The Dalmarnock Fire Tests on a Cast Insitu Concrete Structure

TG 4.3 *fib* 2007 THE DALMARNOCK FIRE TESTS ON A CAST INSITU CONCRETE STRUCTURE

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ABSTRACT

In July of 2006 three full scale fire tests were undertaken on a 23 storey cast in situ concrete structure. This paper provides an overview of the experimental set up of Test One which involved a fully developed post flashover fire in a $17m^2$ compartment. Full scale fire tests on concrete structures are in-frequent and complete data sets rare. This experiment provides a complete data set for both the fire behaviour and the structural response in both the heating and cooling phases of the fire. The fire behaviour and subsequent structural response are examined and explained.

1. INTRODUCTION

Figure 1: Dalmarnock fire test one seen from outside 18.5 min into the fire

The Dalmarnock Fire Tests consisted of three full scale fire tests conducted on a cast in situ concrete structure in Dalmarnock, Glasgow. The tests were led by the BRE Centre for Fire Safety Engineering.

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This paper covers the experimental set up of Test One and the structural details of the compartment in which it was conducted. The fire in Test One is described as the ‘uncontrolled’ fire in that it was allowed to grow into a fully developed post flashover fire. In this experiment it was intended to not only study the fire growth and behaviour but also the structural response to the fire

A brief overview of the fire development and behaviour is provided along with a more detailed examination of the structure’s thermal response to the fire and the mechanical response that was recorded during both the heating and cooling phase of the fire.

For a more detailed account of the experimental set up, fire results and subsequent experiments and analyses please refer to ‘The Dalmarnock Fire Tests: Experiments and Modelling’ [1]

2. OBJECTIVES OF TEST ONE

Test one was an ‘uncontrolled’ fire in that, the ventilation conditions were not controlled by the experimentalists, they remained unchanged from the beginning of the test with the exception of changes caused by glass breakage. One objective of the test was to compare the resulting fire growth and behaviour with that of another fire test conducted in an identical experiment (i.e. the compartment, fuel load and distribution, ignition source etc. were all identical to test one). The only difference between the two was that in the second experiment it was possible to change the ventilation conditions of the compartment during the test through remotely operated openings. Hence this second fire is referred to as the ‘controlled’ fire.

This combination of experiments was performed for the purpose of the FireGrid project which aims to develop tools to capture detailed information on how an incident is unfolding and make super real time predictions of anticipated hazards, fulfilment of this vision involves sensing, modelling, forecast, feedback and response.

The compartment was heavily instrumented in order to obtain a high resolution of several types of data associated with the development of the fire. The high resolution of data captured allows the test results to be used in the benchmarking of field models and hence of the fire modelling process also [1].

Many full scale fire tests have been performed on concrete structures, the structures themselves are often purpose built constructions representing sections of a whole building and the fires are created using regularly distributed wooden cribs. These were the first fire tests on a heated concrete structure where the fire load was real, both the fire and the structure were well monitored, a complete structure was tested rather than an element or set of elements and data was recorded during the heating and cooling phase of the fire.

3. EXPERIMENTAL LAYOUT AND SETUP

3.1 Compartment description

Test One, took place on the fourth floor of a 23 storey cast in situ concrete structure as can be seen in fig 1. Figure 2 shows the layout of the flat in which Test One was conducted. The experimental compartment was the living room of the flat. It was approximately 17 m^2 in plan containing two door ways, one led to the flat corridor and the second to the kitchen, it also contained a set of windows in the west facing wall. The north and west walls of the compartment were external. The south and east internal walls segregated the experimental compartment from bedroom one and the kitchen respectively.

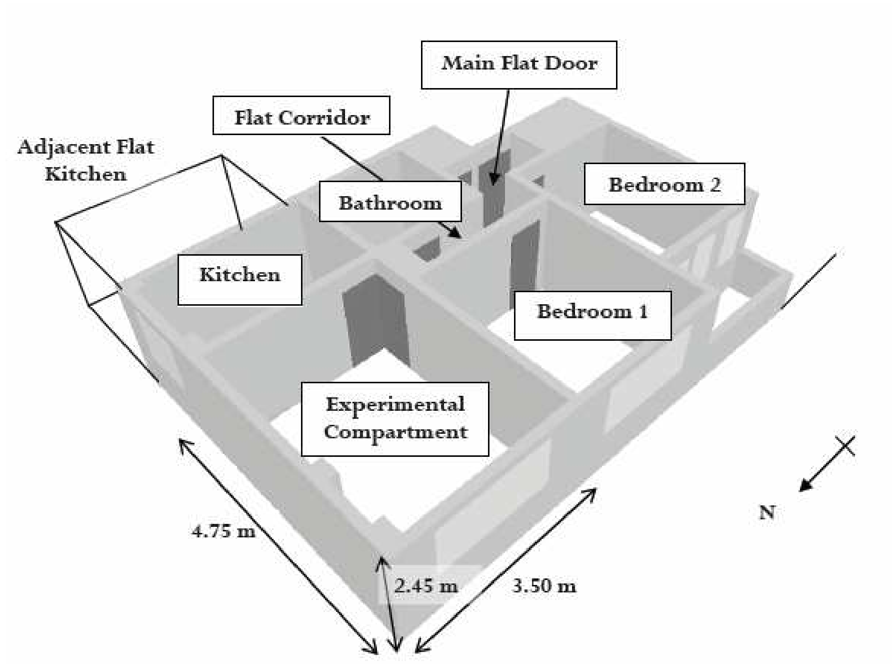

Figure 2: Flat layout, viewed from the north west

The west and south wall were non load bearing, the north wall was largely non-load bearing but did contain two load bearing elements along its length. The east wall separating the experimental compartment from the kitchen was removed along with the door and replaced with a light steel framed wall fitted with sensors. It served no structural function but prevented high temperatures developing on its outer surface (i.e. in the kitchen). The door leading to the flat corridor was also removed.

The ceiling slab of the compartment had complex support conditions but can generally be viewed as one way spanning between fixed supports and was nominally 150 mm thick. Ground penetrating radar was employed to ascertain the details of the reinforcing steel layout. The sagging reinforcement included: 7 mm bars at 80 mm spacing and with 6 mm cover spanning north to south and 9.5 mm diameter bars at 300 mm spacing with 20 mm of cover spanning east to west. Hogging reinforcement was also present this consisted of 14 mm diameter twisted bars at 400 mm spacing.

All furniture and fittings were removed from the flat (with the exception of embedded units in the kitchen). The room was furnished as a typical living room/home office. Figure 3 indicates the general fuel layout. The main sources of fuel were three book shelves in the north east corner of the compartment, loaded with books, magazines and plastics. Just in front of the sofa was a polyurethane sofa. Some computers, desks and chairs were located towards the front of the compartment.

Figure 3: Fuel distribution in compartment fire test

3.2 Fire instrumentation

The layout of the fire instruments is depicted in fig 4. As previously stated the compartment was densely instrumented to capture data at a resolution comparable to field model outputs for benchmarking purposes.

Twenty thermocouple ‘trees’ each carrying twelve thermocouples were positioned throughout the compartment, a further five trees carrying 6 thermocouples each were positioned across the width of the set of windows. More were located externally to capture temperature data from the external spill plume.

In each of the openings bi-directional velocity air probes were located, covering the height of each opening, each with an adjacent thermocouple. To measure smoke density, vertical and horizontal obscuration sensors were located in the compartment also. Web cameras and CCTV provided a visual record of the fire progression.

Heat flux meters were positioned to measure the thermal exposure for the compartment ceiling and the rear wall. Nine heat flux meters were positioned on the ceiling in a grid fashion their locations are indicated in fig 4.

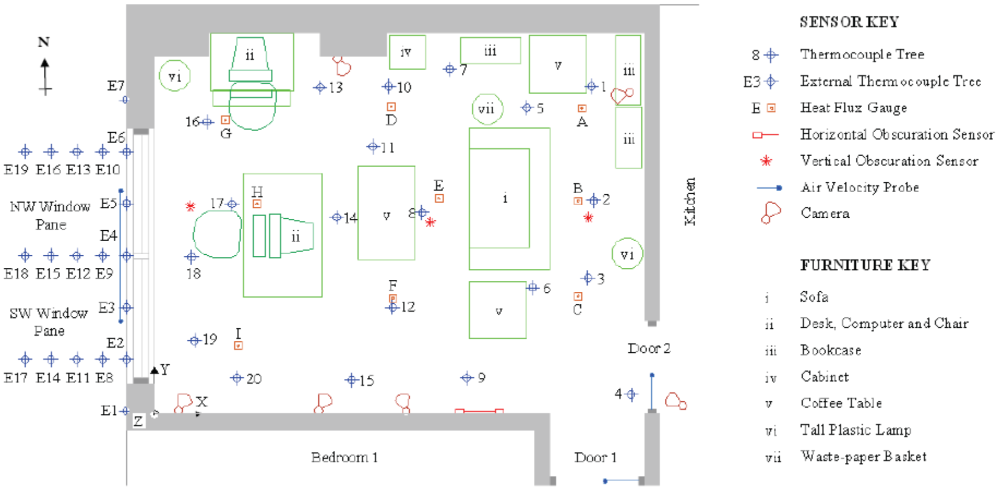

Figure 4: Test One: plan view of experimental compartment including furniture layout and fire sensor locations.

3.3 Structural instrumentation

The thermal response of the slab was measured by placing thermocouples through the depth of the slab at six different locations which are indicated in fig 5. The thermocouples were placed in an 18 mm diameter drilled hole. Four thermocouples were positioned across the height of the core before it was refilled with grout. Care was taken to ensure that a layer of grout protected the bottom thermocouple from the being directly exposed to the hot gases within the compartment.

The mechanical response of the ceiling slab and the partition wall between living room and bedroom was measured with deflection and strain gauges. For the ceiling slab the structural instrumentation was located on the floor of the fifth floor apartment to prevent hot gases from interfering with measurements. Nine deflection gauges were mounted on scaffold bars in the direction of both spans. These scaffold bars were supported at the slab edge, thus all deflections are relative to this location. Twenty-two strain gauges were positioned on the upper surface of the slab, and a further nine strain gauges positioned on the soffit as part of a sub experiment into the performance of fibre reinforced polymers in fire.

Using a similar method as the ceiling slab instrumentation, deflection measurements were taken of the partition wall between the bedroom 1 and the living room. Hot gases entered bedroom one in the later stages of the experiment and so these result cannot be trusted.

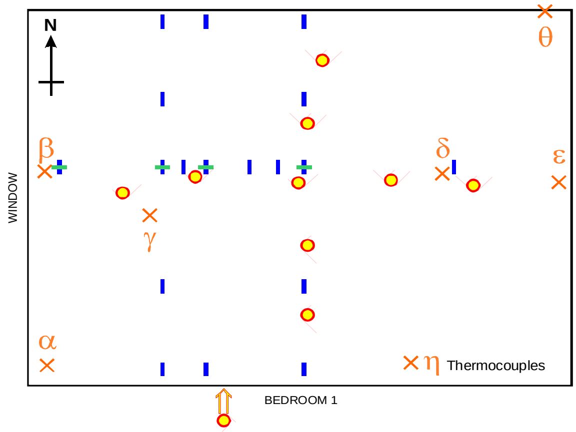

Figure 5: Locations of structural instrumentation Replace with CAD equivalent

4. EXPERIMENTAL RESULTS

4.1 Fire sensor measurements

Figure 6 shows a plot of the average compartment temperature for the duration of the fire which gives an indication of the general fire behaviour over time. For the first 100 s temperatures rise steadily, this represents the localised burning of the sofa. The fire then begins to spread and at 300 s there is a steep spike in average temperatures relating to flashover, the point at which burning engulfs the entire room. Temperatures then drop to a quasi steady state followed by a slow rise. After breakage of the first window pane, there is again a sharp rise in temperature suggesting burning in the compartment prior to this had become ventilation controlled. After 19 minutes the fire brigade entered and extinguished the fire

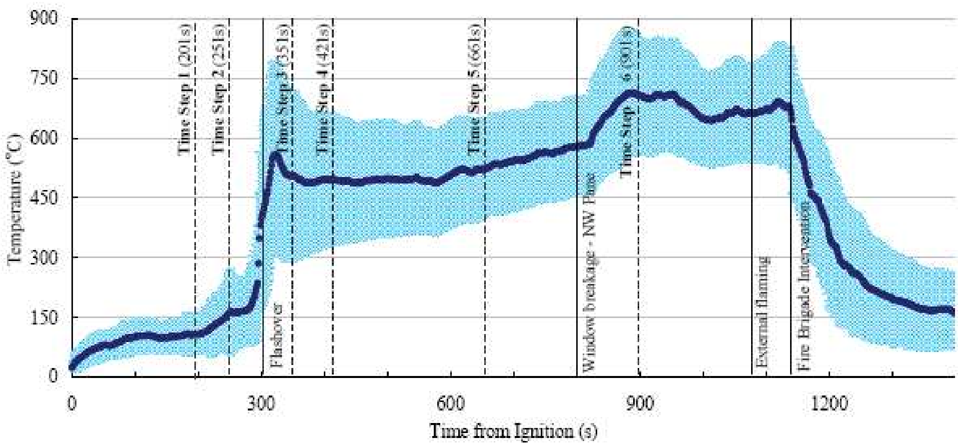

Figure 6: Gas-phase average compartment temperature-time curve variation with shaded regions indicating the standard deviation of temperature throughout the compartment

Nine heat fluxes were located on the compartment ceiling in an approximate grid layout (see fig 4) and spaced so as to give a global perspective of heat flux distribution to the ceiling. To demonstrate the evolution of incident heat flux over time contour plots have been created for selected time steps in fig 7. Coordinates in fig 7 are taken from the global system outlined in fig 4. The pattern of heat flux development over time correlates closely with changes in gas phase temperatures. Between Fig 7b and 7c an almost ten fold rise is seen in incident heat flux to the ceiling, these time steps correlate to the pre and post flashover periods. The peak incident heat flux is located towards the NE corner of the compartment where the greatest fuel concentration was located, a shift in location of the peak heat flux occurs between Fig 7e and Fig 7f when the ventilation conditions in the compartment changed.

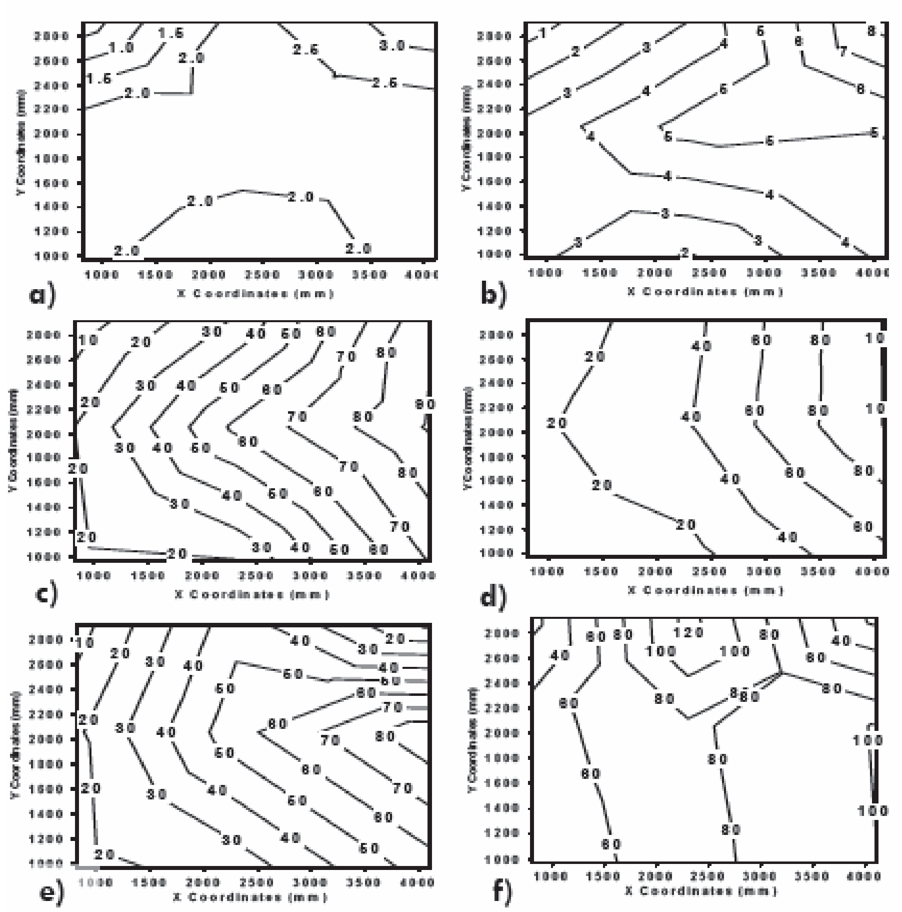

Figure 7: Contour plots of heat flux (kW/m^2) incident on the compartment ceiling at selected time steps a) 201s, b) 251s, c) 351s, d) 420s, e) 661s and f) 901s

Such details of thermal exposure to a structural element are lost when an assumption of average or uniform heating is taken. In both the standard temperature-time curve and the parametric fire curves provided in Eurocode 1 [2] an average temperature is assumed for the whole compartment. It is obvious from the thermal variations seen in fig 7 that depending on the spatial location of an element, these average curves may over or under predict the thermal severity that structural element is subjected to.

4.2 Response of the structure

4.2.1 Thermal

As described earlier the thermal response of the slab was measured at six different locations (see fig 5). Temperatures measured by these thermocouples are displayed in fig 8.

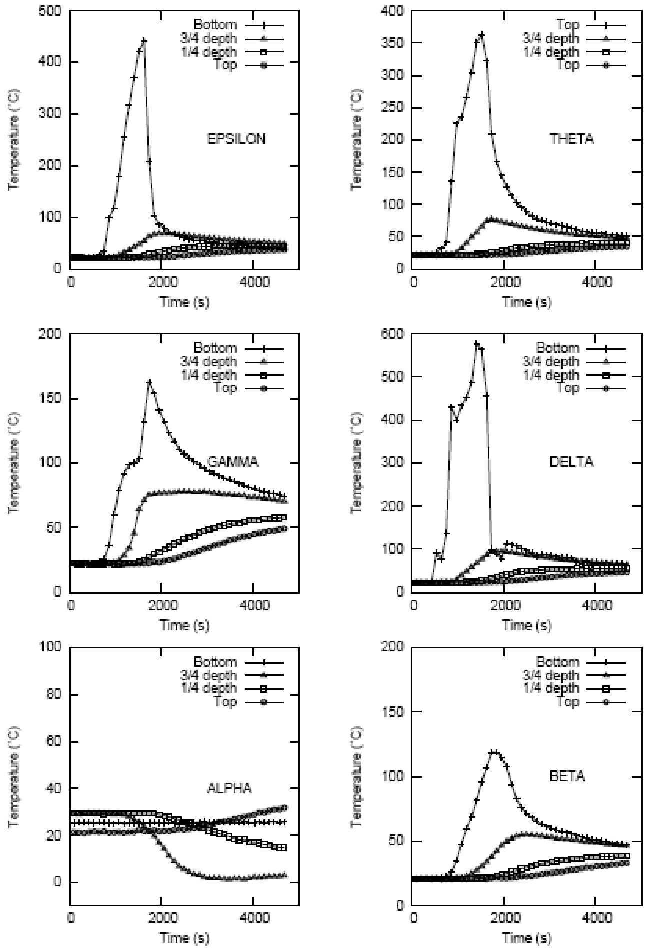

Figure 8: Thermocouple temperatures from the ceiling slab

The most obvious observation from the graphs is the variation of temperatures recorded in the slab, the peak temperatures were recorded at epsilon and theta which were located at the rear of the compartment correlating with the locations of highest recorded incident heat fluxes. These peaks were highly localised as significantly lower temperatures were recorded at gamma and delta at the front of the compartment (where less fuel was sited). The results for alpha are anomalous and it is suspected several of the thermocouples malfunctioned during the experiment.

The temperature profiles recorded through the slab at epsilon, delta and theta locations are comparable with the temperature profiles provided for concrete slabs in Eurocode 2 [3]. These were also the locations were peak temperatures were recorded, therefore at all other locations the profiles in Eurocode 2 overestimate the temperatures achieved in the slab.

If, as is common in design, the fire load is applied as a simple uniform boundary condition it is possible that a conservative estimate is being made of the total energy being absorbed by the slab and the structure is potentially more robust than the design method implies. By applying a more accurate distributed thermal load it follows that a more accurate determination of the mechanical response is possible. Intense debate still surrounds the subject of defining the heat input for structural elements as the result of a fire [4] but techniques are being developed [5,6] and it is important this development is matched with an understanding of the implications more realistic fire loading has for structural performance.

The fire was extinguished at 1140 seconds from ignition, from fig 8 the bottom thermocouple temperatures drop off rapidly from 1500 seconds at all locations, however the interior layers maintained there temperatures and the temperature of the upper layers actually continued to rise.

4.2.2 Mechanical

The deflection profiles for each span of the slab at selected time steps are shown in fig 9, all times after 1140 seconds represent deflections during the cooling period. The maximum recorded deflection was 10 mm at the centre of the slab and a residual deflection of just over 4 mm was recorded at 4262 s when the final measurement taken. As with previously the global coordinates are used, therefore for Fig 9a the right hand side of the plot represents the rear of the compartment and for Fig 9b the right hand side represents towards the north wall. Overall the greater deflections are seen towards the rear of the compartment and the north wall, correlating with the locations of peak temperature measurement.

Distinctive kinks are seen in the deflection behaviour on both spans, for the long span at around 1500 mm and for the short span around 650 mm. The locations of these kinks correspond to crack locations documented on the upper surface of the slab after the fire. It is believed that when the crack forms the position of support shifts in from the wall and differential expansion on the slab soffit affects behaviour in the short span actually causing an upward deflection.

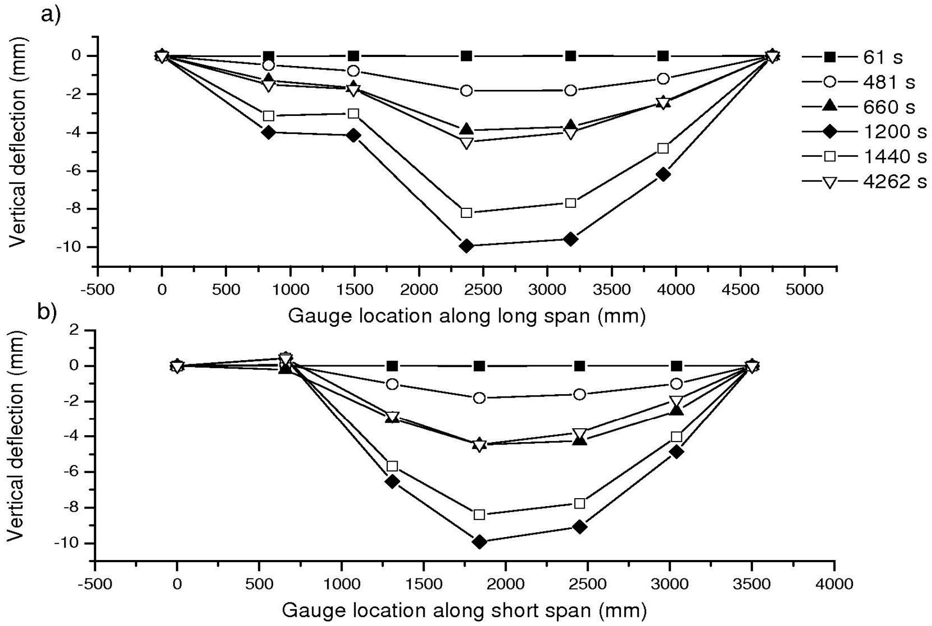

Figure 9: Ceiling slab deflections at selected time steps during the experiment

Details of the reinforcement layout in the slabs were ascertained using ground penetrating radar as described in section 3. It was found that the crack locations which resulted in unusual deflective behaviour coincide with the curtailment of the hogging reinforcement in the slab where a step change in the flexural stifness occurs. This suggests that reinforcement detailing has some significance for the performance of concrete structures in fire. While no loss of compartmentation occurred in this test it is conceivable that in more modern constructions with long spans and thin sections this is a potential risk. It should be noted that the slab in the test was unloaded and therefore it is possible that the cracks would remain closed in the loaded situation. However the major load in a concrete structure is self weight.

Strain measurements were taken across the top surface of the slab, the data collected from this correlate with the results taken from the deflection gauges. The results have not been included here but can be found here [1]. The strain results will be most useful for benchmarking numerical modelling of the slab.

No spalling was witnessed during the experiment and no evidence was found afterwards despite temperatures and heating rates during the fire being of the magnitude where spalling is generally witnessed [7]. Spalling is more likely to occur in concrete that has a high moisture content and often high strength [8]. In Dalmarnock the concrete was considerably aged and therefore likely to be quite dry, it would also be considered low strength by today's standards.

No specific measurements or experiments have been undertaken here focusing on spalling; however the result provides anecdotal evidence in the continuing spalling debate.

5. CONCLUSIONS

Concrete structures are generally perceived to perform well in fire based on concrete's inherent fire resistance, and certainly during this experiment the concrete structure performed well. No loss of compartmentation occurred and the structure provided insulation to the compartments surrounding the fire compartment. No spalling occurred, one of concretes major weaknesses in fire, this is most likely due to the Dalmarnock concrete's low moisture content from age and its relatively low strength.

Safer and more efficient structural arrangements could be found by using more accurate descriptions of the fire load on structural elements. Measurements of incident heat flux to the ceiling slab in the Dalmarnock Fire Tests have shown that the use of single temperature-time curves to represent compartment conditions may lead to designers' over- and/or under-estimating thermal exposure to a structural element.

The results from the thermal instrumentation of the slab confirm that the variation of heat flux incident upon the slab surface have implications for slab behaviour. The temperature profile of the slab was found to have highly localised peaks comparable with the Eurocode 2 slab temperature profiles, thus the profile of the rest of the slab was over estimated by the prescriptive approach.

The detailing of reinforcement has been shown to be significant for concrete performance, in this experiment large step changes in the flexural stiffness (curtailment of hogging reinforcement) resulted in macro cracking of the concrete, which risks loss of compartmentation. Gradual curtailment of hogging reinforcement could offset the possibility of cracking occurring.

Construction techniques and products are fast changing, it is imperative that we fully understand these new technologies but perhaps more imperative that we understand the behaviour of our current constructions. Full scale fire tests on complete concrete structures are infrequent. The results of this test are to the authors' knowledge the only complete data set which covers, fire development and behaviour, and the response of a complete concrete structure in both the heating and the cooling phases. More full scale fire tests where both the fire and the structure are instrumented are needed to benchmark numerical models (and numerical modellers!) whose use are becoming more and more widespread. To be of any use in benchmarking instrumentation must be at a comparable resolution as the output of the models we hope to validate.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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