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

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1. Contribution by S. Chen and D. Cheng

The collapse of the twin towers of the World Trade Center (WTC) on 11 September 2001 is an extreme case that any structure would be subjected to. There are inherent uncertainties in the process of modelling fire, so that complete reconstruction of a fire event and the temperature evolution – and therefore a solid determination of causality – is difficult. The methodology addressed by Torero (2011), based on a combined analysis using modern structural and fire analysis tools, certainly helps in the understanding of complex fire-induced failures and the collapse mechanism of super high-rise buildings and such research reduces the disaster risks that the world is still confronted with, whether they are induced by natural hazards or extreme terrorists.

1.1 Coupling fire dynamics, heat transfer and structural analysis

Four aspects of the forensic assessment are identified but the methodology does not address the coupling effects of fire and structure for a fire-induced structural failure. It follows the parametric approach of establishing likely temperature evolutions, conducting finite-element structural analysis and then comparing likely structural responses to the evidence features of the structure.

In most cases, complex failures or the collapse of buildings is very difficult to interpret by classic cause and origin analysis since many dominating factors and combinations of interactive modes are still not well understood. Spatial and temporal resolution of stress analysis cannot be chosen arbitrarily once the requirements for thermal analysis have been decided (Baum, 2011). Attention must be focused on the coupling of fire dynamics simulations, heat transfer analyses and structural analyses of the damaged building. It is only when these simulations are coupled together in some way that the effect of fire on structures can be quantitatively assessed. This is also a challenge in fire engineering research.

1.2 Evidence of fire-induced structural failures

A forensic investigation is structured like a pyramid: there should be a large foundation of verifiable facts and evidence at the base, which form the basis for analysis according to proven scientific principles. It appears that the pieces of evidence used by a conventional fire investigator are the same as those adopted in the new methodology, as illustrated in Figure 1 of Torero's paper. The approach of 'fire reconstruction' requires understanding of the science underpinning fire and structural behaviour to develop a unique representation of the scenario. It seems there is no clear difference between the two methodologies in a simple case of fire investigation, but fire reconstruction in a forensic assessment of a building should match the evidence. But what are the most important pieces of evidence that will dominate the collapse sequence in the complex scenario of a fire-induced structural failure?

Fire reconstruction is crucial in illustrating fire-induced structural failures and possible scenarios a structure would experience. It is not simply a trial and error approach to reduce the scenarios to a single one, since the evidence identified in most cases will be a mixture of patterns of different damage. The National Institute of Standards and Technology (NIST) report (Sunder *et al*., 2006) used photographic evidence to compare with predicted deformations and to validate the sequence of collapse. It is important to clarify what essential evidence should be identified in a fire reconstruction and it is also necessary to determine the initial state of a structure in a fire reconstruction simulation. For instance, whether or not the fire reconstruction of the WTC twin towers would indicate final collapse of the buildings contradicts the statement of 'the building structure would still be there' (Nalder, 1993). It is suggested that, in this case, the WTC fire reconstruction should also consider the severe damage caused by aircraft impact and the consequent dynamic effects.

2. Author's reply

The author agrees with the contributors in that there are numerous uncertainties when attempting a forensic analysis of fire-induced collapse, especially in a scenario of the nature of the WTC. The contributors also state that, due to these uncertainties, 'a solid determination of causality' is difficult. This may be the case, but it cannot be interpreted as impossible. The correctness of this determination will depend on the evidence available, the tools used in the analysis and, as indicated by Torero (2011), by the objectives of the investigation. The contributors' interpretation of the objective of the investigation is directly assumed to be the precise recreation of the 'timeline' of the events. My paper is much broader than that.

The paper clearly indicates that 'A different approach is to attempt to model the different components of the event (i.e. fires, heat transfer, structural behaviour, etc.)'. A proper heat transfer analysis will of course include the coupling effects of fire and structures when necessary and when the objectives, uncertainty of the conditions and input data merit this inclusion.

The methodology presented espouses a general analysis that will use all available tools not necessarily to recreate the timeline of the event but to understand the sequence of key events in a manner such that the specific objectives of the forensic investigation are attained. Thus, the specific objectives of the investigation condition the method and techniques used.

The uncertainties associated with the fire environment, the amount of ventilation, the damage to the structure and the state of fireproofing in the WTC scenario were very high. In this particular case, it is thus impossible to model the fire and heat transfer to a level of detail that will allow a precise reconstruction of the timeline. As clearly indicated in the paper, the NIST report (Sunder *et al*., 2006) attempts to do this with no small controversy. Furthermore, the paper indicates in the summary section that the NIST forensic investigation had multiple objectives (reconstructing the timeline, improving building design, improving building codes, etc.), thus negatively conditioning the outcome of the investigation.

In contrast, the study by Usmani *et al*. (2003) opted for a different objective, which was to understand the modes of failure; that is, to understand what triggered progressive collapse not to recreate the timeline. Without having to predict a timeline, a parametric treatment of the consequences of a fire on a structure (i.e. temperature evolution of the structure) for a set of scenarios that will adequately cover the range of conditions possible is not only acceptable but is the correct approach. This methodology would not have been acceptable to recreate the timeline nor would a detailed heat transfer analysis of the specific conditions have mastered the uncertainty and potential error to provide the understanding desired by Usmani *et al*. (2003). Thus, in the case of Usmani *et al*. (2003), the objectives were aligned with the method and the conclusions are clear.

The detail of the coupling of fire dynamics simulations is dependent on the objectives of the study. For Usmani *et al*. (2003), parametric analysis is an adequate form of coupling that allows a survey of possible structural behaviour; for the NIST analysis (Sunder *et al*., 2006), the form of coupling required to attempt a reproduction of the timeline is much more complex and probably requires an analysis consistent with the work presented by Baum (2011). Even then, the uncertainty associated with the inputs (i.e. fuel, ventilation, structural damage and displacement of the fireproofing) forces many to conclude that including that level of detail in the analysis is an unjustified approach.

The paper describes forensic investigations where facts and engineering tools have to be used in a manner such that potential paths are discarded until the objectives are met (see Figure 1 of Torero (2011)).

It is only when the objective is 'cause and origin' that the evidence forms the basis for the analysis while the engineering tools are only used for interpretation. The interrelation between evidence and tools, as defined loosely in Figure 1, is conditioned by the objective. This is indicated in numerous sections of the paper.

When describing Figure 1, I indicate that fire dynamics techniques need to be used to reduce the different hypotheses to one. Everything that follows emphasises that the gaps left by the discrete points of evidence need to be filled with the application of engineering tools. The author believes very strongly that rigorous use of engineering tools is not a 'trial and error process'.

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