

# **Precast Concrete Hollow Core Slabs in Fire**

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## **Synopsis**

Following concerns expressed in the media in relation to the performance of hollow core slabs in fire two full-scale fire tests have been carried out at BRE's Cardington test facility. The objectives of the experimental programme were to assess the adequacy of this form of construction in terms of the functional requirements of Approved Document B of the Building Regulations. This paper explains the background to the work, describes the test parameters in some detail and summarises the main results and conclusions from the project.

## **1. Introduction**

The performance of pre-cast hollow core planks in fire has been the subject of some concern in the press<sup>(1)</sup> with discussions highlighting perceived problems of spalling in fire. There is considerable test data covering the effect of moisture content on spalling of concrete under fire conditions, all of which shows that high moisture content in concrete can lead to premature spalling in the event of a fire. Hence, it is important to control moisture content at the time of a fire test, in accordance with the requirements of BS476. Additional concern over shear failure in fire has been highlighted in recent European research<sup>(2,3)</sup>. These issues have been addressed through two full-scale fire tests undertaken at BRE's Cardington test facility.

The issue of spalling arose following a fire test carried out at Cardington in support of the European Natural Fire Safety Concept in February 1999. The slabs supplied had two hours fire resistance. It was anticipated that the slabs would remain intact for several tests before replacement was necessary particularly as they were only there to form the ceiling to the fire compartment and were not subject to any applied load. The first test had to be terminated 40 minutes after ignition due to the extensive cracking of the slab. Spalling began approximately twenty minutes from ignition with large lumps of concrete being removed in an explosive manner. This continued to the point where the reinforcement was completely exposed on the majority of the units and cracking had extended the full length of the 6m span. The damage to the underside of the units is shown in figures 1 (general view of underside of floor slab) and 2 (close up showing exposed reinforcement). The explanation for the damage was that the units had not been properly conditioned or stored and that consequently the moisture content was too high at the time of the fire test. One of the important objectives was to see if this behaviour could be replicated where the history of the precast units was known.



Figure 1 Spalling



Figure 2 exposed reinforcement

Anecdotal evidence has suggested that a number of units had failed prematurely in standard fire tests. This was confirmed by Danish research<sup>(2)</sup> where anchorage failure was shown to reduce the fire resistance compared to that obtained from calculation. There is some debate as to whether this form of failure is a function of the standard test itself and is unlikely to occur in practice due to the continuity provided by reinforcement or structural topping. The European Commission on Prefabrication (fib) have suggested some simple solutions to overcome this localised failure<sup>3</sup>. These solutions have been incorporated into the Cardington tests.

## 2. Experimental Programme

During the planning stage for this project BRE decided to cease research activities at Cardington and to close the hangar at the end of September 2001. This imposed a number of constraints on the programme. Attempts were made to resolve the conflicting requirements of the availability of the test facility and the need to allow sufficient time for curing of the units. Discussions between BRE and national and international industry representatives resulted in a revised test programme consisting of two tests. The two tests will consider two alternative approaches to providing the required restraint to the floor units:

Slab A – all joints filled. Structural topping consisting of 50mm (minimum) depth of concrete and a mesh reinforcement (A98 mesh with 300mm lap between sheets) – see figures 3 to 5.

Slab B – all joints filled and hooked reinforcing bars placed in the joints over the supports – see figures 6 and 7.

For slab A the structural topping was 50mm thick at midspan. The concrete grade was specified as a minimum design strength of 25N/mm<sup>2</sup> with a maximum aggregate size of 10mm. A pump mix was specified to facilitate placing the concrete. The measured compressive strength of the 3 test cubes at 28 days was 42.5, 43 and 43.5N/mm<sup>2</sup>.

For slab B the hooked bars sat in the joints between the units to give top cover and cover between the end of the slab and the bar of 25mm. Over the central beam the bars had an overall length of 500mm. Over the front edge beam the length was 775mm to allow for the overlap at the front.



Figure 3 A98 mesh

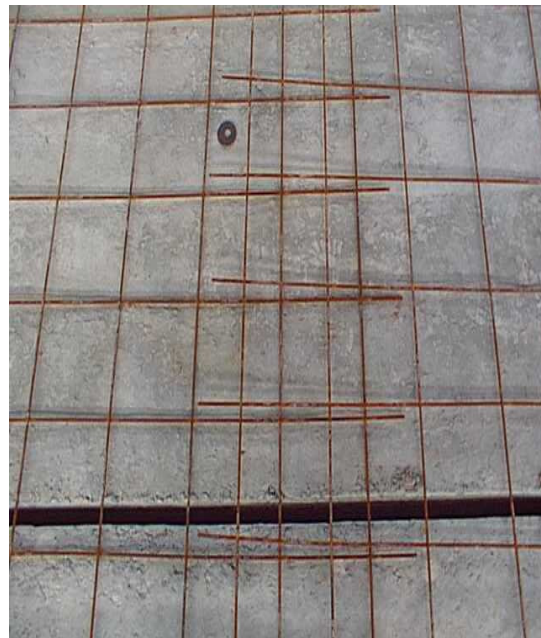


Figure 4 overlap of mesh



Figure 5 structural topping – slab A



Figure 6 hooked bar over edge beam



Figure 7 joints filled – slab B

### 3. Fire Design Scenario

The design fire load is based on a value of  $570\text{MJ/m}^2$  consisting of  $30\text{kg}$  of wood per square metre of compartment floor area multiplied by a calorific value for wood of  $19\text{MJ/kg}$ . This is a typical design value and is based on the design fire calculation in the most recent version of the fire part of the Eurocode for Actions<sup>(4)</sup> assuming normal fire detection measures are present. The layout of the cribs on the floor of the compartment is shown in figure 8.



Figure 8 Crib Layout

#### Thermal Properties of the Compartment Boundaries

The linings to the compartment walls, floor and ceiling are summarised in table 1 below:

Construction	Material	Thermal inertia (b value) J/m <sup>2</sup> s <sup>1/2</sup> K	Area (m <sup>2</sup> )
Roof	Concrete	2280	36
Floor	Plasterboard	520	76.8
walls	plasterboard	520	36

Table 1 thermal properties of compartment linings

The figures above correspond to an average b value of approximately 945J/m<sup>2</sup>s<sup>1/2</sup>K.

#### Opening Factor

The ventilation condition chosen for the test is a single opening in the front of the compartment 3.6m wide by 2m high. This corresponds to an opening factor of 0.065.

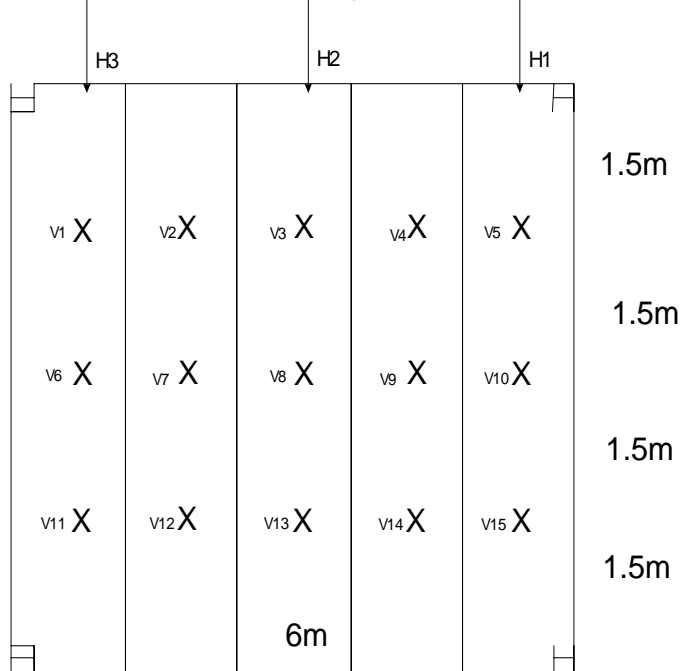
The predicted time-temperature response for the design fire scenario is shown in figure 21. The imposed load on each of the floor slabs was 3.66kN/m<sup>2</sup>. This load was applied through 12 1.1tonne sandbags spread uniformly over the floor area of approximately 36m<sup>2</sup> and corresponds to a realistic value for the fire limit state.

## 4. Instrumentation

The thermal response of the compartment and the structural performance of the slabs was measured using a number of thermocouples and displacement transducers. In addition indicative column sections protected with an intumescent coating were located in the centre of the compartment to quantify severity in relation to standard fire test time. Plate thermometers are located alongside traditional bead thermocouples to provide a direct comparison between the two methods of measuring time-temperature response. Additional instrumentation was installed to measure radiative heat flux opposite the openings.

Figure 9 shows the location of the vertical and horizontal displacement transducers. Figure 10 shows the location of the thermocouples used to measure compartment gas temperatures.

Slabs supported on flange of central beam



Front opening slabs supported on  
RSJ lintel spanning between piers

Figure 9 Location of displacement measurements

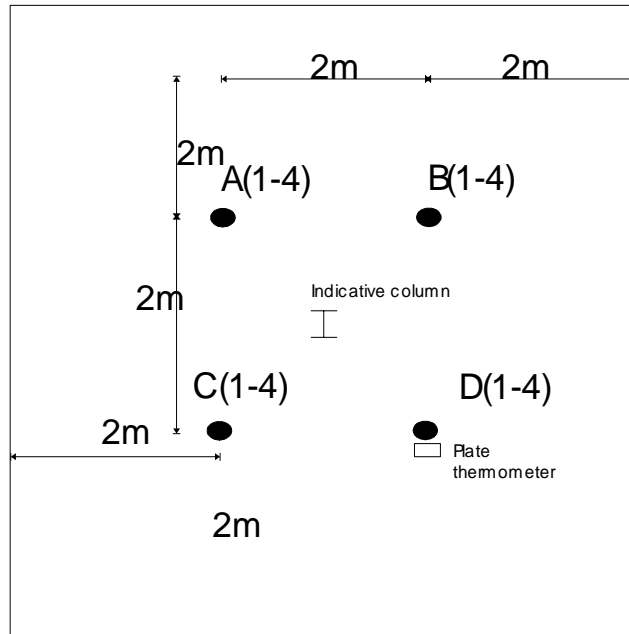


Figure 10 location of temperature measurements

## 5. Results – Slab A

The location of the thermocouples used to measure the atmosphere temperature within the compartment is shown in figure 10. Figure 11 shows the temperature of each thermocouple for the duration of the fire test. Two things are immediately clear from looking at these figures: firstly the fire was very severe in terms of peak temperatures and secondly the temperature within the compartment was uniform. The average value shown in figure 12 is therefore a reasonable approximation of the thermal exposure throughout the compartment. Figure 12 also includes the standard furnace time-temperature profile for comparison.

Two methods were used in an attempt to provide a more comprehensive picture of the thermal environment within the fire compartment. Indicative test specimens sprayed with an intumescent coating were used to derive time equivalent values for the test and, in the light of the changes to standard test procedures a plate thermometer was located in the compartment close to one of the standard thermocouples used to measure the atmosphere temperature. The indicative temperatures from the test are plotted alongside approximate values taken from a BS476 test in figure 13. The results indicate a time equivalent value of well in excess of 60 minutes for the test fire.

Precast hollowcore fire test 17.9.01

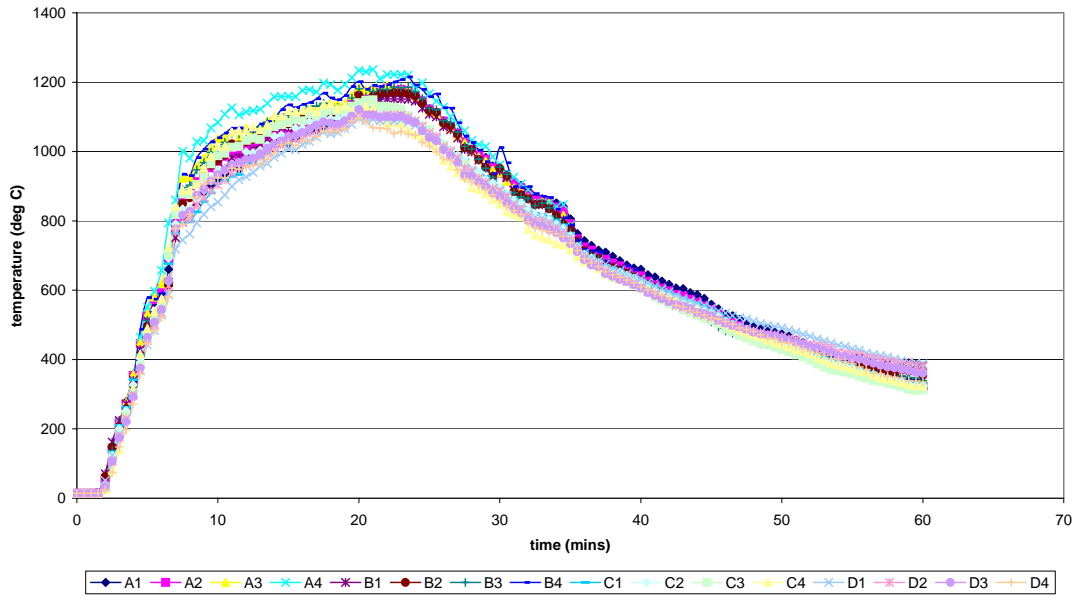


Figure 11 Atmosphere temperatures – slab A

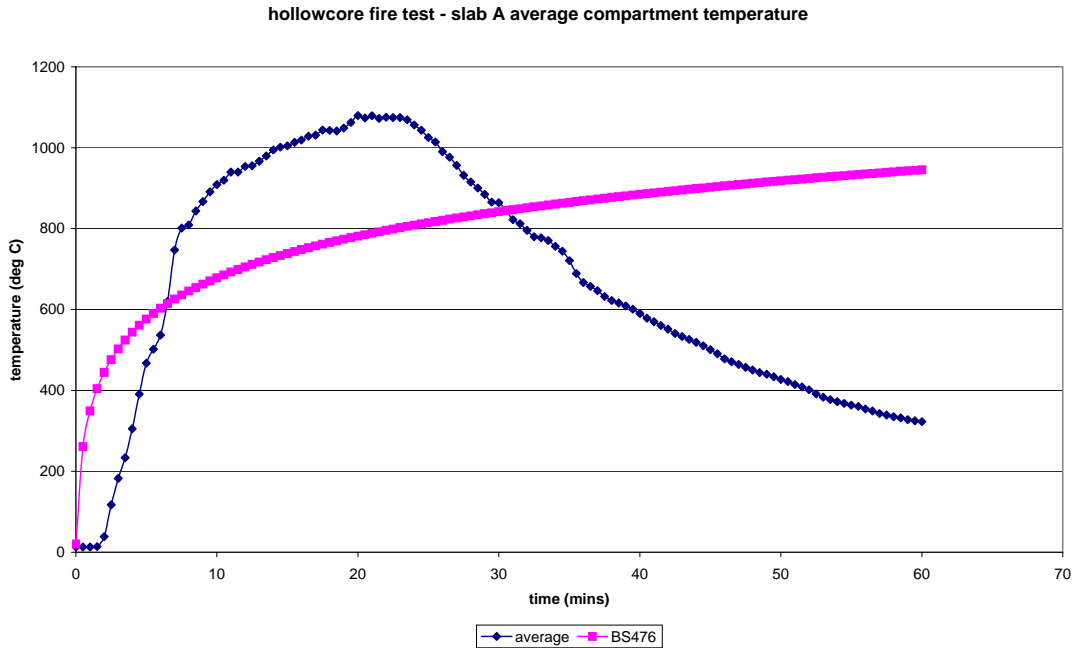


Figure 12 Average atmosphere temperature – slab A

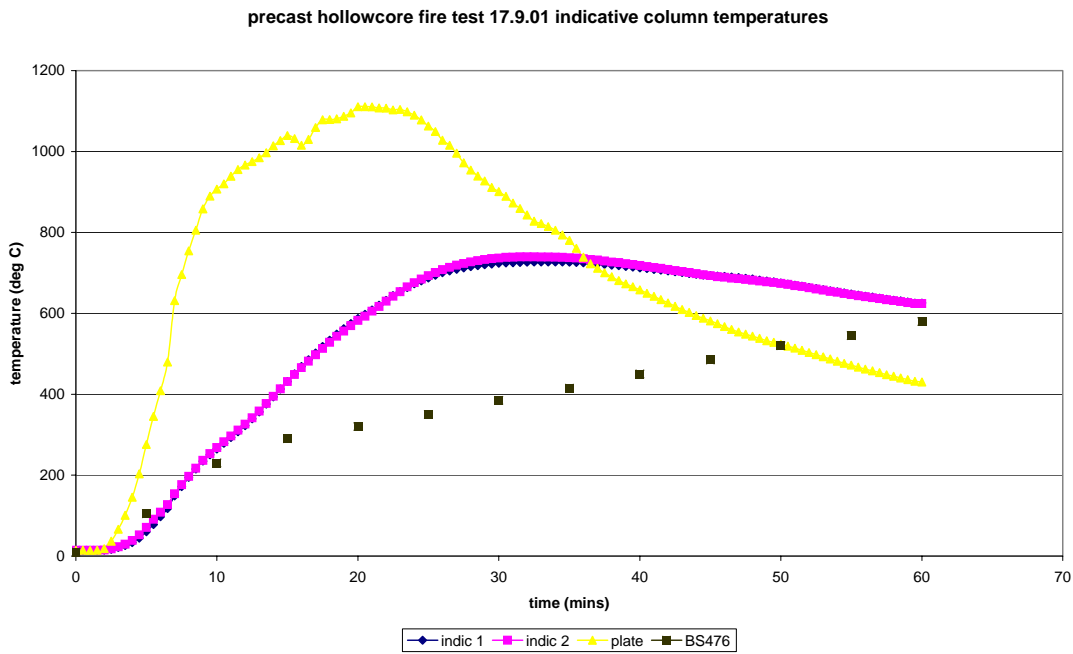


Figure 13 Comparison of indicative column temperatures from fire test and standard test

Figure 14 shows the measured value of vertical deflection at all measurement positions. Not surprisingly the maximum deflection occurred in the centre of the central unit. The maximum displacement recorded during the test was 100mm. Figure 15 shows the central deflection plotted against average atmosphere temperatures. The figure clearly shows the heat sink effect of the concrete slab with the deflection continuing to increase as the

atmosphere temperature reduces. Readings were taken overnight and the central deflection recovered to a residual displacement of 32mm by the following morning.

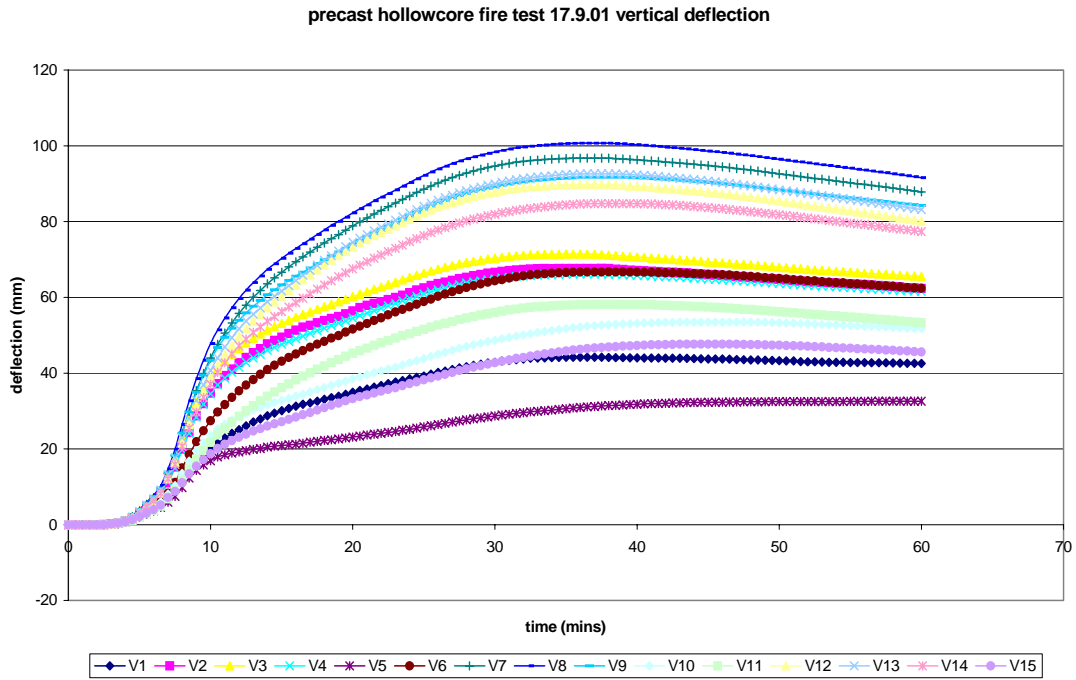


Figure 14 Measured values of vertical deflection

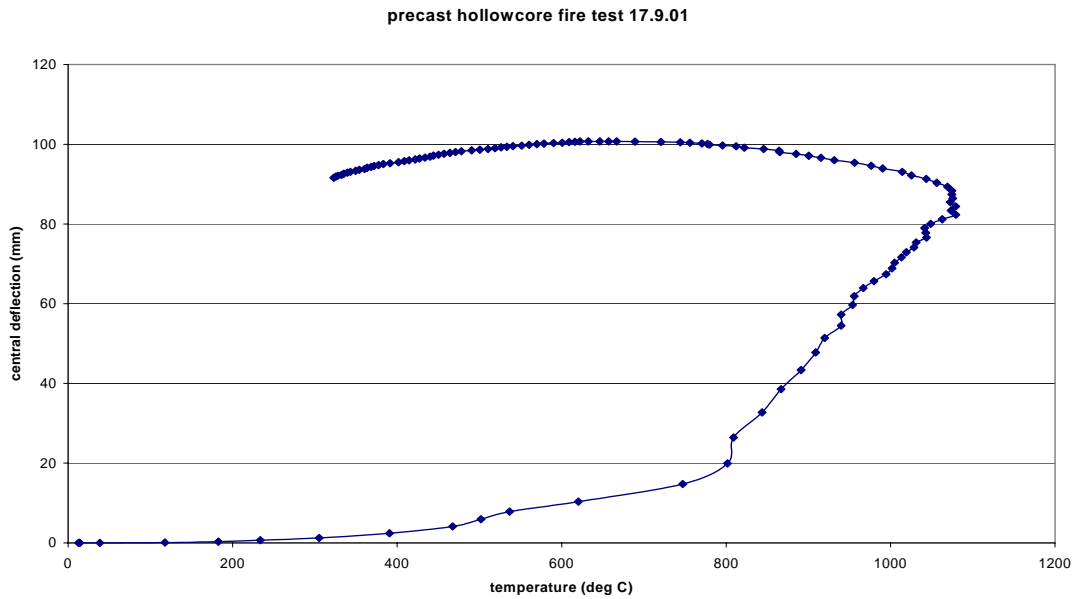


Figure 15 central deflection against temperature

The measurement positions for horizontal displacement are as indicated in figure 9. During the test flames and hot gases were seen to emerge from the rear of the compartment. This would have caused some extension of the cables attached to the transducers. The residual readings the next morning were 1.75mm, 3.03mm and 4.69mm for locations H1, H2 and H3 respectively. In this case a positive reading indicates movement away from the fire compartment. It was not possible to take readings at the front of the compartment because of the flames and hot gases emerging from the opening.

The concrete used to provide the structural topping was specified as 25 N/mm<sup>2</sup> minimum value. The cube tests carried out on the same day as test 1 (28 day period) show an average strength of 43N/mm<sup>2</sup>.

## **6. Results – Slab B**

The test conditions and construction of the compartment were identical with the exception that the second test did not include a structural topping. Hooked reinforcing bars were inserted in the joints at the end of each unit and the joints were filled with concrete from the same batch as was used to cast the structural topping for the first test.

The instrumentation locations were the same as those used in the first test. Figure 16 shows the measured temperature values from all the thermocouples used. Again the fire temperatures are relatively uniform justifying the use of average values for subsequent comparison and analysis. Figure 17 shows a comparison between the average values for tests 1 and 2. It can be seen that test 2 is slightly more severe in terms of maximum temperature and duration. This may have been due to the fact that, in the second test, the plasterboard linings stayed intact for longer and the gap between the two adjacent compartments remained closed for a longer period. Small differences in the moisture content of the timber may also have had a contribution. However, the two tests are comparable in terms of overall severity.

Figure 18 shows the plate thermometer reading together with the indicative column temperatures. There is some uncertainty about the thickness of the intumescent coating for this test so there are no comparable BS476 results.

The measured values of vertical deflection are shown in figure 19. The maximum measured deflection (centre of the slab) is shown in figure 20 and compared to that for test 1. The greater displacement associated with the second test is due to two factors: the absence of a structural topping over the pre-cast units, and the increased severity of the fire. Of these the absence of a restraining force from the topping is the most important. The maximum deflection for test 2 was 115mm compared to 100mm for test 1. The residual displacement for test 2 was 40mm.

In terms of horizontal displacement the gap between the top of the compartment wall and the underside of the pre-cast units was more effectively sealed during this second test. The results are therefore felt to be more reliable than the previous test. By the next morning the residual movement was 5.76mm, 5.24mm and 4.33mm for H1, H2 and H3 respectively.

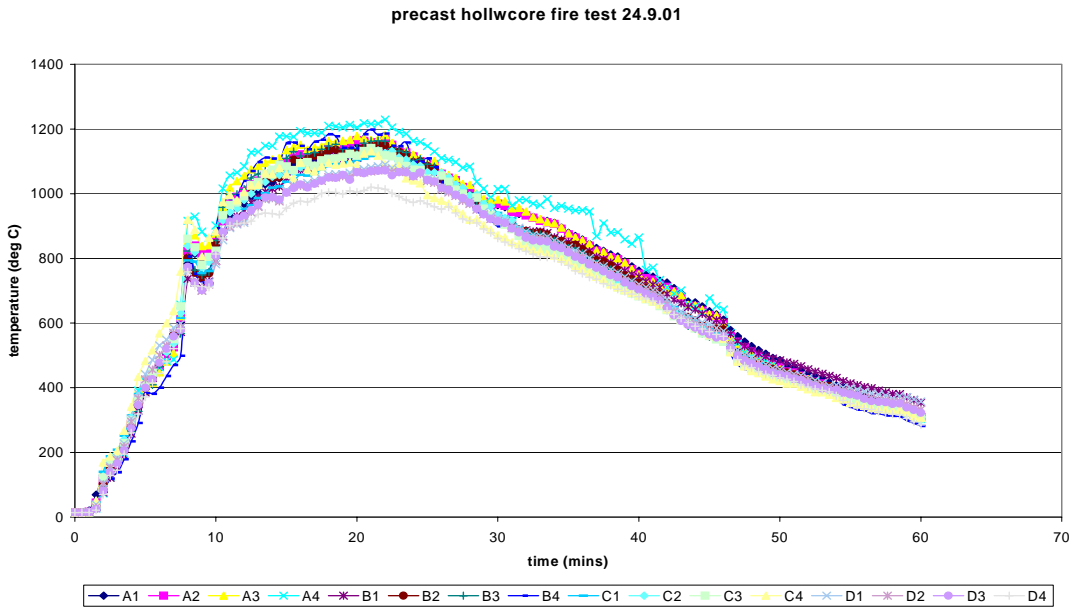


Figure 16 Atmosphere temperatures – slab B

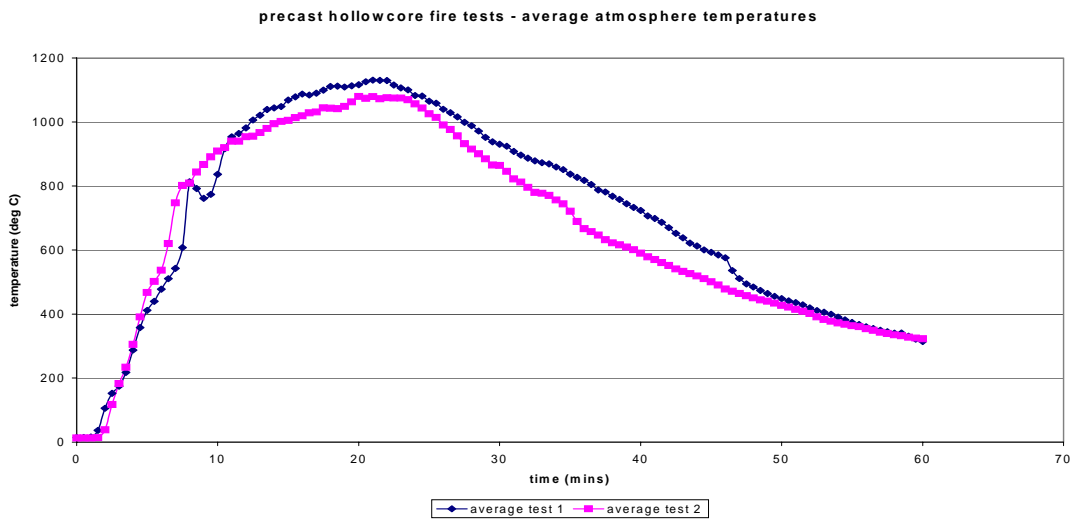


Figure 17 Average atmosphere temperature – Slabs A and B

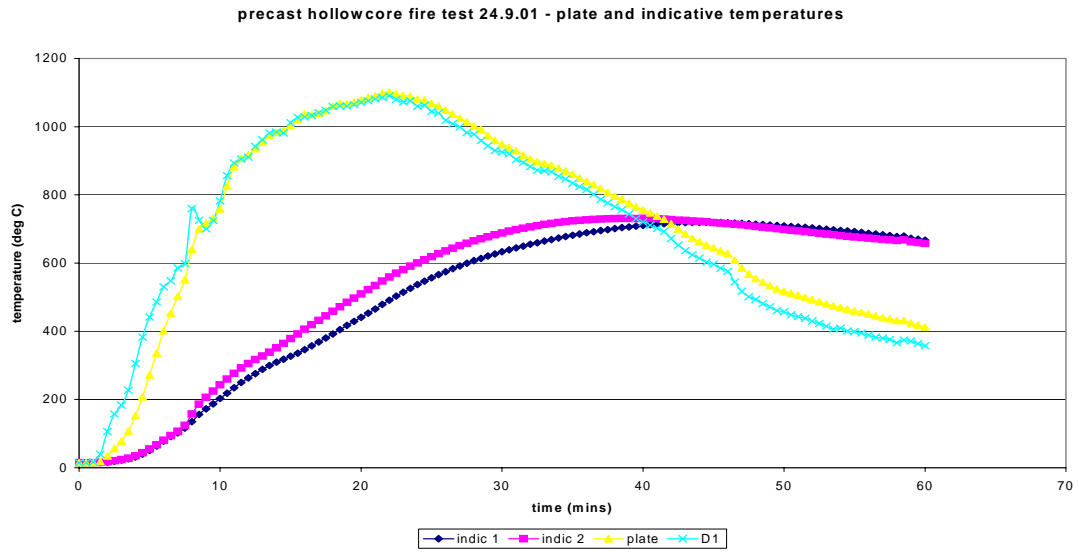


Figure 18 Plate and indicative temperatures – Slab B

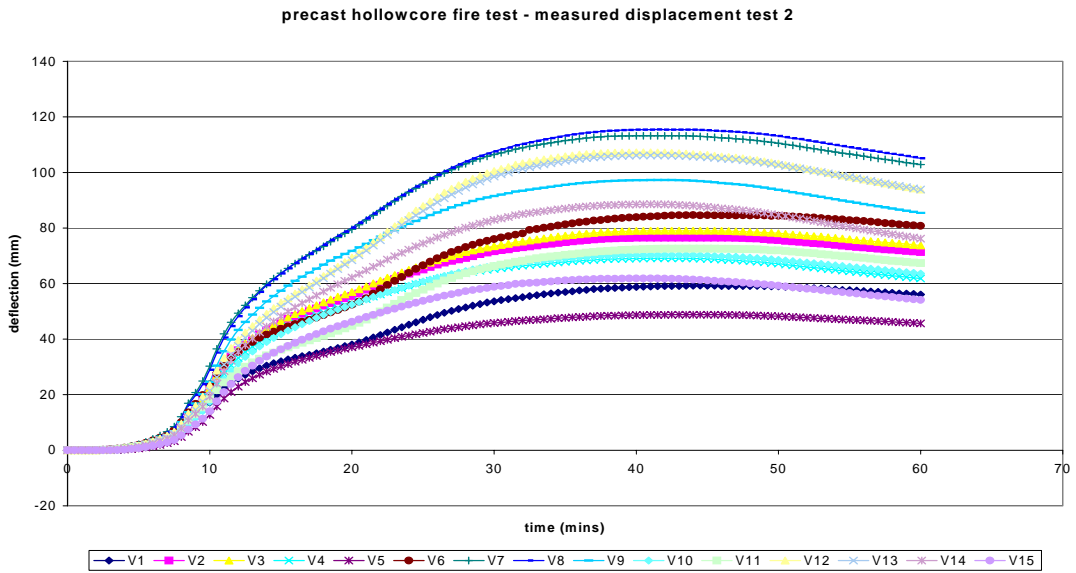


Figure 19 Measured vertical displacement – slab B

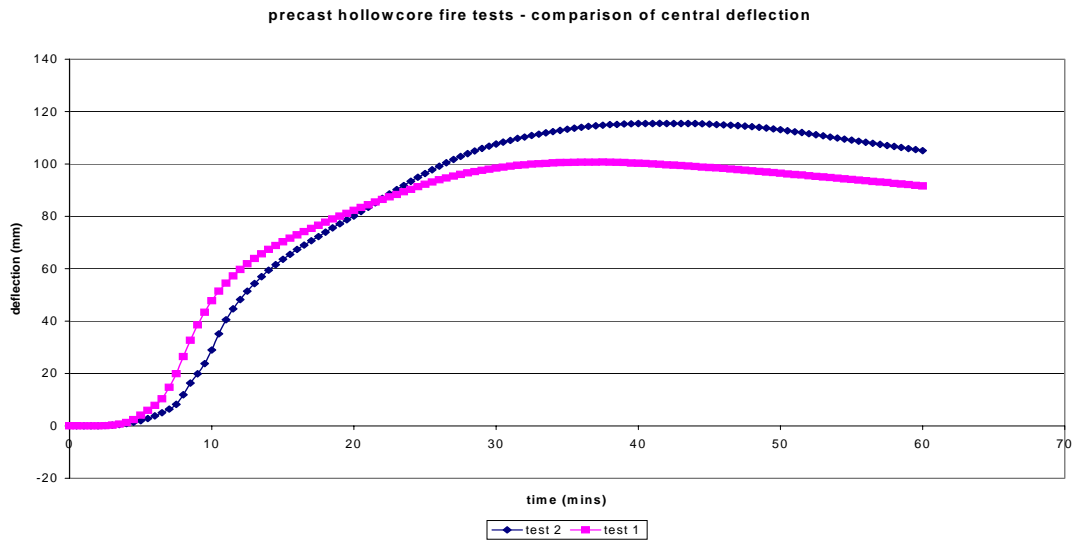


Figure 20 Comparison of central deflection – Slabs A and B

### 7. Comparison with Eurocode Parametric Calculation

The two tests described in this report provided further evidence to assess the calculation procedure for compartment temperature presented in Annex A of the latest version of the fire part of EC1. Figure 21 is a comparison between the predicted temperature based on the parameters described in the section, fire design scenario, and the measured values for the two tests. The calculated thermal exposure is very close to the measured values both in terms of maximum temperature and overall duration. The parametric approach would be appropriate for compartments with similar parameters in terms of fire load, insulation characteristics and opening factor.

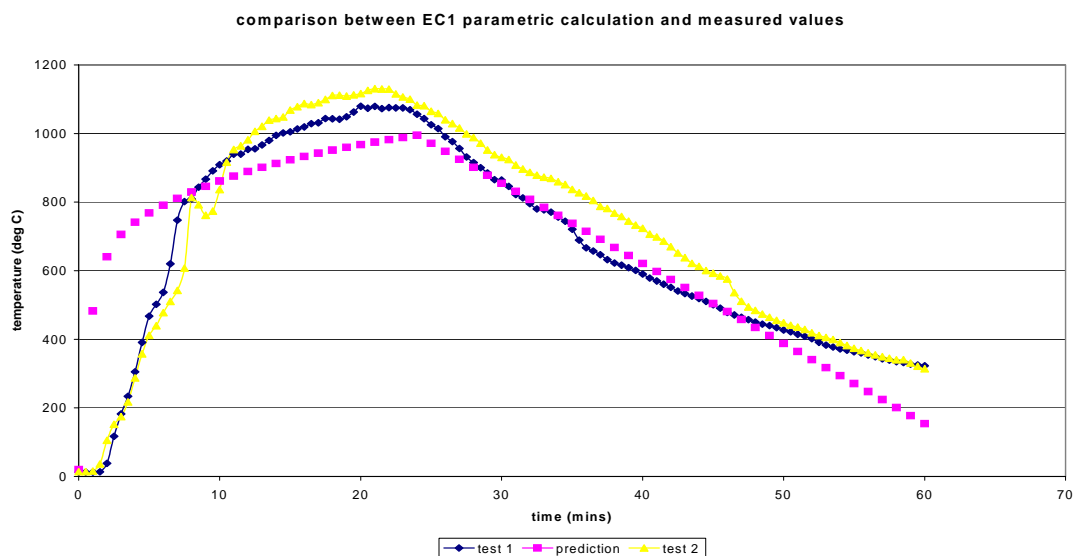


Figure 21 Comparison between Eurocode calculation and measured values

## 8. Discussion

The intention in carrying out this work was to look at the performance of hollowcore slabs subject to natural fire exposure and, in particular, to investigate performance in terms of spalling of the slabs and premature shear failure at the supports.

No significant spalling took place in either of the tests despite maximum temperatures in excess of 1200°C in both tests and a very rapid rate of heating. The measures taken to reduce the potential for premature shear failure in fire appear to have worked. There was no evidence of cracking around the supports either during or after the tests.

Figures 22 and 23 show the front of the compartment for each test following flashover. The length of the flame plume leaving the opening gives some indication of the intensity of the fires. Figure 24 shows the underside of the hollowcore units following test 2. In the first test localised surface spalling occurred. However, this had no effect on the ability of the units to sustain the applied load and would require only surface filling to reinstate the original appearance. Although there was no evidence of spalling in test 2 there was some cracking along the length of one of the edge units. Throughout the tests and for many months afterwards the slabs continued to support the applied load without any sign of distress.



Figure 22 Slab A Post-flashover fire



Figure 23 Slab B post-flashover



Figure 24 Underside of slab B post-test

## 9. Conclusions

The tests carried out to date at Cardington have been limited in number and in scope. However, a number of preliminary conclusions can be drawn on the basis of the work carried out to date:

- Spalling of the underside of the units was not a problem in either test. It is suggested that previous problems with this form of construction were due to inadequate curing periods prior to testing. It is accepted that spalling is, in part, a function of the moisture content of the concrete.
- There was no evidence of premature shear failure of the units in either of the fire tests. The measures taken to mitigate this behaviour were successful. Some cracking along the length of one of the edge units occurred in the second test.
- The precast hollowcore floor units used in these tests performed very well under severe natural fire conditions. There was no sign of any integrity failure or loss of load bearing capacity. The displacements which occurred during the tests recovered to reasonable limits and the floors maintained the applied load for a long period following the tests.
- In terms of the performance of the slabs in relation to the requirements of the Building Regulations and the associated guidance in Approved Document B the criteria for integrity and insulation have been met.

- The Precast Flooring Federation have indicated their willingness to support further work on fire resistance to demonstrate compliance with requirements in terms of the European testing method. Any further work should include both hollow core slabs and beam and block floors.

### **Acknowledgements**

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