The Cardington Fire Test

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Introduction

The collapse of the World Trade Centre on 11 September 2001 and several recent tunnel fires in Europe have focussed attention on the performance of structures and materials in extreme fires. Progress in structural design and materials technology has made structures easier to construct, more durable and more efficient in the use of materials. The question remains whether some structures should also be designed to survive extreme events. Concrete is very durable under most conditions and can make a vital contribution to the reserve strength and robustness. The objective of this article is to consider the effect of fire on concrete structures and design guidance for fire safety.

The results of a large-scale fire test recently undertaken as part of the European Concrete Building Project, Cardington (supported by a consortium led by the British Cement Association) are discussed to identify the key issues relating to concrete in fire.

Concrete in fire

Concrete is a versatile material and, when appropriately specified, is inherently 'fireproof' because of its non-flammability and thermal insulation properties. In recent years, 'bespoke' concrete mixes have been developed that provide structural strength and robustness under extreme fire loading(1).

From the material science point of view, a number of changes occur in concrete when exposed to high temperatures. Firstly, as the concrete temperature rises beyond 100°C, moisture is driven off and the cement paste begins to dehydrate. The aggregate particles start to expand, generating large differential strains. This might be expected to cause extensive micro-cracking of the cement paste and eventually to disintegration of the concrete. However, this is not usually observed. The process of 'transient creep' (or load-induced thermal strain), occurring when concrete is first heated, is generally credited with relieving the differential thermal strains between the paste and aggregate, and preventing disintegration.

As the concrete temperature rises above 350°C, some aggregates (particularly flint gravels) dehydrate and begin to break up. Other aggregates, such as crushed granite, can withstand much higher temperatures. With further increases in temperature, other phase transformations - such as the successive dissociation of calcium hydroxide and calcium carbonate - occur before the onset of melting above 1200°C.

Owing to the good thermal insulating properties of concrete, temperatures away from an exposed surface will be considerably lower than the flame temperature of the fire itself. This protects embedded steel reinforcement from the effects of high temperatures.

Figure 1: Cardington concrete building frame.

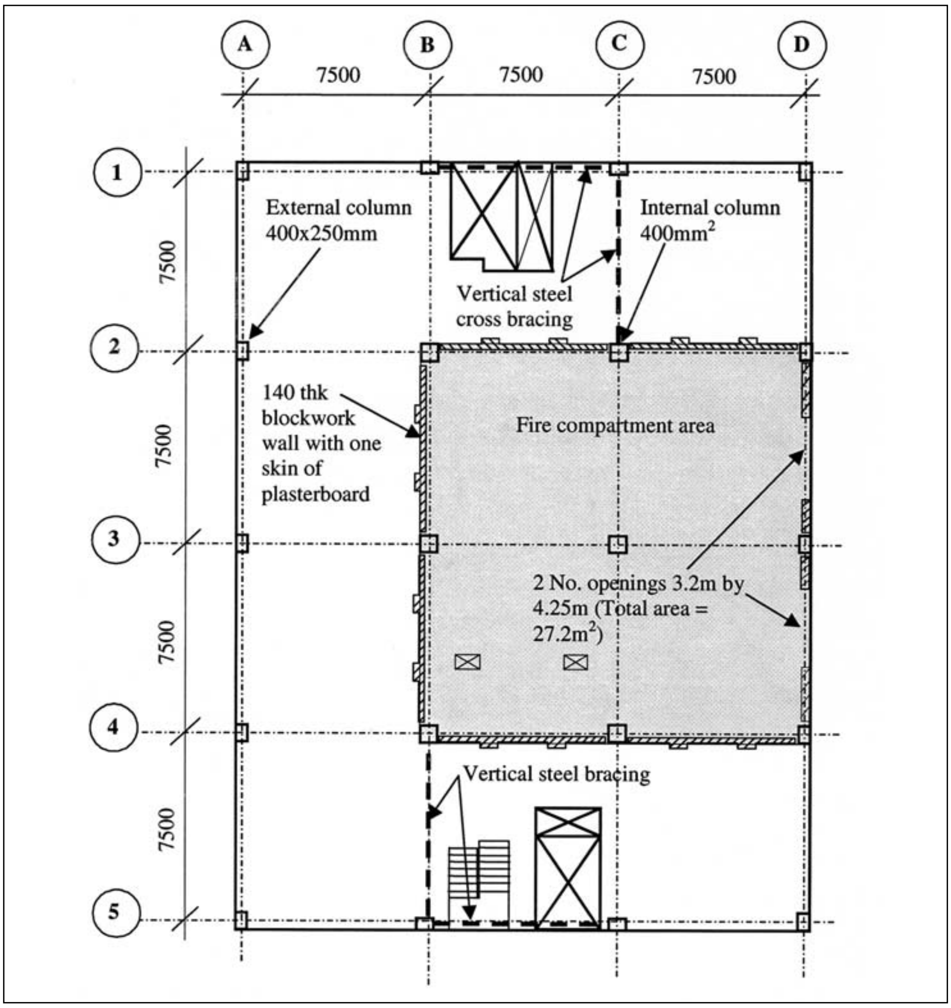

Figure 2: Plan of building showing location of fire compartment.

Figure 3: Fire compartment before ignition.

The strength of concrete exposed to high temperatures will be reduced locally, although this will rarely be structurally significant for concrete temperatures below 300°C. Fire damage to concrete surfaces can also usually be easily repaired(2). When concrete is exposed to fire, layers or concrete fragments can break off from the exposed surface or ‘spall’, sometimes violently. This behaviour results from the properties of the constituent materials of the concrete and the rate at which moisture vapour can move through the concrete. Thermally unstable aggregates, such as flint gravels, will break apart and spall from the concrete, but the main cause of spalling is the high pore vapour pressure generated in the heated concrete. If this is not relieved by movement of water vapour (steam) away from the heated surface, the pressure can cause violent loss of fragments from the concrete surface. Consequently, spalling is most likely in concrete with a high internal moisture content and/or low water-vapour permeability. High-strength (low-permeability) concrete is thought to be particularly susceptible to spalling. The incorporation of synthetic fibres, which melt during fire to produce channels through which steam can escape, is often recommended to reduce this risk(3,4). Restrained thermal expansion increases the likelihood of spalling but is also beneficial as the additional compressive forces enhance the load-carrying capacity.

A materials-based approach is not sufficient on its own to explain the performance of a real concrete structure in a fire. Additional factors, such as the influence of loads and the three-dimensional behaviour of the concrete structure as a whole, are also significant. Modern codes of practice such as in the forthcoming Eurocode 2 for fire design, EN 1992-1-2(5), allow a performance-based approach to be used in design. This code uses the fire safety engineering principles to take into account actual fire-loading scenarios, physical material parameters, and analysis of the whole structure.

The Cardington test

While tests on individual structural elements are useful to increase knowledge of the structural effects of fire, there is no substitute for a realistic fire test on a complete structure or significant part of a larger structure, when all the above factors come into effect.

The Concrete Building at Cardington was constructed as a seven-storey, 25.2m tall structure, three bays by four in plan, each square bay being 7.5m. It was of column-slab construction, with 250mm thick flat

Figure 4: Fully developed fire.

floor slabs (see Figure 1). Internal columns were 400mm square and external (edge) columns 400 x 250mm. The column cross-sections were kept constant throughout the height of the building, by using higher-strength concrete at lower levels. Minimum cover to the reinforcement was 20mm in the slab soffits and 40mm on the columns. The building was designed to the limits of EN 1992-1-2, with a fire resistance of 60 minutes, representing a typical office building in a medium-sized town.

The focus of research on the 'lean' structural frame was to investigate process issues; the frame design was optimised for construction speed and, in some respects, fell short of modern design code requirements. However, the opportunity was taken to investigate the behaviour of the frame under accurately simulated applied static loads in a realistic compartment fire. This is in contrast to the fire programme on the steel building at Cardington, where the building was designed specifically to conduct a programme of fire tests.

The concrete floor slabs of the building were to have been constructed from a C37 concrete with a flint aggregate. However, to investigate early striking of slab formwork and falsework, a higher-strength concrete - over 60MPa at 28 days, and 74MPa at the time of the fire test - was used for the first-floor slab. The concrete of the tested slab can therefore be considered essentially as a high-strength concrete, which would normally require the inclusion of polypropylene fibres to prevent spalling.

Concrete in the ground-floor columns was a high-strength (C85) mix containing silica fume and limestone aggregate. Its standard 28-day cube strength was 103MPa. This concrete also contained 2.7kg/m^3 of polypropylene fibres. At the time of construction, no guidance on minimum fibre content for improved fire performance was specified in EN 1992-1-2. Subsequently, however, a requirement for a minimum fibre content of 2kg/m^3 has been included in the Eurocode.

The building was constructed inside the main hanger at Cardington and was not exposed to normal outdoor drying. Consequently, the moisture content of the concrete measured just before the fire test was much higher than normally expected. The floor slab had a moisture content of 3.8% by weight and the columns 4.2% by weight, compared to a typical 2% for a concrete in a conventional building exposed to normal drying conditions.

Fire test procedure

The fire test was undertaken in a four-bay (2 x 2) ground-floor compartment, with a total floor area of 225m^2 and floor-to-soffit height of 4.25m. The test was designed to simulate a fully developed fire with a third of the ground floor plan area on fire. Thus, an internal column was fully exposed to the fire and other internal and edge columns were partially exposed (Figure 2). The fire compartment walls (blockwork lined with plasterboard) were sealed to the soffit of the first floor slab with a ceramic fire blanket. Openings for ventilation were left in the external wall of the fire compartment. The first-floor slab was uniformly loaded with sandbags to 3.25kN/m^2 and additional sandbags to produce an axial load of 925kN in the fully exposed internal column.

A safety cage was placed around the exposed internal column, but not actually in contact with the soffit of the floor slab. This was to support the floor slab if the column should fail during the test. Timber cribs were positioned in the compartment to provide a fire load of 40kg/m^2 (720MJ/m^2), representing typical office fire loading to the British Standards (Figure 3).

Instrumentation was installed to measure horizontal and vertical displacements of the slab and columns, atmospheric temperatures, surface temperatures, temperatures within the slab, and surface strains on the slab.

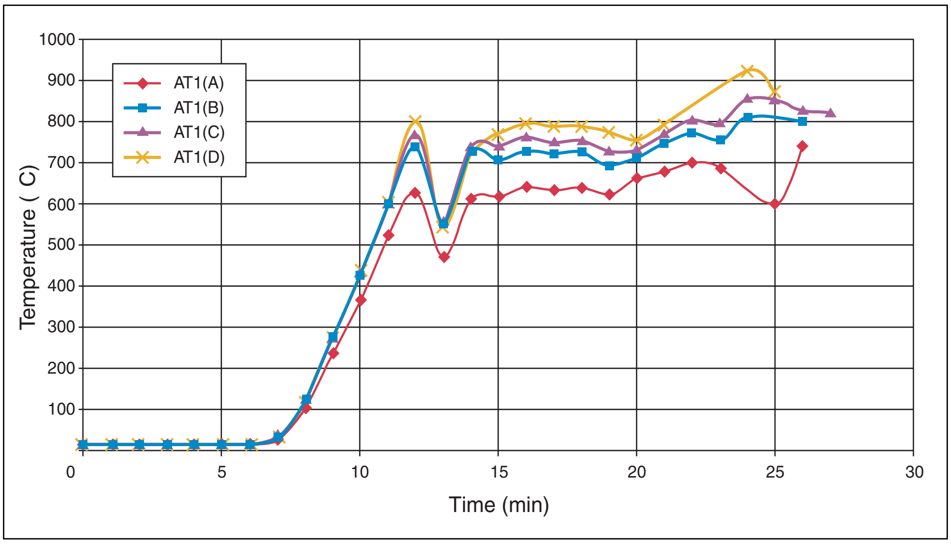

Figure 5: Recorded atmospheric temperatures.

Figure 6: The extent of spalling after the fire.

Observations and results

The fire test was carried out on 26 September 2001. Figure 4 shows the compartment with the fully developed fire and Figure 5 demonstrates the time-temperature response.

Approximately 10 minutes after ignition, popping sounds were heard and small particles were seen spalling from the soffit, probably due to flint aggregate spalling. After a further three minutes, more violent (explosive) spalling was observed. At this stage, the atmosphere temperature within the compartment was over 800°C. It was noted that the larger concrete fragments falling from the soffit were suppressing the fire below. Violent spalling continued until, about 25 minutes after ignition, reinforcement in the slab began to be exposed. As the test progressed, large areas of reinforcement were exposed and concrete continued to spall. This continued (with decreasing severity) as the test proceeded to its conclusion. Figure 6 shows the extent of spalling at the end of the test.

Unfortunately, the fixings of the ceramic fire blankets sealing the compartment walls to the first floor slab failed about 25 minutes into the test due to concrete spalling around the fixings. This allowed the fire to escape from the compartment and melt the instrumentation leads, causing some data to be lost. At this stage the temperature in the compartment just below the soffit was 950°C.

The main observations from the test were:

1. The concrete structure designed to the limits of EN 1992-1-2 survived an intensive fire without collapse, even when the concrete spalled extensively and reinforcement was exposed over large areas and sometimes lost from the concrete slab. The building satisfied the relevant performance criteria of load bearing function (R), insulation (I) and integrity (E), when subjected to a realistic fire, as defined in EN 1992-1-2 (5).

2. The maximum atmosphere temperature recorded was 950°C, before malfunction of some instrumentation. This confirms the severity of the fire test and it is probable that higher temperatures occurred.

3. Extensive spalling of the soffit to the first floor slab was observed but did not compromise the structural integrity of the floors under the imposed loads. The spalling was not surprising because:

    - The concrete in the slab was much stronger (74MPa) than normal, which would have increased its likelihood of spalling; no polypropylene fibres were included in the concrete mix.

    - As a result of the closed environment around the building in the hangar, the moisture content in the concrete was unusually high (3.8% by weight); this is higher than the 3% limit, below which spalling can be ignored, as specified in EN 1992-1-2(5). Typical moisture contents in a dry internal environment are below 2%.

    - High compressive forces were induced in the slab when it was heated, which increased the likelihood of spalling.

    - Flint aggregates, which are particularly susceptible to spalling, were used in the concrete in the floor slabs.

4. The horizontal displacements of the floor slab due to thermal expansion were significant, a maximum horizontal residual displacement of 67mm being recorded. The lateral displacements of the external columns, due to the thermal expansion of the floor slab, induced some additional column moment. However, the thin columns showed no signs of distress and this is unlikely to be a problem in practice. Simple rules are being developed to check for this effect in design. UK concrete design practice requires minimum reinforcement ties to be provided at all connections, which leads to inherently robust construction.

Figure 7: High-strength column after fire.

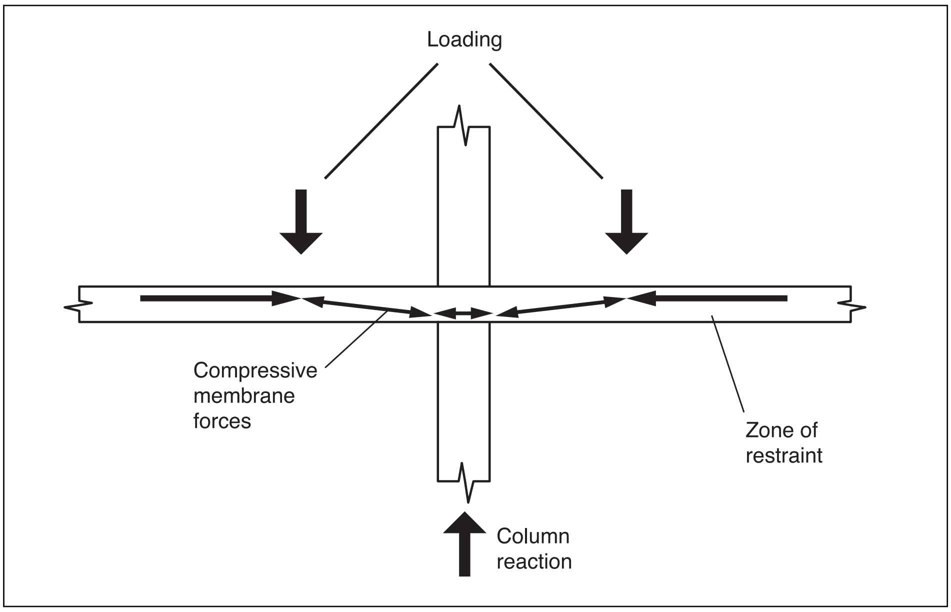

Figure 8: Compressive membrane action.

5. The high-strength concrete columns (103MPa), which contained polypropylene fibres, performed very well (Figure 7). Some non-violent corner spalling was evident, but this was considered to be insignificant to the columns' stability. Corner spalling can usually be repaired easily after a fire[2].

6. The slab was able to carry the imposed loads with low residual vertical displacements (maximum 78mm). Observations from the test suggest that the floor slab was acting as a compressive membrane (Figure 8). This behaviour needs to be considered more fully in computer simulations, so simple design methods can be developed to incorporate the beneficial effects of compressive membrane action.

Implications for structural performance

These tests have shown the benefits of developing an understanding of the true behaviour of concrete structures in fire, which should lead to more economical structures. In the UK, innovation by designers has been constrained by the use of 'deemed-to-satisfy' fire design tables in current codes of practice. The minimum cross-section sizes of members and cover to reinforcing bars specified in these tables are based on fire tests conducted on single members in standard small-scale furnaces. This information does not reflect the inherent fire resistance of actual concrete structures and ignores recent advances in materials. It is accepted that these current tabulated design procedures are unduly conservative when entire building performance is considered. It should be noted that the use of analytical structural fire engineering methods is permitted in EN 1992-1-2(5).

The results and observations from the Cardington test on a complete frame demonstrate that current codified methods are not based on a correct model of structural behaviour. In particular, membrane action occurred in the heated floor slab, which helped the building survive. The compressive membrane action seemed to support the heated floor slab, even though the concrete to the soffit spalled extensively, exposing large areas of the main flexural reinforcement.

Current codes and design methods do not consider membrane action: if present design procedures were applied to the observations and behaviour in the test, the resulting design calculations would suggest that total collapse should have occurred. The phenomenon of membrane action is well-known in structures at ambient temperatures. It may be noted that, in recent design guidance on the fire design of steel structures[6], the concrete composite floor slabs support the steel beams in fire. This indicates that similar guidance for concrete structures should be possible and the current design approach for concrete is unduly conservative.

Research is now underway to develop computer models to simulate the test and understand the load-path mechanisms that occurred. These models will be used to investigate a range of different structural layouts and fire scenarios. The intention is to use the model as a tool to develop simple design guidance for practitioners.

Concluding remarks

This full-scale fire test on a lean reinforced concrete frame designed to the limits of the design codes demonstrated the excellent performance of concrete structures in fire. The concrete industry has embarked on a programme of development of advanced fire design methods. The aim is to put into practice the design benefits from previous and new research and deliver more economical concrete frame construction while maintaining current high levels of safety. This will be achieved by developing new fire engineering methods from the study of whole concrete structures rather than isolated member behaviour. This takes into account the inherent fire resistance and robustness of concrete construction. Consideration of materials characteristics and structural design are required to optimise the behaviour of real concrete structures in a fire.

As part of this development, a network group with an interest in developing solutions and promoting the performance benefits of concrete is to be established. Participation from researchers, specialists, design professionals, material scientists and suppliers is welcome. This important issue has highlighted the need for structural engineering and materials science knowledge to be considered together if practical knowledge is to be advanced.

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