THE BEHAVIOUR OF CONCRETE STRUCTURES IN FIRE

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This paper provides a 'state of the art' review of research into the effects of high temperature on concrete and concrete structures, extending to a range of forms of construction, including novel developments. The nature of concrete-based structures means that they generally perform very well in fire. However, concrete is fundamentally a complex material and its properties can change dramatically when exposed to high temperatures. The principal effects of fire on concrete are loss of compressive strength, and spalling – the forcible ejection of material from the surface of a member. Though a lot of information has been gathered on both phenomena, there remains a need for more systematic studies of the effects of thermal exposures. The response to realistic fires of whole concrete structures presents yet greater challenges due to the interactions of structural elements, the impact of complex small-scale phenomena at full scale, and the spatial and temporal variations in exposures, including the cooling phase of the fire. Progress has been made on modelling the thermomechanical behaviour but the treatment of detailed behaviours, including hygral effects and spalling, remains a challenge. Furthermore, there is still a severe lack of data from real structures for validation, though some valuable insights may also be gained from study of the performance of concrete structures in real fires.

Key words*: concrete, fire, high temperature, modelling, spalling, review*

1. Introduction

Historically, the fire performance of concrete has often been taken for granted considering its non-combustible nature and ability to function as a thermal barrier, preventing heat and fire spread. Design criteria have been based on the results of testing to "standard" fire exposures [*e.g.* 1] typically expressed in terms of required reinforcement cover. However, the general applicability and usefulness of this approach may be debated since the heating regimes in real-world fires may be quite different. In particular, initial heating rates can be more rapid and all real fires have a distinct "cooling phase"; both of these conditions are recognized as imposing additional stresses on *in situ* structures which may be highly restrained. Thus there are still obvious gaps in knowledge of the true behaviour of concrete structures in fire.

In fundamental terms, the fire behaviour of concrete is linked to the temperature-dependent material properties. Since the thermal diffusivity is rather low, compared to steel, strong temperature gradients are usually generated within fire-exposed concrete members. Together with the high thermal inertia, this means that the core region may take a long time to heat up. Thus, whilst the compressive strength of concrete is rapidly lost beyond a critical temperature, which is not too dissimilar to the equivalent temperature for loss of steel strength, structural effectiveness is not affected until the bulk of the material reaches the same temperature. This requires an analysis of the thermal response of the entire structural element.

Another problem which occurs when concrete is exposed to fire is spalling [2]. This is the phenomenon involving explosive ejection of chunks of concrete from the surface of the material, due to the breakdown in surface tensile strength. It is caused by the mechanical forces generated within the element due to strong heating or cooling, i.e. thermal stresses, and/or, by the rapid expansion of moisture within the concrete increasing the pore water pressure within the structure. Spalling may occur under a variety of circumstances where strong temperature gradients are present, both in the heating and cooling phases.

The performance of concrete in fire depends both on the details of its composition and its type, i.e. normal-strength, high-performance (HPC) or ultra-high-performance (UHP); the main focus of this review is the former two categories, though the latter will also be mentioned. Each of these issues is explored in more detail in the sections below.

2. Physical and chemical response to fire

Concrete and fire have a complex interaction, due to the composition of concrete and the extreme thermal conditions often found in fire. Concrete is far from being a homogenous material, consisting of a composite of cement gel, aggregate and, frequently, steel (or other) reinforcement. Each of these components has a different reaction to thermal exposures in itself, and the behaviour of the composite system in fire is not easy to define or model [2]. Furthermore, the low thermal conductivity of concrete precludes the use of the "lumped parameter" simplification commonly adopted in thermal analysis of metal structures such as steel, where thermal gradients within the solid are ignored. It is common for design codes (*e.g.* BS 8110 [3]) to bypass the complexities of temperature distributions by simply specifying a certain depth of concrete cover to the reinforcement bars in a composite structure, providing an insulating effect upon the steel. The uncertainties in the details of the thermal response are thereby substituted by extensive testing, mostly based on standard heating curves and presented as a "fire resistance" time, typically a function of thickness or cover, for different types of concrete [3].

There are a number of physical and chemical changes which occur in concrete subjected to heat [2,4,5]. Some of these are reversible upon cooling, but others are non-reversible and may significantly weaken the concrete structure after a fire. Most porous concretes contain a certain amount of liquid water. This begins to vaporise if the temperature exceeds 100°C, usually causing a build-up of pressure within the concrete. In practice, the boiling temperature range tends to extend from 100 to about 140°C due to the pressure effects. Beyond the moisture plateau, when the temperature reaches about 400°C, the calcium hydroxide in the cement will begin to dehydrate, generating more water vapour and also bringing about a significant reduction in the physical strength of the material. Other changes may occur in the aggregate at higher temperatures. For example quartz-based aggregates increase in volume, due to a mineral transformation, at about 575°C, whilst limestone aggregates will begin to decompose at about 800°C. In isolation, the thermal response of the aggregate itself may be straightforward but the overall response of the concrete due to changes in the aggregate can be much different. For example, differential expansion between the aggregate and the cement matrix may cause cracking and spalling.

In combination, these physical and chemical changes in concrete will have the effect of reducing the compressive strength of the material. In practice, the critical temperatures for significant strength reduction depend strongly on aggregate type, approximate values being: sand light-weight concrete (650°C), carbonate (660°C) and siliceous (430°C). At lower temperatures the influence of temperature on strength can also be very variable, depending both on composition and environmental factors, such as the degree to which the concrete is "sealed" due to moisture [2]. There is also an influence of concrete strength, with the hot strengths of UHPC concretes declining more than for other concretes [2]. Nevertheless, as noted above, all of these temperature relations provide only indirect links to the fire resistance performance of concrete structures due to the steep temperature gradients typically exhibited within the depth of the material. Structural failure often only occurs when the effective strength of any steel reinforcement is lost through heating.

The details of the physical and chemical transformation of concrete with elevated temperatures have been a subject of significant research effort over many years. Unfortunately, most of these studies have been conducted with respect to certain predetermined heating regimes, which might not be very representative of heating in real fires, i.e.: 1. the temperature-time curve used in standard fire tests, 2. slow heating, leading to reduced internal temperature gradients, or 3. using other temperature-time relationships appropriate only for specific applications. Thus, the combined effect of physical and chemical changes in relation to the thermal gradients typical of fires has, in most cases, not been assessed. Therefore, an important area of research that has yet to be addressed is the systematic variation of the thermal exposures, at the surface and within the depth of the material, and the interpretation of such studies with respect to likely conditions in real fires, i.e. determining "worst case scenarios".

After a fire, changes in the structural properties of concrete do not reverse themselves, as opposed to steel structures where cooling will often restore the material effectively to its original state. This is due to the irreversible transformations in the physical and chemical properties of the cement itself. Such changes may be used as indicators of maximum exposure temperatures, based on post-fire examination of the state of the concrete surface [6,7]. It should be noted that, in some circumstances, a concrete structure may be considerably weakened after a fire, even if there is no visible damage.

Several conceptual models are available for the mechanical behaviour of concrete at elevated temperatures. A number of these are reviewed by Li & Purkiss [8], in particular those developed by Anderberg & Thelandersson [9], Schneider [10], Khoury & Terro [11], in order to establish a general methodology for use in finite element analysis of a structure. It is noted that most of these thermomechanical models break the strain imposed on the concrete into four different types: 'free thermal strain' resulting from the change in temperature, 'creep strain' due to the dislocation of microstructures within the material, 'transient strain' caused by changes in the chemical composition of the concrete and 'stress-related strain' arising from externally applied forces.

The models examined by Li & Purkiss each handle these strains differently [8]. "Free thermal strain" is solely a function of the temperature of the concrete member, however creep, transient and stress-related strains are functions of stress, temperature and time, making it difficult to separate which strains are being influenced during an experiment. In order to reduce this level of complication, some of the models gather two or even all three of these strains together into one effective term. Typically, this is the ‘transient creep strain’, incorporating the creep strain and transient strain together, also referred to as the ‘load induced thermal strain’ (LITS). The importance of accounting for this strain, which is specifically relevant to concrete amongst structural materials, and may be dominant over elastic strains, has been emphasised by a number of authors, including Khoury [2] and Nielsen [12]. In fact, it is generally recognised that the presence of transient thermal creep is an important reason that concrete does not degrade completely when heated beyond 100°C, as this effect provides a degree of relaxation [13], helping to minimise the stress gradients originating from thermal incompatibilities and temperature gradients. Furthermore, beyond 100°C LITS depends mainly on temperature, rather than time, which renders it more amenable to modelling [2].

Based on the work of these earlier researchers, Li & Purkiss created a new model and used it to demonstrate the significance of transient strain [8]. It was shown that models that do not include transient strain are unconservative for high temperatures, though at low temperatures transient strain appears to have less effect. It was also noted that the full stress-strain curves provided in EN 1992-1-2 (the structural Eurocode for concrete design [14]) for higher temperatures are unconservative, i.e. compared to the values from the models examined in the paper.

Ultimately, concrete members may fail in a number of different ways [2]. For load-bearing reinforced slabs, if the strength of the steel reinforcement is lost due to heating then there bending or tensile strength failure. This mechanism is conventionally characterised by mid-span deflections of L/30, where L is the span. Reinforced members may also fail when the bond between the concrete and the reinforcement bars is lost, with associated concrete tensile failure. Shear or torsion failure are also influenced by concrete tensile strength, but are poorly defined experimentally. Finally, compressive failures are usually associated with temperature-related loss of compressive strength of the concrete in the compression zone.

In practice, many of these conditions are related to the structural performance of the member *in situ*, i.e. in relation to the restrains and supports provided by other parts of the structure, and cannot be considered in isolation. Indeed, collapse of concrete structures in real fires has been variously attributed to poor continuity of reinforcement/poor workmanship, and perhaps more realistically to the inability of a structure to accommodate or resist large horizontal displacements caused by thermal expansion of floor slabs [15]. These aspects are discussed in more detail in section 9 below. Other cases can be attributed more directly to simple loss of concrete cover to the reinforcement due to severe spalling; this phenomenon is discussed next.

3. Spalling

One of the most complex and hence poorly understood behavioural characteristics in the reaction of concrete to high temperatures or fire is the phenomenon of ‘explosive spalling’ [2,16]. This process is often assumed to occur only at high temperatures, yet it has also been observed in the early stages of a fire [17] and at temperatures as low as 200°C [18]. If severe, spalling can have a deleterious effect on the strength of reinforced concrete structures, due to enhanced heating of the steel reinforcement. Spalling may significantly reduce or even eliminate the layer of concrete cover on the reinforcement bars, thereby exposing the reinforcement to high temperatures, leading to a reduction of strength of the steel and hence a deterioration of the mechanical properties of the structure as a whole.

Another significant impact of spalling upon the physical strength of structures occurs via reduction of the cross-section of concrete available to support the imposed loading, increasing the stress on the remaining areas of concrete. This can be important, as spalling *may* manifest itself at relatively low temperatures, before any other negative effects of heating on the strength of concrete have taken place.

The mechanism leading to spalling is generally thought to involve high thermal stresses resulting from rapid heating and/or large build-ups of pressure within the porous concrete, which the structure of the concrete is not able to dissipate, due to moisture evaporation. These actions lead to the development of fractures and expulsion of chunks of material from the surface layers. More specifically, the main prerequisites for spalling have been established as: moisture content of at least 2%, and steep temperature gradients within the material. For the latter, a value of 5K/mm is a rough minimum and at 7-8K/mm spalling is very likely [19]. Temperature gradients are dependent not only on gas-phase temperatures but also heating rates, so that it is not possible to define a threshold temperature *per se*; rather, an equivalent limit can be defined in terms of heating rates, this being of the order of 3K/min [2]. However, these critical values for spalling may also be affected by the type of concrete, including the strength of the material and the presence of fibres [2], as described below.

There has been a large amount of research recently on the potential for inclusion of various types of fibres into concrete to mitigate the effects of spalling. Some studies [20-24] have included polypropylene fibres into the concrete matrix. The main theory is that when the concrete is subjected to heat, the polypropylene will melt, creating pathways within the material for the exhaust of water vapour and any other gaseous products, which will thereby reduce the build-up of pressure. There has been some debate as to whether mono-filament or multi-filament fibres are better able to mitigate spalling [25]. It has also been suggested that the melted polypropylene fibres can form a barrier to the transport of moisture further into the concrete, preventing pressure build-up at greater depth and forcing the moisture to escape instead [21]. On the other hand, the polypropylene fibres may provide a mechanism for cracking deeper within the concrete, which could mitigate spalling at the surface, but may itself have adverse structural consequences [21]. Other studies have added steel fibres to concrete systems [25], based on the idea that the steel will increase the ductility of the concrete and render it more able to withstand the high internal pressures. However, results so far are inconclusive [25].

Recently there has been increasing use of ‘high-strength’ (or ‘high-performance’) concrete. This material typically has considerably higher compressive strength than normal-strength concrete, but it is markedly less porous and moisture absorbent. While this generally reduces the water content of the cement, it is also harder for water vapour to escape during heating. It is sometimes argued that high-strength concrete is more prone to spalling, due to its lower porosity and hence the increased likelihood of high pressure developing within the concrete structure [20]. However, other recent research has shown that this is not necessarily the case, with some testing showing higher spalling resistance in these materials [21], attributable to the fact that their improved tensile properties can effectively counteract the increase in forces which promote a tendency for spalling.

Finally, it should be noted that despite severe challenges derived from the complexity of the relevant phenomena, modelling of spalling is beginning to show promise [2,26,16], though with more work still needed. Modelling aspects are discussed further in section 10 below.

4. Cracking

The processes leading to cracking are generally believed to be similar to those which generate spalling. Thermal expansion and dehydration of the concrete due to heating may lead to the formation of fissures in the concrete rather than, or in addition to, explosive spalling. These fissures may provide pathways for direct heating of the reinforcement bars, possibly bringing about more thermal stress and further cracking. Under certain circumstances the cracks may provide pathways for fire to spread between adjoining compartments.

Geogali & Tsakiridis [27] made a case study of cracking in a concrete building subjected to fire, with particular emphasis on the depths to which cracking penetrates the concrete. It was found that the penetration depth is related to the temperature of the fire, and that generally the cracks extended quite deep into the concrete member. Major damage was confined to the surface near to the fire origin, but the nature of cracking and discolouration of the concrete pointed to the concrete around the reinforcement reaching 700°C. Cracks which extended more than 30 mm into the depth of the structure were attributed to a short heating/cooling cycle due to the fire being extinguished.

The importance of the stress conditions in the concrete should be noted. Compressive loads which may arise from thermal expansion can be very beneficial in compacting the material and suppressing the formation of cracks [2]; this results in much smaller degradation of compressive strength and elastic modulus than in specimens bearing reduced loading.

5. Use of supporting materials

Research has been undertaken on the effects of wrapping a concrete member in a variety of fabrics in order to assess any improvement of spalling resistance that this may provide [28]. It was found that a metal fabric had a beneficial effect on spalling resistance, with less effect using carbon fibre and glass fibre fabrics. All tests were noted to have less or no spalling when polypropylene fibres were added to the concrete mixture [22]. Steel fabric reduces spalling by providing lateral confinement pressure to the concrete member which is greater than the internal vapour pressure causing spalling. The reduced effect of carbon and glass fibre fabrics is due to the bond strength of these materials reducing at high temperatures and the corresponding reduction of the ability of the fabric to provide confinement. It does not appear that the technique induces cracking deeper within the structure.

6. Performance of reinforcement in fire

The performance of steel during a fire is understood to a higher degree than the performance of concrete, and the strength of steel at a given temperature can be predicted with reasonable confidence. It is generally held that steel reinforcement bars need to be protected from exposure to temperatures in excess of 250-300°C. This is due to the fact that steels with low C-contents are known to exhibit ‘blue brittleness’ between 200 and 300°C. Concrete and steel exhibit similar thermal expansion at temperatures up to 400°C; however, higher temperatures will result in significant expansion of the steel compared to the concrete and, if temperatures of the order of 700°C are attained, the load-bearing capacity of the steel reinforcement will be reduced to about 20% of its design value. Bond failure may be important at high temperatures, as discussed in section 2.

Reinforcement can also have a significant effect on the transport of water within a heated concrete member, creating impermeable regions where water may become trapped. This forces the water to flow around the bars, increasing the pore pressure in some areas of the concrete and therefore potentially enhancing the risk of spalling. On the other hand, these areas of trapped water also alter the heat flow near the reinforcement, tending to reduce the temperatures of the internal concrete [29].

A large area of current study is the effects of using glass or carbon fibre reinforcement rather than steel reinforcement in concrete [30-34]. Much of this research is due to the relative lack of information on Fibre Reinforced Plastic (FRP) reinforcement at high temperatures. However, most of this testing indicates that with sufficient cover to the reinforcement, FRP reinforcement will have adequate fire endurance [30,31]. Also, externally-bonded FRP may be used for strengthening existing structures; in this case, the provision of fire protection materials may also need to be considered [35].

7. Composite structures

A common form of construction for floor slabs is known as ‘composite construction’. In this method, a concrete slab is cast upon steel beams. The formwork for the slab is a profiled metal sheet, known as decking, which spans between the beams. ‘Shear studs’ are welded to the top of the steel beams, through this profiled decking. These studs allow a mechanical bond to be formed between the concrete and the steel member, and therefore allow the beam and the slab to act as a single element with an increased strength. The steel decking is left permanently in place after the concrete has been cast. Steel reinforcement is typically added above the profiled decking.

There has been a significant amount of work carried out on the fire performance of composite steel and concrete structures, for example the Cardington research included a number of full-scale fires on a steel-framed structure which used composite concrete floor slabs. These structures have been found to have considerable resistance to fire, more than initially expected [36]. This is in part due to the concrete floor having capacity to act as a tensile membrane due to the addition of steel reinforcement above the decking, allowing the load to redistribute through the structure when the properties of steel are reduced. In some cases this may lead to a reduction in the requirement for fire protection on the steel areas of the structure, typically the secondary beams.

8. Fire resistance

In common with other structural members, performance assessment of concrete elements is normally carried out with respect to a standard heating curve developed in a fire resistance test furnace [37-39]. This heating regime is defined purely in terms of a temperature-time curve, originally conceived as being representative of the development of a fire in a standard living room, and expressed in essentially identical form in a number of standards, both internationally, i.e. the ISO-834 fire curve [1], and nationally, i.e. the BS-476 curve in the UK, ASTM E-119 in the US. Other standard fire curves exist which are intended to replicate the temperature developments in other assumed scenarios [2]. For example, the ‘hydrocarbon curve’ [40], is commonly used in the chemical processing industry to represent the development of a fire involving liquid fuels. This curve has a much more rapid growth phase and high temperatures (over 1000°C) are attained within the first 20 minutes of the fire. In The Netherlands, the Rijkwaterstaat and TNO established a standard fire curve

(RWS) to simulate the temperature development of a tanker or large goods vehicle fire in a tunnel [41]. This curve has a very fast temperature development and attains a peak value of 1350°C after about an hour. It has also been used in testing of non-tunnel structural members.

Whilst these test methods have the advantage of providing a degree of standardisation of heating regimes, their intrinsic limitations are widely recognised [37-39]. Firstly, though temperature development is standardised via furnace control, the actual heating impact on the structure is dependent on other variable factors, including the optical properties of the furnace gases and the thermal response of the structure. Secondly, the test results provide very little information on the likely performance of structural elements *in situ*, i.e. taking into account the interaction between different parts of a structure, the effects of restraint, etc. Thirdly, whilst there may be gradients in thermal exposures even within the "uniform heating" environment of fire resistance furnaces [42], even steeper gradients are common in fully-developed compartment fires [43]. The effects on structural performance of spatial non-uniformities in heating are poorly known, though it has long been recognised that spalling can be linked to these conditions. Finally, standard curves make no attempt to account for the important post-fire cooling stage of a fire [44]. The potential significance of cooling on concrete performance was demonstrated during a test of some concrete structural elements at Hagerbach test gallery, Switzerland [45]. During the test a concrete sample resisted temperatures of up to 1600°C for two hours without failure, but half an hour into the cooling phase the sample collapsed explosively. It is not currently known, in the majority of cases, how much spalling exhibited in a real building fire takes place as a result of cooling rather than heating. Although considerable research has been conducted to understand the behaviour of steel structures during cooling, no equivalent effort has so far been made for concrete.

As is clear from the above, standard fire tests can only simulate a very limited range of heating conditions. Recently there has been some discussion on the different response to fire behaviours of concrete in 'short hot' fires compared to 'long cool' ones. While many of these scenarios are covered by the so called 'parametric curves' [46], most testing is still conducted with the standard furnace. Methods to establish equivalency between standard testing and real fire behaviour are very crude and mostly designed for steel members and not for concrete or thermal insulation [47]. 'Short hot' fires provide severe thermal stresses to structures but are of limited duration. During 'long cool' fires, peak temperatures are lower, but due to the longer fire duration the concrete member may be heated to a much greater depth. Debate on which of these conditions is more harmful to concrete is ongoing [48]. Lamont *et al.* [48] have carried out some finite element modelling of such fires for composite steel and concrete structures, and while no specific work has yet been undertaken for purely concrete structures many of these results will be applicable. The different fire exposures were generated by use of a constant fire load of 250 MJ/m^2 being applied with differing opening areas, representing realistic models of real-world fires with differing degrees of ventilation failure. However, no validation based on test results is available in the literature.

More specifically, due to the nature of 'standard fire' furnace tests, the heat transfer to and within the structural member under test can be quite different according to the nature of the component being assessed. For example, a steel beam and a concrete slab subjected to the same furnace test will respond very differently. The thermal conductivity of the steel is many times higher than that of the concrete thus, during the test, the net heat transfer from the furnace gases to the member surface is many times greater than that to the concrete member. Hence, after the initial rapid heating of the face of the slab, the same standard test exposes a steel beam to a significantly higher net heat flux than it does to a concrete beam [42].

Another approach to standardising heating is adoption of *constant* exposure temperatures. Hertz & Sorensen [20] have developed a bench-scale test method for study of spalling using concrete cylinders. An oven temperature of 1000°C was used to generate surface temperature of 800°C within 20 minutes; in principle, this type of method could be used to examine the effects of both exposure temperature and heating rates.

9. Whole structure performance

While it is important to understand the performance of individual concrete members during a fire, the behaviour of the same structural elements within the context of a complete structure can vary widely from their independent responses. For example, thermal expansion of members which have been subjected to heating may lead to forces being exerted upon the cooler members due to differential expansion, with compression forces within the heated members due to restraining forces provided by the rest of the structure. The effects of thermal expansion have long been recognized with steel and composite members [49], but little research is available for concrete structures; nevertheless, this phenomena has potential to precipitate the collapse of concrete structures during a fire and its role in actual fire-induced collapses has been debated [15]. Equally, it must be recognised that in situations where an individual concrete member might have failed, the overall structure may nevertheless remain intact, due to the inherent redundancies and load redistribution. This is a common phenomenon in composite structures (see section 7).

Modelling has been undertaken of various individual concrete elements, for example concrete columns, during a fire [50]. These have been used in particular to compare predictions with the structural Eurocodes and validate against the behaviour of real concrete columns during full-scale fire testing. Work has been carried out to study the boundary conditions of the column as well as the effects of heating on the concrete itself [51], and hence give a closer approximation to the effects of fire on a whole structure. This is important, considering the need to relate the behaviour of a structural member to the structure it is contained in, and to examine the effects of the member on the adjacent structure during heating. These tests showed that the additional forces generated were low, around 15% of the design load of the columns. The columns tested were 125mm x 125mm cross-section x 1.8m high with 108 N/mm^2 high-strength concrete. This is small for a concrete section and it is uncertain whether this data would be scalable to larger members or applicable to members with normal-strength concrete. The study concluded that further work is required in this area.

The main reports on the effects of fire on whole buildings have been produced as a result of tests carried out at Cardington by the Building Research Establishment (BRE) [17,15,52]. One of the full-scale structures inside the Cardington laboratory was a seven-storey concrete building. A fire test was performed on this structure, using a fire load provided by wood cribs in an open compartment on the ground floor, surrounding a high-strength concrete column. The thermal exposures resulting from the fire were not particularly high but they did serve to indicate that the column performed very well with little visible damage; the column contained polypropylene fibres which may have assisted in achieving this performance. However, unexpectedly large amounts of spalling were caused in the concrete ceiling slab, made of normal-strength concrete. This nevertheless remained fully intact, largely due to “compressive membrane action” as the expansion of the concrete slab was restrained due to the presence of cold surrounding areas of structure, and therefore load was supported by the compressive strength of the concrete. Such compressive membrane action can only take place at relatively small displacements. At larger displacements “tensile membrane action” may also support a floor slab, with the reinforcement itself restraining the displacement of the slab; however this mechanism relies on the reinforcing bars retaining sufficient strength. In the case of the Cardington test the near-surface reinforcing bars are unlikely to have retained large amounts of strength due to being directly exposed to high temperatures as a result of the extent of the spalling, so it is uncertain how the slab may have responded at higher displacements.

The Cardington data has been used to provide input data for a finite element model which made a large number of assumptions with respect to the performance of concrete in fire (for example, the effects of spalling were neglected) [17]. Further study of the effects of fire upon full-scale buildings would be extremely useful.

Another useful source of information on the performance of whole buildings in fire is information derived from the observed behaviour of real fire incidents. This is an active area of current work, for instance with respect to the Windsor Tower fire in Madrid (February 2005) [53], and other historical fires [15]. The main challenge here is to reproduce the fire conditions which might have existed in the fire, and here advanced modelling tools can be of great assistance, combined with interpretation of various forms of the record of the fire, *e.g.* video evidence. Improved documentation of concrete performance in other fires will be very useful in advancing knowledge in this field.

10. Detailed models

Comprehensive analysis of structural concrete is an intricate problem for which conventional analytical methods are rarely sufficient and where computational modelling tools provide the only realistic alternative. If the results from complex numerical analyses are to be relied upon, the constitutive relationships on which they are based must be as accurate as possible and capture all experimentally-observed phenomena. Furthermore, the engineers involved in this process must have a thorough knowledge of the physical processes involved in order for them to make a reasonable judgement during the analysis, design and assessment procedures.

Some commercially-available ‘Finite Element Analysis’ packages are able to describe the thermomechanical behaviours of reinforced concrete. However, with a few exceptions, they are typically crude, as they over-simplify the complex problem of modelling concrete and often lack algorithmic robustness. These codes simplify thermal effects by applying a temperature dependency to the material properties (*c.f.* description under section 2 above); however, this cannot adequately account for the complex coupled processes that cause many of the observed phenomena and these codes are therefore unsatisfactory for detailed modelling of concrete behaviour in fires.

The true behaviour of concrete subjected to an aggressive environment is controlled by the history of the multi-axial stress state, temperature and moisture content [2,26]. In the past, inadequate modelling of the complex coupling of these variables has resulted in an over-simplification in the simulation process and therefore failed to provide fully meaningful, quantitative predictions of the behaviour of concrete structures. In fact, concrete under such conditions should be considered as a multi-phase system where the voids are partly filled with liquid and partly with a gaseous mixture composed of dry air and water vapour. To realistically simulate structural concrete under complex loading scenarios a model must involve a coupled heat-mass transfer and mechanical analysis. The three main physical processes to be considered in such a coupled formulation can be identified as mechanical, thermal and hygral.

Previous modelling studies have generally represented the thermo-mechanical response of concrete by extending isothermal models to incorporate thermal dependency. In most commercial finite element codes, mechanical material properties such as strength and stiffness are simply related to temperature, although such an approach does not account for the irreversible change these material properties undergo. A sophisticated, thermodynamically consistent thermo-mechanical model was presented by Stabler [54]; temperature effects were included via a thermal damage model and the governing thermal and mechanical equations were solved in a fully-coupled manner. However, hygral considerations and transient thermal creep were not included in the model, and these are important phenomena in representing the response to heating, as described above.

Tenchev [16] developed a numerical model for heat-mass transfer in which all phases are explicitly modelled but without any mechanical coupling. The latter aspect would be a natural extension as it is the dehydration and mass transport under heating that results in significant changes in the mechanical material properties and thus the loss of decohesion and stiffness. There are very few fully-coupled hygro-thermo-mechanical models proposed in the literature. Notable exceptions include the work of Khoury *et al.* [26,2], Grasberger & Meschke [55] and Ulm *et al.* [56]. All of these models are computationally expensive and application to full-scale problems is challenging.

11. Conclusions and areas for further research

The behaviour of concrete in fire is not well characterised at present, and further research is required in almost every aspect of this field. The response of concrete materials to heating is fundamentally complex; for example, degradation in the physical properties of concrete varies strongly depending on the details of the concrete mix, including the moisture content, and relevant environmental parameters, such as the maximum fire temperature and fire duration. Systematic studies are required on the effects of different heating conditions on concrete.

A more significant challenge arises in relating these detailed small-scale behaviours to the performance of whole structures in realistic fires. Though good progress has been made on modelling the mechanical behaviour of concrete structures, particularly when the significant role of LITS is properly accounted for, the use of detailed models to predict spalling behaviour remains a significant challenge. Moreover, capability to predict structural interactions, which may have a role in failures, is poorly developed.

Historically, very simple treatments have often been adopted to describe fire environments, referencing simple temperature-time curves or assuming homogeneous temperatures, which are poor representations of real fires. More extensive research into the effects of temporal and spatial variations in heating, on a range of concrete compositions, is now required. This demands further testing of complete concrete structures in realistic fires, to observe their holistic behaviour, including the interactions between different parts of a structure, and in order to facilitate the validation of advanced computer models. Detailed studies of the performance of concrete structures in actual fire incidents can also assist greatly in advancing knowledge of real-world behaviour.

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