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# Fire-induced structural failure: the World Trade Center, New York

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**Fire investigation has generally concentrated on determination of the cause and origin of a fire. Methodologies developed for this purpose have thus focused on the dynamics of fire growth and investigation of its effect on different objects within the structure affected by the fire. It is unusual to see a fire investigation emphasising structural damage as a way to obtain information for fire reconstruction. The series of dramatic fire events that occurred on 11 September 2001 within the World Trade Center, New York complex have emphasised the need to introduce structural analysis as a companion to evaluation of a fire timeline. Only a combined analysis is capable of providing a complete reconstruction of the event and therefore a solid determination of causality. This paper presents a methodology to establish, by means of modern structural and fire analysis tools, the sequence of events leading to a structural failure. This analysis will be compared with classic cause and origin techniques, emphasising the importance of a comprehensive study. Specific structural features and fire conditions that lead to unique forms of failure will be discussed, establishing the complexity of linking fire, structure characteristics and failure mode. The collapse of buildings 1 and 2 of the World Trade Center will be used to illustrate different forms of failure and the fires that cause them.**

## 1. Introduction

The collapse of buildings 1 and 2 of the World Trade Center (WTC) represents one of the major structural failures of modern construction and has thus been the subject of a notable fire investigation – first by the Federal Emergency Management Agency (FEMA, 2002) and then by the National Institute for Standards and Technology (NIST) (Sunder *et al.*, 2006). Several other studies have been reported in the literature, the most relevant to this paper being those by Quintiere *et al.* (2002) and Usmani *et al.* (2003). These investigations clearly indicate that the failures originated from the interactions between unique structural forms and the fires. Many factors, such as structural damage, removal of insulating material and aircraft fuel, accelerated the collapse but none of these factors triggered the progressive collapse. Furthermore, it has been shown that other structural systems under more severe fire conditions will not result in similar failures (Usmani and Lamont, 2004). While many claim that the number of independent investigations and the funding devoted to the forensic analysis were too small and not consistent with the magnitude of the event, it is clear that the investigations cited above are comprehensive in nature and cover great detail and breadth. The present work therefore does not aim to add to these studies or to provide new information or theories; instead, it focuses on putting the investigation of the WTC collapses in the context of a methodology that enables the investigation of complex failures.

## 2. Fire investigation

The process of investigating a fire starts with site analysis. The site analysis methodology has been the subject of many books (e.g. DeHaan and Icove, 2003) and standards (NFPA, 2007). These treatises present a detailed description of how evidence should be gathered, arranged and saved so that the legal process that follows an investigation can make proper use of the evidence. Recommendations on what typical patterns are to be further analysed (fire patterns, pour patterns, etc.) are presented with a number of suggested interpretations. Although the suggested interpretations tend to be useful to the expert eye, in many cases they can be misleading. The main reason for this is that many paths can lead to the same outcome. This is especially true in fire investigation where scientists, engineers or investigators have to work mostly with debris or the building needs to be rapidly demolished. The case of the WTC buildings is a perfect example of this situation. As described in the official reports (FEMA, 2002; Sunder *et al.*, 2006), the debris of the WTC buildings was dug out of the site and rapidly disposed of; investigators thus had only a short period of time to extract as much information as possible from the debris. A further complexity of the WTC fire scene was the size of the collapse. In a collapse of that magnitude, identification of pre-collapse damage from collapse-induced damage is very difficult. Furthermore, repositioning the debris to its original location represented an insurmountable challenge, and only a very limited number of debris elements could be placed in their original locations (FEMA, 2002).

The process of a fire investigation results in the collection of a finite number of evidence elements. These could be remnants of the building, images or testimonies. The NIST report (Sunder *et al.*, 2006) provides what is probably the most comprehensive collection of images and testimonies ever collected for a fire investigation. The evidence allows a finite series of events to be established but does not tell the story of the failure. Different techniques have been developed to link finite evidence points in a manner such that a story can be told. Brannigan and Torero (1999) presented a geometric analogy to describe this process (Figure 1(a)). The points represent the evidence and the geometric figures the potential scenarios.

The most conventional of these techniques is generally called 'cause and origin' in the investigation community. During a cause and origin analysis, a fire investigator will attempt to interpret the evidence in a way that establishes how the fire started (origin) and what caused it (cause). This technique has been used for many years and has proven to be adequate for simple fires where fire safety engineering techniques have not been implemented. A different approach is 'fire reconstruction'. This technique uses understanding of the science underpinning fire and structural behaviour to establish which of the paths (geometrical shapes) corresponds to the unique representation of the scenario. This implies an understanding of how the damage originated and how the fire safety systems performed. Fire reconstruction is a more suitable technique for modern buildings.

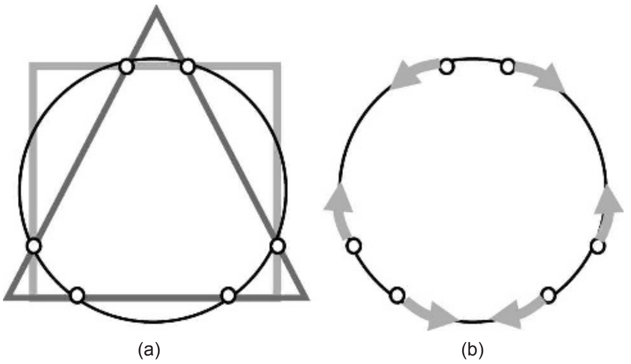


Figure 1. Schematic illustration of the process of fire investigation. (a) The dots represent discrete points of evidence while the shapes all possible scenarios that fit the evidence. (b) The arrows represent the interpretation that allows one to eliminate all shapes and reduce the scenarios to a single one (circle)

Cause and origin analysis has been well documented (DeHaan and Icove, 2003; NFPA, 2007) and consists mainly of rigorous gathering of evidence and simple interpretation of this information. Fire dynamic techniques (Drysdale, 1999) need to be used in many cases to validate theories and establish a single pattern for the scenario (Figure 1(b)). Nevertheless, these techniques tend to be a very simple set of physical equations and empirical correlations. Detailed analytical techniques have also been employed in the past to establish chemical compositions (i.e. for identification of hydrocarbons) (DeHaan and Icove, 2003) or to define if certain components, such as smoke detectors, have operated or not (Worrell *et al.*, 2001). Only recently have complex numerical models been used to support cause and origin analysis (McGrattan, 2004; Olenick and Carpenter, 2003; Sunder *et al.*, 2006).

When the scenario is as complex as the WTC collapses, fire reconstruction techniques involve the use of numerous methodologies. Parametric analysis of the potential conditions experienced during the event represents a useful way to try to identify similarities between the response of the building and specific conditions. These techniques were used by Usmani *et al.* (2003). A different approach is to attempt to model the different components of the event (i.e. fires, heat transfer, structural behaviour, etc.). For this purpose, simple empirical correlations or analytical models can be used. However, while they provide useful information, they are not able to describe many of the details that enable a reconstruction of the events.

Torero *et al.* (2002) tried to eliminate some flawed hypotheses associated with the nature of the fires in the WTC by using simple analytical formulations and empirical data. NIST (Sunder *et al.*, 2006) used complex computational fluid dynamics (CFD) models to link discrete images and to provide a description of the fire propagation. Furthermore, the model allowed defining the heat release rates of the fires. Validation of these heat release rates was obtained by combining weather information of the day with images of the smoke plume and the model output. At the structural level, both NIST (Sunder *et al.*, 2006) and Usmani *et al.* (2003) used complex finite-element models (FEMs) to describe the evolution in time of the deformations and the ultimate collapse. Quintiere *et al.* (2002) used analytical expressions to describe the structural behaviour. In the NIST report (Sunder *et al.*, 2006) the predicted deformations are qualitatively compared to photographic evidence validating the sequence of collapse. In general, there is consistency between the NIST report (Sunder *et al.*, 2006) and the work of Usmani *et al.* (2003). Quintiere *et al.* (2002) reached mostly the same conclusions obtained in a qualitative manner by the FEMA investigation (FEMA, 2002); these conclusions were shown to be incomplete by the two other studies.

An added complication originates from the fact that most modern buildings require the use of different fire safety measures. These can include detection and alarm, active fire suppression, smoke management techniques, compartmentation and passive fire proofing. These techniques allow rapid egress of occupants, control or deceleration of fire growth, management of smoke migration and protection of the structure. If these measures operate adequately, then the fire will be controlled in a restricted location and a simple cause and origin analysis will suffice. If the fire continues to grow, resulting in significant damage, then the different protective measures would have not performed adequately and a fire reconstruction will be necessary. The mechanisms by which these systems can fail represent the inherent weaknesses of the infrastructure (Torero, 2006). Fire reconstruction analysis will establish the performance of each safety component as well as the performance of the structure and its occupants. In an ideal scenario, a fire reconstruction could result in an artificial recreation of the events.

In the WTC, it was established very early on that water-based fire suppression systems did not work due to the aircraft-induced damage. This simplifies the investigation by eliminating a component of the analysis. Nevertheless, the failure of compartmentation and fire proofing induced by the aircraft impact required an impact analysis of dramatic complexity (Sunder *et al.*, 2006). The impact analysis allowed determination of the nature of the damage and its implications on the fire safety strategy. To achieve the impact analysis it was necessary to build a detailed model of the building and the aircraft. The model described the damage to the exterior columns, which could be compared with photographic evidence, giving confidence in the model and allowing its use to describe interior damage. The NIST report concludes that while damage to the external columns was extensive it did not lead to global collapse nor did it significantly breach the compartmentation provided by the floors. Thus the fire spread only within the region where there was significant damage and did not continue to spread vertically. Instead, damage to the internal core columns and partitions compromised egress paths, resulting in a reduced capability for people above the fire to exit the building. The NIST report emphasises that the aircraft impact stripped out large sections of fire proofing. While this is highly probable, the amount of stripped insulation and its impact on the nature of the ultimate failure remain a matter of controversy.

Currently there are no well-defined methodologies for fire reconstruction. As mentioned earlier, evidence collection does not provide sufficient information to define the progress of a fire and its impact on people and structures, and thus there is a need to have clearly defined techniques to combine evidence and engineering models to support investigation. The WTC investigations have shown the lack of maturity of this field. Investigators improvised the methodologies used, making planning for evidence collection and analysis difficult. In more than one instance the analysis remained inconclusive due to the absence of evidence that potentially existed but had already been disposed of. Massive amounts of evidence were collected for the WTC investigation, but a conclusive reconstruction of the fire timeline that led to the collapse was not achieved. In this case, state-of-the-art fire and structural models were deployed, but the absence of a rigorous method hampered the investigation.

This paper presents a methodology to analyse the failure of a structure due to fire. A description of existing tools and the ways in which they can be used is presented.

## 3. Methodology

The methodology described in this study was applied to the WTC study conducted by Usmani *et al.* (2003); details of the specific analyses can be found in this reference but the methodology is presented only in an implicit manner. In the following sections, highlights of this application will be used to illustrate in detail the methodology followed. Emphasis is put on the method not on the detailed analyses.

A complex forensic investigation needs to start by defining the objectives of the study. Without clear objectives it is difficult to reach conclusions. Usmani *et al.* (2003) clearly establish that their analysis is intended to understand the response of the undamaged building to a fire, so that design-related conclusions can be made. The other investigations lack a well-defined objective and they are more directed towards providing plausible reconstructions of the events. The NIST report (Sunder *et al.*, 2006) extracts conclusions on the different vulnerabilities of the specific buildings and provides many design recommendations. The recommendations appear as general improvements to buildings of a similar nature but not necessarily as consequences of the analysis. An excellent example of this situation is the set of recommendations associated with the dimensioning of egress stairs. The report identified the extensive time associated with egress from such tall buildings and concludes that improvements need to be made to egress stairs. Nevertheless, it is not demonstrated that these improvements would change the fate of the occupants of the building (Sunder *et al.*, 2006). If the objective had been to establish why there were so many fatalities, clear conclusions could have emerged, leading to improvements that could potentially change the outcome.

Once the objectives of an investigation have been defined, the main components of the fire strategy need to be addressed

(Torero, 2006). Four aspects need to be considered when conducting a forensic assessment of a building that has undergone a fire:

(*a*) fire growth
(*b*) performance of protection systems
(*c*) egress analysis
(*d*) structural performance.

The event can only be described by the ensemble of these factors leading to the construction of a timeline for the event. Such a timeline has been presented by Torero (2006).

### 3.1 Fire growth

Fire growth is a complex combination of transport and chemical processes. Materials degrade, producing fuel that will then burn in the gas phase, generating heat. As the materials heat up the fire spreads, increasing in size. These complex physical processes can be modelled using different tools. Tools range from simple close-form mathematical models to more complex computer simulations. Computer simulations can vary in level of complexity and the two best-known techniques are zone models and CFD. The capabilities and limitations of these models are described by Olenick and Carpenter (2003) who also compile a list of the different tools available.

Analytical and zone models provide quantitative estimates of temperatures and concentrations of different species. Nevertheless, they cannot provide the spatial or time resolution necessary to assess the performance of fire protection systems or structural behaviour. Their advantage is their simplicity and capability to produce estimates in reduced times.

For spatial and time resolution, it is necessary to resort to CFD models. CFD models compute, on the basis of detailed input parameters, the time and spatial evolution of temperature and species. This information can then be used to reconstruct the fire timeline and as an input variable for fire safety systems and structural performance assessment. Comparison of the earlier studies (FEMA, 2002; Quintiere *et al.*, 2002; Usmani *et al.*, 2003) with the NIST report (Sunder *et al.*, 2006) shows the potential advantages of CFD tools.

Figure 2 shows an example of heat flux distributions on a ceiling for a typical compartment fire. These heat flux distributions evolve in time and are obtained by post-processing CFD results using a numerical tool called FDS (Jowsey *et al.*, 2007). Given the nature of the system that is being studied, this level of resolution might be necessary.

An issue of great concern is the capability of these tools to provide a robust answer. There are inherent uncertainties in the process of modelling a fire. Fuel quantity and distribution and ventilation conditions can have a major impact on the characteristics of a fire, as can the nature of the fuel materials and the physical characteristics of the compartment. Given that it is impossible to define the exact nature of fuel and ventilation, the capability of models to establish a timeline for fire growth is not clear. Furthermore, even if many of these parameters were fixed, the choice of input properties still remains a very difficult task. A blind round-robin of the modelling of two large-scale experiments recently showed that even when most of the conditions are well defined, the results are not necessarily robust or consistent (Rein *et al.*, 2007; 2009).

Given the limitations of models and the capability to provide exact input parameters, fire reconstruction cannot rely on the predictive capabilities of these tools. It is therefore necessary to utilise models in a different manner. Simpler models can be used to cover a parameter field and establish an understanding of the range of conditions that could be present during a fire. CFD models, which are more computationally intensive, can be used to refine certain specific scenarios for analysis.

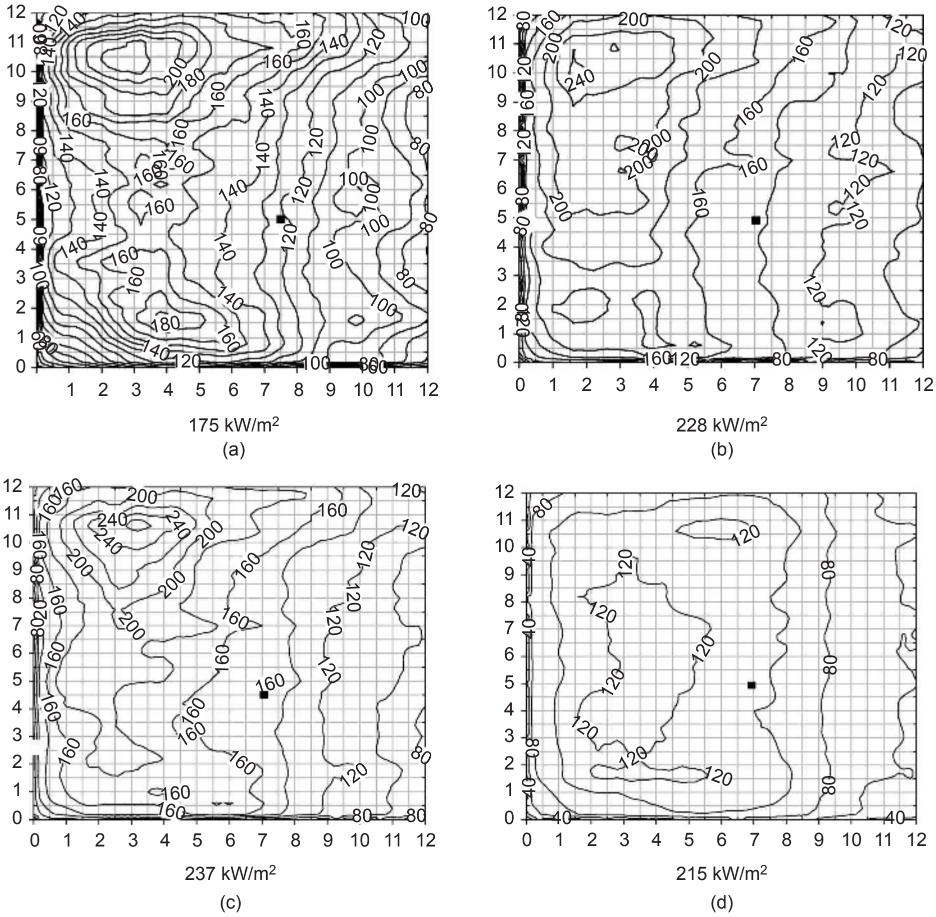
The reconstruction of the fires in the WTC investigation is probably the most successful element of this analysis. The NIST report (Sunder *et al.*, 2006) uses an elegant combination of CFD modelling with evidence (photographs) to supplement lacking information in such a manner that at each step consistency is guaranteed. Further consistency is attained by means of analytical formulations and experiments conducted with reproductions of the office floors. In a similar manner, the phenomenological models described by Torero *et al.* (2002) are used as a basis for the parametric studies of Usmani *et al.* (2003). In this case, uncertainty is accounted for through a parametric study. All these approaches are valid and necessary for a complex scenario like the WTC.

### 3.2 Fire safety systems and egress

Fire safety systems are of two kinds – those intended to control or affect fire growth and smoke migration (smoke management, compartmentation and fire suppression) and those that have no physical effect on the fire but are used to start the process of egress (detection and alarm).

Fire suppression and detection systems have to be activated. Activation has been modelled for both smoke detectors and suppression systems, and numerical tools of different levels of sophistication are available (Olenick and Carpenter, 2003). These tools provide an adequate estimate of activation and are generally reliable if the fire is a predefined input to the model. Precision in activation times can only be equal to or less than the precision in the fire model.

The performance of fire safety systems is a completely different scenario; in general it cannot be modelled. Smoke detector



175 kW/m$^2$
(a)

228 kW/m$^2$
(b)

237 kW/m$^2$
(c)

215 kW/m$^2$
(d)

**Figure 2.** Heat flux map over compartment ceiling from the model. The number below each plot indicates the measured billet reading at the black square at the corresponding time. The compartment openings allowing for air to enter the compartment are located on the right-hand side of each plot. Contour labels are in kW/m$^2$ and axis labels are room dimensions (in metres). (a) 10 min; (b) 20 min; (c) 30 min; (d) 40 min

performance is characterised by significant sources of error but this is not an issue because the errors are smaller than the large error bars associated with egress models and human behaviour. Fire suppression systems are most difficult because they can either have a large impact on the fire or almost no effect. There is currently no model that can properly predict suppression system performance. Fire suppression systems affect the fire in its early stages and, if effective, will completely suppress the fire. If the fire exceeds a specific level of growth the suppression system will be overwhelmed and will only have a minor impact on the fire. Given the two extremes, prediction of performance might truly not be necessary. Detailed observation of the evidence can allow clear definition of the performance of a suppression system without the need to model it. If the suppression system does not operate it is important to establish the causes of the failure. Such failure is generally associated with installation or maintenance errors and establishing these errors requires intimate understanding of these systems.

Smoke management systems are also very difficult to analyse. The efficiency of natural or forced smoke management systems is directly dependent on the characteristics (temperature and velocity) of the smoke. While this is very difficult to model and any analysis will include a significant error, a simple assessment of the system under design conditions is of great use in forensic analysis. The presence of smoke leaves observable traces and understanding smoke management systems thus helps in the interpretation of these traces. Compartmentation is also a form of smoke management; its failure will be dealt with in the next section.

Penetration of the building from the impact of the aircraft defined ventilation and smoke movement in the WTC. Analysis of the ventilation resulting from the observable damage was used to estimate fire temperatures and localised burning duration. Ventilation was addressed using CIB (Conseil International du Bâtiment) empirical correlations (SFPE, 2004; Thomas and Heselden, 1972) by Torero *et al.* (2002) and it was modelled explicitly by NIST (Sunder *et al.*, 2006). While both approaches differed in detail and precision they were consistent in defining the duration of localised burning and average temperatures of the fires. It is important to emphasise that being a 'ventilation-limited' fire, both studies conclude that the temperatures were not unusual for fires of that magnitude. Furthermore, the role of the aircraft fuel was deemed as being mostly related to ignition of the fires: the kerosene evaporated rapidly and contributed little to the heating of the structure. Average temperatures during the entire extent of the fire were capped at about 1000°C (Torero *et al.*, 2002) but most likely were never higher than 800°C throughout most of the burning period (Sunder *et al.*, 2006).

### 3.3 Structural behaviour

The behaviour of structures in a fire has evolved significantly in the last decade (Usmani and Lamont, 2004). Many processes previously not understood and mostly associated with thermal expansion are now being modelled with significant precision. The thermal inertia of a structure and the insulation used to protect it result in structural heating times that are much longer than the characteristic times that establish the evolution of a fire. The difference in characteristic times tends to buffer many of the uncertainties associated with the fire. Forensic analysis of structures is thus becoming a reality.

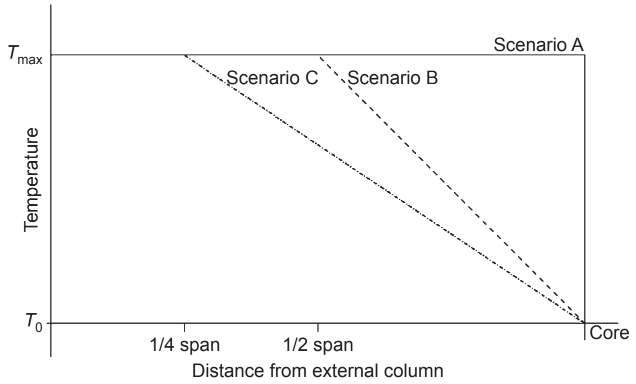


Figure 3. Spatial distribution of the temperature within a floor of the WTC towers. Three scenarios are presented: the fully-heated floor (A) and two levels of partial heating (B and C). $T_0$ is the ambient temperature and $T_{max}$ a pre-specified maximum value for the compartment temperature (Usmani *et al.*, 2003)

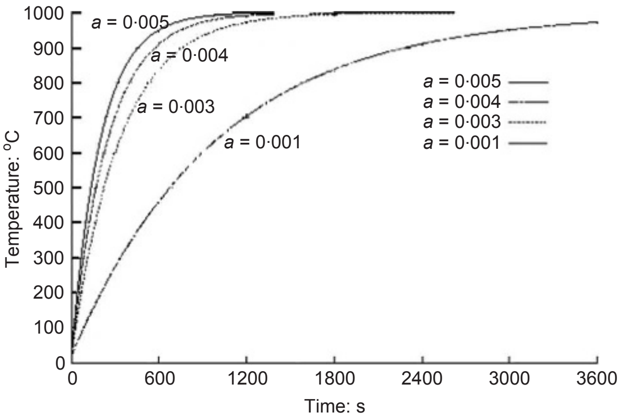


Figure 4. Temporal evolution of the temperature of the WTC compartment. Four heating rates are presented and the value of 'a' corresponds to the exponential growth function $T_{(t)}=T_0+(T_{max}-T_0)(1-e^{-at})$ postulated by Usmani *et al.*, (2003) where t is time and $T_0$ and $T_{max}$ are defined in Figure 3

For forensic modelling of structural behaviour in fire, the parametric study described earlier (Usmani *et al.*, 2003) can be translated into a series of simple temperature plotted against time and space curves that represent the range of most probable conditions for the fire. As an example, Figures 3 and 4 show the distributions used by Usmani *et al.* (2003) for their study of the WTC towers. This temperature distribution covered all typical fire conditions according to the earlier study of Torero *et al.* (2002). The study focused on a parametric analysis and thus the formulation of a series of 'typical' temperature histories (Figure 4). Similarly, the size of the fire was also studied in a parametric manner (Figure 3). The uncertainty is covered by the range of cases studied and these temperature distributions were thus deemed sufficient for the modelling of the structural behaviour.

Once temperature evolutions have been established, FEMs of the structure can be constructed. These models can allow an investigator to establish the conditions under which certain features can appear. Figure 5(a) shows a lower flange yield observed in the Cardington tests (Usmani and Lamont, 2004). These tests showed that these are low-temperature failures that occur early on in a fire. The same type of feature appears in Figure 5(b), but this case is a real fire where a steel frame shows similar features as those presented in the Cardington tests. The modelling and identification of such failures can provide further support towards the reconstruction of a fire. Figure 6 shows how these features also appeared in a scaled-down WTC unprotected truss.

Global structural behaviour needs to be approached in a systematic manner. General behavioural trends can be established

**Figure 5.** Lower flange buckling in (a) Cardington test and (b) a real fire

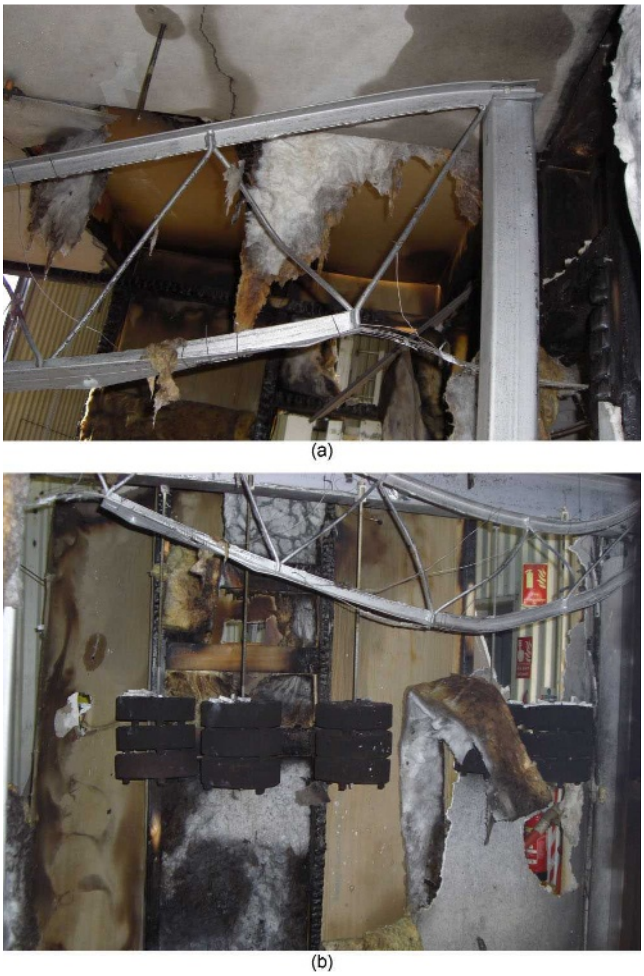


**Figure 6.** Demonstration of a compartment fire with a scaled-down WTC truss: (a) low-temperature lower flange buckling; (b) high-temperature deformations (centenary). The truss was left unprotected and the fire lasted for approximately 20 min

when there are areas that could have a severe impact on the structure. These areas tend to be those where major structural elements are present. Long-span beams are also another feature that needs to be looked at carefully. Once the areas of interest have been established, there will be a number that can be discarded because there is no possibility of a severe fire or the evidence shows no permanent deformation of the structural elements; for example, these could be areas with little fuel or ventilation. Those that cannot be discarded need to be studied to identify features that coincide with evidence.

Images obtained during the investigation of the WTC collapse indicated that the columns initially showed outward bowing but, close to collapse, the columns moved inwards until collapse was observed. These features have been reproduced by the models (Sunder *et al.*, 2006; Usmani *et al.*, 2003). The simple one-dimensional model obtained by Usmani *et al.* (2003) is presented in Figure 7. The sequence shows both the local deformations and the observed global behaviour. Similar deformations were observed by NIST (Sunder *et al.*, 2006).

One of the most complicated features of structural fire reconstruction is to create adequate timings for the different observed events. The combination of the usual uncertainty in insulation (or concrete spalling in the case of concrete structures) and fire growth makes reproducing the time sequence of events very difficult. The times presented in Figure 7 cannot be considered as a faithful reproduction of the timeline. The NIST report (Sunder *et al.*, 2006) goes to great lengths to reproduce the timeline. While this could be done for

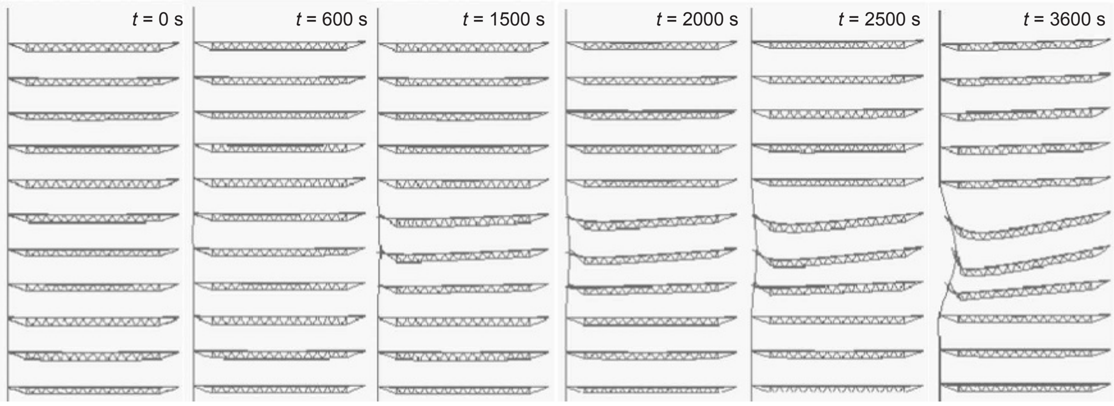


Figure 7. Sequence of deformations induced by heating in the one-dimensional model presented by Usmani *et al.*, 2003. The second image from the left shows outward bowing of the columns; from the third to the sixth images, bowing is inwards

the fire because visual evidence allowed anchoring the progression of the fire, uncertainty associated with the structural timeline is great. Again, a parametric approach seems to give the best results because it allows understanding of the main behavioural patterns of the structure and their association with the characteristics of the fire.

Failure of compartmentation is a complex process that couples thermal and mechanical effects. So far, there is little precedent of successful modelling of the failure of this type of structural element. None of the WTC investigations addressed this issue in detail despite its relevance to compromise of the egress paths. The subject is discussed in one chapter of Rein *et al.* (2007), but focuses on a specific type of wall assembly.

## 4. Summary

Modern buildings cannot rely on cause and origin analysis. They require a fire reconstruction. Complete forensic analysis of structures in fire is currently very difficult. Complex tools (CFD and FEMs), together with other simpler tools such as analytical formulations, experimental data and parametric studies, are currently being used to attempt fire reconstruction. The published investigations on the WTC collapse made extensive use of all these tools in a manner that is unprecedented and pushed the boundaries of the fire reconstruction methods that existed prior to 11 September 2001.

Uncertainty can be found at all levels but is greatest in the modelling of the fire. The large thermal inertia of structures does not require a detailed understanding of the fire growth and therefore the uncertainty can be compensated for with a parametric analysis of the structure for a number of representative (probable) fire scenarios. Contrasting the different studies of the WTC allows analysis of the validity of the different approaches and the adequacy of different mechanisms to compensate for uncertainty (visual evidence, parametric study).

Structural analysis is not only concerned with the global behaviour of the building but also with the reproduction of features that can be linked with specific characteristics of the fire. Study of the WTC pushed existing understanding of global structural behaviour but detailing of component failures could not be addressed, despite their importance in terms of egress.

An essential component of a fire investigation is its objective. In the case of the WTC, these were poorly defined and this conditioned the conclusions of the investigations.

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