Turning up the heat – full service fire safety engineering for concrete structures

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There are two basic approaches to providing design methods for concrete structures. The first is the traditional, prescriptive code-based approach that addresses the various aspects of life safety independently of one another, using generic rules and formulas. As designs for new concrete structures have increased in complexity, so the prescriptive codes are falling outside their applicable realms.

The alternative is to adopt a performance-based, fire engineering design approach that is described in an SFPE guide[1]. The performance-based approach takes into account the complexity of modern structures and the interrelationship between the various fire safety measures and systems. Provided any deviations from the Standard can be proven by engineering analysis (often supported by a qualitative or quantitative risk assessment) to be equivalent or superior to the required Standard, then a performance-based approach is considered acceptable. Engineering and risk analyses are based on fundamental research into issues such as fire and smoke spread, the behaviour of people and response of facilities to fire, to establish a performance-based solution.

The performance-based approach allows the development of innovative structural solutions and provides the structure with the required level of safety at the lowest cost, in both financial and environmental terms. The strategy considers fire safety engineering as an integrated package of measures designed to achieve the maximum benefit from the available methods for preventing and controlling the consequences of fire. The performance-based design procedure is summarised below:

Identifying risk factors

The structural fire engineer should identify all risk factors that could affect the fire performance of the structure. All the fire safety measures that are part of the overall fire strategy and could impact on any assumptions/decisions made subsequently should be considered.

Predicting the temperature distribution in the fire compartment

Predicting the worst-case temperature distribution involves calculating the fire severity curve according to the different characteristics of the fire compartment. Depending on the complexity of the building geometry, different types of analysis can be adopted.

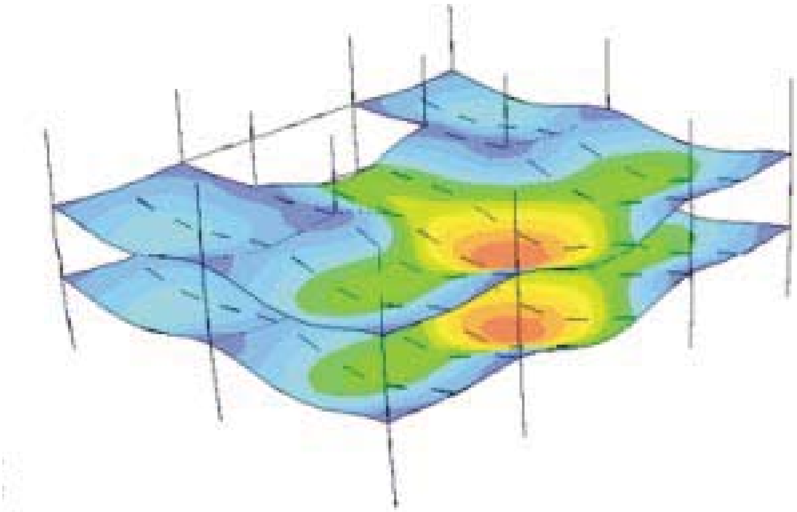

Figure 1: Finite element analysis of the deflection profile for a composite concrete floor slab at elevated temperatures.

Predicting the temperature of structural members

This stage depends on the location of the structural member within the fire compartment, the cross-section factor (exposed perimeter to the cross-sectional area) and the applied fire protection to the structural member.

Structural fire analysis

This involves carrying out the necessary structural fire analysis to predict the stability of the whole structure, based on the results of the previous stages, using a computer model (see Figure 1). It is important to note that the stability of the member and overall structure depends on the following factors:

- maximum temperature and temperature distribution (including penetration)
- material properties
- the applied load
- the level of composite action with slab
- the restraints provided by the surrounding structure
- the continuity/interaction with other cold/heated members
- engineering factors.

Consideration of these factors permits the stability of

Figure 2: The concrete frame of a ten-storey building that was fire-damaged during construction.

Figure 3 right: View of the interior of a fire-damaged building showing spalling of a reinforced concrete slab soffit.

Figure 4 far right: View of a fire-damaged concrete column showing red discoloration of flint fine aggregate particles.

the structure to be predicted, so that protection requirements can be specified to meet the fire hazard.

Assessing the effect of fire compartmentation

Depending on the proposed use of the structure, Building Regulations recommend different levels of compartmentation in different types of building to take account of the likely risk of fire in a particular building type, together with the consequences of rapid fire spread. This ranges from very little compartmentation in low- and medium-rise office buildings or single-storey industrial and storage buildings to very high levels of compartmentation in blocks of flats, hospitals, hotels and schools.

Construction information

It is useful to produce structural fire drawings with an appropriate colour-coded scheme that shows the fire protection strategy applied to the different members to provide clear information for site staff.

Assessment of fire-damaged concrete structures

Concrete structures most likely to be subjected to fire include buildings such as offices, warehouses and schools. Other common scenarios involve vehicle fires in car parks or tunnels. In recent years a number of notable fires have occurred during construction of concrete-framed buildings, when formwork and falsework has caught fire (see Figure 2). Fortunately, even after a severe fire, reinforced concrete structures are generally capable of being repaired rather than demolished. Guidance for the assessment and repair of fire-damaged concrete structures is provided in Concrete Society Technical Report 33[2]. This publication is currently being revised by a Concrete Society Working Group that includes Halcrow engineers.

After a fire, an appraisal is normally required as soon as the building can be safely entered and generally before the removal of debris. To ensure safety, temporary falsework may be required to secure individual members and stabilise the structure as a whole.

The primary on-site investigation technique is visual inspection, which is used to classify the degree of damage for each structural concrete member. Visually apparent damage induced by heating includes collapse, deflection, spalling, cracking, surface crazing, colour changes and smoke damage. Visual survey of reinforced concrete structures is performed using a classification scheme from Concrete Society TR 33 (see Table 1). This uses visual indications of damage to assign each structural member a class of damage from 1 to 5. Each damage classification number has a corresponding category of repair, ranging from decoration to major repair.

Spalling of the surface layers of reinforced concrete is a common effect of fires. Explosive spalling (see Figure 3) is erratic and generally occurs in the first 30 minutes of the fire. A slower spalling (‘sloughing off’) occurs as cracks form parallel to the fire-affected surfaces. Forms of cracking include those caused by differential thermal expansion, and thermal shock from quenching by fire-fighting water. Also, differential incompatibility between aggregates and cement paste may cause surface crazing.

Heating can change the colour of concrete and this may indicate the temperature attained. At above 300ºC a red discoloration is important as it coincides approximately with the onset of significant strength loss. Consequently, any pink/red discoloured concrete should be regarded as being potentially weakened. Actual concrete colours observed depend largely on the types of aggregate present in the concrete. Colour changes are most pronounced for

Table 1: Simplified visual concrete fire damage classification (after Concrete Society, 1990[2] and Smart, 1999[3])

	Features observed						
Class of damage	Finishes	Colour	Crazing	Spalling	Reinforcement bars	Cracks	Deflection
0 (Decoration required)	Unaffected	Normal	None	None	None exposed	None	None
1 (Superficial repair required)	Some peeling	Normal	Slight	Minor	None exposed	None	None
2 (General repair required)	Substantial loss	Pink	Moderate	Localised	Up to 25% exposed	None	None
3 (Principal repair required)	Total loss	Whitish grey	Extensive	Considerable	Up to 50% exposed	Minor	None
4 (Major repair required)	Destroyed	Buff	Surface lost	Almost total	Up to 50% exposed	Major	Distorted

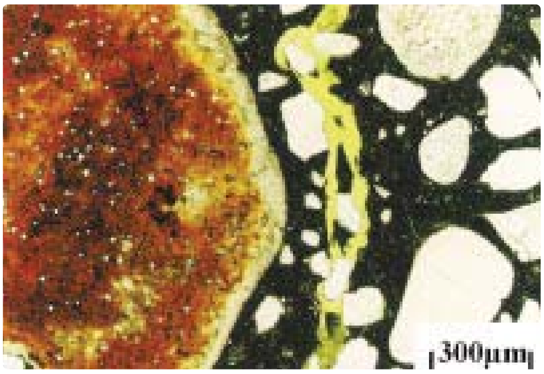

Figure 5 right: A photomicrograph of fire-damaged concrete showing a crack running parallel to the outer surface and red discoloration of a flint fine aggregate particle.

Figure 6 far right: Removal of fire-damaged concrete by water jetting.

siliceous aggregates and less so for limestone, granite and sintered pulverised fuel ash. Perhaps the most striking colours are produced by flint (see Figure 4). The red colour change is a function of (oxidisable) iron content and it should be noted that not all aggregates undergo colour changes on heating. Also, due consideration must always be given to the possibility that the pink/red colour may be a natural feature of the aggregate rather than heat-induced. A number of complementary non-destructive techniques can be used to assess material strength in-situ. These include Schmidt (rebound) hammer and ultrasonic pulse velocity (UPV). Samples of damaged material (and undamaged references) may be removed for laboratory investigation, often by diamond drilling of cores. If it is suspected that the reinforcement bars have been heat damaged it will be necessary to obtain samples and test the tensile strength in the laboratory.

The temperature profile for each concrete element is commonly estimated using a combination of on-site visual inspection and testing, and petrographic examination of samples in the laboratory. Petrographic examination performed in accordance with ASTM C856[(4)] is invaluable in determining the heating history of concrete, as it can determine whether features observed visually are actually caused by heat rather than some other cause[(5)]. In addition to colour changes, the heating temperature can be cross-checked with changes in the cement matrix and evidence of physical distress such as cracking (see Figure 5). The combined investigative findings are used to prepare key diagrams and schedules detailing the damage. A comparison between the cost of repair and the cost of removal and replacement is then made for each damaged element, taking into account its function. Following this, a repair strategy may be drawn up.

Repair of fire-damaged concrete

Up to 300ºC the residual strength of structural quality concrete is not severely reduced. Between 300ºC and 500ºC the compressive strength reduces rapidly and concrete heated in excess of 600ºC is of no use structurally. Three-hundred degrees centigrade is normally taken to be the critical temperature above which, concrete is deemed to have been significantly damaged and normally this is replaced if possible. Otherwise the dimensions are increased (for example, by reinforcing columns), depending upon the design loads. At 200-400ºC prestressed steel shows considerable loss of strength, at >450ºC cold-worked steel loses residual strength and at >600ºC hot-rolled steel loses residual strength.

Concrete element repair will usually include three main processes, the first being removal of damaged concrete by using either power breakers or water jetting (see Figure 6). After a severe fire it is likely that the second process will comprise removal of weakened reinforcement and connection of new reinforcement. The final part of the repair stage will comprise reinstatement of concrete to provide adequate structural capacity, the necessary durability and fire resistance, and an acceptable appearance (see Figure 7). An alternative to providing additional steel reinforcement is the use of fibre composite materials (FRPs), bonded to the surface using an epoxy adhesive.

Concluding remarks

With concrete being used in ever more challenging building and infrastructure projects there has never been a greater need for fire safety engineering. To fulfil these requirements, fire safety practitioners provide bespoke, cost-effective fire engineering solutions for a wide range of concrete structures. When fires do occur, their relatively high fire resistance means that concrete structures are generally capable of being repaired rather than replaced. Specialist structural and materials engineers can assess fire-damaged structures and specify well-informed repair solutions. As an alternative to demolition this provides very substantial savings in capital expenditure and also savings in consequential losses, by permitting much earlier reoccupation. ■

Figure 7: Application of sprayed concrete to repair a fire-damaged slab soffit following removal of fire-damaged concrete.

References:

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