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The Risk Imposed by Fire to Buildings and How to Address It

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Abstract

The history of fire science originates in the desire to enhance destruction of infrastructure by means of fire. Many of the basic principles of fire growth and the behaviour of structures in fire were developed within the context of an organized and deliberate attempt to use fire as a tool for urban destruction. Buildings are inherently vulnerable to fire due to their use, thus they have to be designed with the objective of minimizing the probability of fire occurrence and of damage potential. Nevertheless, the design criteria rely mostly on scenarios that are considered to be consistent with the building use. Within the design process there is no consideration to premeditated fires or those corresponding to a strategy for destruction. Furthermore, generally design is done in a prescriptive manner and thus is framed by rules and regulations that do not provide an estimate of performance. Only a detailed understanding of the performance of a building or structure in the event of a fire can allow estimating and understanding its vulnerabilities and can result in a strategy to minimize the impact of fire as a tool for terrorism.

Introduction

The introduction of practises that result in an increase level of safety dates probably to ancient times. Observations of the devastating effects of fires lead from very early on to the establishment of prescriptive requirements. These requirements can stand on very basic principles such as building separation and maximum escape distances or on more complex specifications like the need for sprinkler systems and compartmentation. These requirements became formalized at the beginning of the 20th Century in a series of codes and standards. A good example is the fire resistance standard test methods and the “Standard Fire” curve embedded in it. This standard prevails as a commonly used method to assess the performance of structural elements in a fire [1]. The first building codes in the USA where developed after the Baltimore Fire in 1904. Since then, institutions like the National Fire Protection Association (NFPA) and Underwriters Laboratories have guided the development of codes and standard test methods, NFPA started in 1896 and Underwriters Laboratories in 1900. A similar history can be constructed for many countries. Since its initial formalization “fire safety” has been prescriptive, and despite the technical origin and empirical observations supporting most standards, these are incapable of assessing the performance of a building in the event of a fire. Instead they assume adequate levels of safety based on the scientific and empirical information that forms the basis to the codes. Clearly, scenarios that escape the experiments that support the standards result in undefined safety levels.

Systematic generation of scenarios that escape the prescriptive design specifications became a destruction tool during World War II and the origin of modern fire science. Hoyt Hottel describes in great detail the process that lead to the establishment of active fire research programmes at Harvard and MIT, in the United States, as part of the war effort and with the specific objective of maximizing urban destruction via fire [2]. Hottel indicates that a meeting of the National Defence Research Committee convened by the presidents of Harvard and MIT in 1941 concentrated on the replacement of magnesium and rubber-thickened naphtha as incendiaries and on the radiative ignition of wood. This meeting lead to what might be considered one of the first 20th Century explicit scientific publications on fire research [3]. A number of well known discoveries followed this initiative, among the best known is the generation of Napalm by Louis Fieser (Harvard University). Already, by 1942, gasoline thickeners such as Napalm where being tested to demonstrate their fire setting potential on wooden structures. Architects Mendelshon (of German Background) and Raymond (with 18 years of practice in Tokyo) where then summoned to carefully design structures that resembled those present in German and Japanese cities. Careful attention was given to between floor and ceiling cinders developed in Germany to stop the lateral spread of fire. Test of incendiary bombs were carried on these structures in May 1943. Similar studies where simultaneously in progress in Britain under Professors Finch and Egerton at Imperial College.

Wartime events show that society has recognized the potential of fire as a tool for deliberate destruction and as a mechanism to undermine morale. Furthermore, it brought top scientist to recognize this potential and devote their careers to the study of fire. The war effort focused on destruction was thus followed by a peace effort focused on understanding, controlling and preventing fires. In 1956 a Committee on Fire Research was formed bringing Professor Howard Emmons from Harvard University, a participant of the war fire research programme, into the centre of post-war fire research. Howard Emmons is now regarded as the father of modern fire science. The efforts of Howard Emmons lead to the Fire Research and Safety Act of 1967 and the formation of the Fire Centre at the National Bureau of Standards. A similar process followed the war in the United Kingdom through the Fire Research Station at the Building Research Establishment (BRE) and in Japan through the Building Research Institute (BRI). Notable are the scientific contributions of Thomas and Kawagoe.

The post war efforts lead to dramatic progress in the understanding of fire and the recognition of the vulnerabilities inherent to prescriptive design of infrastructure. Scientifically based tools that quantify fire growth, its impact on buildings, fire detection, smoke management and suppression followed [4]. These tools strengthen the believe that building design can include elements of performance. Thus performance-based design alternatives for fire have been subsequently included in many legal frameworks around the world [5]. Performance based design has the capability of enabling predictions of the behaviour of a building in the event of any particular scenario, therefore is ideally suited to lead to solutions that respond well to premeditated fires, resulting arson, war or terrorism. This paper will discuss the current state of the art of performance-based design for fire in what relates to premeditated events.

Principles of Performance Based Design

It was indicated above that from the perspective of a Fire Safety, the design of a building can be approached in two different ways. The first is for the building to comply with existing regulations, and the second one is to achieve certain safety goals. Regulations have not been developed to fully specify the design of unique and complex buildings such as high rise buildings and even, in the event that they existed, they are of questionable effectiveness. Furthermore, if a scenario such as the one of September 11th, 2001 needs to be considered as a possible event during the life of the building, design on the basis of safety goals is the only path that can be followed. This section will illustrate a simple framework that describes the concept of performance-based design for fire.

The schematic presented in Figure 1 could represent the behaviour of a building in the event of a fire. It could be argued that the safety objective should be that the time to evacuation (t_e) at each compartment (i.e. room of origin, floor, building) be much smaller that time necessary to reach untenable conditions in the particular compartment (t_f). Characteristic values of t_e and t_f can be established for different levels of containment, room of origin, floor, building. Furthermore, it is necessary for the evacuation time to be much smaller than the time when structural integrity starts to be compromised (t_S).

In summary:

$$t_e \ll t_f$$

$$t_e \ll t_S$$

It could be added to these goals that full structural collapse is an undesirable event, therefore:

$$t_S \rightarrow \infty$$

Although these criteria for safety times can be considered as a simplified statement, it is clear that it describes well the main goals of fire protection.

With the objective of achieving these goals a number of safety strategies are put in place. These include those strategies that are meant to increase t_f which include active systems, such as sprinklers, or the intervention of the fire service. As shown by Figure 1 (dotted lines), success of these strategies can result in control or suppression of the fire. Passive protection such as thermal insulation of structural elements becomes part of the design with the purpose of increasing t_S. Finally, but most important, evacuation protocols and routes are designed to minimize t_e at all stages of the building. It is important to note that within the estimation of t_e the safe operations of the fire service need to be included.

The events following the attack on the World Trade Center showed that these safety goals were not attained and illustrated why it is essential to have the best possible understanding of how structures will behave in the event of a fire. For this purpose an adequate understanding of the nature of the possible event and the characteristic of the structure and its safety systems is necessary. This requires a detailed understanding of the fire conditions, the interactions between the fire and the structural elements and the sequence of the intervention and evacuation processes. Different methodologies and tools have been developed to study each of these aspects and to quantify the different values to t_e, t_f and t_S, nevertheless many gaps of knowledge are still evident.

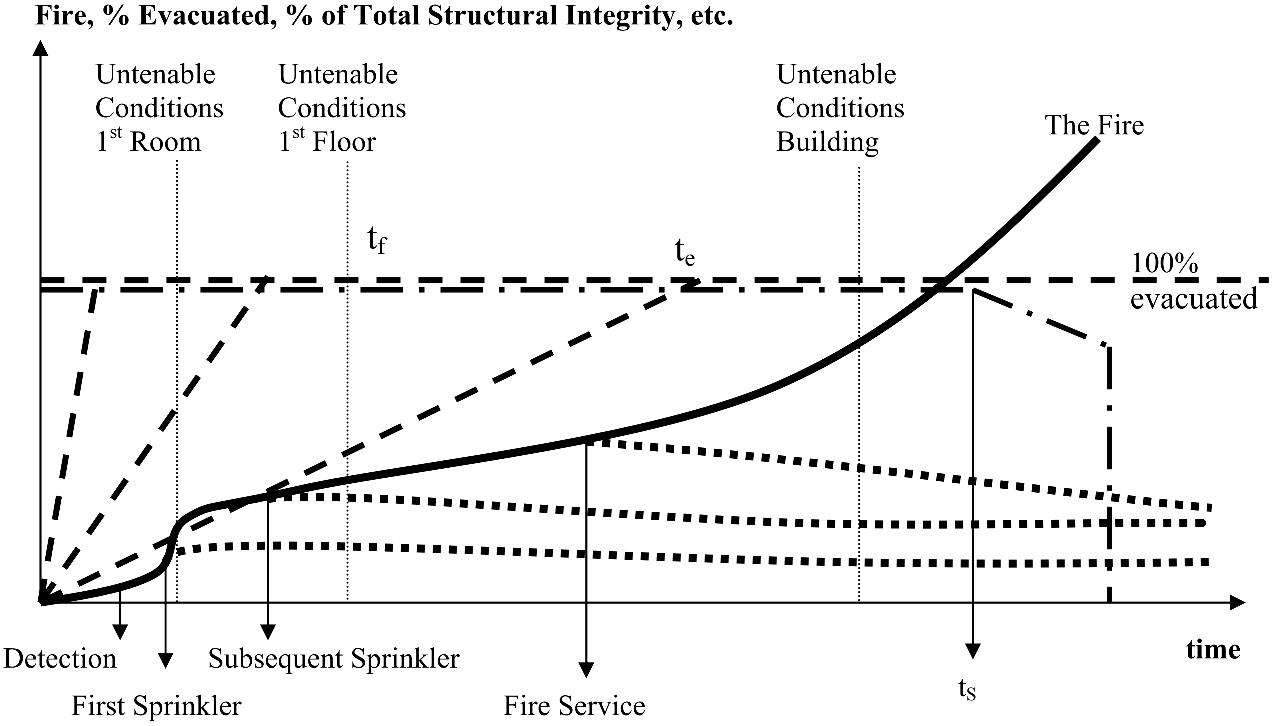

Figure 1 Schematic of the sequence of events following the onset of a fire in a multiple story building. The thick line corresponds to the "fire size," the dotted lines to the possible outcome of the different forms of intervention (sprinkler activation, fire service). The dashed lines are the percentage of people evacuated, with the ultimate goal of 100% represented by a horizontal dashed line. The dashed & dotted line corresponds to the percentage of the full structural integrity of the building.

Current Engineering Methodology

Disasters, whether natural or manmade, are a test to design practices and in many cases prove the vulnerability of our infrastructure. Disasters force us to revisit our perception of the safety inherent to the environment in which we carry our everyday activities. Therefore, associated to disasters there is always anxiety and pressure to revisit those practices that lead to unsatisfactory performance. The behaviour of structures in a fire has faced, in the events of September 11th 2001, one of those disasters that have directly challenged our current design practices. Anxiety has spread over those individuals linked to infrastructure that can be considered as potential targets for terrorist activity. As we understand more about what happened with the World Trade Center Buildings questions are being raised about our current design practices, proposed amendments and the tools that we use to evaluate the performance of structures in the event of a fire. Furthermore, as mentioned before, the collapse of the World Trade Center buildings 1, 2 and 7 occurred within a period where design practices were being pushed out of an environment of prescriptive requirements to one where structures will be evaluated on the basis of their performance as predicted by engineering tools.

To analyse the response of the designers to this disaster it is necessary to pose a series of questions. The first question relates to the actual nature of the disaster that is provoking the reaction. Why did these buildings collapsed carrying the lives of so many people? The answer to this question will be the product of a forensic investigation [6] that we do not intend to discuss here. Nevertheless, from this investigation will result different conclusions, some pertaining to the nature of the event, some pertaining to the nature of the buildings themselves and some pertaining to the design and construction practices involved in the development of these buildings. The latter point is the one of greatest interest to the public since it is associated to the safety of current and future buildings designed under the same principles. Significant information on the advantages and limitations of current design practices has already emerged from this introspection. The general question then becomes: in which way is fire incorporated into the design of structures? This question is then followed by a series of interrogations that relate to the details of the design practice, which are of a more fundamental nature but still directly concern the safety of our built environments.

Deepening into the detailed processes, a fire affects a structure through the heat it supplies to all the constructive elements. Thus the first pillar of a design process is the understanding of the fire, the growth process it undergoes and the heat it supplies to the structural elements. In other words, the different values of t_f need to be quantified. As much as it is clear to everyone that a fire affects a structure, it is not as common to understand how a structure can have an impact on the growth of a fire. Nevertheless, it is the case that as the structure heats-up energy will be provided by the structural elements to the fuels enhancing the rates of fire growth. Furthermore, deformation and failure of different structural components will affect the air supply to the fire and consequently the heat released. As a result structural and fire behaviour are coupled (t_S and t_f depend on each other). Once the relationship between the fire and the structural elements has been defined it is important to understand how the structure will react to that external heat input. Material properties will change and it is accepted that all parameters describing the material strength will deteriorate, but this is only one part of the process. The geometrical features of structures are also affected by fire since materials expand with temperature and the constraints inherent to the geometry of the structure result in significant generation and redistribution of stresses.

Once these fundamental questions have been addressed it is important to establish sources of uncertainty. Uncertainty or “error” can range from the purely probabilistic nature of the fire event to deterministic estimation of the variability of the thermal properties of insulation materials used for fireproofing. The combination of analysis on the basis of fundamental physical principles, simplifying assumptions and error estimates represent the design tools. Structural Fire Safety Engineers have numerous tools that can provide quantitative estimates of the performance of a structure in the event of a fire (i.e. t_S).

The design tools used by engineers address the different aspects explained in the previous paragraph. It will be the designers' hope that all these tools were based on sound and fundamental engineering principles and that the answers obtained were exact thus include no potential for "error" or "variability." The reality is that fire and structures are very complex problems whose complexity increases exponentially when coupled. No tool can solve the integrity of the structures in fire problem, thus all tools rely on a number of assumptions. Many of these assumptions have been thoroughly studied, their error bars established and their results validated. Therefore, it has been the believe of the designer that the tools provide accurate and robust results that have been the basis of the design process.

The progression towards performance and the precedent set by the collapse of the World Trade Center buildings require from the engineer to revisit the design procedures and the tools with the objective of improving, modifying and gaining confidence. The following paragraphs will schematise design practices commonly used and present those areas that are being revisited through fundamental research.

Table 1 provides an attempt to schematise some of the design methods commonly used to analyse the performance of structures in the event of a fire. The design framework defines a sequence of events. The architects provide a design from which the structural engineers will develop a structural analysis that will take into account all requirements that will guarantee that the building will support its own weight and perform adequately to its intended use. The architectural design and structural analysis do not include at this stage the potential for a fire. Any considerations for fire introduced by architects at this point are mostly associated with prescriptive requirements but include no evaluation of the impact that these measures can have on the structure's performance. Once the structure has been designed the fire needs to be incorporated. This can be done either through prescriptive requirements that are fundamentally based on the use of the building or through an engineered analysis of structural performance. The former provides no indication of the behaviour of the structure in the event of a fire thus is unsuitable for any event that will escape the range covered by the historical data that support prescriptive design. An important aspect of the latter methodology is to establish a design fire. The choice of design fires can be achieved in a number of different ways. It could include a series of most probable events, "worst case scenarios" or could lead to the definition of protection systems and maintenance protocols that will constrain the fires to an acceptable level. The main limitation of the "Design Fires" is that any event (i.e. terrorist attack, arson) that escapes the chosen range of fires could lead to an unacceptable performance. A further limitation of this approach is that definitions such as "worst case scenario" or "most probable event" are difficult to establish. The outcome variables such as structural behaviour, life safety, property damage are all coupled and in most cases a function that minimizes all negative outcomes is not possible. Probability based decisions are limited by then lack of a comprehensive set of statistics. Fires are, by definition, rare events. Given a building, its usage, its life and the potential threats, it is for many cases difficult to establish a probability database that gives adequate confidence.

Given the “Design Fires” a series of sophisticated tools can be used to establish the growth of the fire and its impact on the structure. The main constraint of these tools is associated to the interface between the fire and the structure. Most models are computationally intensive therefore solutions are obtained for the fire without accounting for the structure and the impact that its heating can have on the fire. Furthermore, close to the interface there is significant uncertainty associated to the performance of these tools. Finally most tools treat fire protection devices, such as sprinklers or smoke extraction systems, in a very crude manner.

The coupling of the structure and the fire is then done in an artificial manner. The classical approach is to test each individual element against a standard fire curve and obtain a rating that indicates the time lag until the structural element reaches a pre-defined critical temperature. Time to failure is the fine when an individual component reaches the critical temperature. The test could be substituted by calculations that use as input the standard fire (ISO-834 [1]), “parametric curves” [7], or the output of the calculations performed from the design fires. It has long been recognized that fires are affected by multiple factors, thus a single “standard fire” does not suffice. On the basis of this, time equivalences between the standard tests, the “parametric curves” and “computed fires” can be established [8]. The last stage of the design process is to introduce fire proofing to obtain the desired rating. Numerous methods exist to establish the required insulation [9] but they all imply a component of empirical data and uncertainty. As indicated in Table 1, this component of the design process has strong limitations and represents a very active area of research. These limitations and the proposed solutions will be discussed in a later section of this paper.

The above description clearly establishes areas where improvements can be made and that represent the new face of structural design for fire. There is a strong evolution towards an integrated design process that incorporates fire behaviour into the architectural and structural design processes. The benefits of this approach are significant because it allows optimisation of the structural design to meet the architectural, structural and fire safety needs. To achieve integration it is necessary to address areas where the tools are not coupled, one important area is the interface between the structure and the fire. Numerical models used to predict structural behaviour and methods to quantify fire growth are being coupled to encompass the dynamic interactions between the fires and the structures [10]. Furthermore, optimisation of fire growth models has become necessary given the constant evolution of the architectural features of buildings.

Design Step	Tools	Assumptions	Limitations
Architectural Design			
Structural Design	Analytical design methodologies Experimental Values Finite Element Numerical Simulations	Structural design is conducted without the inclusion of a fire	The global evolution of the structure with the fire is not included as part of the evaluation of the design alternatives The uncertainty in the properties necessary for the calculations increases because high temperature data is limited and not-well-understood phenomena such as “spalling” needs to be included.
Design Fires	Historical evaluation of occurrence probabilities Analytical tools to quantify fire growth Numerical Simulations of Fire Growth (Zone Models, CFD Models) Empirical/Analytical/Numerical methods to analyse heat input to structures Fire Protection Methods (i.e. sprinklers, fuel control, venting) to define fire scenarios	The structure is design to fit a fire that has a high probability of occurrence. The definition of the fire is given on the basis of an assumed performance of a multiplicity of elements (i.e. smoke evacuation, sprinklers)	Ignores events that escape the pre-defined scenarios. The performance of these fire control elements has been defined only for a reduced number of conditions.
Fire Resistance	Standard testing of individual components to assess fire resistance (Fire Rating) Parametric Curves for more realistic scenarios	The fire can be defined by a standard Temperature vs. Time curve. The test furnace (ISO-834 [2]) provides a realistic representation of a fire. If the standard fire is deemed not to represent the “Design Fire” an equivalent Rating can be extracted from a different Temperature vs. Time curve (parametric curves) The feedback from the structure to the fire can be ignored. Failure is defined by attainment of a critical temperature of an individual structural element.	Does not address the fundamental heat transfer mechanisms controlling heat exchange between a fire and a structure Ignores the impact that geometrical effects have on structural behaviour (i.e. restraint thermal expansion) Time equivalencies are only valid for a very small set of conditions, many unrealistic to fires
Fire Protection	Fire Proofing to achieve required Fire Ratings	Properties of insulating material are well characterised An adequate extrapolation from furnace test behaviour to a real fire can be expected. Application, maintenance and life time have no bearing on the performance of fire proofing	There is not enough data to support the assumptions. Furnace can only be extrapolated to a fire for a very limited set of conditions.

Table 1 Commonly used design methods

The Broadgate Phase 8 fire in London, UK and the subsequent Cardington frame fire tests have allowed researchers to fully investigated and understand the behaviour of whole frame composite steel-concrete structures in response to fire [11, 12, 13]. In June 1990 a fire developed on the first floor of the 14-storey Broadgate building. The total duration of the fire was in excess of four-and-a-half hours, with a severe period for about two hours. Flames temperatures in excess of 1000°C were noted. The structure of the building consisted of composite steel deck/concrete floors. The steel structure was partially unprotected at this stage of the construction. Despite some large deflections, there was no collapse of any of the columns, beams, or floors. The Broadgate fire prompted BRE to conduct a large-scale test program on an 8 storey composite steel frame at their test facility in Cardington, UK. The Cardington Frame fire tests provided a wealth of experimental evidence about how whole frame composite steel-concrete structures behave in fire. The main conclusions were that composite framed structures possess reserves of strength by adopting large displacement configurations with catenary action in beams and tensile membrane behaviour in the slab [12, 13]. Furthermore, for most of the fire duration thermal expansion and thermal bowing of the structural elements rather than material degradation or gravity loading govern the response to fire. Large deflections were not a sign of instability and local buckling of beams helped thermal strains to move directly into deflections rather than cause high stress states in the structure. Only near failure, gravity loads and strength will again become critical factors. These findings and the additional motivation provided by the WTC collapses have resulted in drastic shift of the design process, away from fire resistance principles and towards a global structural analysis. Broadgate and WTC show two different potential outcomes that can only be predicted via a detailed global analysis of the structural behaviour through the fire event.

The need to use “Design Fires” still remains an unresolved problem. The volume of the calculations required to address the different aspects of a fire implies that only a reduced number of scenarios can be fully studied, thus educated engineering solutions are still necessary. Important strides are currently being made to optimise the necessary tools to allow for a more systematic evaluation of a multiplicity of scenarios where the “Design Fires” can be substituted by concepts such as design to obtain a “Minimum Damage Potential.”

The concept of a “Minimum Damage Potential” implies a systematic evaluation of the different physical variables that will control the growth of a fire, the

Current Practises and Environment

In the realm of fire safety, two distinct areas emerge, fire safety systems and structural fire safety. Fire safety systems include detection, suppression and smoke control systems as well as evacuation. Structural fire safety concerns the integrity of structural elements in the event of a fire. Building authorities will have to approve these designs thus justification for all departures from prescriptive rules will have to be justified and understood by those in charge of approval. Engineered solutions require deep understanding of all physical principles underpinning the design methodology as well as the modern tools used in the process of design (CFD Fire Codes, Finite Element Models, Evacuation Models). This level of understanding is currently only available to a very reduced number of professionals (for example approximately 30 new graduates enter the building-design and construction industry per year in the UK [14]).

Currently, architects receive a very restricted amount of information on fire safety matters, most of which is directed towards the understanding of prescriptive methods. Structural engineers follow a similar path. Fire Safety Engineers are a small minority that will only be consulted once a problem is identified [15]. Thus most Fire Safety Engineering professionals remain either in the Building Control areas, Fire Brigades or in consultancies. The result is an uncoupled approach to the design of structures to be fire safe.

Traditionally it has been assumed once the steel is protected, or enough concrete cover is provided, no further response in fire can be expected, nor any further improvements can be made to enhance a structures response to fire. But, as mentioned above, powerful analytical tools and comprehensive understanding as a result of Cardington (tests and modelling)[13] has enabled us to predict structural response to fire with a high level of detail evidencing some positive traits on our current design practices. The key findings from modelling Cardington were rather unexpected: Instead of showing how the declining strength of individual structural elements progressively destroys the strength of a frame, the calculations revealed that steel frame composite structures of this kind have large reserves of strength through adopting large displacement configurations, and that thermal expansion, not material degradation was the dominant phenomenon. This means that structures are far more robust in fire than previously understood, and that total reliance on passive fireproofing is unnecessary. Detailing of connections, core construction and design, even the span of the structural frame all contribute to the robust response of the building in fire. Current code fire ratings are not based on this understanding and as such can over or under estimate building safety in fire.

The realization that the geometrical characteristics of a structure can have a significant effect on the evolution of its strength in the event of a fire, opens the door to a much closer interaction between architects, structural and fire safety engineers. The basic architectural design of the built environment and its interpretation by a structural engineer now can be influenced by criteria that will make the structure safer.

Two important conclusions emerge from this new understanding. The first is that traditional ratings based on fireproofing and standard testing methodologies [1, 16, 17] are clearly insufficient when assessing the performance of a structure in the event of a fire. Current testing practices deliver information on the thermal behaviour of a structural element but do not establish its structural performance. An aposteriori analysis of the collapse of WTC 1 & 2 gives a good example of the limitations introduced when there is complete reliance on current testing practices [18].

The second conclusion indicates that an optimal solution can only be achieved if building geometry, structural design and fire safety considerations are included simultaneously in the design process. This requires convergence of architectural, structural and fire safety concepts. Integration of separate disciplines allows the development of buildings that are explicitly designed, more robust, more valuable, and satisfy better the needs and requirements of clients and society. It allows these integrated disciplines to develop innovative solutions and allows engineers and architects with a means of being more valuable.

It is important to note that both performance based design and integration of disciplines comes associated with a drastic increase in the average training provided to professionals exercising design and building control. Furthermore, tackling fire event in complex engineered buildings require a different level of skills from the fire brigade. Thus, in an ironic manner, authorities many times conclude that the elevated training requirements for those involved in the process is one of the main disadvantages of performance-based design [19] and thus forget that this problem can be resolved by consistent investment in higher education and research in this area.

The accelerating trend to depart from prescriptive regulations towards engineering solutions and the reduced number of properly trained professionals has begun to worry those involved in the process. A recent Scottish survey [20] of fire brigade and building control personnel, fire safety and civil engineering consultants as well as architects gave alarming results. When those surveyed were asked if they believed that there were sufficient amount of trained professionals to cope with the change, 100% of the fire engineers consulted responded that there was insufficient number of well trained professionals, 80% of all building control officials indicated that not only there was not enough well trained people but they recognized that many of those professionals competent in a prescriptive world will be significantly limited when addressing complex engineering solutions. A similar response was provided by 74% of those consulted within the fire brigades. Interestingly enough 76% of the civil engineers and 82% of the architects consulted believed that the knowledge base was there and the transition will represent no problem. Given the different training of all different groups it is easy to conclude that it is difficult to understand a problem when you do not know that the problem exists. Clearly, building designs currently deemed to spouse performance principles are being designed as hybrids that are unfortunately limited by prescription and by performance, thus the conclusion by Buchanan [17].

The Potential of Integrated Design in Fire

Integrated design of structures relies on the definition of built environments in a manner that will optimise "use" and "safety." Options can be analysed from the onset of the design process leading to a sequence of optimal decisions. The advantages of this approach are many.

- Integrated design allows for simultaneous optimisation of all variables.
- Architectural concepts can be tested to achieve optimal fire safety and structural solutions. Therefore alternate solutions can be weighted in a quantitative manner. Therefore, space definition, safety and structural designed can be optimised in an integrated manner.
- It is not constraint by prescriptive design or by any "equivalency" concept. Equivalency concepts require engineered solutions to provide equivalent levels of safety to prescriptive solutions. Since prescriptive solutions include no estimates of performance, this approach is clearly inadequate [17].
- It eliminates the need for a "design fire" since it allows to define in a parametric manner the impact that a fire can have on a specific environment. Currently, engineering based solutions require the definition of "design fires" and the evaluation of the building performance to these fires. The choice of design fires could include a series of most probable events or "worst case scenarios." Being able to

use “building geometry” as a variable allows the choice of modifying the space to minimize the potential growth of a fire. Thus a new concept of “minimum damage potential” can be embraced.

- Elimination of the “design fire” and substitution for a “minimum damage potential” allows for a better treatment of extreme events. “Design Fires” require a “choice” of “extreme events” if their inclusion is explicitly required. The need for a “choice” clearly shows the limitation of the approach. Terrorist activities and such are designed to lie outside the realm of any forecasted design scenario. As mentioned before, a perfect example is the events of September 11th, 2001, where the “structures and fire” analysis unveiled design shortcomings of the WTC Towers [18].

Summary

Fire is a rare event with a large potential for damage, its low frequency does not encourage governments and industry to invest in more adequate tools. Nevertheless, the potential for large damage has made fire a favourite tool to inflict destruction and weaken morale in the event of a war. These inherent properties make infrastructure vulnerable to voluntary fires.

The last decades have seen the development of sophisticated tools and a desire to migrate from a prescriptive to a performance based approach. Fire Safety Engineers have in their hands a large number of reliable and sophisticated design tools. These tools can still be improved but currently are in many cases appropriate for design purposes. Modern structural design for fire is making more and more use of these tools. The advantage of this approach is that it introduces more physical analysis to the design process and allows a more adequate quantification of performance and uncertainty. The evolution of design, and of the tools used in the process, is geared towards an increase in integration and efficiency and a constant reduction in uncertainty and error.

The current limitations are mostly associated to gaps of knowledge within the underpinning processes controlling the behaviour of people and infrastructure in the event of a fire. Furthermore, the extreme computational cost of integrated analysis results in a need to stipulate “Design Fires.” Design Fires inherently limit the potential of the engineered based methodology to address voluntarily induced fires

Finally, these tools require detailed understanding of the principles underpinning them, thus proper training is essential, not only for the designers but also for those professionals interacting with Fire Safety Engineers and those involved in the approval and inspection process.

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