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Review

The role of modelling in structural fire engineering design

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ABSTRACT

This paper discusses structural fire engineering modelling, and how modelling techniques have allowed practicing engineers to learn lessons about global structural fire performance. Some of these lessons have been adopted in the design of new buildings, and some are also being fed-back into the design process to improve structural performance in fire and mitigate known structural vulnerabilities. The complexity of this modelling has permitted structures to be designed and lessons to be learned about whole frame behaviour in response to fire. This paper examines how the lessons learned from finite element modelling may be further disseminated to the structural engineering community through the creation of full frame design guidance. The benefits of this would be to improve the delivery of structural fire safety by increasing the impact of the discipline across structural engineering, while facilitating and encouraging the use of more in-depth structural fire models as appropriate.

Contents

1. Introduction

Structural engineers are expected to deliver buildings and infrastructure that resists a wide range of conditions. To do this, they employ a variety of modelling tools to capture an adequately conservative version of the conditions that a structure may experience, and a sufficiently accurate representation of how the structure will respond. Exposure to fire is one of the conditions that structures are frequently required to resist; structural fire models are the techniques used to represent the structural response.

Consequently, structural fire modelling is a broad term and encompasses any design method employed to assist in understanding or capturing the physical phenomena associated with structural response to fire. The tabulated data found in documents such as the concrete Eurocode [1] represent a model whereby the behaviour of the concrete structure subject to a standard temperature-time curve can be represented based on the parameters of reinforcement cover, and element thickness. More complex models are the finite element methods that are used to represent the behaviour of a wider structure when subject to a pre-defined thermal attack.

The selection of a model for any task must be driven by the information that is being sought. Structural engineers routinely employ linear elastic analyses to create designs and to better understand the behaviour of large structures. The complexity of these models is not in the material models used, but in the

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geometrical arrangements and interaction between different elements of the super structure. In the event that the structural engineer has concerns regarding the detailed behaviour of specific elements, additional checks (or redesigns) are conducted to ensure that the elements can adequately resist the applied forces. This approach recognises that, in structural engineering, an understanding of the global interactions is equally important in representing the structure as the details associated with each element.

A common approach to discussions of models for structural fire engineering is to refer to three types of model: tabulated data; simplified calculation; and complex analysis [2]. This is often accompanied by a discussion of how the model used to represent the thermal conditions induced by the design fire can become more advanced as the complexity of the structural analysis increases. An example of this is the matrix presented by the CIB W14 Design Guide for Structural Fire Safety [3].

There is also a narrative around the differences between prescription and performance based design which holds that prescriptive design uses simplified models, and that performance based design requires complex models. This narrative is false as any design methodology must necessarily be performance based – prescriptive approaches simply have a predefined set of performance metrics, assessment methodologies and acceptance criteria. The three types of model identified above therefore represent points on the continuum of design. The less complex analyses are frequently enshrined within a legal framework that provides the designer with a legal justification for not considering more complex phenomena.

In contemporary design, the more complex models often take the form of a finite element analysis that is able to represent the phenomena (material non-linearity, geometric non-linearity, and thermal expansion) that have been identified as the key drivers for the reaction of a structures to a fire [4]. These approaches account for the interactions that are ignored by the so-called simpler models and often attempt to account for real fire behaviours, and real structural behaviours [5].

There can be little doubt that this approach to structural fire modelling in design is both a rational and well founded attempt to account for the known fire and structural behaviours. In practice, however, it is so complex that the approaches become impenetrable to the non-specialist. This was recognised by Bailey [6] in asking whether structural fire engineering was a core or specialist subject.

The level of expertise required to characterise true structural behaviour in fire creates a significant barrier for the structural engineer to engage the fire design of the building as the fields of knowledge required are complex and unfamiliar. Consequently, a structural engineer (who is not fluent in these skills) may perceive the structural fire performance of a building as solely within the scope of the fire engineer.

However, this view is confounded by models such as the tabulated data provided in guidance documents (e.g. the Eurocodes) which represent the widespread dissemination of knowledge gained from standard fire resistance testing (a.k.a. furnace testing), and have become an indispensable part of a structural engineer's toolkit.

Structural engineers are, therefore, able to engage in the delivery of structural fire safety if they are able to readily apply the relevant tools (again, a point made by Bailey [6]). To understand these two extremes, and consider how structural fire engineers may maximise their impact on the structural engineering community, it is necessary to analyse the role that models play in design, and how they can best be deployed and their outcomes disseminated.

2. Feedback in design

Structural engineers are able to learn from failure. Indeed, failure is often cited as one of the most effective learning tools available to structural engineers [7]. The broad definition of failure (e.g. from non-catastrophic concrete cracking, to well known cases such as the Tacoma Narrows bridge) permits a proliferation of examples from which structural engineers can learn.

Structural fire engineering has relatively few examples of failure that allow feedback into the design process to occur. This is somewhat ironic (because the foundations of modern structural fire engineering as a discipline lie in the actions taken to respond to fires in iron buildings [8]), but is also a testament to the efficacy of the fire precautions that have been taken over the last century – and the previous learning that has taken place [9]. Furthermore, there is a profound absence of learning from the (relatively few) failures that do occur. This is due to several reasons: the rarity of uncontrolled fire events; the unknowns associated with the fire-induced thermal conditions prior to any structural failure (due to the difficulty of making observations, and retrospectively modelling fire behaviour); and the complexity and costliness of characterising the structural fire phenomena involved.

There are some notable examples of forensic or retrospective failure analyses in structural fire engineering. These include the analyses associated with the collapse of the World Trade Centres [10]; the Gretzenbach car park fire [11]; and the Windsor Tower fire [12]. However, it is worth noting that conclusions and lessons learnt from fire investigations often focus on the spread of fire rather than the response of a structure [13]. Rein also observed that *there has been a lack of progress in the ability of fire safety engineers to explain convincingly to other professionals the events of the* [World Trade Centre] *disaster and the lessons to be learnt from them* [14]. It was noted by Torero that fire engineering communities have *produced the science to unveil many of the phenomena, but not to transform that knowledge into design methodologies and tools* [15].

There are also examples of where structural fire resistance has led to lessons learned about how alternative load paths can be exploited to deliver fire resistance [16]. In some cases, this knowledge has been captured [17] and transformed into guidance documentation for application in design [18]. There have also been large scale tests were behaviours have been observed and characterised [19].

Consequently, although there is some knowledge gained from large scale testing and real failures, the primary mechanism for learning about the performance of structures subject to fire conditions remains the single, isolated element testing associated with the standard furnace test. This is, of course, inherently limiting for the reasons summarised by Bisby et al. [19].

3. Models as a tool for design

The rarity of fire events described above does not obviate design engineers from considering fire as a relevant environmental condition. However, this absence of information about the failure of structural assemblies due to fire does precipitate the need for something to fill the gap. Structural fire modelling is an obvious surrogate for studying real failures.

Engineering consultants are increasingly being commissioned to verify the performance of a structure subject to fire. These analyses often involve the most complex aspects of structural fire modelling: single or multi-floor fires are analysed [5]; non-uniform temperature distributions are considered [20]; and the impact of different fire protection and structural measures can be considered [21,22].