]Astute Fire Ltd., Bush House, Edinburgh Technopole, Edinburgh, EH26 0BB, UK

Abstract

In any subject area related to the provision of safety, failure is typically the most effective mechanism for evoking rapid reform and an introspective assessment of the accepted operating methods and standards within a professional body. In the realm of tall buildings the most notable failures in history, those of the WTC towers, widely accepted as fire induced failures, have not to any significant extent affected the way they are designed with respect to fire safety. This is clearly reflected in the surge in numbers of Tall Buildings being constructed since 2001. The combination of the magnitude and time-scale of the WTC investigation coupled with the absence of meaningful guidance resulting from it strongly hints at the outdatedness of current fire engineering practice as a discipline in the context of such advanced infrastructure. This is further reflected in the continual shift from prescriptive to performance based design in many parts of the world demonstrating an ever growing acceptance that these buildings are beyond the realm of applicability of prescriptive guidance. In order for true performance based engineering to occur however, specific performance goals need to be established for these structures. This work seeks to highlight the critical elements of a fire safety strategy for tall buildings and thus attempt to highlight some specific global performance objectives. A survey of tall building fire investigations is conducted in order to assess the effectiveness of current designs in meeting these objectives, and the current state-of-the-art of fire safety design guidance for tall structures is also analysed on these terms. The correct definition of the design fire for open plan compartments is identified as the critical knowledge gap that must be addressed in order to achieve tall building performance objectives and to provide truly innovative, robust fire safety for these unique structures.

Keywords: Tall buildings, Fire safety strategies, Performance based design

1. Introduction

The number of tall buildings constructed is increasingly ever more rapidly (Fig. 1). They are evolving in height, construction materials, use, and compartmental composition. The evolution of height is staggering when it is considered that until January of 2010, the tallest completed building (Taipei 101) stood at 508 m, a mantle now held by the Burj Khalifa at 828 m. The increasing number of 600 m+ buildings being conceived has led to the recent coining of the term mega-tall. According to statistics from the Council on Tall Buildings and Urban Habitat (CTBUH 2012), 17 of the tallest 100 buildings in the world, as of the end of 2011, were completed within that year. The driving forces behind this progression are inevitably financial, political and environmental, but it is modern technological developments, both structural and material, which have truly enabled the continued evolution of these buildings. The tall building of today is a completely different entity to that of a decade ago with the propensity for change even greater in the immediate future. Advancements in structural engineering have arisen to make possible the increase in height, size and complexity, the reduction of cost and carbon footprint as well as architectural imagination and economic versatility of these buildings. In what is coming to be considered the era of the tall building, the recent explosion in numbers has caused a number of engineers and governmental organizations to look at this genre with specific focus, not least from the perspective of fire safety (SFPE, 2012).

The only recorded structural failures in tall buildings in the last 30 years are earthquake and fire related, and in the case of mechanical failure resulting from earthquakes, it was failure to adhere to building code requirements or accepted engineering practices that ended with the undesired result. Where strong code enforcement and/or adequate engineering is prominent, major earthquakes have resulted in no significant damage to tall structures, thus there is a strong feeling that structural design, in particular with respect to seismic loading, is evolving in step with the transformation of tall buildings. The case of fire failures is clearly different with the last decade or so seeing the collapses of tall buildings of different structural forms as a result of fire. In this period we have seen the collapses of steel buildings such as the World Trade

†Corresponding author: José L. Torero
Tel: +61-7-3365-3619; Fax: +61-7-3365-4599
E-mail: j.torero@uq.edu.cn

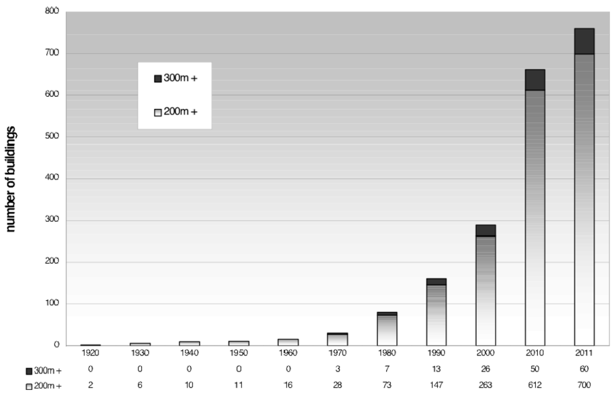

Figure 1. The plot demonstrates the evolution in number of tall buildings completed of greater than 200 and 300 m. Statistics have been taken from the Council on Tall Buildings and Urban Habitat database (CTBUH, 2012).

Center buildings 1, 2, 5 & 7 (USA) (NIST, 2005; NIST, 2008), of buildings of mixed construction such as the partial collapse of the Windsor Tower (Spain) (Parker, 2005; Fletcher, 2009), and of concrete buildings such as the Delft University office (Netherlands) (Meacham et al, 2009) and Caracas "Central" tower (Venezuela) (BBC, 2004). Furthermore, we have seen how classic prescriptive solutions failed to manage smoke (Cook County Building (USA) (Madrzykowski et al., 2003) and Camberwell fire (UK)) (Knight, 2009) and modern buildings using state-of-the-art fire engineering failed to contain the full propagation of a fire (TVCC, China) (China TV, 2009).

Forensic analyses of these fires (NIST, 2005; NIST, 2008; Fletcher, 2009; Meacham et al., 2009; Usmani et al., 2003, Meacham et al., 2010; Madrzykowski et al., 2003) have indicated that the needs of modern tall buildings are beyond the scope of applicability of current fire safety codes and engineering practices. The fire that burned an entire 28-storey residential building in Shanghai (15/11/10), killing 58 people (Wall Street Journal, 2010) clearly illustrates the disastrous consequences of fire not being adequately considered or integrated into the design process. The fire spread rapidly via the external façade through the entire building disabling egress. The material allowing for the fast spread was external insulation being installed as part of a government pilot scheme to boost energy efficiency. This failure emphasises the lack of proper design tools required to ensure safety in a rapidly evolving construction industry where issues other than fire safety (in this case energy) are the main drivers for innovation. Analyses of several of these failures (NIST, 2005; NIST, 2008; Fletcher, 2009; Usmani et al., 2003) and current design practises reveal that fire safety codes are not necessarily capable of providing implicit safety for the rapidly evolving needs of modern tall buildings and are being extensively substituted by non-validated performance based design methods. This work endeavours to provide an assessment of the state-of-the-art of fire safety engineering for tall buildings. It seeks to define the specific performance objectives to enable a successful tall building fire safety strategy, and assesses failure statistics which provide an indication of our current ability to successfully engineer the principle issues identified.

2. From Prescription to Performance: The Tools of the Fire Safety Engineer

The most successful investigations are those conducted in an atmosphere where all those involved have sufficient knowledge to make the most of the investigation and to transfer that new knowledge into the design process. Possibly the greatest leap forward in fire engineering knowledge came as a result of such a failure investigation (Hottel, 1984). In this instance however it was the extensive research carried out by both sides during World War II, specifically with the intention of the creation of failure. The extensive development of understanding of methods by which failure could be induced by fire meant that later, following a wide ranging international research collaboration, this could be translated into state-of-the-art design guidance (Thomas, 1986). This example is also typical of how social responsibility associated to fire safety has historically been translated into codes and standards establishing prescriptive requirements for buildings.

Prescriptive requirements induce safety factors by constraining design output to pre-established bounds. A specific form has been studied, and its range of performance established. An acceptable performance objective is identified thus so is the extent to which the form can be changed whilst still achieving the performance objective. This methodology forms the bounds that are then implied by prescriptive rules. If a designer follows these rules, they will fall within the bounds and the safety of the design will be implicit. The implemented solution will inherently carry a significant safety factor because it has to be robust to the variations permitted within the bounds of the prescriptive rules. The magnitude of this safety factor is however, never explicitly defined. Critically, this system is founded on the initial form identified for analysis; change the system drastically, and the safety factor can no longer be implied. There have been periods in which codes and standards had enough embedded knowledge that they could respond to all variants of innovation in construction. In these periods infrastructure can be comprehensively classified into some group that is fully addressed by a specific set of rules. Few exceptions appear outside the codes and standards and require individualised solutions. The post WWII period was perhaps the most significant example of this. In periods of great urban or technological development, codes and standards do not envelop the evolution imposed by the drivers of the construction industry and performance based solutions are necessary.

Performance based design allows practitioners to apply a rational engineering approach to provision of life safety and property protection goals. This is accomplished by identification of specific goals, functional objectives and performance requirements (Buchanan, 2002). An engineer is then given license to demonstrate the required performance using an acceptable solution, approved calculation method or performance based alternative design. Achievement of the specified goals is thus defined explicitly. The WTC epitomised innovation and most of the technical solutions involved were evaluated using the most sophisticated engineering tools of the time; a time when Fire Safety was still established in a purely prescriptive manner. In the aftermath of the WTC collapses, the Tall Buildings community turned towards the investigation to derive the necessary lessons that would enable an adequate performance based analyses. Nevertheless, extracting requisite knowledge from a failure and conveying that knowledge into the design process requires a minimum level of understanding of what went wrong and how it can be adequately guarded against in future designs. The unprecedented magnitude and novelty of the WTC failures caught the fire safety and structural communities unprepared for the investigation. Somewhat ominously, while it has taken the professional communities the better part of a decade to produce the science necessary to unveil many of the phenomena, and while they are still to find the capability to transform the knowledge into relevant design methodologies and tools, this lack of capability has gone widely unnoticed by the wider construction community, and the last decade has been a period of great all-round innovation for Tall Buildings with numbers soaring (Fig. 1).

This strongly indicates the insignificance of fire safety engineering practice as an overall driver in the wider construction industry. Likewise, it reveals the practice's inability to demonstrate the relevance of our solutions to that industry. As a consequence, new requirements have emerged, not always because they were needed or because the community was ready to define them, but mainly because society demanded an answer in some form. Tall buildings are the optimal example of innovation outstripping prescribed (implicit) safety. A one size fits all approach cannot be considered for scenarios so complex and unique. This is becoming an increasingly accepted fact in most facets of modern fire safety engineering, evidenced by the recent shift in many parts of the world towards a performance based framework. As tall buildings are such a unique scenario, it is essential that specific, tall building relevant performance objectives are defined before an attempt to perform such a design is made. Only then can practitioners understand what they are actually required to achieve, establish the goals of the performance based hierarchy (Buchanan, 2002), and assess the level of performance of the system that they are proposing. To identify the critical tall building performance objectives, it is first essential to define the specific fire safety problems inherent in tall buildings.

3. Fire Safety Strategies for Tall Buildings

A holistic Fire Safety Strategy for a tall building is essentially a function of time. It contains two principle components; egress strategy and building performance. Building performance can be further broken down into structural performance and fire spread mitigation e.g. compartmentation. The evacuation strategy is concerned with defining the time required to safely evacuate all building occupants. Building performance concerns the time that the structure can withstand the effects of the fire and the compartmentation remain in place and functional. In everyday design scenarios, the two components can usually be dealt with separately. Times associated to evacuation are typically of the order of minutes while structural / compartmentation times are more typically of the order of hours. It is thus usually inherent that the structure and compartmentation will remain intact for a period that comfortably allows for the implementation of the egress strategy. This is not the case however for tall buildings. The ever increasing heights combined with the limited number of vertical escape routes results in these two components becoming coupled. Evacuation times are extended to an order of magnitude comparable with that of the heating times of structural elements and by extension, the potential failure times of these structures. Evacuation and structural / compartmentation failure are therefore at risk of overlapping as was the case of the WTC towers. This problem will only be further exacerbated as buildings become taller and more complex. These principle components are discussed here along side data collected from reports of some 50 tall building fires occurring internationally. This survey has been made in order to assess trends associated to the fire safety strategy and to help establish if the base assumptions made in design are credible. A list of the events surveyed is described in Appendix A.

3.1. Survey of tall building fire events

In total this survey considered 50 buildings reaching from 10 to 110 storeys, the first building being completed in 1924, with the majority being completed in the last 30 years. The majority of the fire incidents occurred in the last 20 years, in countries including UK, USA, Thailand, Hong Kong, China, Canada, Spain, and Venezuela. A list of the buildings included in the survey along with the selection of details relevant to this paper, is presented in the appendix at the end of the paper. It is important to recognize that this selection is highly influenced by the availability of information, thus the examples are geographically skewed towards locations where information is freely available and does not reflect in any way on the level of safety provided by the regulations in those locations, rather the proactive nature of the authority to learn and improve. In North America particularly, the USA National Fire Protection Association has commissioned fire investigations into several high rise building fires, with the fire investigation reports being publicly available. The Federal Emergency Management Agency had conducted several fire investigations for high rise buildings, with the reports being publicly available. Another source of information was the Line of Duty Death Investigation reports undertaken by various fire authorities in the USA. The quality, quantity and detail contained in the fire investigation reports varied considerably, but overall they contained general details on the building construction including fire protection features, fire incident including cause and origin, fire and smoke spread, fire fighting operations including search and rescue. Although some reports did provide outline details of the fire protection systems, a degree of caution had to be applied in that it could not be assumed that just because a feature was not addressed by the report, it did not necessary mean that it was not present, and secondly the majority of the reports did not investigate the design criteria, installation or maintenance of such features.

3.2. Evacuation

Safety, with respect to evacuation, is measured in time, predominantly the time required for all occupants to reach the outside of a building. The shorter this time, the safer the building is deemed to be. The height of many modern tall buildings, combined with the limited number of vertical escape routes, extend travel times such that the stairwells must act as the outside. They must be designated a ‘safe zone’ which should guarantee the safety of occupants once reached and allow safe transit to a place of refuge, within or outside the building. In effect the tall building becomes a collection of single storey buildings. This then allows for different evacuation philosophies (staged, phased, total) to be applied to tall buildings. Furthermore these travel distances extend evacuation times to a magnitude comparable with that of the heating times of structural elements and, by extension, comparable with potential failure times. An increase in vertical escape provisions (stair numbers and widths) and novel technologies (egress lifts, etc.) will not yield sufficient impact to prevent this overlap. The considerable time that occupants spend within the stairwells means that for any fire strategy to be successful, stairwells must remain smoke and heat free and the entire building structurally sound. Without adequate protection the number and width of stairwells is irrelevant, as smoke-logged stairwells are unusable and the Fire Safety Strategy is therefore void. Figure 2 shows the rates of premature loss of stairwell tenability levels i.e., significant levels of smoke within at least one stairwell whilst still being used for egress by occupants, reported in the surveyed fire investigations and reports. One significantly reoccurring theme reported was that failure occurred early in the evacuation process although exact failure times were not given. Another was that fire fighting activities were associated to approximately a

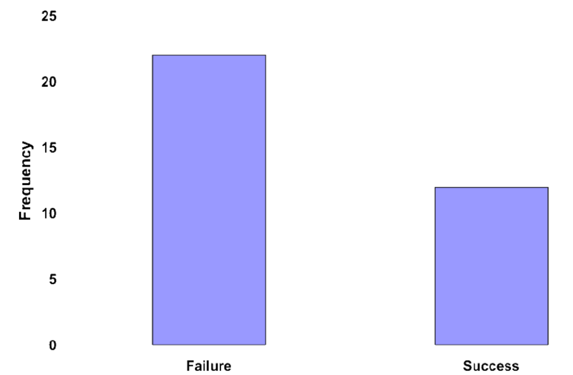

Figure 2. The chart shows reported rates for premature loss of stairwell tenability from a survey undertaken of fire reports from 50 tall building fires.

third of the reported failures.

A common method to ensure smoke free stairwells is the provision of pressurisation systems. Stair pressurisation was developed in the 1960-70s through experimental work (Tamura, 1983). This work identified criteria that enabled the definition of a pressure range (upper and lower bounds). Systems are then designed such that the pressure difference between the stairwell and its surroundings remains within this range under both everyday and operational conditions in order to maintain the smoke free requirement. The upper bound pressure exists to ensure that occupants never struggle to open doors leading to a stair, thus not hindering evacuation. This pressure is usually defined by the force that an average person can exert. The lower bound pressure is designed to maintain gas flow from the stairwell to its surroundings. It is therefore defined in terms of the pressures produced by the fire. If the pressures induced by the effects of the fire are greater than those of the lower bound, smoke will flow through doors and smaller gaps and openings into the stairwell thus rendering it unusable. It is therefore crucial to correctly determine the pressures that a typical fire might produce. While this model has been expanded to account for the complexities brought about by modern stairwell geometries (Klote and Milke, 1992), the resulting pressurisation systems have been shown to be limited by their narrow ranges of operation (Bellido et al., 2009) and the uncertainties associated to the nature of the fire. The experiments (Tamura, 1960) on which this approach is based were conducted in a 10 storey tower, with surrounding compartment floor area of approximately 18 m^2 containing a propane burner. The experiments tested a variety of stair pressurization systems to assess the effects of doors opened into the stairwell during evacuation on the ability of the systems to continue to keep smoke out of that stair. Clearly, a fire in a large, open plan environment containing combustible furniture may have considerably different fire dynamics, thus the lower bound pressure definition used for these systems has little relevance for modern open plan scenarios. Reported failure rates for stairwell smoke

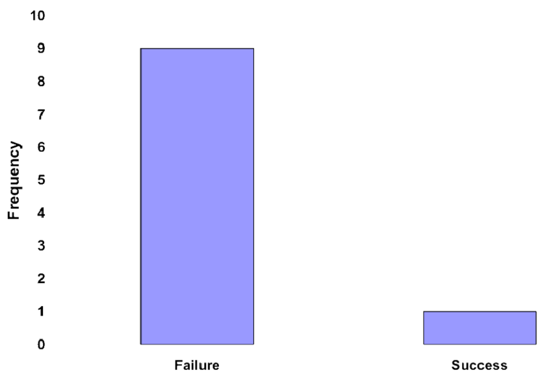

Figure 3. The chart shows the reported success / failure rates where pressurisation or extract systems were reported as being installed to maintain tenability in vertical egress paths.

control systems from the fire report surveys are shown in Fig. 3 and account for 90% of cases where such systems were mentioned. This implies that safe stairwell tenability levels are currently not guaranteed, thus the cornerstone of contemporary tall building fire safety design may not be valid. A fundamental component for the success of this element of the Fire Safety Strategy is the correct definition of the lower bound pressure, and thus also the exact nature of the fire.

3.3. Building performance

3.3.1. Structural performance

The structural design of modern tall buildings is governed by the need to efficiently transfer loading, particularly that from wind, whilst providing increasingly complex building functionality. The development of complex, inspired and highly optimised structural framing systems (Carroll et al., 2006; Abdelrazaq, 2010; Moon et al., 2007) (often deemed tall building technologies) has enabled efficient load transfer mechanisms, thus, in the event of a fire, locally induced deformations and resultant loading will be effectively redistributed throughout the structure. While this could help maintain structural integrity, research has demonstrated that these structural systems are particularly sensitive to the size and nature of the fire (NIST, 2008; Usmani et al., 2003).

Fire resistance has traditionally been defined as a function of a standard temperature time curve (Babrauskas and Williamson, 1978), with structural elements tested as single elements and their ratings defined as the time to attain a pre-specified failure criteria, traditionally a critical temperature. More recently, through the Cardington Tests (Martin and Moore, 1997), it has been recognised that this is not a realistic way of determining the performance of structures in fire. Post-Cardington analyses have used Parametric temperature vs time fire curves and time equivalence concepts as input to the structure showing significant effect of the heating rates, period and cooling. Furthermore, numerous studies have emphasised that the presumed "worst case" fire loading imposed by homogeneous heating might not represent the most onerous scenario. Systems with long span light-weight floors where the load is shared by a stiff core and external structure are particularly vulnerable to multiple floor fires (Usmani et al., 2003). While for regular I-beams homogeneous heating seems to be a "worst case" condition, it is not for light-weight cellular beams which are vulnerable to localised heating (Rini, 2006). In the analysis of WTC-7, NIST (NIST, 2008) concluded that long spans can induce progressive collapse if the detailing of the connections and the symmetry of the beam arrangement is not adequately characterised. Finally, the potential for failure during cooling has been identified in many of these modern systems (Roben, 2010), showing the need for a heterogeneous heating/cooling assessment as an essential component of a detailed analysis of the behaviour of a structure in fire. The advocating of performance-based design for tall and innovative buildings acknowledges the inability of furnace testing of individual structural elements to assure the provision of adequate structural fire safety.

The survey conducted showed that there was some degree of structure failure in 13 of the 50 buildings. While the literature reviewed was often lacking on the specific details of structural failures, there were numerous mentions of localized failures, such as sagging of beams, failures of connections, collapsing of decking, and deformation of fire rated compartmentation assemblies and some more extensive failures such as the partial collapse observed at the Windsor Tower or in the cases of the WTC buildings, total collapse. Such behavior could be identified at the design stage though true performance assessment. Such an assessment requires an understanding of the likely fire conditions. Continuing to design for a uniform or standard fire when the greatest challenge to the structure might be a "traveling fire" (Stern-Gottfried and Rein, 2012a, 2012b) is potentially flawed, especially when for many tall buildings the latter case could be the most realistic.

The performance of a structure is a fundamental component of a fire strategy, thus its performance within the context of this strategy needs to be defined. Acceptable performance is therefore a relative term that will vary depending on the requirements posed by the strategy on the structure. Different strategies and buildings will require different acceptance criteria depending on what the structure is intended to deliver. In an industrial storage facility structural failure could be an acceptable performance given that the structure has only secondary life safety functions. In contrast, in a tall building, stringent requirements of structural integrity are necessary because the structure has a fundamental role in life safety. Independent of the specific requirements to be met, a true assessment of performance for a structure needs to be established. Only then failure criteria can be stipulated to meet the needs of the fire strategy.

To be able to define the temporal and spatial evolution of a structure during the event of a fire, the following issues need to be resolved:

1. The temporal and spatial evolution of the fire needs to be specified in a manner that gas phase temperature, the velocity field and the concentration of different species (CO, CO_2, H_2O, soot, etc.) concentrations can be defined.
2. The evolution of the gas phase will enable to quantify the temporal and spatial evolution of the heat exchange between the structural elements and the gases. Thus a real thermal boundary condition can be stipulated.
3. With the boundary condition defined heat transfer through the structural elements needs to be resolved. For materials like steel the transient energy equation consists only of heat conduction and enthalpy terms with variable thermal properties but for other more complex materials such as concrete or plaster board, complex mass transfer equations need to be resolved to account for the vaporization enthalpy as well as moisture migration.
4. The spatial and temporal evolution of the temperature of the structural elements allows then to compute the solid mechanics equations to determine stresses and deformations within the structure.
5. The results of these calculations can then be used to establish quantitative failure thresholds.

The comprehensive formulation of the problem requires the coupling of gas and solid phase because the evolution of the structure can influence the evolution of the fire. Explicit finite element models coupled with transient CFD models become a necessity if the complete interaction is to be resolved. Despite many attempts to do this (Welch et al., 2009), there is currently no combination of models that solve the coupled effects of fire and structure. Furthermore, there is currently no CFD model that comprehensively resolves the fire at the necessary scale and with full detail. Finite element models are more advanced but many of the mechanical and thermal properties that serve as inputs are still unavailable.

Numerous alternative approaches can be found in the literature and within engineering solutions, some of them are well argued simplifications that use the characteristics of the problem to either relax the coupling between gas and solid phase or to simplify certain terms of the equations. Among these simplifications are simplified connection models, constitutive property models, total heat transfer coefficients and spatial and temporal averaging of the gas phase. These simplifications take advantage of the very different time and length scales of the solid and gas phase problems to decouple and simplify many of the processes. When correctly argued these approaches are perfectly valid and provide a true assessment of the performance of the structure as well as quantified error bars linked to uncertainties and simplifications.

A second approach that is equally valid is that of establishing a series of constraints in the form of codes and standards. These constraints guarantee a simplified environment that can be quantified by means of a simple representation. The most common of these code based constraints are the requirements for compartmentalization. By reducing all buildings to a summation of standardized compartments, the evolution of the fire can be reduced to an energy balance and thus both gas and solid phase behaviour can be deeply simplified. This particular approach still provides a true assessment of performance. The error bars, in this case, are linked to the simplifications of the physical models defining the gas and solids but also to the potential deviation of the real compartments from the standardized ones.

An approach that is acquiring popularity is that of using simplified models coupled with probabilistic estimations of error. These methods, based on theories of risk and reliability, are only valid if the representation of the physical phenomena incorporates in a correct manner all the necessary variables and couplings and the probabilistic distributions for all poorly defined properties are available. In this case a probabilistic distribution of true performance can be established.

A final method is the relative assessment of performance. This method creates a realistic scenario and assesses the performance of a system against it. The realistic scenario can be a standardized temperature vs. time curve, a parametric temperature vs. time curve to provide a relative performance of a structural component or system but also a standardized compartment to assess the relative severity of a fire. While this approach can be used for the purpose of understanding or for classification, it will never provide true performance assessment.

3.3.2. Standard Fire Analysis

The history of explicit fire modelling is not very old with the first attempts done at the beginning of the 20^{th} century but only formalized in the 1960's and 70's (Hottel, 1984). Probably the first descriptions of the fire are associated to fire resistance and attempts to guarantee adequate structural behaviour. In the absence of most of the fundamental knowledge of combustion, heat and mass transfer, the fire was modelled by attempting to reproduce reality within a furnace [34]. A combustion reaction was sustained within a realistic scale compartment in which the structural element was introduced. Heat transfer was bypassed by measuring directly the temperature of the structural element and the fire was generalized by attempting a "worst case" condition. The worst case condition was generated by reproducing the fastest possible temperature rise to the highest possible temperature. This "worst case" fire was formalized as the "standard fire" and the "standard fire" gave birth to the "structural temperature vs. time" concept. The "standard fire" could then be reproduced in a furnace according to a pre-defined "temperature vs. time" and structural systems tested within that furnace. No real fire could produce a faster temperature rise nor attain the temperatures obtained in the furnace. The exposure time was defined on the basis of attaining burn-out of the estimated fuel load, thus no real fire could last longer. The time required for burn-out was labelled the required structural fire resistance rating. While this "worst case" scenario allowed for confident extrapolation, it is clear that an important safety factor was embedded in this primitive form of fire modelling.

Understanding of structural behaviour at high temperatures was limited to the characterization of the material properties as a function of temperature. Typical safety factors for structural design established how far the loss of mechanical properties could be tolerated. This loss of mechanical properties was then correlated with a temperature resulting in a failure temperature criterion. The time necessary for the structural element to attain this critical temperature in the furnace was then established as the failure time. If the failure time was greater than the required fire resistance rating then the structural element could be used without any thermal protection, if not, thermal protection should be added in quantities that enabled the time to attain the failure temperature to exceed the required fire resistance rating (Ingberg, 1928; Buchanan, 2002).

An important concept associated to the extrapolation between thermal behaviour in the furnace and real fire behaviour was the compartment size. While there was no clear understanding of the role of compartmentalization, it was inferred that extrapolation could only be robust if the conditions of burning were similar. Furthermore, accepting that single element behaviour, based only on material properties, could be extrapolated to real scale structural behaviour could only be tolerated heating was localized. If a zone of comparable size to the furnace was the only heated area, then the surrounding structure will remain cold and maintain its strength. Any stresses generated in the heated area could then be transferred (redistributed) to the rest of the building and will be of lesser magnitude than those tolerable by the cold structure. In modern terms this represents a requirement of mechanical restraint that is guaranteed by effective compartmentalization. As a consequence, very restrictive compartmentalization requirements were imposed by building codes of the time.

Combustion science progressed through the 20^{th} century nevertheless these issues will not be revisited until the 1960's. Advancement in the understanding of fluid mechanics, heat transfer and combustion did not permeate into fire modelling because the complex problem of fire could not be effectively linked to fundamental knowledge in any of these areas. Modelling the fire from fundamental principles was not possible, the gain was not evident and the existing design methods seemed to provide satisfactory results. At the time excessive safety factors were not a matter of consideration.

The 1960's brought two fundamental changes to the construction industry, (1) the relaxation of compartmentalization and (2) the introduction of plastic materials. In the past, "worst case" fires were defined on the basis of burning wood and were limited to a compartment of a size and characteristics regulated by building codes. As buildings became more complex and features such as ventilation ducts and false ceilings were introduced, it became unclear how to maintain compartmentalization. Given that the link between compartmentalization and fire safety performance had not been established on the basis of fundamental principles, it was difficult to establish the implications of the changes associated to new forms of construction. The loss of some level of compartmentalization occurred unnoticed. The consequences of losing compartmentalization were made evident in several tragic fires (NFPA, 2003). In a similar manner, the migration towards plastics introduced novel failure modes induced by physical phenomena such as melting or dripping. These failure modes resulted in burning conditions that were different to those defined by the burning of cellulosic materials (e.g. wood). The need to better representation of the fire by incorporating these new features became the driver to a significant research effort that for the first time brought combustion knowledge into fire safety (NFPA, 2003).

In what concerns assessment of structural performance a better understanding of the burning behaviour lead to the better characterization of the compartment fire temperature distributions (Thomas and Nilsson, 1973; Thomas, 1967) and the development of design "temperature vs time" curves that were meant to be realistic representation of the evolution of the temperature of a compartment. Notable is the study by Pettersson et al. (1976) that lead to the parametric curves. Nevertheless, all these work relies on the principle of compartmentalization and requires the dimensions of the compartment to be such that mixing dominates and results in a homogeneous compartment with very thick smoke (small extinction distance) that can be described with a single temperature that is spatially homogeneous and only a function of time. Thomas (1967) explores the limitations of homogeneity, but only Harmathy (Harmathy and Lie, 1970; Harmathy, 1981) discusses the role of the compartment and its dimensions. Figure 4 presents the comparison between the standard fire and the parametric curve corresponding to a realistic fire (The Dalmarnock Fire Test - DFT (Rein et al., 2007)). The average temperature of the compartment is also presented. As it can be seen, the parametric curve brings some of the realistic features of the fire, nevertheless tends to be overdimensioned. This is mostly due to the nature of the compartment used which had a very low thermal conductivity and thus retained the heat. For a similar reason the cooling curve was not introduced because it is defined by the walls, thus is not a representation of the gas phase. A very simple heat transfer calculation towards a beam was introduced only to show that the temperature evolution of the gas phase could potentially have drastic consequences on the structure. So, even without taking any heat transfer considerations or the limitations of the compartment, none of the design curves is a true representation of the fire. It is clear that the capability of these procedures to lead to a true performance assessment is doubtful. No performance can be defined beyond establishing very simple failure criteria and methods to define if failure is attained.

3.3.3. Temperature vs. Heat Flux

When analysing the heat transfer from the fire to a structural element the problem needs to be formulated in terms of heat fluxes. While temperatures result from the solution to the energy conservation equation, all quantities to be balanced are energies (Incropera and DeWitt, 2002; SFPE, 2002).

Heat is transferred from gases to surfaces via radiation and convection resulting in a total heat flux, $\dot{q}''_{Tot}$, where

$$\dot{q}''_{Tot} = \dot{q}''_{rad} + \dot{q}''_{con} \quad (1)$$

and $\dot{q}''_{rad}$ is the heat transfer via radiation and $\dot{q}''_{con}$ is the heat transferred via convection. For simplicity the problem will be assumed as one dimensional, then the boundary condition for a solid element (structural element) becomes

$$\dot{q}''_{Tot} = -k_i \frac{\partial T}{\partial x} \quad (2)$$

Where the thermal conductivity (k_i) is a property of the solid and the gradient of temperature is taken at the surface. In other words all the heat arriving is conducted into the solid. If there are multiple layers then at each interface the following boundary condition should apply:

$$-k_i \frac{\partial T}{\partial x} = -k_s \frac{\partial T}{\partial x} \quad (3)$$

Where the gradients correspond to each side of the interface and the sub-index "*s*" is a generic way to represent the next layer of solid. Once the boundary conditions are defined, the energy equation can be solved for each material involved. In the case where two layers of solid are involved ("*i*" and "*s*"), then the energy equations take the form

$$\rho_i C p_i \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_i \frac{\partial T}{\partial x}\right) \quad (4)$$

$$\rho_s C p_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_s \frac{\partial T}{\partial x}\right) \quad (5)$$

If the geometry is complex, then the problem needs to be resolved in all dimensions. If the properties vary with temperature then, as the temperature increases, these properties need to evolve with the local temperature. Variable properties thus require a numerical solution. If a simple analytical solution is to be obtained then adequate global properties need to be defined. It is important to note that whatever the solution methodology adopted, the temperature of the structure is the result of the resolution of equations (4) and (5) using potential boundary conditions such as those presented in equations (2) and (3).

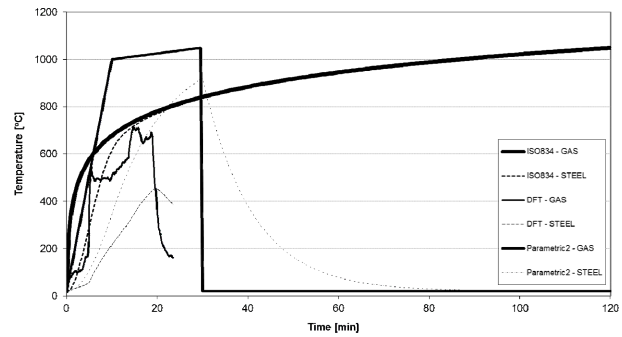

Figure 4. Temperature evolution of the gas phase of a compartment fire and a small cross section unprotected steel beam. Standard temperature time curve per ISO-834 (1999), DFT stands for Dalmarnock Fire Test as per Rein et al. (2007).

To obtain the numerical solution it is necessary to input material properties for the different layers ("*i*" and "*s*"). The material properties required are all a function of temperature and are as follows:

ρ_i, Cp_i, k_i

ρ_s, Cp_s, k_s

For some materials such as steel the properties of are well known and thus very little difference can be found between the literature (European Standard, 1993). For other materials such as concrete, wood or different thermal insulations the scatter is much greater (Buchanan, 2002; UL, 1962, 1965). The uncertainty is associated to the presence and migration of water, degradation, crack formation, etc.

Furnace data is generally used as a substitute for the uncertainties associated to property definition. In many cases global properties are extracted by fitting temperatures to the furnace data. These properties are then extrapolated and many times used in equations such as (2) to (5) for performance assessment. Nevertheless, this practise has also its unique complexities. First of all the model needs to include all the physical variables necessary, so if physical processes such as the degradation or water are not included in the model, the properties used from the furnace calibration become hybrids that include these physical parameters. Introducing physical phenomena into constants inevitably narrows the range of application, thus most of these calibrated properties can only be used to re-evaluate furnace data. Extrapolation to drastically different scenarios such as fire becomes doubtful.

An important aspect many times overlooked is the need to make sure that the boundary conditions are properly represented. The heat exchange between a furnace and a sample is extremely complex and many times simplifications relevant to furnaces are not valid for fires. It is essential to understand all those simplifications.

The differences between furnace behaviour and fire behaviour are all manifested in the boundary condition associated with Equation (1).

When defining the total heat flux: $\dot{q}''_{Tot}$, it is common to utilize a constant convective heat transfer coefficient (a common value used is 23 W/m^{2}K) and a constant emissivity (a common value used is 0.9) (Drysdale, 1998). These are the single parameters used in the boundary condition applied to the solution of an equation like Equation (3) when modelling the furnace data.

In the furnace the convective component of the total heat flux has been well characterized and is defined as

$$\dot{q}''_{con} = h_c(T_g - T_{i,0}) \tag{6}$$

Where T_g is the gas temperature of the furnace and $T_{i,0}$ the surface temperature of the insulation. And as mentioned before, it is typical that the constant $h_c = 23$ W/m^{2}K.

Radiation exchange should be defined in the following manner

$$\dot{q}''_{rad} = \dot{q}''_{rad,W} + \dot{q}''_{rad,g} \tag{7}$$

For a furnace

$$\dot{q}''_{rad,g} = \varepsilon_g \sigma(T_g^4 - T_{i,0}^4) \tag{8}$$

Where T_g is the gas temperature and e_g is the emissivity of the gas. The emissivity of the gas has been quoted to be between 0.2-0.3 (Bohm and Hadvig, 1983) due to the lack of soot particles, nevertheless many times it is approximated to zero for the furnace. For a fire, emissivities are above 0.8 due to the black smoke [49], thus it is common practise to approximate the emissivity to 1. So for the gas radiation:

$$\text{Furnace:} \quad \dot{q}''_{rad,g} = \varepsilon_g \sigma(T_g^4 - T_{i,0}^4) \approx 0 \tag{9}$$

$$\text{Fire:} \quad \dot{q}''_{rad,g} = \sigma(T_g^4 - T_{i,0}^4) \tag{10}$$

Radiation in between a structural element (sub-index 1) and a wall (sub-index 2) is defined as

$$\dot{q}''_{rad,W} = \frac{\sigma(T_{i,0}^4 - T_W^4)}{\frac{1-\varepsilon_1}{A_1\varepsilon_1} + \frac{1}{A_1 F_{1-2}} + \frac{1-\varepsilon_2}{A_2\varepsilon_2}} e^{-xL} \tag{11}$$

Where "*A*" is the area, F_{1-2} the view factor, T_W the wall temperature, κ the extinction coefficient of the gas between the wall and the structural element, and *L* the distance between the wall and the structural element. For the furnace, $\kappa \approx 0$ and for a fire κ is very large($\kappa \rightarrow \infty$) thus

$$\text{Furnace:} \quad \dot{q}''_{rad,W} = \frac{\sigma(T_{i,0}^4 - T_W^4)}{\frac{1-\varepsilon_1}{A_1\varepsilon_1} + \frac{1}{A_1 F_{1-2}} + \frac{1-\varepsilon_2}{A_2\varepsilon_2}} \tag{12}$$

$$\text{Fire:} \quad \dot{q}''_{rad,W} \approx 0 \tag{13}$$

Therefore the total heat flux to the surface is therefore defined as:

$$\text{Furnace:} \quad \dot{q}''_{Tot} = h_c(T_g - T_{i,0}) + \frac{\sigma(T_{i,0}^4 - T_W^4)}{\frac{1-\varepsilon_1}{A_1\varepsilon_1} + \frac{1}{A_1 F_{1-2}} + \frac{1-\varepsilon_2}{A_2\varepsilon_2}} \tag{14}$$

$$\text{Fire:} \quad \dot{q}''_{Tot} = h_c(T_g - T_{i,0}) + \sigma(T_g^4 - T_{i,0}^4) \tag{15}$$

As it can be seen, furnace and fire have very different heat fluxes, one coming mainly from the walls of the furnace and the other from the hot smoke close to the structural element.

The fundamental message behind this section is that furnaces and fires are very different in nature and any use that is made of the furnace requires a detailed analysis of heat transfer. Equations (14) and (15) provide the coarsest possible simplification that can be made of the heat transfer within a fire and a furnace. While in the case of a fire the interaction between the optically thick smoke and the structure allows the use of a single gas temperature, the complexity relies on the description of the heat transfer coefficients. In the case of the furnace, the optically thin medium requires the inevitable introduction of two temperatures, that of the furnace lining and that of the gas, neither can be automatically neglected. Only under very specific conditions where thermal properties of the lining and the sample can be matched up, the exchange can be simplified to one of two temperatures. Therefore, it is clear that if any true performance assessment of a structure is to be done using furnace data, this will have to be resolved with great attention to the different forms of heat transfer.

3.3.4. (Vertical) compartmentation performance

As discussed above, the extended egress times intrinsic to tall buildings combined with the limited vertical evacuation routes force the evacuation strategy to operate in stages or phases. Occupants not immediately adjacent to the floor of fire origin are left in-situ while those in more immediate danger are evacuated. Fire Fighters may also then make use of the vertical passages in order to fight the fire from within should it be situated out with the reach of their ladders / platforms. In order that occupants can remain safely in-situ, adequate vertical compartmentation must be provided in support of the evacuation strategy. It is essential that the fire be prevented from spreading upwards or downwards from the floor of origin, endangering the lives of those waiting on more remote floors.

Internally, the floor slab provides a robust barrier so long as it remains firmly supported by the structure. Historically, an extension of the floor slab past the external façade would provide a means of inhibiting external fire spread (Fig. 5(a)). However changes in building technologies to meet architectural, sustainable and economic ob-

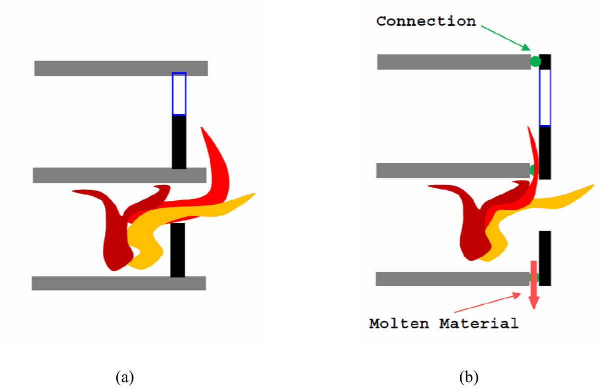

Figure 5. The images show an idealized representation of the change in floor slab - façade connection from (a) the pre-curtain wall method where the slab formed a continuous barrier between floors, and (b) the modern approach where the façade system is the continuous barrier.

jectives has seen the wholesale introduction of the use of curtain walling offering compartmentation challenges which the construction industry has not fully accounted for. Not only has the curtain wall transformed the method by which vertical compartmentation is achieved; it has also introduced flammable materials into both the wall linings and external cladding. The methodologies used to define the fire resistance of these systems have not evolved since the late 1970's and these standardized methods do not take into account deformations possible with evolving fires (Fig. 5(b)).

The deformation of the system as a whole when exposed to fire can expose gaps and flammable materials which can lead to spread both upwards through flaming, and downwards through dripping molten materials. Once fire starts spreading away from the floor of origin the safety of the occupants is compromised. Figure 6 below demonstrates the number of instances of reported vertical fire spread. The data demonstrated some ten cases of fire spreading to three or more floors. The most severe cases re-

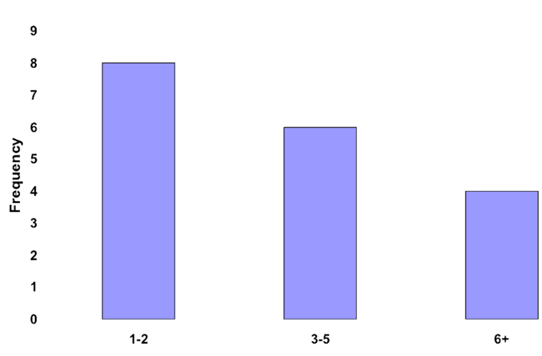

Figure 6. The chart demonstrates the occurrence of multiple-floor fires, indicating the number of floors reached by the fire beyond the floor of origin. The 18 cases of spread beyond the floor of origin represents just over a third of the surveyed buildings.

ported were:

- Las Vegas Hilton, USA: 22 Storeys in approximately 25 minutes
- Caracas Tower, Venezuela: 17 floors in a 24 hour period
- Windsor Tower, Spain: 19 floors, ~7 hours for spread, 24 hours total fire duration
- TVCC Tower, China: 44 floors, around 15 minutes

In the case of the TVCC Tower, fire spread was predominantly external following an ignition in the cladding from a firework. In the case of the Windsor Tower, spread was a mixture of internal and external, travelling both upward and downward (Fletcher, 2009). Upward fire spread was reported at a rate of approximately 6.5 minutes per floor, whereas downward was a slower 20-30 minutes per floor. Generally though, vertical fire spread was attributed to spread internally (ducts, shafts, penetrations etc.). A fire of this nature will generally propagate extremely quickly without any hope of being controlled by sprinklers and has the potential of almost simultaneously compromising the life of everyone remaining within the building. Thus the thermal loading imposed by the fire and the mechanical forces generated by the thermally induced deformations of the structure is key to understanding holistic façade system performance. Once again, correctly defining the design fire as an input for this design process becomes a necessity for the provision of a fire safety strategy.

4. Guidance for Tall Building Fire Safety Design

In the ten years following the collapse of the WTC towers, society has demanded answers as to why such a catastrophic outcome could occur. The unprecedented nature of the event resulted in the largest forensic investigation in the history of fire safety engineering. As alluded to earlier, this has resulted in societal pressure to produce guidance on fire safety design for tall buildings. The most recent and significant guidance produced (Guidelines for Designing Fire Safety in Very Tall Buildings) (SFPE, 2012) is analysed here in comparison to these authors' current conceptualisation of the problem and resulting performance objectives. The most striking aspect of this guidance, is that it fails to define the principle issues and thus the clear global performance objectives for tall buildings in the event of a fire. While defining every single issue that could occur in any building in the event of a fire together with a comprehensive list of tools at the disposal of the fire safety engineer, it does not provide the context of the problem in which the resulting strategy is required to operate.

In discussion of emergency egress, the SFPE guide highlights a wide range of options available to an engineer forming a egress strategy, in each case discussing the potential gain with respect to total egress time reduction associated to each strategy. The chapter relates that tall buildings result in exaggerated egress times so the engineer should consider pooling all available strategies in order to minimise egress times as far as possible. It does not however discuss the concept of egress times in terms of the wider context of the fire safety strategy, i.e., that the associated times will always be comparable to those of structural failure and thus the two are inevitably interlinked. Instead, it describes reliance on ever increasing levels of strategy and management complexity that the engineer could employ in an attempt to achieve reductions in overall egress times. It also advises of the significant potential for strategy failure, either complete or in part, generally for reasons associated to heat and smoke infiltration, and unknowns associated to occupant behaviour and breakdown in management. The overall message is one of a necessity for reliance on a complex solution with significant potential to lack robustness. Another source of egress guidance (Lay, 2010) focuses specifically on the justification of the use of elevators as a primary method of egress. The author propses that this should enable the use of a single stair system for an unlimited building height given the appropriate occupancy and egress strategy / philosophy. Regardless of the level of correctness behind the justification given for this solution, it remains fundamentally reliant on vertical compartmentation, successful occupant management, and core robustness.

As discussed in this paper, a tall building fire safety strategy needs to be built on the understanding that evacuation will take a significant length of time, akin to that of structural system failure times, no matter how well optimised the procedure(s) in place. The SFPE guidance (SFPE, 2012) alludes to this principle; "In order to make use of any of these strategies, it is important that a structural analysis of the building design is also completed to demonstrate that the integrity of the building and its systems during design fires/events under consideration." This is a hugely important statement acknowledging that every element of the egress strategy becomes null and void if the structure does not stand, yet it is not afforded significant discussion, and only mildly reflected in the chapter on fire resistance. This statement also alludes to the importance of the design fire in providing this underpinning element of emergency egress while likewise failing to adequately address its importance.

From a structural performance perspective, an important lesson resulting from the WTC failures (NIST, 2005, 2008, Usmani et al., 2003), which reinforced the lessons that came out of the Cardington Fire Tests (Martin and Moore, 1997), is that prescriptive fire resistance ratings of individual building elements do not guarantee a building system that as a whole will perform adequately. As identified above, extended evacuation times necessitate holistic structural performance. The SFPE guidance document repeatedly alludes to this fact yet does not state clearly and definitively that this the case and thus that design solely by means of resistance ratings implies acceptance of ignorance with respect to the level of structural performance in fire. Indeed, while repeated making such allusions and declining to make a definitive statement, the document does state that, "Catalogues of fire tested elements are available (such as the UL Fire Resistance Directory), and it is possible to assemble a complete building from such components." By failing to clearly formulate and describe the critical role that adequate structural performance plays in a complete and integrated design of a tall building fire safety strategy, the weight that this statement carries combined with the lack of emphasis of the limitations of such a system is a significant omission. Again there is discussion of the potential for a variety of fire types to exist and acknowledgement that they may induce different behaviours in the structure. There is also recognition of the potentially detrimental effects of both heating and cooling as well as other fire induced behaviours such as concrete spalling. With this in mind, it is illogical that prescriptive design by fire resistance ratings can be presented alongside holistic performance-based analysis as a method to provide an adequately fire resistant structural system.

A similar pattern emerges when discussing façade performance. The SFPE document provides a thorough and clear description of the mechanisms that can lead to vertical fire spread when considering modern configurations. It clearly describes the variables with respect to façade configurations that affect flame behaviour at the building perimeter and the considerations. Like other chapters though, it lacks the context describing the critical importance of preventing vertical fire spread within the overall fire safety strategy and the effect of failure on the egress strategy and the structural resistance. While discussing at length the various individual elements of the fire safety strategy deemed critical by this paper, the new SFPE Guidelines (2012) do not discuss and convey the importance of the interrelatedness of these problems and as such, their importance in the context of the global fire safety strategy is lost. In failing to conceptualize the interrelatedness of the issues affecting tall building fire safety, the document thus also fails to identify essential performance objectives. Given the highly optimized and engineered nature of the tall building system, only an optimized, holistic performance based solution, addressing each aspect of the problem in consideration of the others, will be capable of providing adequate safety. Such a solution requires a proper understanding of the problem. The guide instead advocates an extended application of traditional prescriptive solutions; the engineer needs to provide extra levels of redundancy and prescriptive complexity when considering a tall building system, rather that attempt to quantify the overall system performance. A decision as to which of the multitude of available options to use and why one may be more relevant given the context is left to the designer. The critical issue is that purely prescriptive design, while having the potential to be perfectly safe, does not verify whether that potential has been realized.

5. A Design Fire for the Design of Tall Buildings

The common theme underpinning the robust provision of the fire safety strategy for tall buildings is the description of the fire. If not adequately provided, the fire safety strategy cannot be sufficiently optimised and still be said to be robust. The results of the Cardington Tests (Martin and Moore, 1997) and the subsequent increase in sophistication of finite element modelling (FEM) showed that structural systems need to be analysed holistically in order to truly understand how a system will perform under fire loading. Crucially though, while the structural analysis side of this process evolved with this new knowledge, the fire loading that is prescribed during this holistic modelling still adopts the same forms such as the Standard Fire (ISO, 1994) and Pettersson's Parametric Curves (Pettersson et al., 1976), which are neither realistic nor necessarily conservative.

The experimental basis upon which all these methods were founded uses a small cubic compartment (generally ~4 m side), and thus has little relevance when applied to large open floorplans. Majdalani and Torero (2011) in their revisiting of literature on post-flashover fires have demonstrated that initially, two regimes of post-flashover compartment fires were identified (Thomas, 1967). Regime 1, the under-ventilated post-flashover fire, is typical of a smaller compartment with basic (limited) openings. Regime 2, the over-ventilated post-flashover fire is likely to occur in larger spaces with larger openings and thus plenty of air to feed the fire. Regime 1 being both better understood from a technical point of view and more typical of the smaller compartmentation of the time at which the underpinning research was completed, became the basis of the description description of compartment fire dynamics. Regime 2 was far less physically understood and far less likely to occur in practice, thus was sidelined as a direction for research where it has largely remained. Crucially now though its irrelevance can no longer be justified, as open floorplans with highly glazed perimeters have become the norm and innovation has moved the typical scenario away from our base description of under-ventilated post-flashover compartment fire dynamics.

The WTC fires, in particular WTC-7, showed that fully developed fires in open floorplan offices travel through large compartments generating both areas of intense localised heating, and of slow pre-heating, as well as areas of cooling. These occur simultaneously within the floor naturally producing both "long-cold fires" and "short-hot fires" (per the nomenclature of Lamont et al. (2004)) as well as asymmetries introduced through differential thermal expansion. All these scenarios have been demonstrated to induce unique structural behaviour and it is the combinations of these characteristics that provide the true test of a structure's performance. An assessment of existing compartment fire data by Stern-Gottfried et al. (2010) provides evidence that significant spatial temperature gradients exist even in small compartments. Jowsey et al. (2007) demonstrate that the effects of these heterogeneities are emphasised when translating temperature into heat fluxes to define the thermal loading.

With the acceptance of performance based design solutions in complex infrastructure, there followed a rush to define alternatives to the standard fire curves, driven largely by industry desire to optimise designs. While stopgap methodologies have been established (Stern-Gottfried and Rein, 2012a, 2012b) that incorporate travelling and heterogeneous fires to the calculation of the boundary condition for structural FEM analyses and potentially provide an adequate approach for design, the fundamental basis of these tools is in correlations derived from small compartment fire data, analysed and extrapolated via CFD models that have not been validated for that purpose. NIST followed a similar approach in their forensic study of WTC 1, 2 & 7 (NIST, 2005, 2008) but using video images to calibrate the model. While this approach can provide an accurate description *a posteriori*, it cannot be used for design. The method developed by Stern-Gottfried et al. (2012a) offers a further methodology that divides the compartment into near and far field. The result is a family of curves that pose different challenges to the design. Again though, this method uses models and simplifications that while generally appropriate have not been fully validated for or developed within the framework of the open plan scenarios typically posed by tall buildings and indeed the majority of modern infrastructure. Nevertheless, these methods of analysis have been adopted and used by the fire safety engineering practice.

6. Conclusions

Failure provides a great motivation for us to assess the limitations of our tools. These tools can be anything from best practice guidelines to prescriptive codes, analytical expressions to complex computational models. If we never loose perspective of the limitations of these tools, we will always recognise in advance when we need to refine or even redefine them. The limitations of our tools are defined by the knowledge and scenarios on which they are based and our knowledge of how these tools can be scaled to larger problems.

The numbers of tall and very tall buildings are increasing year upon year and, as ever, society demands that an acceptable level of safety is provided. Through this paper evidence is presented that the unique challenge that current tall buildings present are too far removed from the basis on which prescriptive requirements were founded. Thus inevitably, performance based design becomes essential.

A performance based design is only relevant given a complete assessment of the problem i.e., the goals that the design must achieve. The most significant design guidance unveiled thus far fails to conceptualise the implications that current tall buildings present to the traditional fire safety approach.

When the strategy as a whole is dissected, it is evident that the ability to provide such performance hinges on our ability to describe the fire dynamics in the spaces typical of tall buildings. Historically, an atypical regime of fire dynamics was identified (over-ventilated post-flashover), but at the time deemed irrelevant given the conventional compartmentation of the era. Prescriptive fire safety tools were thus built on a regime that has since become somewhat irrelevant in the context of many tall buildings. Only once we understand fires in modern compartments can we truly assess the critical components of the fire safety strategy and begin to provide relevant, refined, innovative fire safety that truly reflects the nature of tall buildings.

Acknowledgements

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Appendix A. Survey Details

Buildings surveyed to establish failure rates of the critical elements of tall building fire safety strategies.

Building Name	Location	Floors	Pressurisation / Extraction	Smoke in Stair	Vertical Fire Spread	Structural Damage
Alexis Nihon Plaza	Montreal, Canada	15	No	Yes	Yes	Localised
Schomberg Plaza	New York, USA	35	Unknown	No	Yes	No
One Meridian Plaza	Philadelphia, USA	38	No	Yes	Yes	Localised
Interstate Bank Building	L.A., USA	62	Yes	Yes	Yes	Localised
New York City Bank Building	New York, USA	42	Yes	Yes	Yes	Localised
High Rise Office	Atlanta, USA	10	No	Yes	No	No
Clearwater Condominium	Clearwater, USA	11	No	Yes	No	No
Residential High Rise	New York, USA	29	No	Yes	No	No
Prudential Building	Boston, USA	52	Yes	Yes	No	No
Rockefeller Centre	New York, USA	11	Yes - 1 Stair	Yes - Not in Pressurised	Yes	No
Howard Johnson Hotel	Orlando, USA	14	No	Yes	Yes	No
Alexander Hamilton Hotel	Paterson, USA	8	Unknown	Yes	No	No
Cook County Administration Building	Chicago, USA	37	Yes	Yes	No	No
John Sevier Centre	Johnson City, USA	11	Yes	Yes	Yes	No
MGM Grand Hotel	Las Vegas, USA	21	Yes	Yes	No	Localised
Garley Office Building	Honk Kong	16	Unknown	No	Yes	No
Royal Jomtien Resort	Thailand	17	No	Yes	No	No
Windsor Tower	Madrid, Spain	32	Unknown	Yes	Yes	Partial Collapse
Parque Central East Tower	Caracas, Venezuela	56	No	Unknown	Yes	Localised
TVCC Tower	Beijing, China	44	Unknown	Unknown	Yes	Unknown
Four Leaf Tower Condominium	Houston, USA	41	Yes	Yes	Yes	No
Westin Hotel	Boston, USA	38	Yes	Yes	No	No
Howard Johnson Hotel	Cambridge, USA	11	Unknown	Unknown	No	No
Lakanal House	Camberwell, USA	12	Unknown	Unknown	Yes	No
Toryglen Residential Tower	Glasgow, UK	20+	Unknown	Unknown	No	No
Great Western Road	Glasgow, UK	12	Unknown	Unknown	No	No
Waddell Court	Glasgow, UK	18	Unknown	Unknown	No	No
Las Vegas Hilton	Las Vegas, USA	30	Yes	Yes	Yes	No
50 St Apartment Building	New York, USA	10	No	Yes	Yes	Localised
Dupont Plaza Hotel	San Juan, Puerto Rico	20	No	Yes	No	Localised
Alexandria Condominium	Alexandria, USA	18	Unknown	Yes	No	No
Vandalia Avenue Apartment Building	New York, USA	10	Unknown	Unknown	No	No

Building Name	Location	Floors	Pressurisation / Extraction	Smoke in Stair	Vertical Fire Spread	Structural Damage
Vandalia Avenue Apartment Building	New York, USA	10	Unknown	Unknown	No	No
Apartment Block	Missouri, USA	27	Unknown	Unknown	No	No
Great Thornton St	Hull, UK	15	Unknown	Unknown	No	No
Montrose Avenue	New York, USA	16	Unknown	Unknown	No	No
La Frak City Apartments	New York, USA	16	Unknown	Unknown	No	No
Park Avenue, Bronx	New York, USA	20	Unknown	Unknown	No	No
Beach Channel Drive	New York, USA	13	Unknown	Unknown	No	No
Lincoln Place	New York, USA	42	Unknown	Unknown	No	No
West 60th Street	New York, USA	51	Unknown	Unknown	No	No
Waterside Plaza	New York, USA	37	Unknown	Unknown	Yes	No
Confucius Place	New York, USA	44	Unknown	Unknown	No	No
Beach Channel Drive	New York, USA	13	Unknown	Unknown	No	No
Moshulu Parkway	New York, USA	41	Unknown	Unknown	Yes	No
Bedford Avenue	New York, USA	25	Unknown	Unknown	No	No
Grand Avenue	New York, USA	26	Unknown	Unknown	No	No
Shutter Avenue	New York, USA	22	Unknown	Unknown	No	No
WTC 1	New York, USA	110	No	N/A	No	Complete collapse
WTC 2	New York, USA	110	No	N/A	No	Complete collapse
WTC 7	New York, USA	47	Unknown	Unknown	No	Complete collapse

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