

The performance in fire of structural insulated
panels
BD2710

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BRE

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Department for Communities and Local Government

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Executive summary

Sustainable Buildings Division of Communities and Local Government commissioned BRE to carry out a project titled 'The Performance in Fire of Structural Insulated Panel Systems'.

Structural insulated panel systems (SIPs) are being increasingly used in the UK. The market is driven by the ease and speed of construction and the energy efficiency of the system. Structural insulated panels are prefabricated lightweight building units, used as principal load bearing components in residential and light industrial construction. They are currently used for residential single or multi-occupancy buildings up to four storeys high.

A structural insulated panel consists of two high density face layers bonded both sides to a low density, cellular core substrate. The structural bond between the layers is essential in providing the required load bearing capacity of the panel. The face layers may be cement or gypsum based boards or wood based boards such as oriented strand board (OSB). The materials used for the core substrate range from synthetic rigid foam cores such as extruded or expanded polystyrene, polyurethane, polyisocyanurate to inorganic mineral fibres.

Most currently available structural insulated panels have been subject to a national technical approval. This generally includes fire resistance testing. However, the damage sustained by a structure beyond the declared fire resistance time is not typically assessed and so the post-fire stability of structures is not addressed directly through standard fire resistance testing. Therefore, there was a need to undertake a research project in collaboration with manufacturers to establish the relationship between the results from standard fire tests and performance under realistic conditions.

The overall aim of the project was to undertake an experimental programme to determine the performance of a typical structural insulated panel system in response to a realistic fire scenario and to compare the results with the outcome from standard fire tests. The project was intended to identify modes of failure associated with system performance in fire.

This report describes the project, the findings and detailed conclusions based on the work programme undertaken.

The project started with the formation of a Stakeholder Group, which comprised representatives of a range of stakeholder interests. This Stakeholder Group provided invaluable input throughout the duration of the project. The programme of work has also included the following tasks: a literature survey and review; selection and identification of potential design solutions; small-scale fire tests; developing a large-scale test methodology; numerical modelling and large-scale fire tests. Additionally, three large-scale fire tests were carried out on engineered floor joists.

The project has identified collapse of the floor as the predominant mode of failure of the building systems tested as part of this work programme based on fire penetration into the floor/ceiling void and combustion of the oriented strand board webs of the engineered floor joists leading to loss of load bearing capacity and runaway deflection.

This report will be of interest to key stakeholders including the fire and rescue service, regulators, national and local authority building control bodies, insurers, manufacturers and clients.

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Appendix A – Summary of the research		

1 Introduction and objectives

Sustainable Buildings Division of Communities and Local Government commissioned BRE to carry out a project titled 'The Performance in Fire of Structural Insulated Panel Systems'.

The overall aim of the project was to undertake an experimental programme to determine the performance of a typical structural insulated panel system in response to a realistic fire scenario and to compare the results with the outcome from standard fire tests. The project was intended to identify modes of failure associated with system performance in fire.

2 Programme of work

The programme comprised eight key tasks which are described as follows.

2.1 Identification and engagement with stakeholders

The programme of work required key stakeholder involvement to ensure broad representation and consultation. In addition to the project team, a number of organisations have participated in the project. These organisations represent key stakeholders including regulators, insurers, the Fire and Rescue Service, manufacturers and building control bodies. Wherever possible, industry groups or associations were involved rather than individual companies or named individuals. Initially, the project was complicated by the fragmentary nature of the small to medium-sized companies that made up the UK structural insulated panels industry. During the course of the project, a UK SIP Association has been formed which enabled constructive progress to be achieved with a single representative body for the industry. One of the significant achievements of this project is that it served as an impetus for the formation of the UK SIP Association (UKSIPSA).

The organisations consulted cover the key stakeholders involved in the commissioning, design, manufacture and control of buildings constructed from Structural Insulated Panels. Four Stakeholder Group meetings were held over the course of the project held at BRE, Garston on 28th November 2008, 21st April and the 30th July 2009 and 27th January 2010. In addition, all members of the Stakeholder Group were invited to view the large-scale fire tests held at BRE's North East test facility in Middlesbrough. Many members of the Stakeholder Group took advantage of this opportunity and attended at least one of the large-scale fire tests.

The Stakeholder Group meetings and subsequent discussions and correspondence have been a key element in the success of the project. In particular, the project could not have been completed successfully without the active participation of the UK structural insulated panel industry and their supply chain partners. Their involvement ensured that design, detailing and specification of the elements and structures tested were reflective of current practice.

Table 1 shows the constitution of the Stakeholder Group.

Table 1 Stakeholder group

Name	Representing
Tom Lennon	BRE
Danny Hopkin	BRE
Julie Bregulla	BRE
Paul Jenkins	Fire and Rescue Service
Dave Sibert	FBU
Adam Heeley	LABC
Ian McCalister	Building control
Colin Hird / John McGregor	Scottish Building Standards Agency
Brian Martin	DCLG
Mike Payne	DCLG
Graham Perrior / Dave White	NHBC
Allister Smith	RiscAuthority
Darren Richards	UKSIPSA
Paul Newman	UKSIPSA
Andrew Orriss	UKSIPSA

2.2 Literature survey and review

In consultation with the Stakeholder Group, BRE has undertaken a thorough review of all available literature and data on the performance of structural insulated panels in fire, including work undertaken within Europe and North America. During the course of the project, BRE utilised existing contacts with structural insulated panel manufacturers to access relevant data particularly in relation to the results from standard fire tests.

The literature survey has informed subsequent decisions regarding the parameters to be investigated in the experimental programmes and has been used to identify the most common construction details currently used within the UK.

2.3 Selection and identification of potential design solutions

Structural insulated panels consist of a thick layer of insulation sandwiched between two timber-based layers to provide web and flange structural strength across the panel. There are a variety of different insulants (typically polystyrene or polyurethane) and a variety of different outer panels (typically oriented strand board, plywood or fibre cement board). The various options in terms of material selection and construction details have been investigated in relation to market share and end-use applications to ensure the most appropriate combinations were selected for subsequent testing. This task has investigated the available information with regard to the various generic systems on the market and considered variations with regard to:

- type of insulant used
- type of panel used
- jointing and sealing techniques
- provision of openings for windows and doors
- provision of services
- selection of dry lining system
- additional structural support

The detailed information on the variation between systems is described below.

2.3.1 ANALYSIS OF MANUFACTURER'S DATA – TYPICAL COMPOSITION

1. It became apparent from the literature survey that structural insulated panels (SIPs) are used globally and as a result, a diverse range of materials are used in their production. BRE has undertaken a review of all of the structural insulated panel systems that are currently approved for use in the UK. The study collated and analysed a number of publicly available national technical approval documents produced by the British Board of Agreement (BBA) for a range of manufacturers and the results of the study are summarised in Table 2.

Table 2 Typical panel data for UK structural insulated panel suppliers

Sample	Total thickness (mm)		Face material	Face thickness (mm)		Insulation thickness (mm)		Insulation density (kg/m³)		Core material	FR30		FR60	
	Lower	Upper		Lower	Upper	Lower	Upper	Lower	Upper		Load (kN/m)	Protection	Load (kN/m)	Protection
A	75	150	OSB	11	15	63	128	38	45	PUR	8.33	12.5mm plasterboard directly to OSB or via 38x25mm battens	13	19mm fire resistant board + 12.5mm plasterboard applied directly to OSB.
B	100	180	OSB	-	15	70	150	-	42	PUR	-	-	13	12.5mm fire resistant board + 12.5mm wallboard fixed via 10x50mm battens at 600mm centres
C	-	142	OSB	-	15	-	112	-	33	PUR	13	12.5mm plasterboard via 50x10mm battens	35	12.5mm fire resistant board + 12.5mm wallboard fixed via 10x50mm battens at 600mm centres
D	50	300	OSB	-	12	26	276	-	20	EPS 100E	19.72	12.5mm plasterboard directly to OSB or via 50x10mm battens	-	-
E	117	187	OSB	-	11	95	165	-	-	EPS	24	12.5mm plasterboard via 50x10mm battens	-	-
F	75	150	OSB	11	15	63	128	38	45	PUR	8.33	12.5mm plasterboard directly to OSB or via 38x25mm battens	13	19mm fire resistant board + 12.5mm plasterboard applied directly to OSB.
G	50	300	OSB	-	12	26	276	-	20	EPS 100E	19.72	12.5mm plasterboard directly to OSB or via 50x10mm battens	-	-
H	103	166	Chipboard	3.2	7	97	160	Not Given	Not Given	PUR	No fire resistance requirements for roof panels. Some panels are fitted with 12.5mm of plasterboard on the internal face.			

The results have highlighted that oriented strand board is used predominately for the skin material of the structural insulated panel, whilst expanded polystyrene (EPS) and polyurethane (PUR) most frequently form the core of the panel. The total thickness of the panel may vary from 50mm to 300mm. However, this is likely to be governed by thermal requirements (U values) rather than load-bearing capacity. A more typical panel is likely to have a total thickness of 150mm, based on the findings of this study. Oriented strand board facing thicknesses range from 11mm to 15mm. The required thickness is likely to be governed by load-capacity requirements. All the oriented strand board facings used are a minimum of oriented strand board grade 3 in accordance with BS EN 300¹.

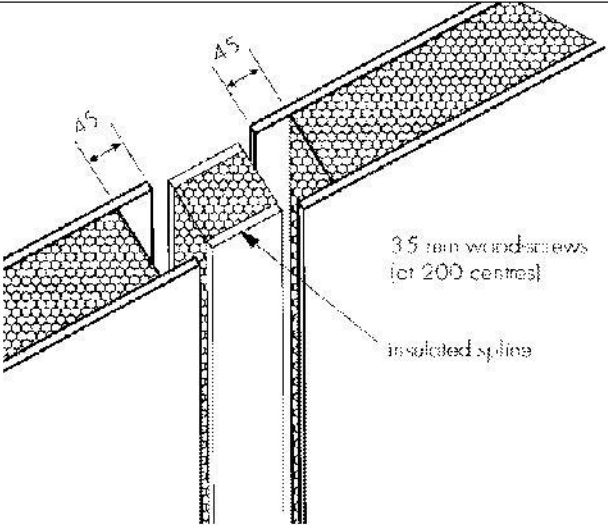
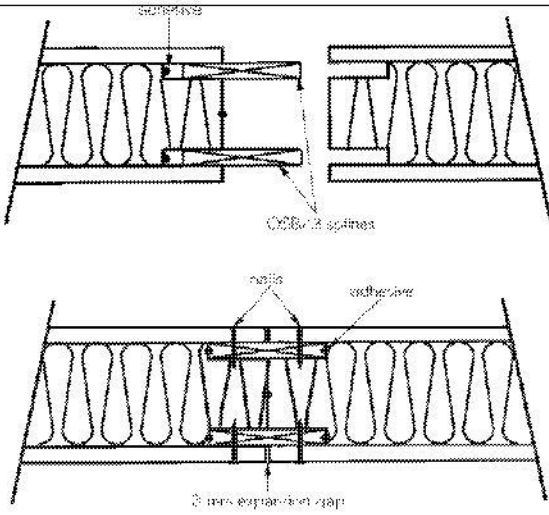
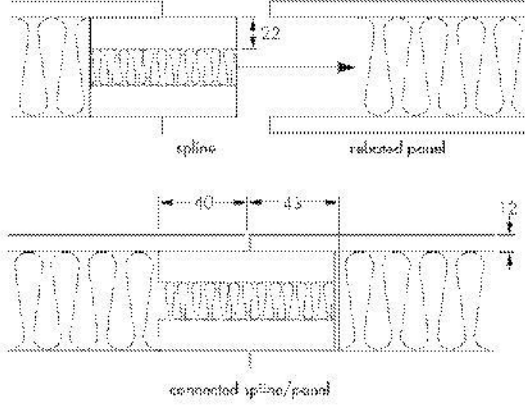
2.3.2 CONNECTION METHODS

A number of connection methods exist for structural insulated panel constructions. The exact nature of the connection methods varies between manufacturers. A large number of technical approval certificates for structural insulated panels are based on the 'system' used, i.e. the adopted connection methods, and not the panel itself. This survey has identified that approximately ten structural insulated panel systems have technical approval certificates in the UK, whilst approximately five panel variants exist. The following sections discuss the type of connections used in structural insulated panel systems which include panel to panel connectivity, panel to foundation connectivity, floor to panel joints, etc.

2.3.2.1 *Panel splines*

Panel to panel connections are a very important part of a structural insulated panel system. They are a structural joint that is critical to the integrity of the building and also have a large influence on the amount of 'air leakage' through the building envelope². In the USA, where structural insulated panels originated, some twenty panel spline systems exist². In the UK, based on the technical approvals for the systems, three spline systems have been found to be the most common. These are highlighted in Table 3.

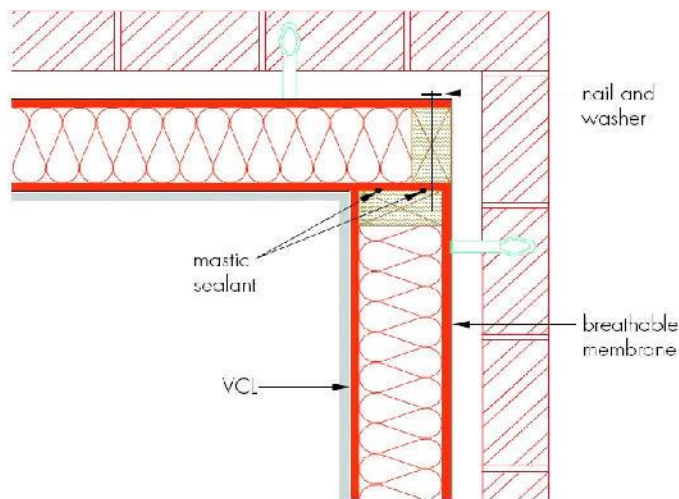
Table 3 Common panel spline connections

Foam block spline ³	 <p>45</p> <p>45</p> <p>3.5 mm wood screws (at 200 centres)</p> <p>insulated spline</p>
Thin OSB dual spline ⁴	 <p>OSB/3 splines</p> <p>nails</p> <p>adhesive</p> <p>2 mm expansion gap</p>
Thick foam block spline ⁵	 <p>22</p> <p>spline</p> <p>released panel</p> <p>40</p> <p>45</p> <p>12</p> <p>connected spline/panel</p>

2.3.2.2 Corner connections

The outside corner connection of the structural insulated panel system does not vary significantly between manufacturers. The two end panels on any wall have a solid stud at the outside corner for nailing and stiffness. The panels are typically connected by applying a panel screw through the cross section of one panel into the end block of another. This is highlighted in Figure 1.

Figure 1 Typical outside corner connection detail⁵



Seven system manufacturers with technical approval certificates with the British Board of Agreement adopt the system above for corner connections. There is one exception of a manufacturer who only manufactures roof panels.

2.3.2.3 Foundation connections

A structural insulated panel structure can be placed on almost any type of foundation². However, given the current restrictions in their use, structural insulated panels are most commonly used in residential and light commercial applications. As a result they are most commonly connected to a cast in-situ concrete strip footing, block starter walls or Insulated concrete forms. Of the seven systems with technical approval certificates with the British Board of Agreement, all use a very similar sole plate connection system. A typical example is shown in Figure 2. Typically a sole plate is fixed directly to the foundation using holding down bolts. The panel, with a recessed core, is then fixed directly to the sole plate via glue and nails, this can be clarified by referring to Figure 3. Alternatively, the sole plate can be fixed to a screed rail which in turn is connected to the foundation via holding down bolts. A typical example is shown in Figure 4.

Figure 2 Typical floor connection detail⁶

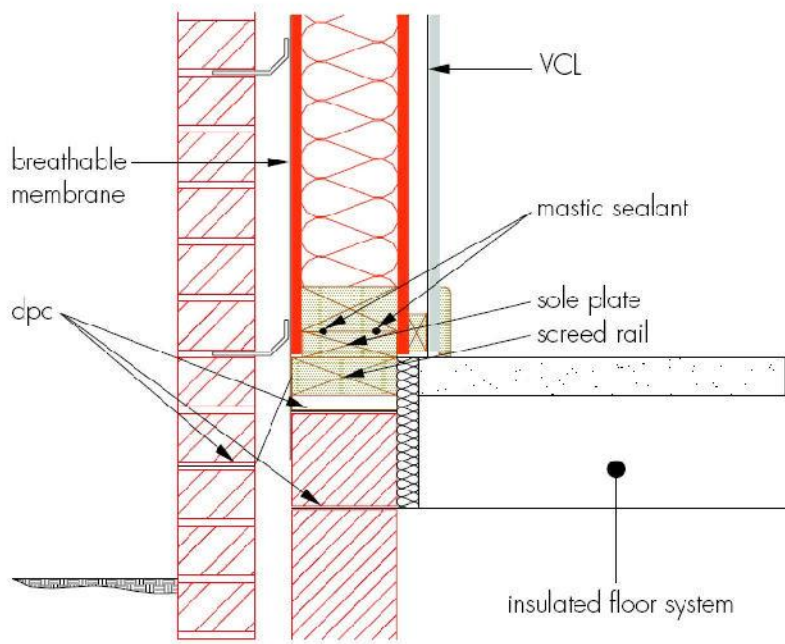


Figure 3 Example of sole plate connection⁴

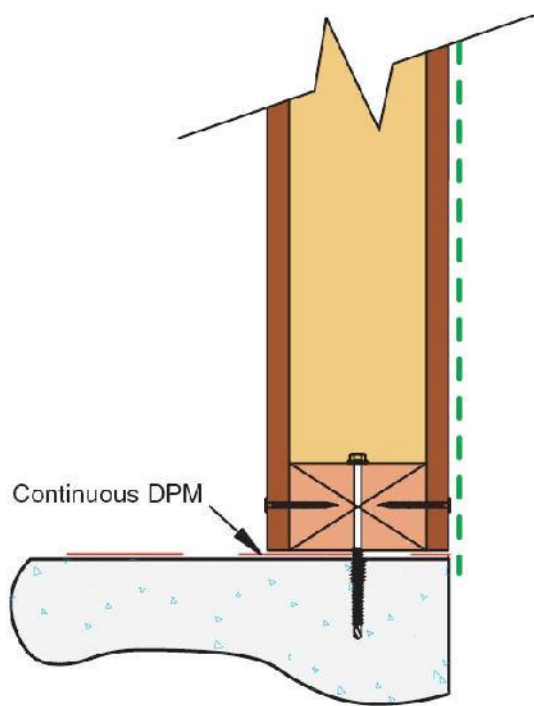
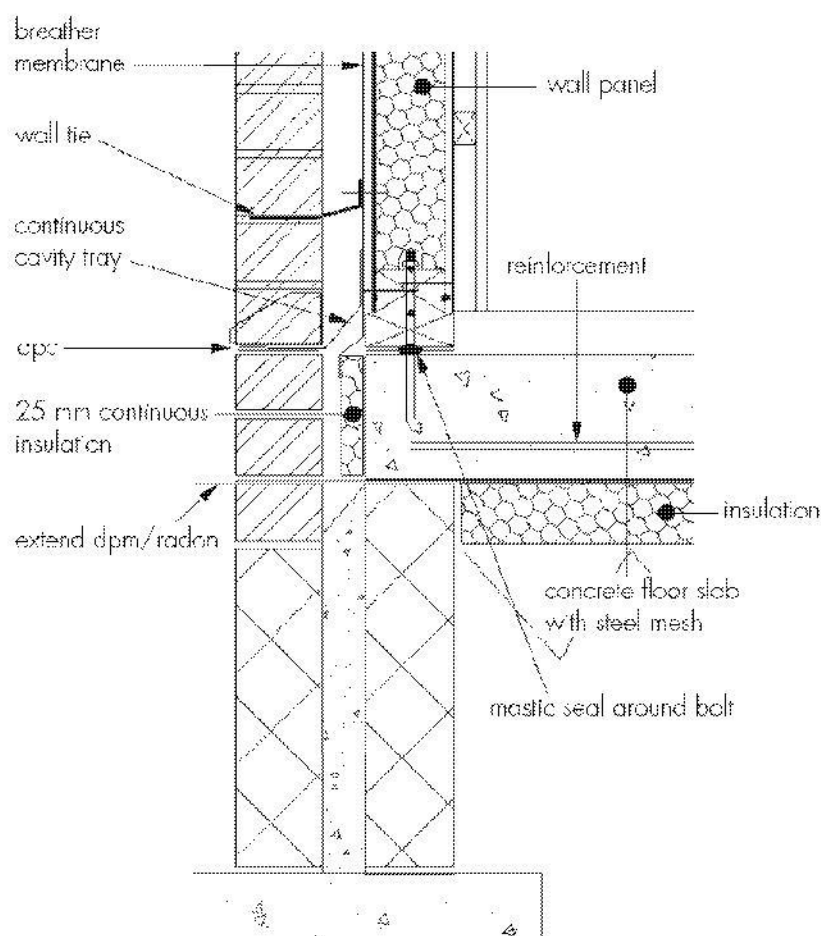


Figure 4 Sole plate with screed rail⁷



2.3.2.4 Roof ridge

One of the major benefits of using a structural insulated panel system is the 'room in a roof' capability. Using structural insulated panels to form roofs is common amongst the systems analysed. However, not all of them utilise structural insulated panels for roof construction. Structural insulated panels can be used to form the roof without the need for internal trusses or large joists. One commonality between all systems is a ridge beam to support the ends of the panels meeting at the roof ridge. However, the detailing of the connection between panels at this point is extremely variable. In some instances the panels are cut and butted such that the insulation is continuous through the entire roof cross section. A typical example is shown in Figure 5. Some manufacturers adopt a variant of the butted ridge detail by introducing 'ridge studs' which results in a discontinuous insulation layer. An example is shown in Figure 6. In both instances, the roof panels are tied to the ridge beam via panel screws which typically penetrate a minimum of 25mm into the supporting beam.

Figure 5 Plumb cut continuous insulation ridge detail⁸

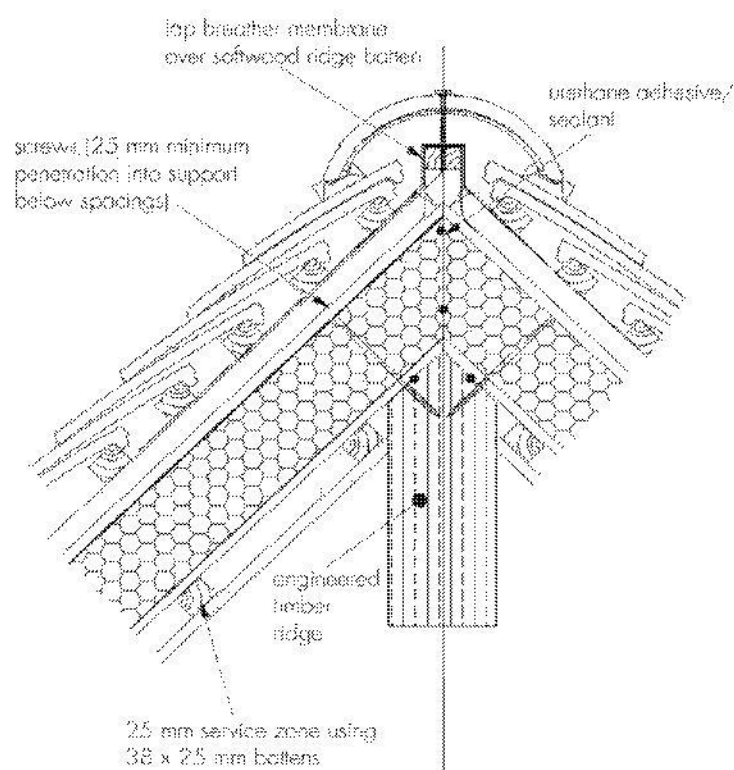
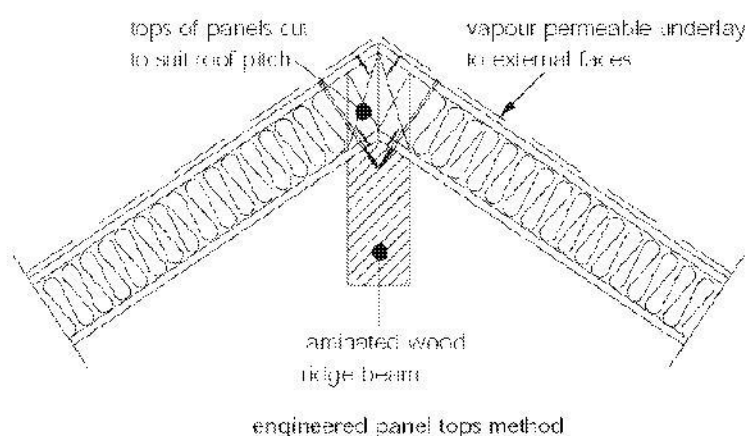


Figure 6 Plumb cut ridge stud detail⁴



Alternatively, some manufacturers utilise a 'square cut' ridge connection. This either requires a filler piece of timber, as shown in Figure 7, or an overlap in the panels at the ridge point, as shown in Figure 8. In both instances, the panels are tied back to the ridge beam via panel screws.

Figure 7 Square cut ridge connection with timber filler⁴

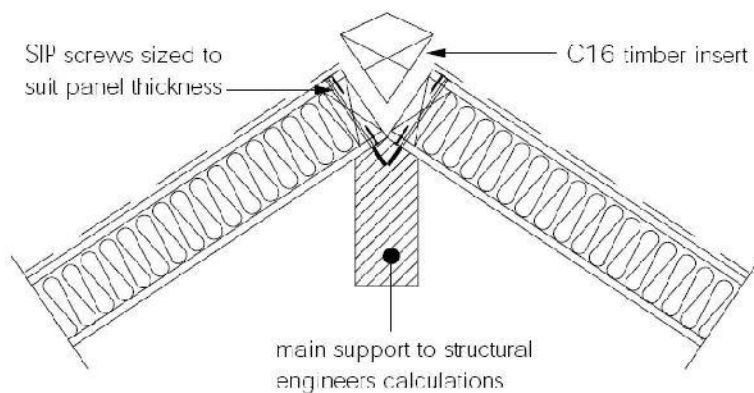
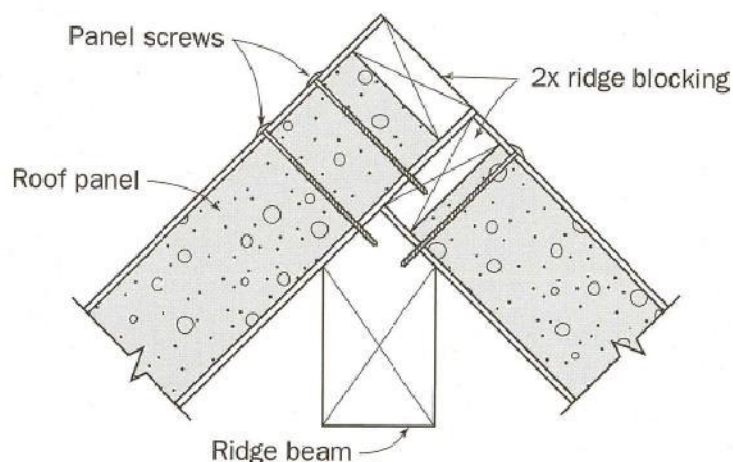


Figure 8 Square cut overlapping ridge detail²



2.3.2.5 Eaves detail

It has been previously noted that not all structural insulated panel systems utilise the panels as roof members. Therefore, it follows that detailing at the eaves, between the structural insulated panel wall and chosen roof element, varies depending on what system is adopted. Where structural insulated panels are used as roof members, typically

two details are used to connect the wall and roof elements. Subtle differences in these methods exist between manufacturers. Manufacturers will typically adopt either a 'square cut connection with wall plate' or a 'plumb cut panel with bevelled top plate'. These are shown in Figure 9 and Figure 10, respectively.

Figure 9 Wall plate eave detail⁴

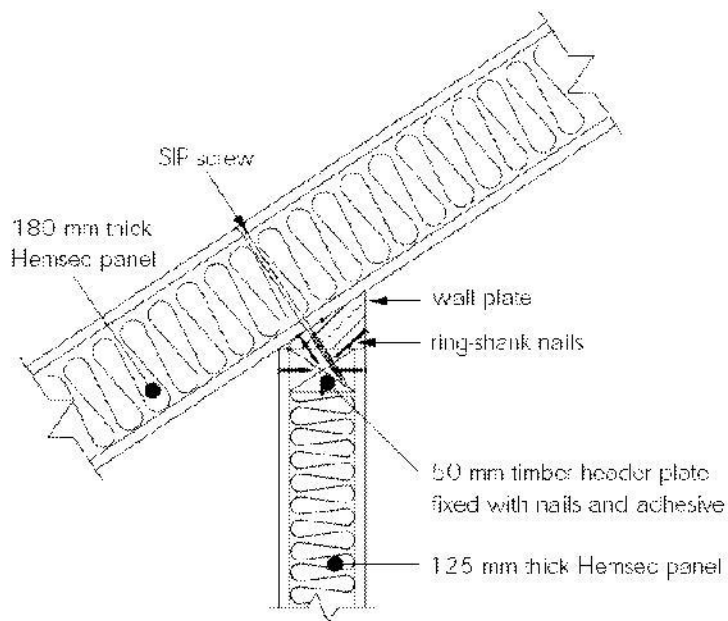
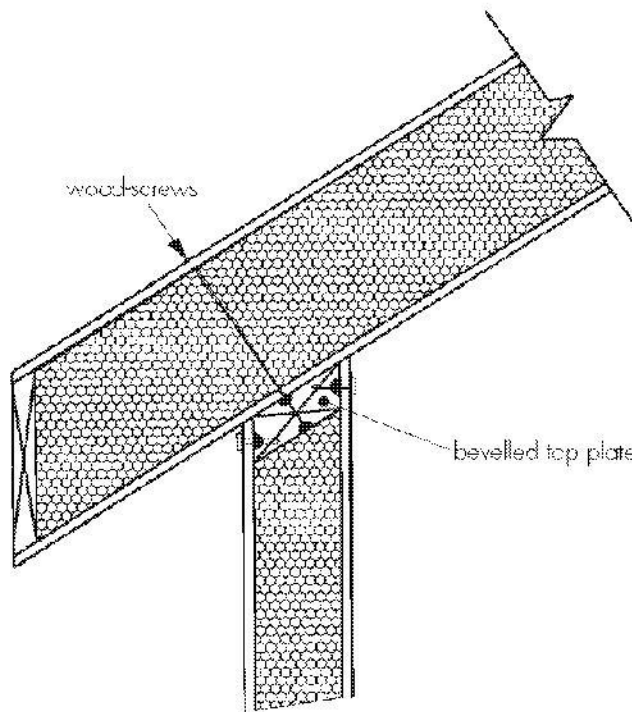
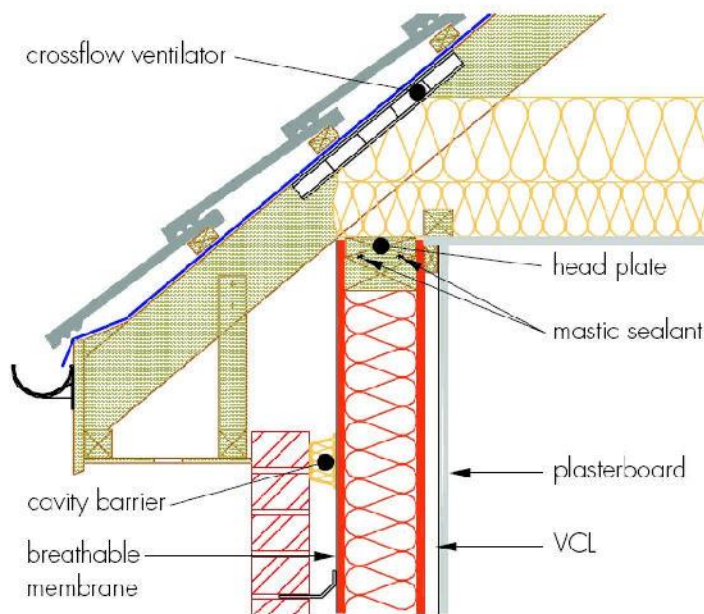


Figure 10 Bevelled top plate eave⁹



Panels that are connected to a more 'traditional' roof such as a truss and rafter adopt a similar connection detail as 'panel to panel' methods. Typically the rafter/truss will be fixed to the header/top plate of the panel via a panel screw as shown in Figure 11.

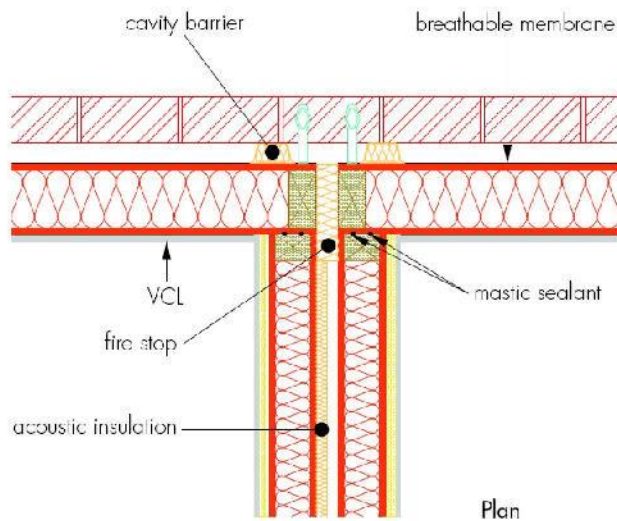
Figure 11 Structural insulated panel wall to trussed roof eave detail⁸



2.3.2.6 Separating walls

The details adopted in the UK for party walls appear to be common amongst all of the manufacturers assessed. Party walls are typically double leafed with an acoustic barrier in the 'cavity' between the panels. A typical example is shown in Figure 12. Typically, for current structural insulated panel applications, the party wall requires a fire resistance of 60 minutes. As a result, it is anticipated that most manufacturers would adopt a layer of fire rated plasterboard, followed by a layer of wallboard, for the internal linings in this area. Table 2 indicates the typical construction for a 60 minute structural insulated panel wall (FR60).

Figure 12 Typical separating wall detail⁶



2.3.2.7 Suspended floors

Essentially, the detail associated with the connection of the floor joists to the supporting walls is similar to that of more traditional wall constructions such as masonry. The floor joists are typically either suspended from joist hangers or 'built' into the wall.

Figure 13 First floor joist hanger detail⁸

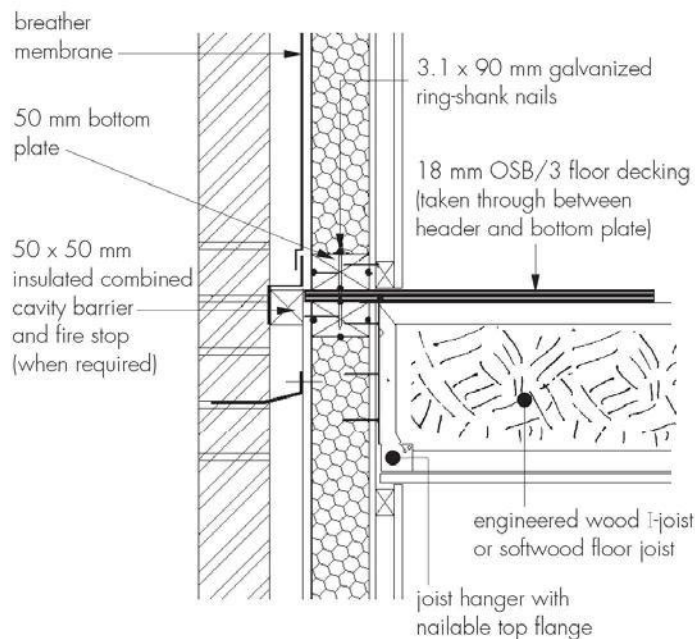
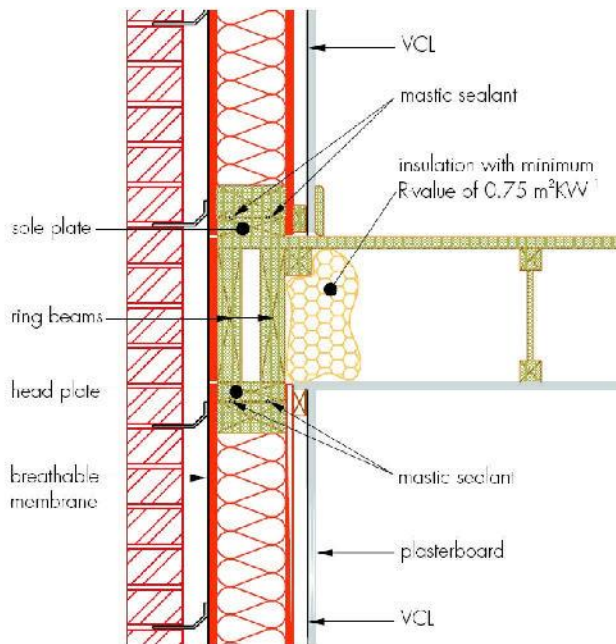


Figure 14 First floor ring beam detail⁵



In the joist hanger configuration (Figure 13) a hanger is placed in the vertical connection between the panels. This is 'locked' into the construction via 'ring shank' nails which fix the two end blocks of the panels together. Typically a panel strap provides further fixity between the panels, inside the 'cavity'. This strap ties the upper and lower level panels together to ensure a continuous wall.

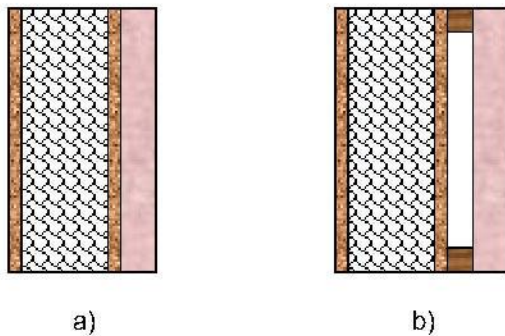
Alternatively, the floor joists can be built into the wall construction and connected to a ring beam or rim plate. A typical example is shown in Figure 14. The lower panel terminates at ceiling level where a ring beam is fixed to the header plate of the panel. The upper panel is in turn fixed to the ring beam to form the upper storey of the structure.

2.3.3 INTERNAL LININGS AND FIRE STOPPING

It is common in the UK to fix the internal linings to the structural insulated panel in two different ways:

1. Direct fixing to the internal skin - this is usually done as part of the automated manufacturing process (Figure 15a).
2. Battening fixing - this is a fairly common onsite practice where battens are fixed to the internal skin of the panel at pre-designated centres. The lining materials are then fixed to the battens (Figure 15b).

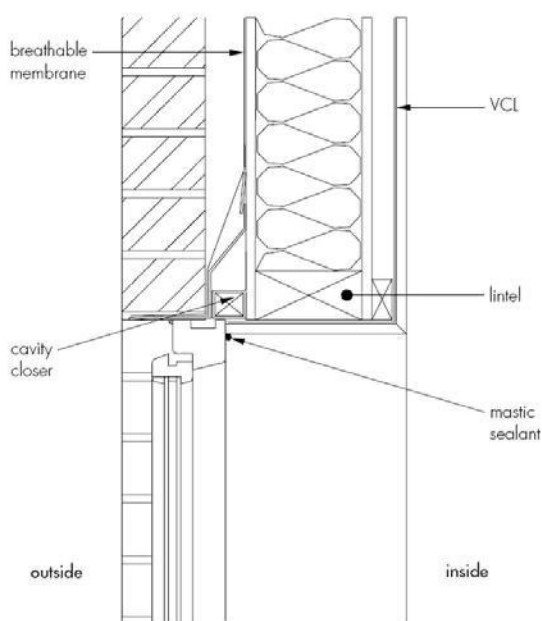
Figure 15 Internal linings a) fixed direct, b) battened



The exact nature of the lining material used largely depends on the fire resistance requirement. Table 2 indicates that many 30 minute systems simply adopt a single layer of non-fire rated plasterboard, usually 12.5mm in thickness. More robust 60 minute solutions typically require a single layer of plasterboard and an additional layer of fire rated board ranging from 12.5mm to 19mm in thickness.

Provisions for fire stopping are comparable to that of 'traditional' timber frame construction. Cavity barriers are placed horizontally in the void between the panel and the cladding system. Vertical cavity barriers are placed in the junction between party walls as shown in Figure 12. Panels are typically 'blocked' with a solid timber header or footer to prevent direct flame entry into the combustible structural insulated panel core. Similarly, the window openings are also 'blocked out' with solid timber members to prevent entry into the insulating core. A typical example is shown in Figure 16.

Figure 16 Lintel detail⁵



2.3.4 CLADDING SYSTEMS

From a cladding perspective structural insulated panel structures do not significantly differ to traditional timber frame construction. A vast array of cladding type and materials can and are adopted on structural insulated panel structures. Many of the details presented in this section combine structural insulated panel internal skins with a brick outer skin. In the United States it is common for structural insulated panels to be combined with timber cladding.

2.4 Small-scale evaluation of performance of structural elements

Based on the results of the previous task, a detailed experimental programme was developed to look at the performance of individual panels, to provide information for numerical modelling and to inform decisions regarding the nature and extent of the large-scale fire tests.

The tests on individual panels have provided information on the relative performance of different solutions designed to achieve either 30 or 60 minutes standard fire resistance. Information has been provided on the contribution of the individual components of the panel system to the overall reaction to fire performance of the structural insulated panel.

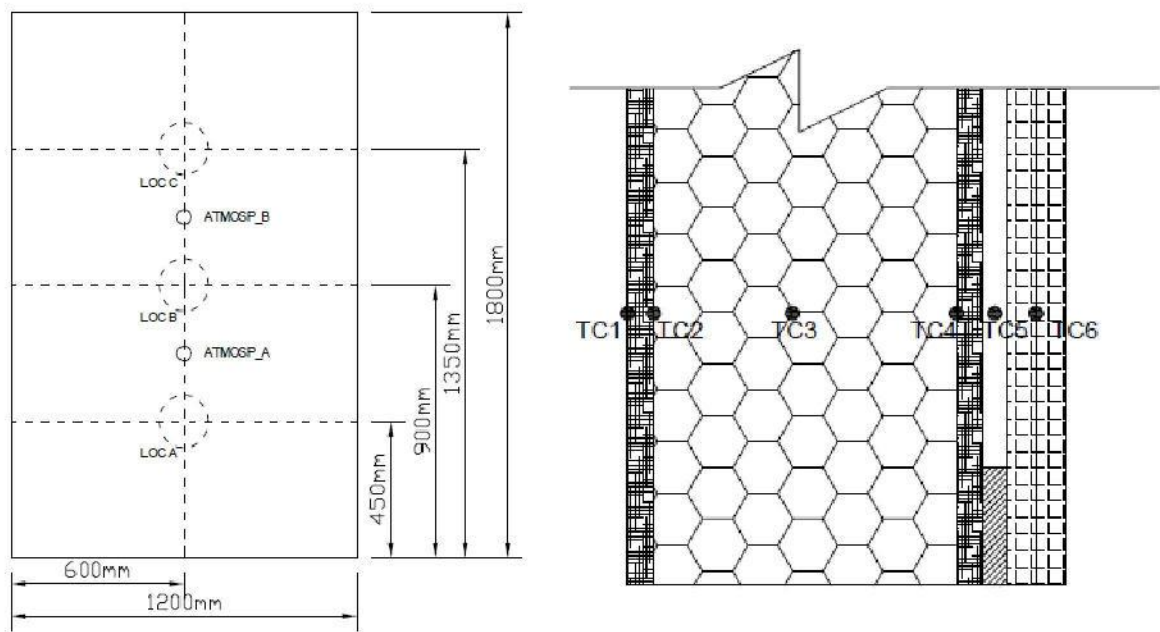
The experimental programme considered heat transfer in isolation and the combined effect of a fire exposure whilst under load. During the course of the project, the panel tests were expanded to include the effect of using a non fire-rated plasterboard lining and to investigate the effects of incorporating electrical sockets within the panel.

2.4.1 INTRODUCTION

A programme of testing was developed which incorporated heat transfer and structural testing. In each case, the panel dimensions were 1.2m wide by 1.8m high (external dimensions) and incorporated polyurethane (PUR) or expanded polystyrene (EPS) core material. For each type of panel, a 30 minute and a 60 minute fire resistance performance was tested by varying the lining materials.

The specimens are considered as generic systems for each type of core material and therefore are not assigned to any specific manufacturer. The first phase of the small-scale fire tests was designed to provide detailed data on the thermal distribution through the depth of the panel for specific periods of fire resistance. Therefore, thermocouples were located on the centre line of the panel in the positions, as illustrated in Figure 17. These tests were undertaken on unloaded test specimens using a gas fired furnace to simulate the appropriate (30 minutes or 60 minutes) fire exposure. For each fire resistance period and core material combination, three specimens were tested to ensure consistency. The test programme for the first phase of small-scale fire tests is summarised in Table 4.

Figure 17 a) Elevation and b) Cross-section showing position of thermocouples



The second phase of the small-scale tests involved loading the test specimens. In order to establish the appropriate load level to be applied, one of each of the test specimens has been subjected to a compression test at ambient temperature to determine the ultimate load and the mode of failure. The remaining specimens were then subjected to the appropriate thermal exposure whilst under a compressive force equal to 50 per cent of the experimentally derived ultimate load. The test programme for this second phase of testing is summarised in Table 5.

Table 4 First phase of small-scale fire tests to determine temperature profiles

Test number	Thickness (mm)	Width (mm)	Length (mm)	Fire resistance period (minutes)	Core material
1	150	1200	1800	30	PUR
2	150	1200	1800	30	PUR
3	150	1200	1800	30	PUR
4	150	1200	1800	30	EPS
5	150	1200	1800	30	EPS
6	150	1200	1800	30	EPS
7	150	1200	1800	60	PUR
8	150	1200	1800	60	PUR
9	150	1200	1800	60	PUR
10	150	1200	1800	60	EPS
11	150	1200	1800	60	EPS
12	150	1200	1800	60	EPS

Table 5 Second phase of small-scale fire tests to determine behaviour under load

Test number	Load level	Fire exposure	Core material	Fire resistance period (minutes)
13	To failure	Ambient	PUR	30
14	0.5 x ultimate load	30 mins ISO	PUR	30
15	0.5 x ultimate load	30 mins ISO	PUR	30
16	To failure	Ambient	EPS	30
17	0.5 x ultimate load	30 mins ISO	EPS	30
18	0.5 x ultimate load	30 mins ISO	EPS	30
19	To failure	Ambient	PUR	60
20	0.5 x ultimate load	60 mins ISO	PUR	60
21	0.5 x ultimate load	60 mins ISO	PUR	60
22	To failure	Ambient	EPS	60
23	0.5 x ultimate load	60 mins ISO	EPS	60
24	0.5 x ultimate load	60 mins ISO	EPS	60

2.4.2 RESULTS FROM FIRST PHASE TESTS

Prior to testing, the specimen was mounted in a frame, pushed into position in front of the furnace and any gaps sealed by ceramic fibre blanket. The specimen was then subjected to a thermal exposure corresponding to either 30 or 60 minutes to the standard fire curve. The furnace was controlled by a plate thermometer. The temperature inside the furnace was measured by type K thermocouples. The results showed that the tests were capable of following the standard fire curve. The differences between the standard fire curve and the measured values were due to the larger thermal mass of the plate thermometer which results in a greater amount of energy required in the early stages of the test to achieve the target temperatures. Figures 18 and 19 show the measured atmosphere (furnace) temperatures for the 30 and 60 minute cases, respectively. These clearly show that the tests provide a consistent and repeatable level of heat flux to the specimens which is comparable in intensity to the standard fire curve used in fire resistance tests.

Figure 18 Measured atmosphere temperatures and comparison with standard curve for the 30 minute fire resistance period

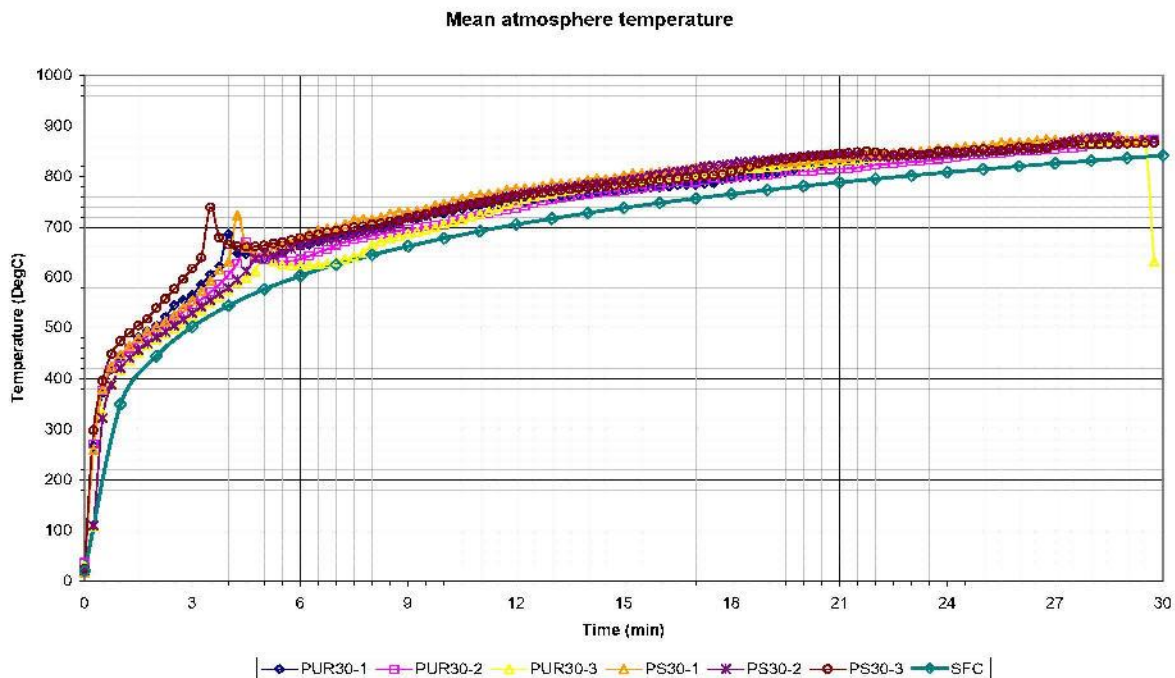
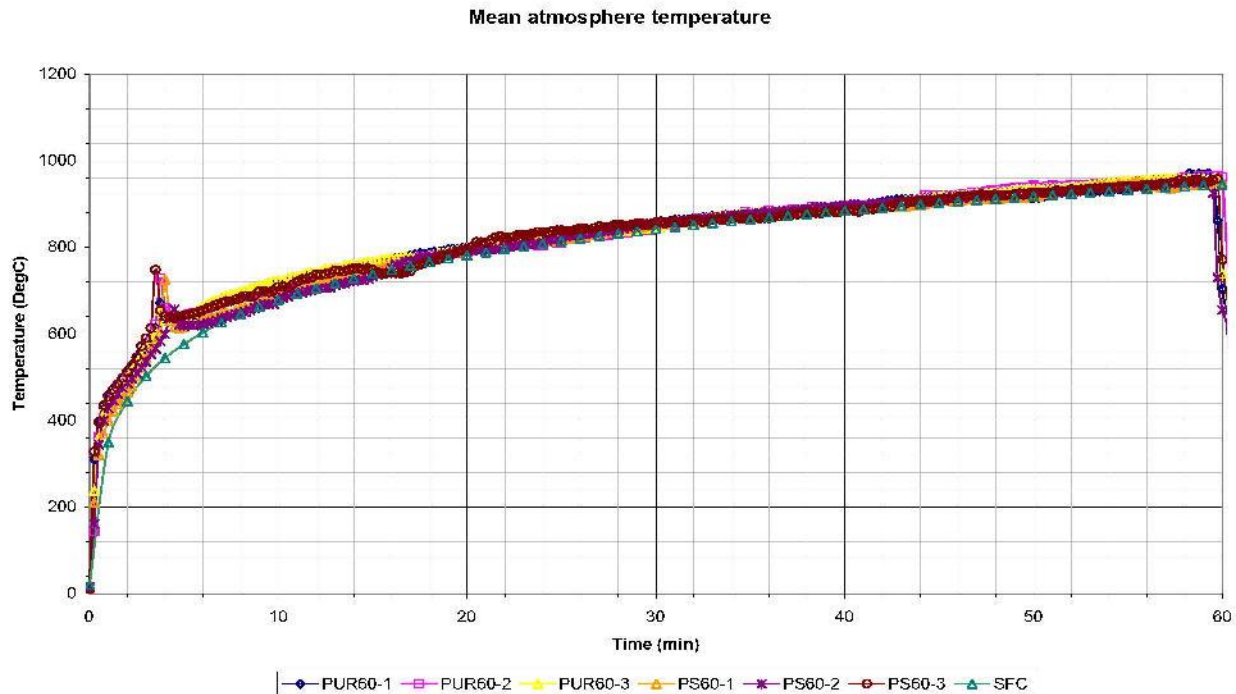


Figure 19 Measured atmosphere temperatures and comparison with the standard curve for the 60 minute fire resistance period



2.4.2.1 30 minute furnace test

The required fire resistance was provided by a single 15mm layer of fire rated plasterboard (Type F¹¹). For each test, five thermocouples were used to measure the temperature gradient through the specimens at the three locations shown in Figure 17.

Figures 20 to 22 show the average values measured immediately behind the plasterboard, behind the inner layer of oriented strand board and in the centre of the core, respectively. The thermal gradient as a function of the atmosphere temperature at 30 minutes is summarised in Table 6. The temperatures either side of the external (unexposed) skin remained at ambient temperature for the duration of the test.

Table 6 Relative temperature profile at 30 minutes (approximate values)

Location	Temperature (°C)	Value relative to atmosphere temperature
Atmosphere	850	1.0
Behind plasterboard	320	0.376
Behind oriented strand board	80	0.094
Centre of core	30	0.035

Figure 20 Average temperature immediately behind the exposed layer of Type F plasterboard

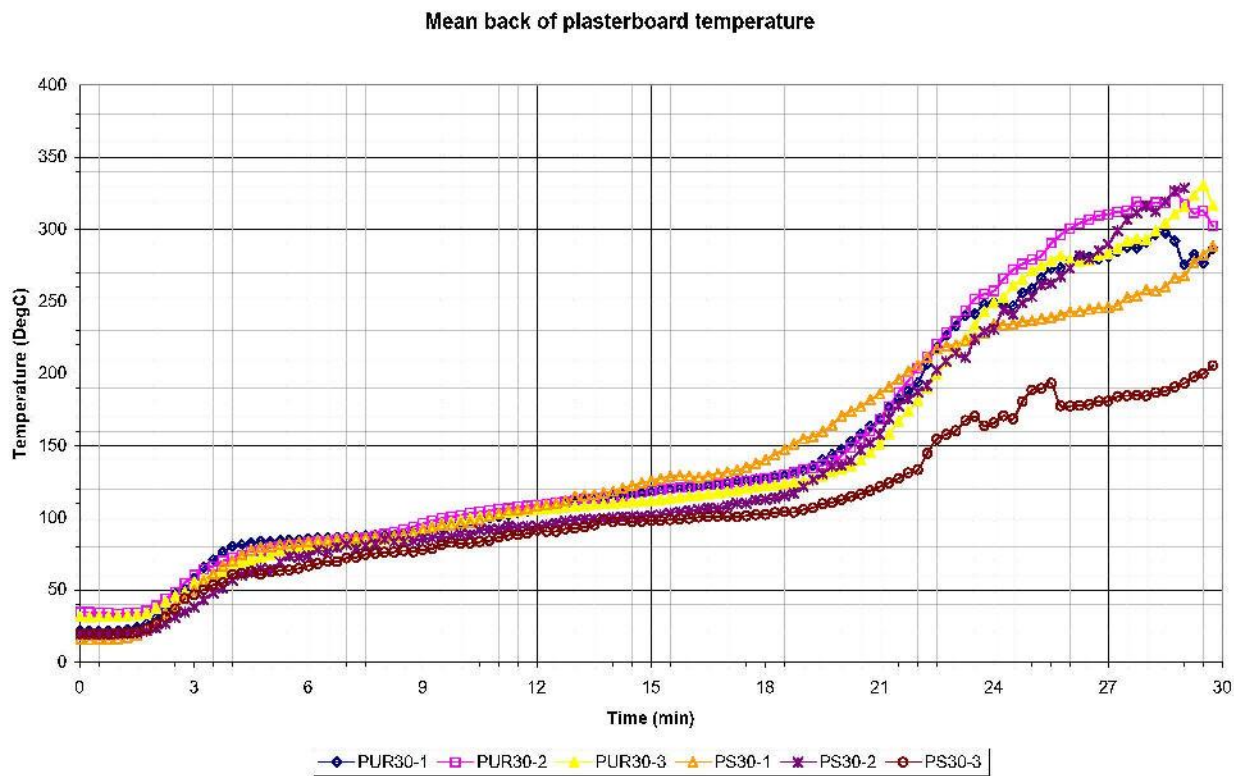


Figure 21 Average temperature immediately behind the inner layer of oriented strand board

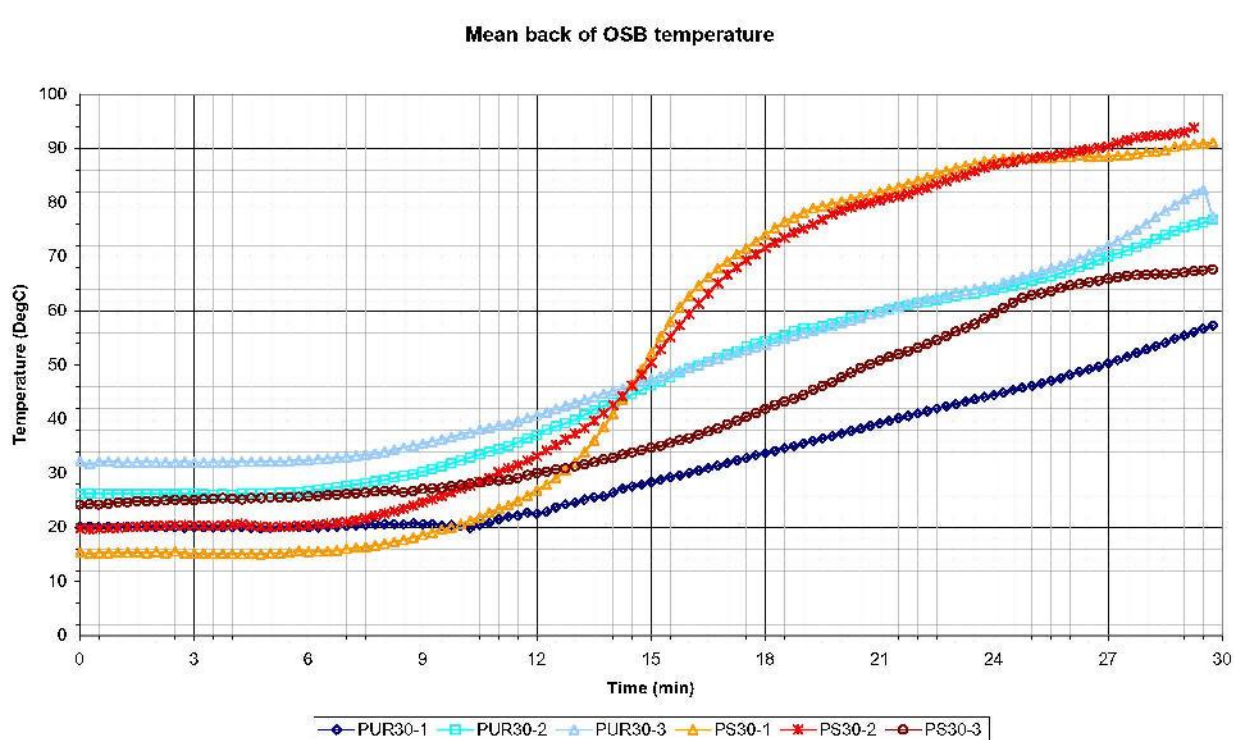
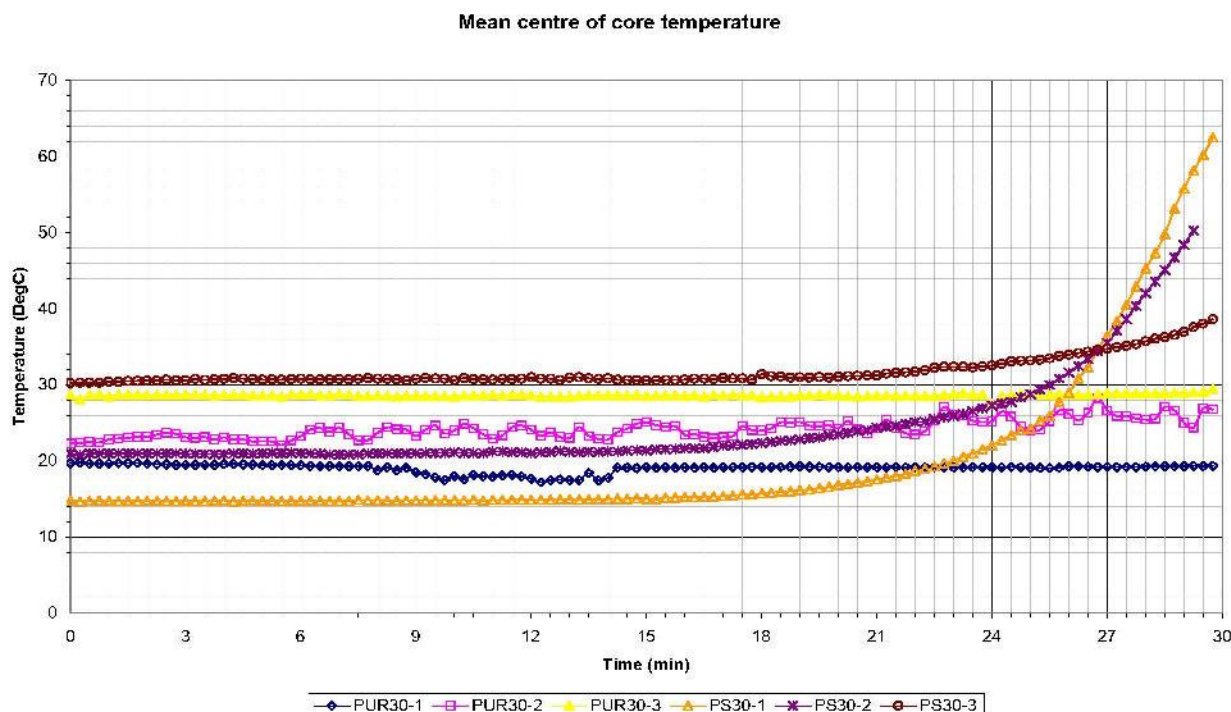


Figure 22 Average temperature in centre of core



Following each fire test, the furnace was switched off and the specimen was moved rapidly outside to reduce the release of combustion products into the laboratory. At this stage, the plasterboard was cracked and steam and some smoke was issuing through the fissures.

The damaged plasterboard lining was removed to reveal evidence of charring to the batten used to fix the plasterboard and limited damage to the surface of the oriented strand board. Charring was more pronounced local to the plasterboard fixings.

Following the test, a core sample was taken through the area of oriented strand board exhibiting the most damage. Figure 23a shows the area around the cut out and Figure 23b shows the sample compared to a similar section taken from a damaged polyurethane core. It can be seen that there is no damage to the insulation nor is there any evidence of delamination between the oriented strand board and the core material. This is consistent with the temperature readings.

Figure 23a Expanded polystyrene core following test

Figure 23b Comparison between expanded polystyrene and polyurethane



For both the polyurethane and expanded polystyrene samples, removal of the plasterboard immediately after the test resulted in ignition of the oriented strand board, see Figure 24.

Figure 24 Sequence of photographs showing ignition of oriented strand board on removal of plasterboard lining



2.4.2.2 60 minute furnace test

The required fire resistance period was provided by two layers of 15mm (Type F) fire rated plasterboard fixed to timber battens. Figures 25 to 27 show the average temperatures measured immediately behind the plasterboard, behind the inner layer of oriented strand board and at the centre of the core, respectively. For a number of specimens, an additional thermocouple was located at the junction between the two layers of plasterboard.

The thermal gradient relative to the atmosphere temperature at 60 minutes is summarised in Table 7. The temperatures either side of the external (unexposed) skin remain at ambient temperature for the duration of the test. Note that the atmosphere temperature is 100°C higher than the thirty minute case due to an additional 30 minutes exposure in accordance with the standard fire resistance curve.

Table 7 Relative temperature profile at 60 minutes (approximate values)

Location	Temperature (°C)	Value relative to atmosphere temperature
Atmosphere	950	1.0
Back of first plasterboard layer	600	0.63
Back of second plasterboard layer	150	0.16
Back of oriented strand board	93	0.098
Centre of core	25	0.02

Figure 25 Average temperature immediately behind second layer of Type F plasterboard

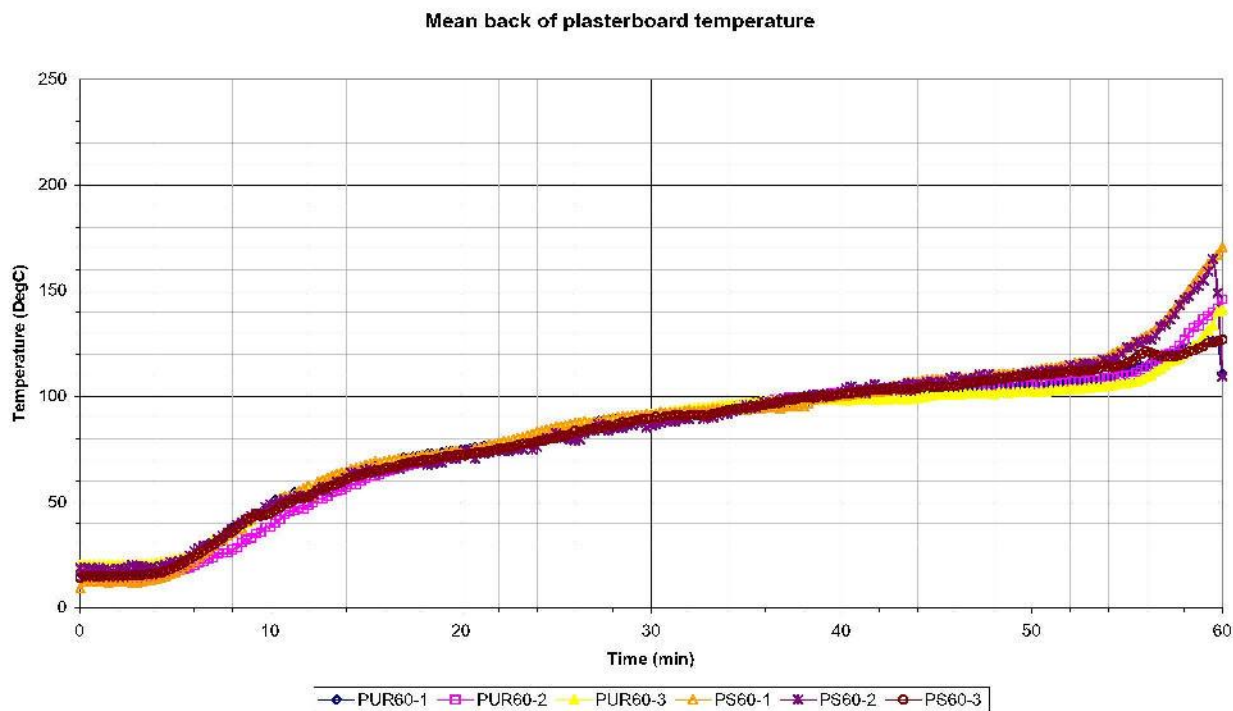


Figure 26 Average temperature immediately behind inner layer of oriented strand board

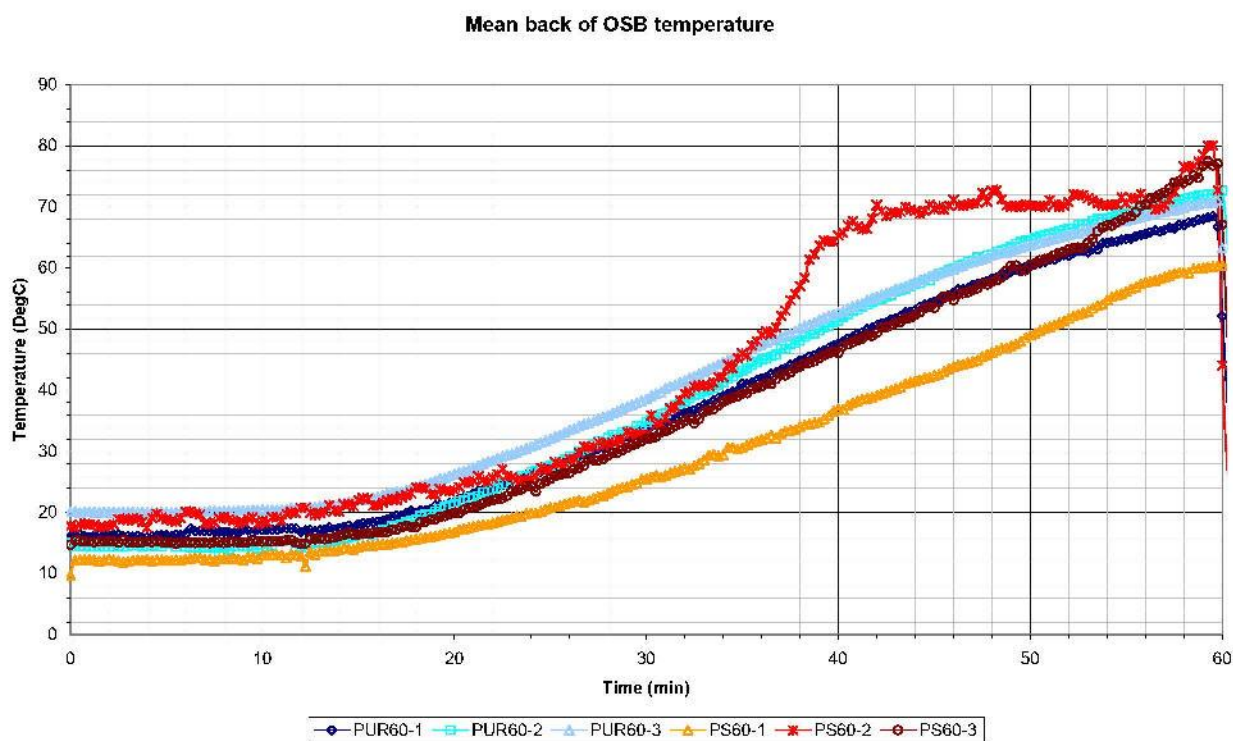
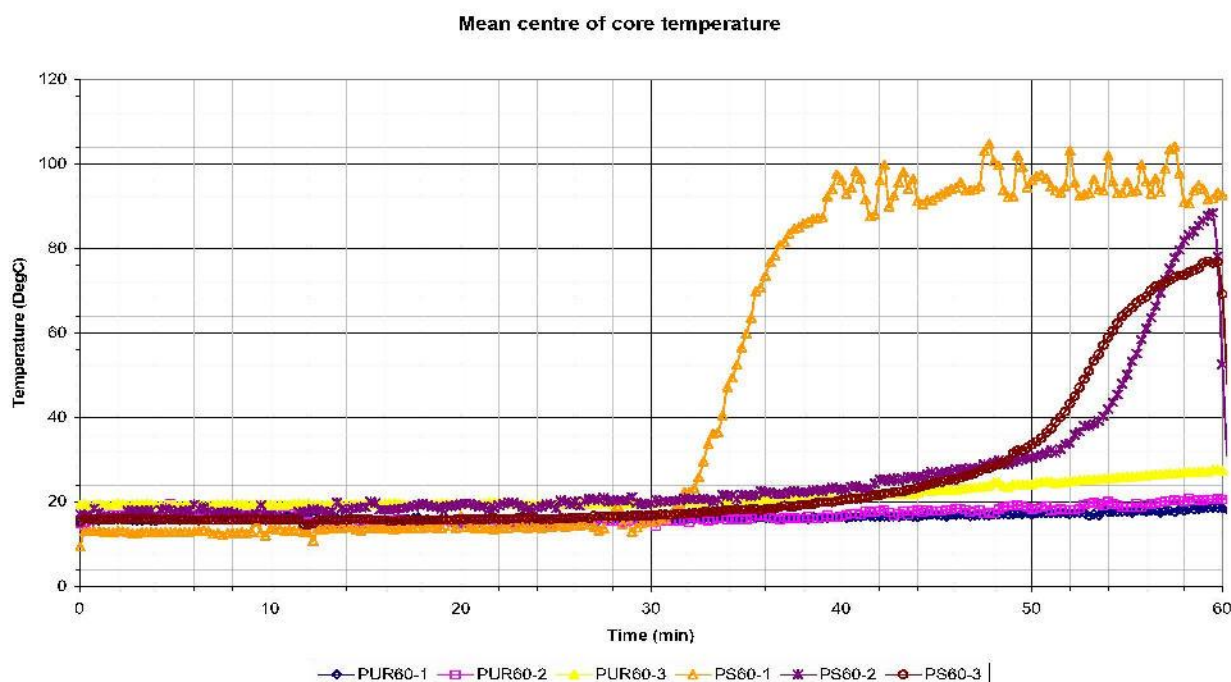


Figure 27 Average temperature in centre of core



The higher values for the polystyrene are a function of steam escaping through the holes drilled for the thermocouples. This was noted for the 30 minute test but is more pronounced in the 60 minute test.

On removal from the test furnace, the exposed layer of plasterboard was cracked with steam issuing from underneath. Once removed, the inner layer of plasterboard was found to be intact. The oriented strand board skin was undamaged. However, de-lamination of the polystyrene core was observed. None of the 60 minute specimens resulted in combustion of the oriented strand board skin. For one specimen, the timber batten ignited once the plasterboard had been removed, and there was evidence of heat conduction through the fixings.

2.4.2.3 Ambient temperature load capacity and residual strength testing

Before carrying out the second phase of fire tests, it was necessary to determine the ultimate capacity of the structural insulated panel sample. Tests were undertaken on both polyurethane and expanded polystyrene samples. However, the expanded polystyrene sample was completely framed in large section timber. This meant that it was impossible to ascertain the capacity of the structural insulated panel. The results are included here for completeness. The measured values of ultimate capacity and associated maximum vertical and lateral deflection are summarised in Table 8 for a single expanded polystyrene specimen (incorporating the timber frame surround) and a number of damaged and undamaged polyurethane samples.

Table 8 Summary of ambient and residual load tests (* incorporates timber frame)

Specimen	Damaged /Undamaged (D/U)	Ultimate load (kN)	Maximum lateral deflection (mm)	Maximum horizontal deflection (mm)
EPS*	D	647	2.7	10.8
PUR	D	298	1.0	9.3
PUR	D	278	1.1	12.4
PUR	D	247	0.24	9.8
PUR	U	331	2.4	16.4
PUR	U	293	8.9	28.7

One of the damaged specimens incorporated an opening in the panel. This made no difference to the ultimate load achieved. It can also be seen that the fire test had no appreciable impact on the ultimate strength of the panel.

In all cases failure was through a fracture of the oriented strand board skin. Some de-lamination was also observed in the region close to the failure surface, see Figure 28.

Figure 28 De-lamination between skin and core around fracture surface



2.4.3 COMBINED HEAT AND LOADING TESTS

Nine experiments were performed on structural insulated panels subject to a furnace heating regime corresponding to a standard fire exposure whilst under a uni-axial compressive load. In no instance did a load bearing failure occur despite the fact that the load levels imposed were well in excess of those typically applied in practice. Measured deflections in all panels were small and characterised by a gradual creep with time. Lateral deflections of the order of 10-15mm were recorded. However, these did not result in any cracking of the plasterboard lining or oriented strand board skins. As a result, the temperatures in the loaded specimens were effectively the same as those in the unloaded tests.

For the 30 minute design solutions (15mm type F plasterboard), there was no discernible difference between the performance of the polyurethane and expanded polystyrene specimens. Because of the susceptibility of polystyrene to ignition it has not been possible to compare the performance of the 60 minute design solution with the corresponding polyurethane panels.

2.4.4 TESTS TO INVESTIGATE THE INFLUENCE OF SERVICE PENETRATIONS

During the project Stakeholder Group meetings, concerns were expressed about the impact of service penetrations on the performance of structural insulated panels. In order to address these concerns, two small-scale tests were undertaken incorporating double gang electrical sockets. In each test it was possible to incorporate two sets of sockets in each sample and to vary the nature and mounting method adopted.

The test parameters are summarised in Table 9. Figures 30 and 31 show the layout of the sockets prior to testing. In both cases the sockets were built into a 30 minute (single layer of fire resistant plasterboard) panel with an expanded polystyrene core. Both samples were subject to a 30 minute standard fire exposure, controlled using a plate thermometer.

Table 9 Test parameters

Test 1		Test 2	
Steel box – flush mounted socket	Plastic box – flush mounted socket	Steel box – flush mounted socket	Plastic box – surface mounted socket

The sockets were installed in accordance with the manufacturer's instructions except for one aspect. In Test 1, both sockets were mounted with the surface flush to the plasterboard. However, only the steel box was designed to be installed in this manner. The panel incorporated battens between the plasterboard and the inner layer of oriented strand board to provide a 20mm cavity for the installation of services. The depth of the steel box was 25mm with the back of the box sitting in the cavity space approximately 5mm to 10mm away from the oriented strand board. The plastic box was 35mm deep and designed to be surface mounted. However, in this case, the box was flush fitted with the back of the box tight up against the oriented strand board. Such a situation could easily occur if modifications were made by a homeowner/tenant instead of a qualified electrician. The position of the boxes is shown in Figure 29. Figure 29 also illustrates the

position of the thermocouple used to measure the temperature in the box. The sockets as tested are illustrated in Figure 30.

In Test 2, the sockets used were identical to Test 1 but were installed with the steel box flush mounted and the plastic box surface mounted as shown in Figure 31.

Figure 29 Location of boxes and position of thermocouples for Test 1



Figure 30 Location of sockets prior to testing for Test 1

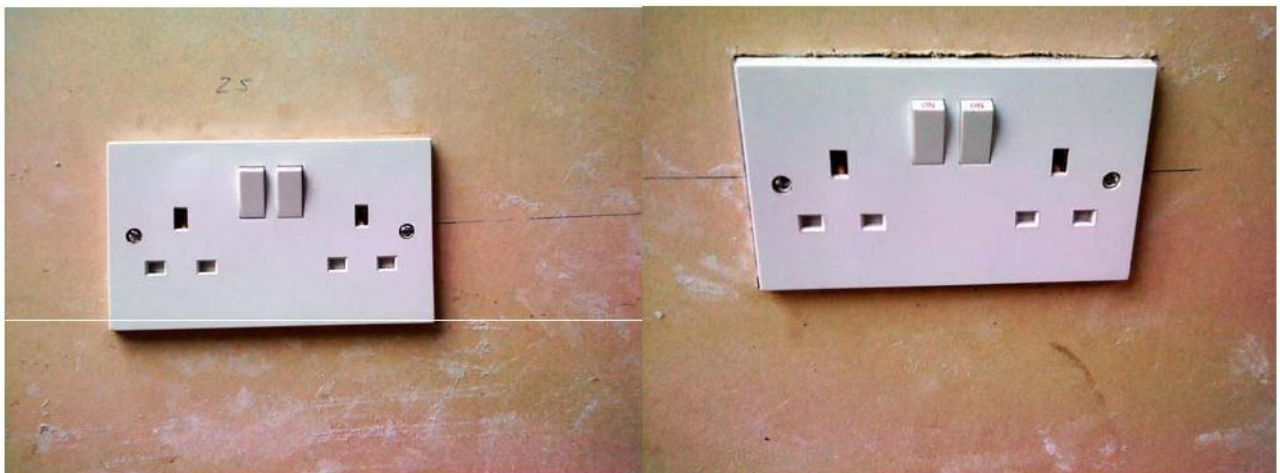
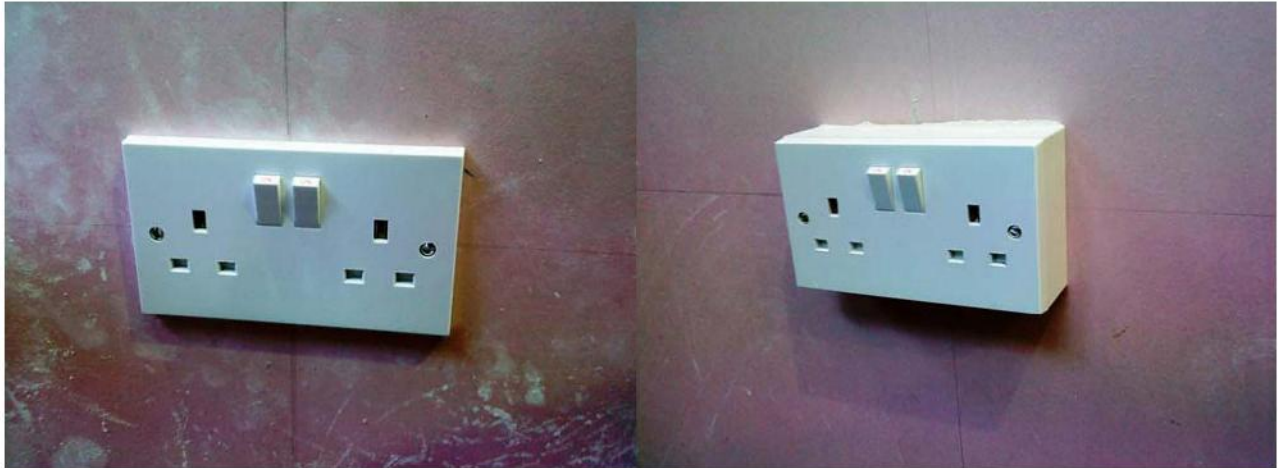


Figure 31 Location of sockets prior to testing for Test 2



In each case, thermocouples were used to measure the temperature within the box, the temperature immediately behind the plasterboard adjacent to the box, the temperature behind the inner layer of oriented strand board, the temperature in the centre of the core and the temperature immediately behind the unexposed face of the oriented strand board.

2.4.4.1 Results from service penetration tests

The condition of the panel immediately following Test 1 is shown in Figure 32. The condition of the boxes is illustrated in Figure 33. The condition of the panel on removing the debris is illustrated in Figure 34.

Figure 32 Panel on removal from the furnace for Test 1



Figure 33 Damage to boxes for Test 1



Figure 34 Damage to panel for Test 1



The condition of the panel following test 2 was very similar. Although the surface mounted socket required a hole to be drilled through the plasterboard this did not lead to any penetration through the oriented strand board.

The measured temperatures are shown in Figures 35 to 37. Figure 35 shows the temperatures immediately behind the plasterboard in the vicinity of the socket. Figure 36 shows the temperature of the inner layer of oriented strand board. Figure 37 shows the temperature in the centre of the core. In each case, a comparison is made between previous samples tested without any penetrations.

Figure 35 Plasterboard temperatures

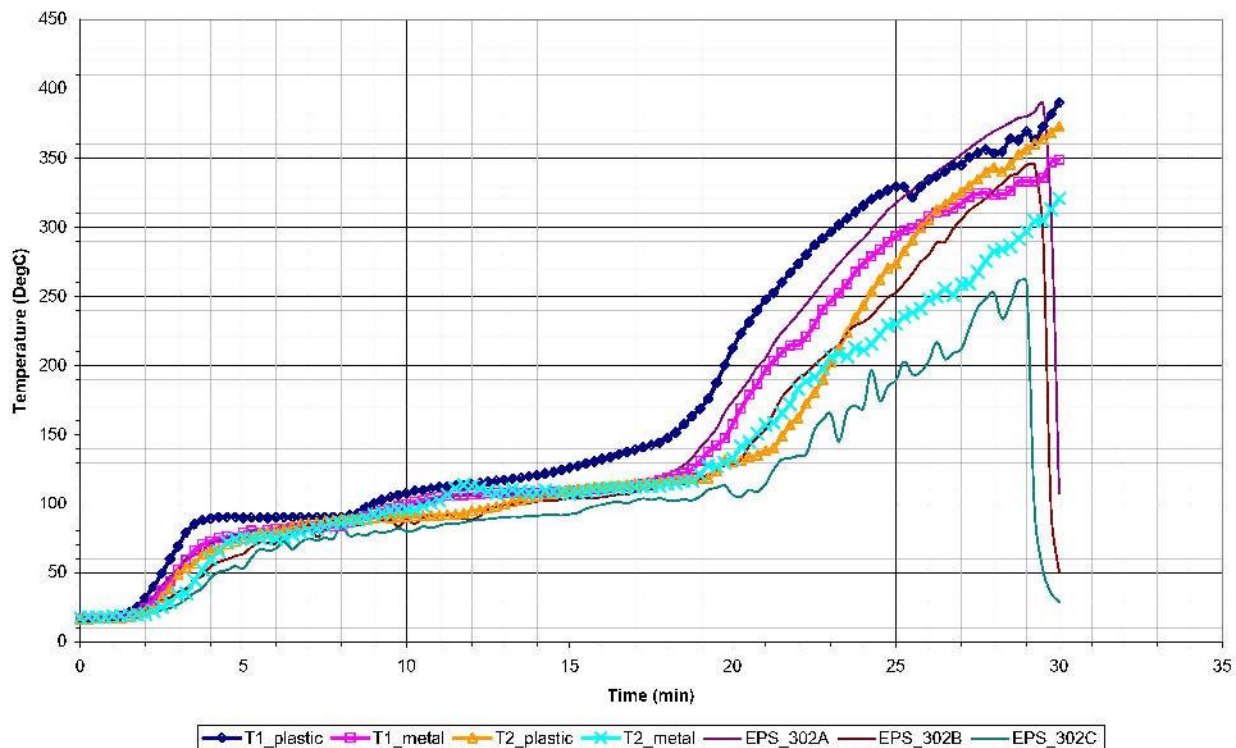


Figure 36 oriented strand board temperatures

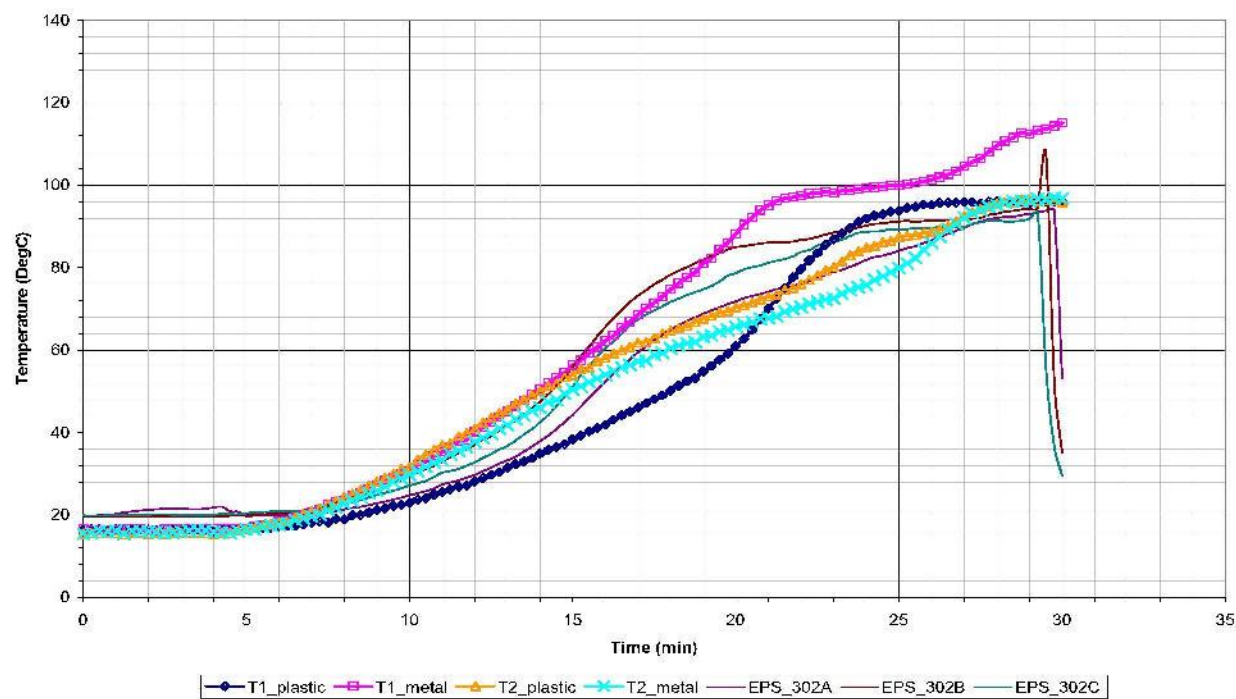
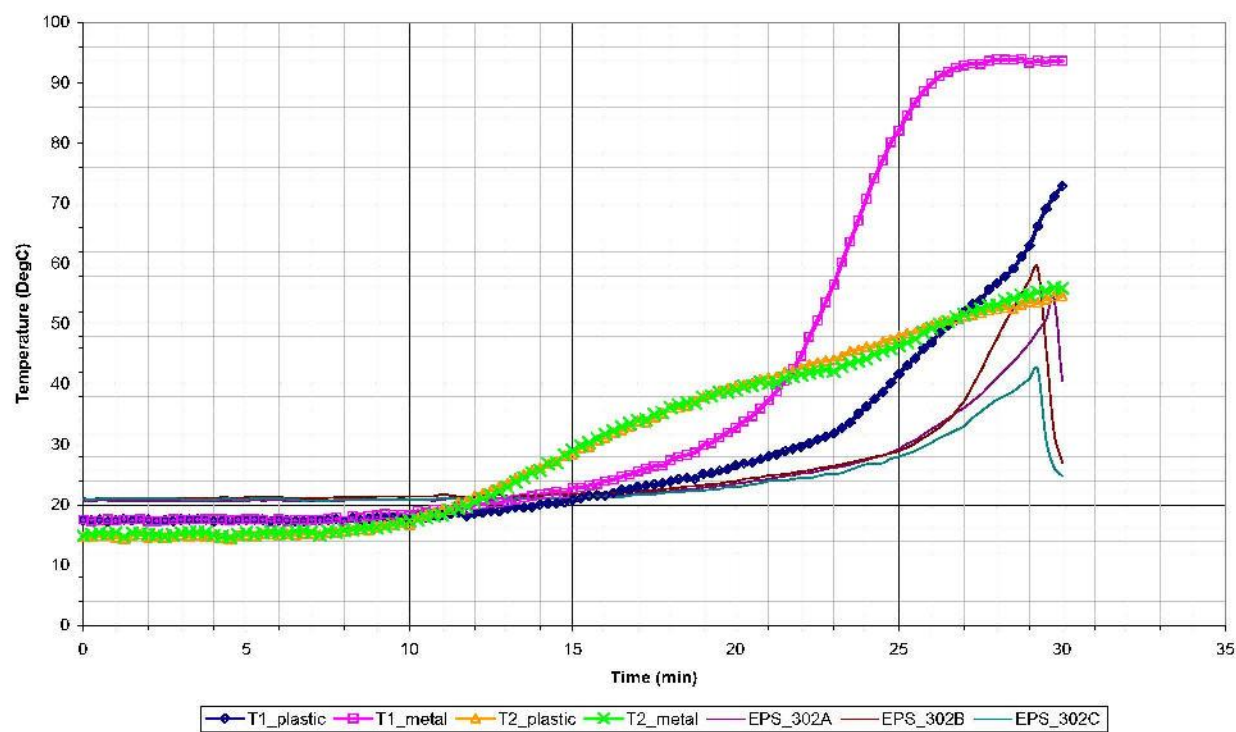


Figure 37 Core temperatures



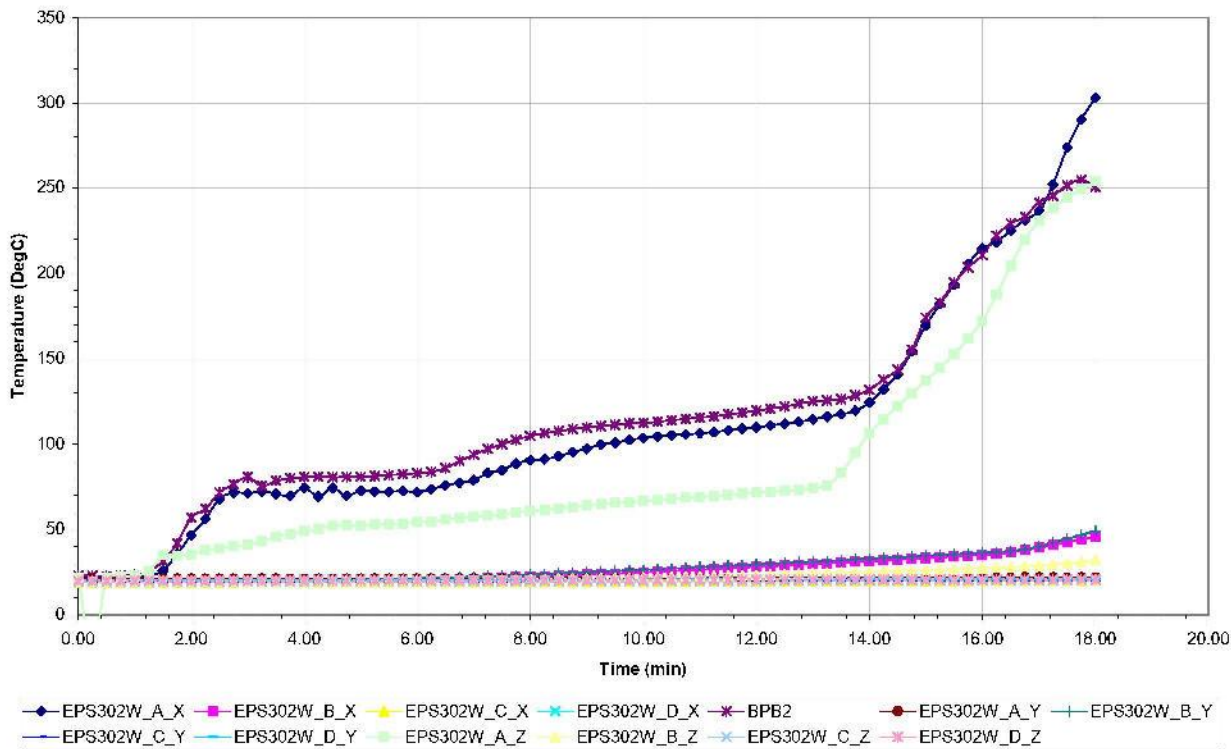
It is clear from the condition of the panels following the tests and from the measured values of temperature through the panels, that the inclusion of the electrical sockets made no appreciable difference to the performance of the structural insulated panels. In each case, the plastic material melted in the early stages. The sockets are designed to fit within the cavity formed by the timber battens and therefore do not penetrate into the core. If battened construction is adopted as general practice then there is no need for services to penetrate the core.

2.4.5 TESTS TO INVESTIGATE ADDITIONAL PARAMETERS

Some tests were undertaken to consider additional parameters. Two fire tests were carried out where the plasterboard was fixed directly to the structural insulated panel rather than using timber battens. Two tests were also undertaken using a single layer of 12.5mm ordinary (Type A) plasterboard fixed to the structural insulated panel via battens.

Where a single layer of 12.5mm Type A plasterboard was fixed to expanded polystyrene panels via softwood battens, the test had to be terminated approximately 20 minutes from ignition due to combustion of the exposed oriented strand board skin. A typical temperature profile is shown in Figure 38.

Figure 38 Temperature profile through expanded polystyrene panel protected with 12.5mm type A plasterboard



The results bring into question the use of such a lining for dwellings.

The consequences of fixing plasterboard linings directly to the internal skin of structural insulated panels were investigated in two tests on panels with expanded polystyrene cores. A single layer of type F plasterboard was fixed directly to the oriented strand board skin using drywall screws. The results indicate an increase in the temperature behind the plasterboard when compared to the similar case with timber battens.

2.5 Development of large scale test methodology

From the outset, the main focus of this research project was to investigate system behaviour by carrying out a fire test on a representative structure to investigate the mode of failure under realistic conditions. The initial intention was that the objective could be achieved through a single large-scale fire test. However, through discussions with the UK SIPs Association, it became apparent that a single test would not necessarily be representative of industry practice and that it would be necessary to include the two most common forms of insulation used in structural insulated panels construction, namely expanded polystyrene (EPS) and polyurethane (PUR).

The principal objective of this project was to evaluate the mode of failure. In order for this objective to be realised, it would be necessary to take the structure up to (or as close as reasonably practical) failure. There was some concern that this would reflect badly on the industry and would not provide them with an opportunity to demonstrate that their solutions were capable of fulfilling the functional requirement of the Building Regulations with respect to performance in fire.

It was therefore decided that the large-scale experimental programme would be expanded to four individual tests to cover a situation representative of a fire in a single dwelling where the fire resistance requirements of the load bearing elements of construction (excluding the party wall) call for 30 minutes fire resistance and a situation representative of a fire in a multi-occupancy building where the fire resistance requirements of the load bearing elements of structure (including the party wall) call for 60 minutes fire resistance. The revised experimental programme would also allow both polyurethane and expanded polystyrene structural insulated panels to be included.

2.5.1 COMPARTMENT FIRE DESIGN

The compartment for the fire tests was representative of typical spans for a domestic dwelling. The overall dimensions were 4m by 3m in plan by 2.4m high. In each case, the floor joists spanned from load bearing wall to wall in the long direction. The compartment was constructed from load bearing structural insulated panel panels to form the walls supporting engineered floor joists consisting of timber top and bottom flanges with an Oriented Strand Board (oriented strand board) web. Such floor systems are typical for buildings incorporating structural insulated panel panels.

The fire was designed to provide an equivalent fire severity of at least 60 minutes to ensure that a failure mechanism was mobilised in at least two of the four tests. An average value of 450 MJ/m² fire load density was adopted. This is consistent with published data for the average measured value for domestic dwellings¹² and is similar to that used in previous research projects¹³.

Two calculation techniques from the fire part of the Eurocode for Actions¹⁴ have been used to determine the time-temperature response for the compartment. These are the equivalent time of fire exposure and the parametric calculations.

2.5.1.1 Time equivalence

Based primarily on tests on protected steel members, the equivalent time of fire exposure, $t_{e,d}$, is calculated using:

$$t_{e,d} = q_{f,d} \cdot k_b \cdot w_f$$

Where:

$q_{f,d}$ = the design fire load density (MJ/m²)

k_b = conversion factor dependent on thermal properties of compartment boundaries (min.m²/MJ)

w_f = ventilation factor (dimensionless)

Where, w_f is given by:

$$w_f = \left(\frac{6}{H} \right)^{0.3} \cdot [0.62 + 90(0.4 - \alpha_v)^4 / (1 + b_v \cdot \alpha_h)] \geq 0.5$$

$\alpha_v = A_v/A_f$, where A_v and A_f are the area of the ventilation openings and the area of the compartment floor, respectively.

H = the height of the compartment (m)

$\alpha_h = A_h/A_f$, where A_h is the area of horizontal ventilation openings

and b_v is given by:

$$b_v = 12.5(1 + 10\alpha_v - \alpha_v^2) \geq 10$$

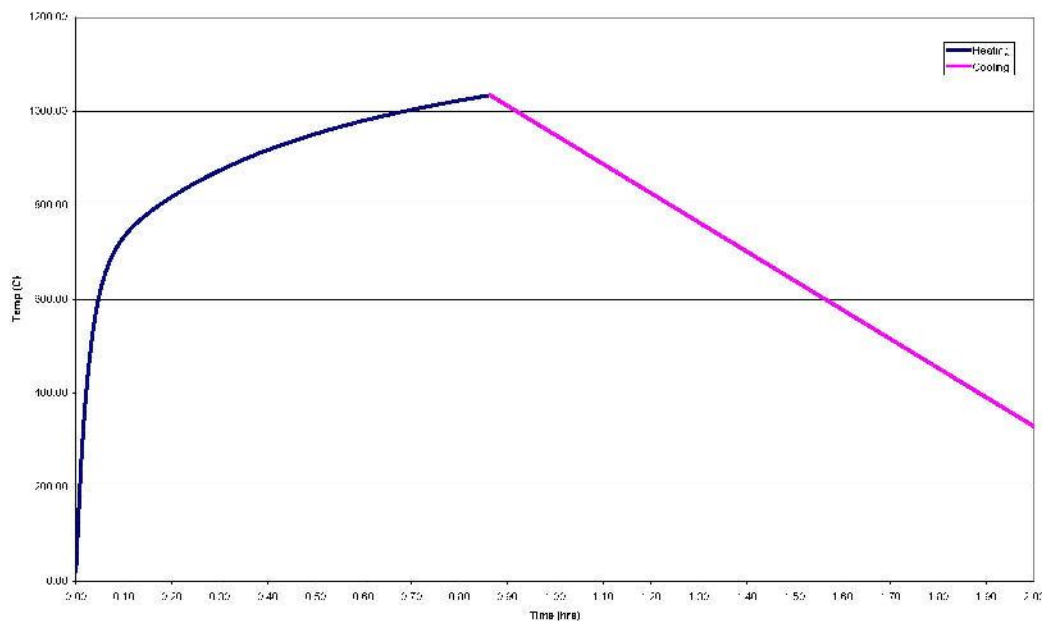
In this case $t_{e,d} = 450 \times 0.09 \times 1.493 = 60$ minutes

With $q_{f,d} = 450$ MJ/m²; $k_b = 0.09$ min.m²/MJ (UK National Annex to BS EN 1991-1-2); $w_f = 1.493$.

2.5.1.2 Parametric fire exposure

The time-temperature curve for the proposed tests has been estimated using the parametric approach. Again, the critical parameters are the fire load density, thermal properties of the compartment boundaries and the ventilation condition. The predicted time-temperature response is shown in Figure 39.

Figure 39 Predicted time-temperature response



The principal fire design parameters are summarised in Table 10.

Table 10 Fire design parameters

Parameter	Value	Units
Compartment floor area A_f	12	m ²
Compartment length	4	m
Compartment width	3	m
Compartment height	2.4	m
Area of ventilation openings A_v	1.5	m ²
Number of ventilation openings	2	-
Height of ventilation openings	1	m
Width of ventilation openings	0.75	m
Fire load density $q_{f,d}$	450	MJ/m ²
Thermal properties of compartment boundaries	520	J/m ² s ^{1/2} K

2.5.2 IMPOSED LOAD

In order to meet the mandatory regulatory requirement related to overall structural stability in fire as set out in the UK Building Regulations (Requirement B3) structural elements require fire resistance. The most common route to ensure compliance with the requirement is to use the prescriptive values as set out in Table A2 of Volume 1 of Approved Document B¹⁵.

For the structural insulated panels market, two of the categories covered by AD B are relevant. The first category is limited to buildings where the height of the top floor from ground level is not greater than 5m (but incorporating three-storey houses under single occupation) and calls for 30 minutes fire resistance for elements of structure. The second category covers buildings with a floor in excess of 5m from ground level and apartment blocks where the height from ground floor to the top floor does not exceed 18m and call for 60 minutes fire resistance.

Based on the available information, the current market for structural insulated panels residential buildings includes single family dwellings and apartment blocks of up to four storeys. In order to determine the failure mechanism in fire and to consider the design methods used to provide the required periods of fire resistance, it was necessary to investigate experimentally both a 30 minute solution and a 60 minute solution.

The 30 minute solution effectively models a two-storey domestic dwelling. For such a structure, the design imposed loading¹⁶ for the floor/ceiling would be a uniformly distributed load of 1.5kN/m². For the fire limit state, the structural Eurocodes¹⁴ allow a reduction in the design value of the imposed load to account for the very low probability of a fire occurring at the same time as the structure is carrying the full design loading. The appropriate partial factor for imposed loads is 0.5. For this reason, the applied load on the floor under test was 0.75 kN/m² per floor. For the 30 minute fire resistance period with two floors, this required a total loading of $2 \times 0.75 \times 4 \times 3 = 18\text{kN}$ or 1835kg distributed evenly over the two floors. The load was applied by sandbags weighing 25kg per bag resulting in 37 bags per floor.

The 60 minute solution models a four-storey building and the loading in the lower wall panels needed to reflect this. Based on the same load reduction factor described above, the second floor was loaded to a value of $3 \times 0.75 \times 4 \times 3 = 27\text{kN}$ or 2752kg made up from 110 sandbags. The design and spacing of the floor joists for the second floor needed to reflect this increased load. The first floor was loaded with $0.75 \times 4 \times 3 = 9\text{kN}$ or 917kg made up from 37 sandbags.

2.5.3 COMPARTMENT LININGS

Structural insulated panels, in common with other structural framing materials such as timber frame, have little inherent fire resistance. They rely, to a very large extent, on the quality and installation of fire protection measures that ensure the temperature of the key components (oriented strand board skins and polymeric core insulation) remain below temperatures at which loss of strength and material degradation have a significant impact on their ability to act as structural load bearing components. These fire protection measures include fire stopping, penetration seals and cavity barriers. However, the most

significant contribution to performance in fire is derived from the correct specification and installation of the boards used to provide the inner linings to the rooms formed from structural insulated panels.

To date, the specification for the linings has been based on the results from standard fire tests, and where necessary supported by expert assessments to extrapolate the results to cover alternative scenarios. This has resulted in a wide range of different solutions to achieve the required regulatory performance. The current research project has provided an opportunity to go beyond the limitations of the standard fire test procedure to evaluate the response of the structure (rather than the response of isolated elements) subject to a real fire and a realistic level of imposed load. The basic specification for the large-scale tests is summarised in Table 11.

Table 11 Specification for compartment linings for the large scale-tests

Test	External walls	Party wall	Floor/ceiling
EPS60	2 layers type F plasterboard on timber battens	2 layers type F plasterboard on timber battens	2 layers of type F plasterboard on resilient bars
EPS30	1 layer type F plasterboard on timber battens	2 layers type F plasterboard on timber battens	1 layer of type F plasterboard on resilient bars
PUR60	2 layers type F plasterboard on timber battens	2 layers type F plasterboard on timber battens	2 layers of type F plasterboard on resilient bars
PUR30	1 layer type F plasterboard on timber battens	2 layers type F plasterboard on timber battens	1 layer of type F plasterboard on resilient bars

2.6 Parametric study

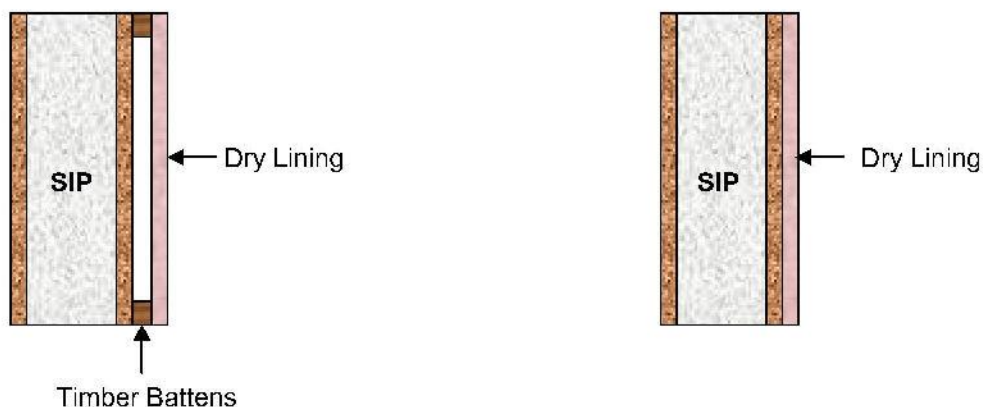
It is not possible to study experimentally the full range of options in terms of choice of board, choice of insulant, presence of additional structural members and level of passive fire protection. A computer model has been developed where variations in the thermal and mechanical properties of the system have been investigated in relation to a range of fire scenarios. The predictions of the model have been validated against the results from the experimental investigation into the performance of individual panels covered in section 2.4. The model has been used to investigate appropriate scenarios for the large-scale test programme and has been refined based on the results from that programme.

The finite element model developed as part of this project has the potential to be used for further investigation including assessing the impact of changing details of existing design solutions or developing new products.

2.6.1 MODEL GEOMETRY

The heat transfer element of the parametric study is largely concerned with the prediction of temperatures behind the dry lining material and in particular, in the insulating core. The study has focused on wall panels which are assumed to be exposed to a uniform heating regime from the inside of the compartment. A 1200mm length has been assumed. This represents the upper portion of a wall fully immersed in the hot gas layer of the fire, hence the uniform vertical temperature gradient. The dry linings are typically fixed using two methods (see Figure 40), either directly or battened. Each case is likely to result in a very different heat transfer dynamic.

Figure 40 Internal lining fixing method



The heat transfer study has utilised a two dimensional transient model. This assumption is valid providing there is no longitudinal temperature gradient, i.e. the compartment temperature remains constant along the length of the wall. This is likely to be the case in most fully developed compartment fires. The model applies a radiative and convective heat 'load' to the internal lining of the panel. The interface between the heated air and the solid internal lining is represented using 'boundary elements' which have specific convective and radiative properties.

In the case of the 'battened' lining, an additional complexity exists where an air void must be introduced. In this case, the model is able to calculate the magnitude of the radiative and convective fluxes in the air space. This results in an increased air temperature which in turn heats the unprotected panel veneer. The complex phenomenon has been incorporated using additional 'hidden' functionality in the DIANA Finite Element package¹⁷. In both instances, the geometry is 'discretised' into a number of elements known as a mesh.

2.6.2 MATERIAL PROPERTIES

The literature review identified that the thermo-physical properties of panel materials, such as oriented strand board and polymer foams, are not well understood at high temperatures. Comparably, the properties of solid timber and plasterboard are well defined at elevated temperatures. Three thermo-physical models for plasterboard have been selected which show the variability of plasterboards conductivity and specific heat with temperature. These are shown in Figure 41 and Figure 42, respectively. Additionally, two material models for oriented strand board will be tested. One material model is adapted from the Timber Eurocode (BS EN 1995-1-2¹⁸) using the density for oriented strand board. Further to this, a model developed by Thoemen and Humphrey¹⁹ was tested. However, the limits of applicability in terms of the range of temperatures experienced in fires is unknown and not documented. Plots of the oriented strand board material properties which formed the basis of the parametric study are shown in Figure 43 and Figure 44, respectively. The chosen thermo-physical properties for polymer foams have been taken from a publication by Hobbs and Lemmon²⁰. These are shown in Figure 45 and Figure 46.

Figure 41 Conductivity v. temperature for plasterboard (Thomas²¹, Harmathy²² and Sultan²³)

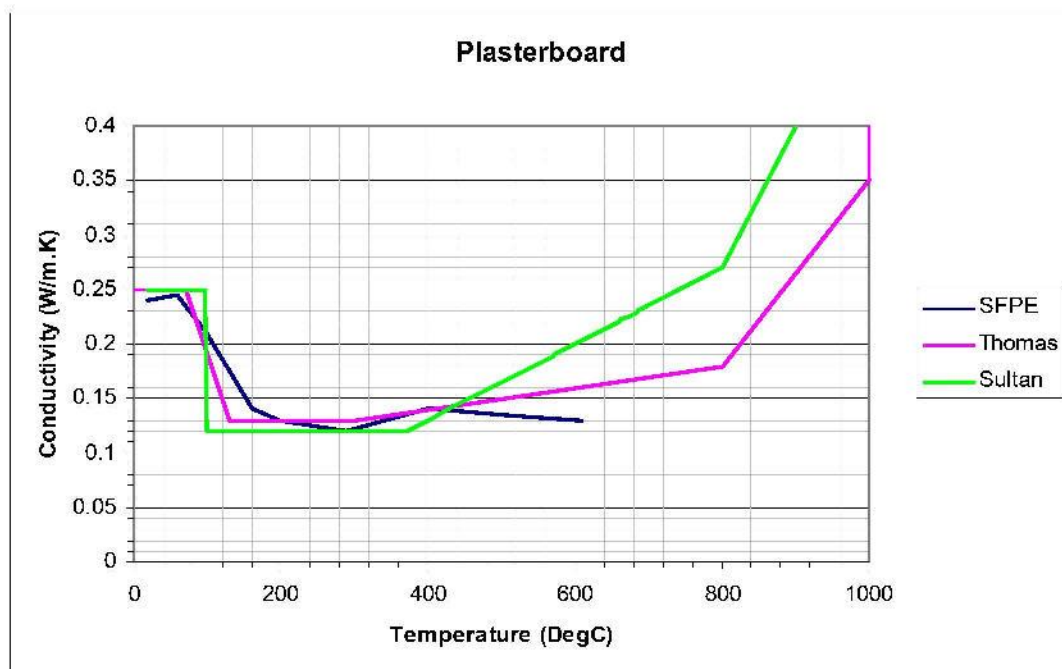


Figure 42 Specific heat v. temperature for plasterboard (Thomas²¹, Harmathy²² and Sultan²³)

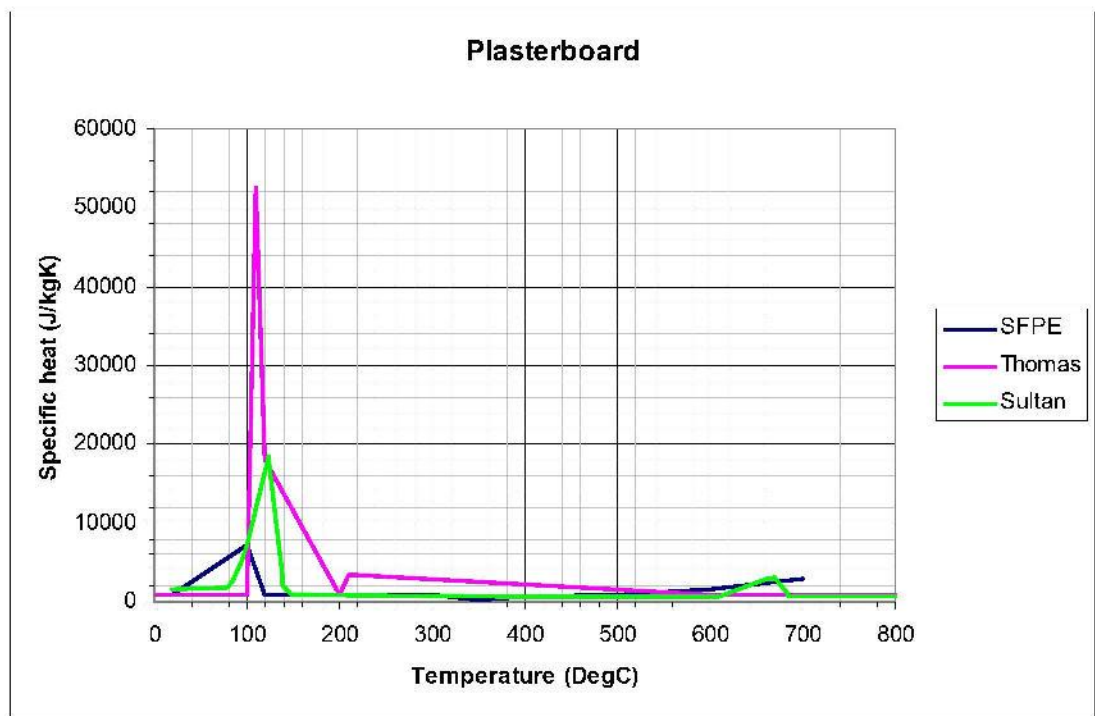


Figure 43 Conductivity v. temperature for oriented strand board (Thoemen¹⁹ and EC5¹⁸)

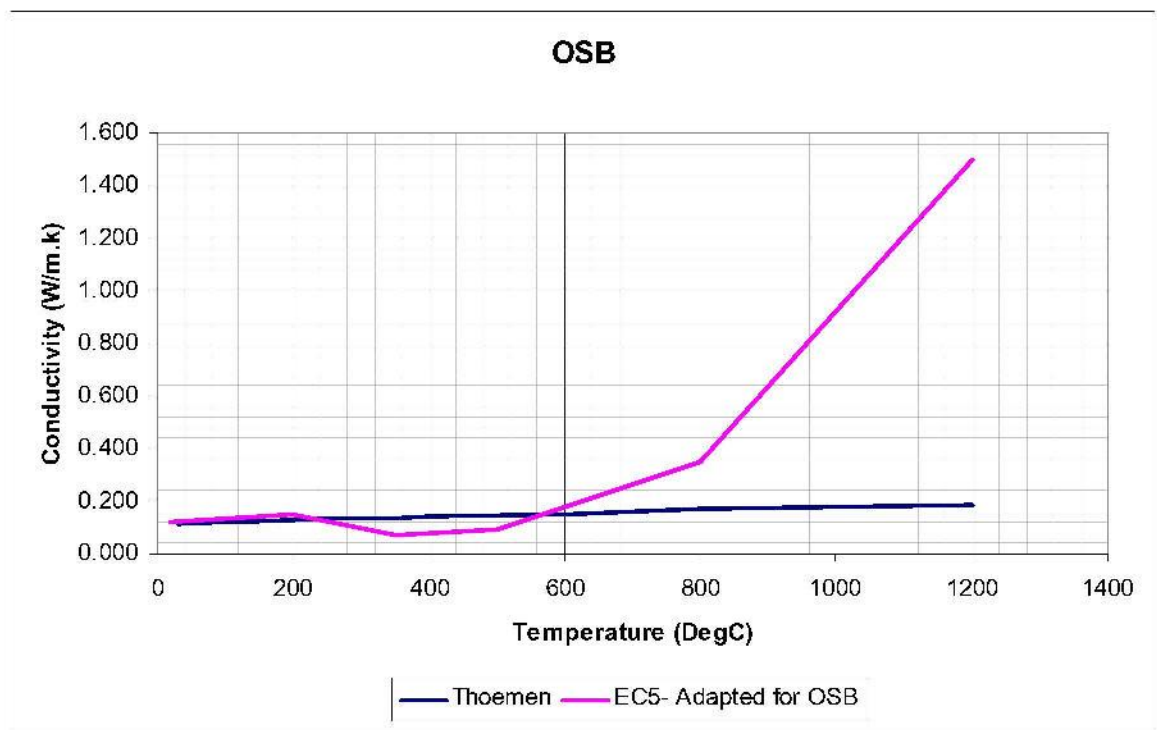


Figure 44 Specific heat v. temperature for oriented strand board (Thoemen¹⁹ and EC5¹⁸)

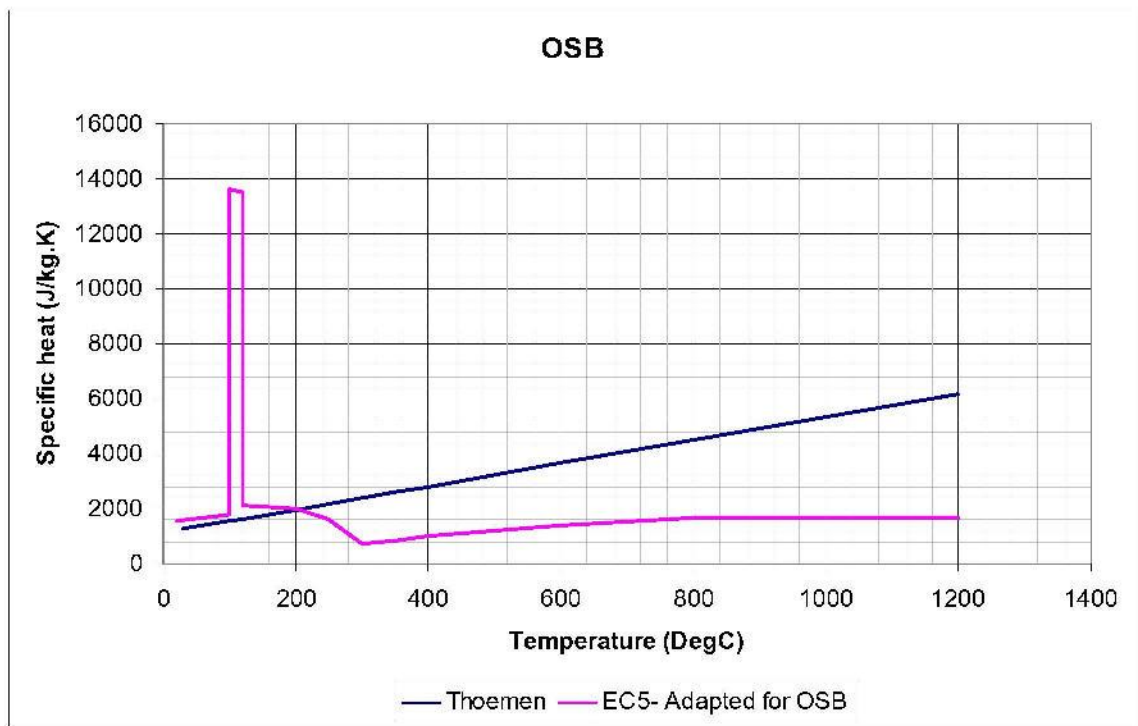


Figure 45 Conductivity v. temperature for polyurethane

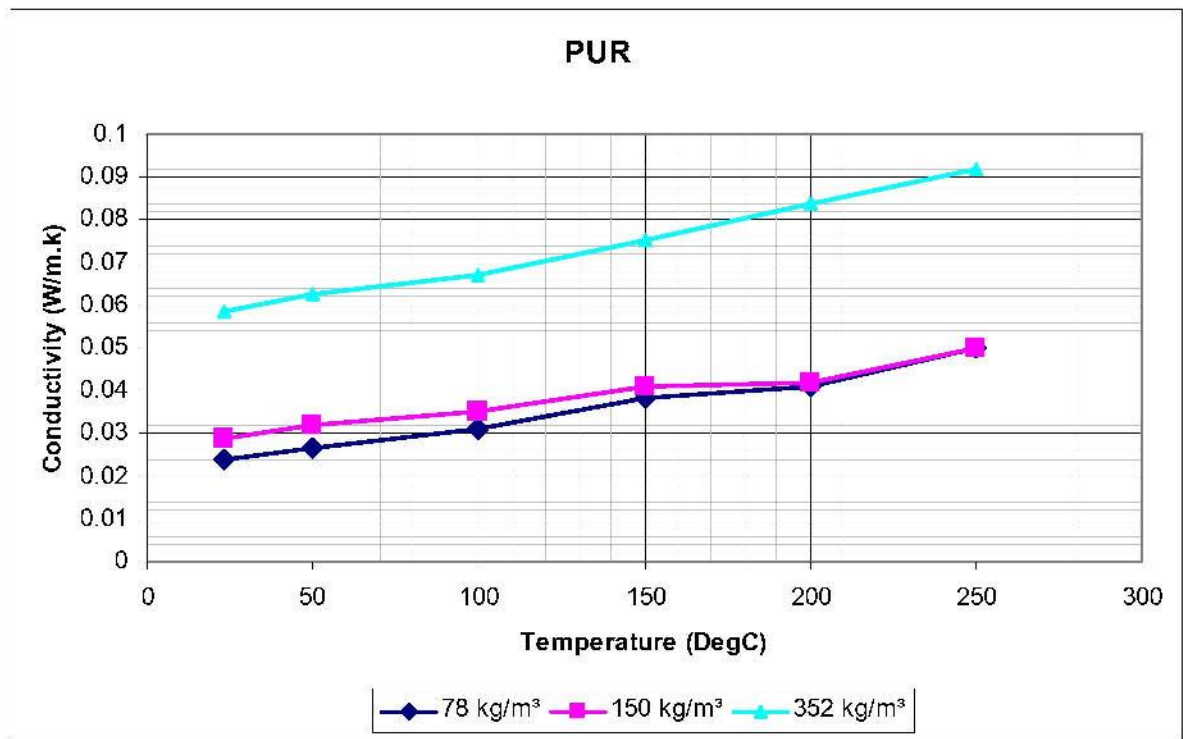
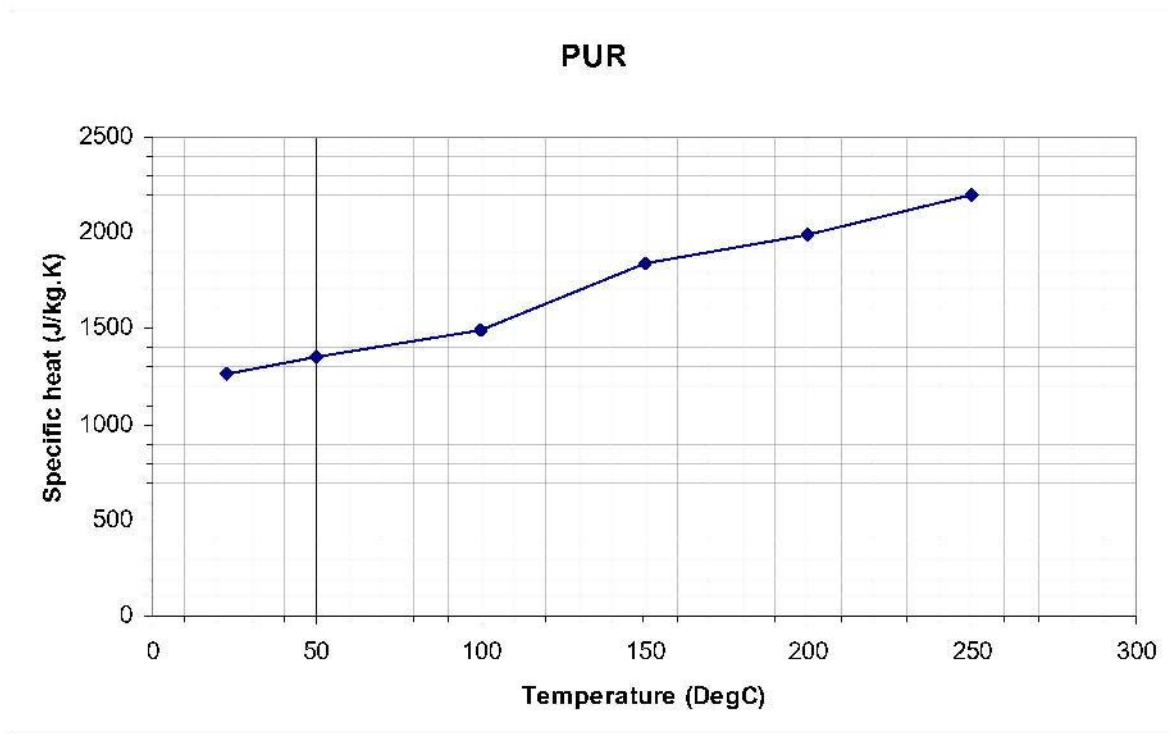


Figure 46 Specific heat v. temperature for polyurethane



2.6.3 PARAMETERS FOR STUDY

Table 12 sets out the heat transfer element of the parametric study. Firstly, the study was to distinguish between fixed and battened internal dry linings. In addition to this, a number of other parameters were to be varied to gauge their relative influence of the heat transfer process:

- The skin thickness would be varied through a range commonly used by the structural insulated panel manufacturers.
- The overall panel thickness would be varied in accordance with the typical range observed.
- The protection requirements i.e. the thickness and type of dry lining would be varied in accordance with those commonly used by manufacturers for 30 minute and 60 minute fire resistance ratings.

Table 12 Study matrix

Study No.	Battened (B) or fixed (F)	Skin thickness	Panel thickness	Protection
1	B	V	F	F
2	F	V	F	F
3	B	F	V	F
4	F	F	V	F
5	B	F	F	V
6	F	F	F	V
V = Variable; F = Fixed				

Table 13 sets out the range of variables which were to be assessed. The skin thickness ranged from 11mm to 15mm. The overall panel thickness was to range from 125mm to 200mm.

Table 13 Variables to be assessed

Skin thickness range	Panel thickness	Protection
11mm	125mm	12.5mm plasterboard
12mm	150mm	25mm plasterboard
15mm	180mm	12.5mm plasterboard and 12.5mm fire resistant board
-	200mm	12.5mm plasterboard and 19mm fire resistant board

Each run of the model exposed the panels to 75 minutes of the standard fire curve. For 30 minute protection systems any results after 45 minutes of exposure were disregarded.

2.6.4 NUMERICAL STUDY

A numerical study has been undertaken to address a wide range of variables that cannot be considered as part of the small-scale testing programme. The methodology adopted comprises a one way coupled flow and stress analysis which can be used to predict both the thermal and mechanical response of a panel in a fire scenario. The study can be split into two components: the heat transfer behaviour of the panel and the combined thermo-mechanical behaviour of the panel.

This section presents the heat transfer aspect of the numerical study, in particular the process of validation and calibration against the behaviour observed in the small-scale experimental programme.

2.6.4.1 Validation/calibration of the heat transfer model

The heat transfer module of the DIANA finite element code¹⁷ has been used to study the temperature development, with time, through the depth of a structural insulated panel using a non-linear transient analysis.

As part of the small-scale testing programme, a number of panels of consistent dimensions were tested which were used to calibrate the numerical model. The wider literature was consulted to determine a range of thermo-physical properties which have been implemented in the model. Based on comparisons with the experimental data, a set of properties for each constituent material was chosen based on their consistency with the test data. A recommended range of properties for modelling heat flow in structural insulated panels is shown in Figure 47 and Figure 48.

Figure 47 Enthalpy versus temperature for plasterboard, solid timber, oriented strand board and polyurethane

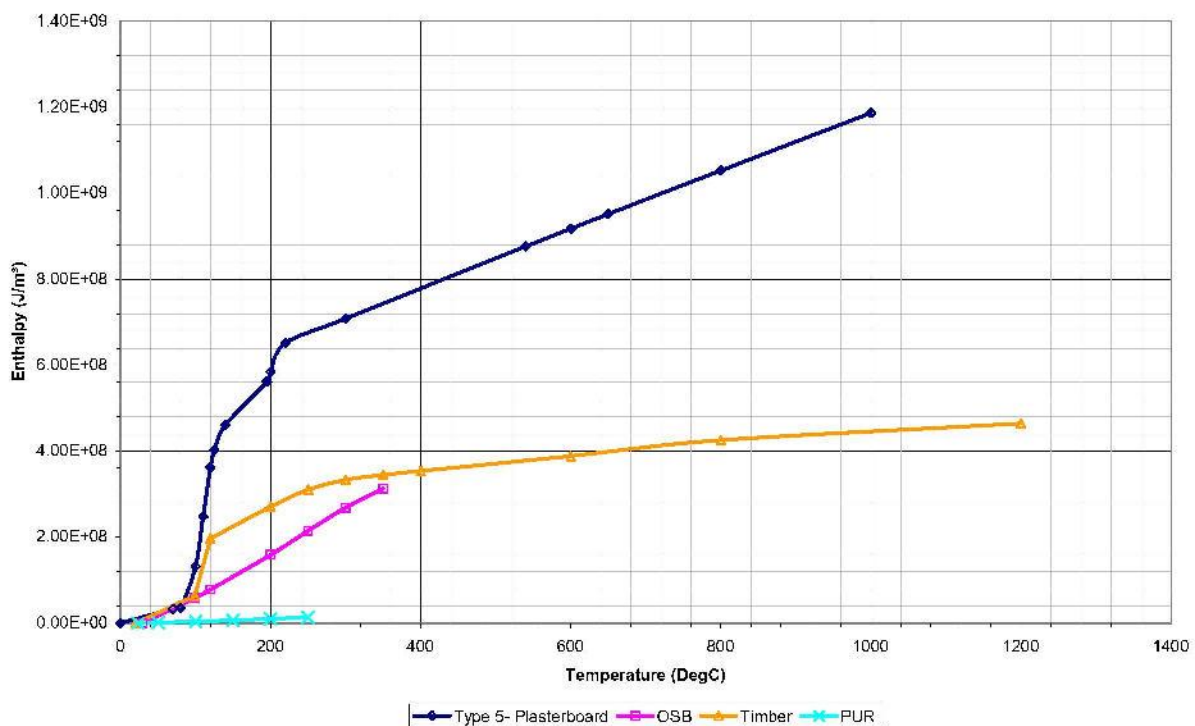
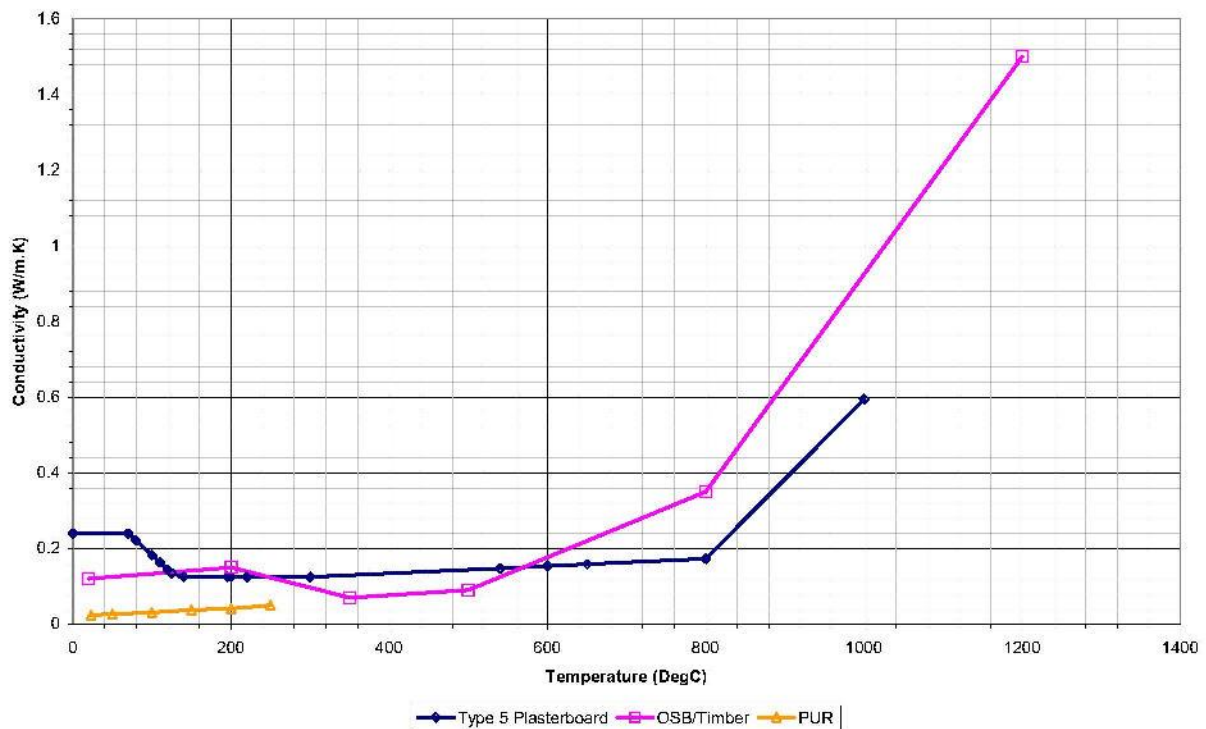


Figure 48 Conductivity versus temperature for plasterboard, solid timber, oriented strand board and polyurethane



The properties chosen for plasterboard were taken from a publication by Thomas²¹. These were modified to reflect the change from Type 1 standard gypsum board to Type 5 fire rated plasterboard. This resulted in a larger base conductivity of 0.24 W/m.K and density of 780 kg/m³ compared to 0.19 W/m.K and 650 kg/m³, respectively. The properties of the polyurethane core were taken directly from a publication by Hobbs and Lemmon²⁰. The conductivity of oriented strand board was assumed to be the same as that of solid timber, as specified in Eurocode 5¹⁸, whilst the specific heat capacity of oriented strand board was assumed to be 70 per cent of the temperature dependent values specified by Thoemen et al.¹⁹ for MDF. The thermo-physical properties of the solid timber studs were assumed to conform to the values specified in Eurocode 5¹⁸ for a moisture content of 12 per cent.

Using these properties, a polyurethane core panel, of the same dimensions as those experimentally tested, was modelled and compared with the corresponding test results. A polyurethane core was used in the study as little or no data was available for the temperature dependant thermo-physical properties of polystyrene. In addition to this, the experimental programme showed some abnormalities in expanded polystyrene core temperature due to steam egress. However, it is apparent from the test results that, in the core temperature ranges observed, there was a nominal difference between polyurethane and expanded polystyrene cores. The resulting time versus temperature plots for the back of plasterboard, back of oriented strand board and mid-point of the core are shown in Figures 49 to 52, respectively.

Figure 49 Comparison between modelled and observed back of plasterboard temperatures

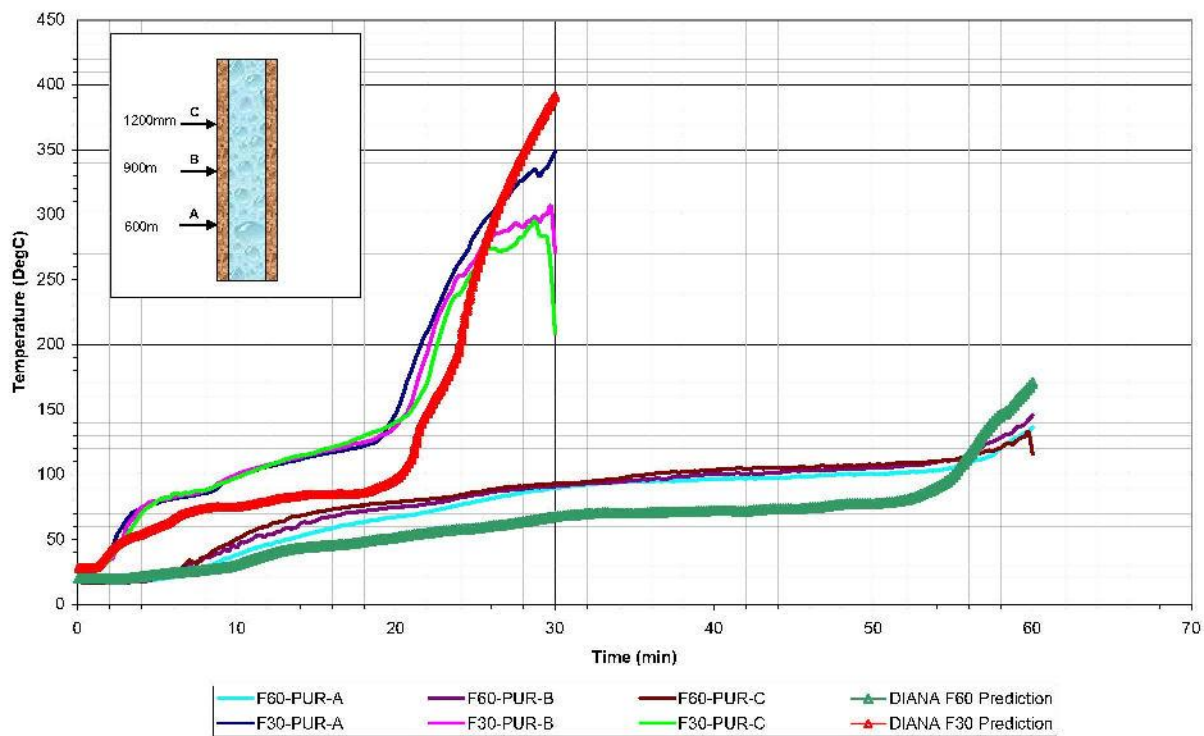


Figure 50 Comparison between modelled and observed mi-depth plasterboard temperatures

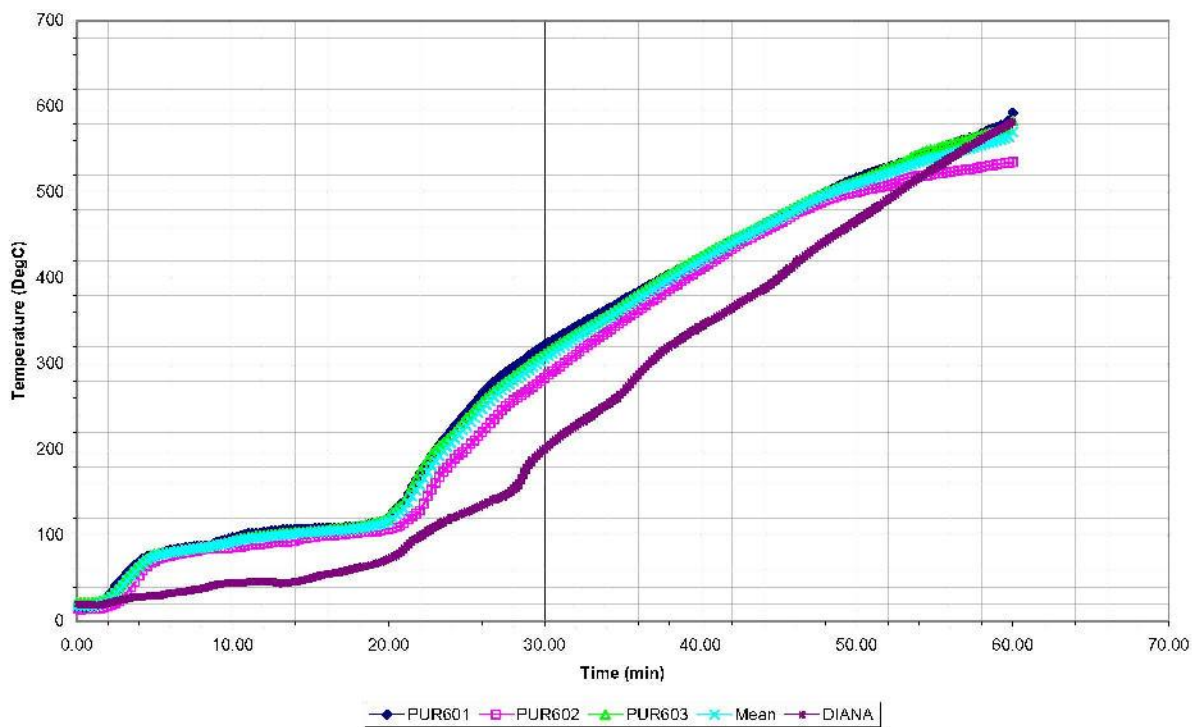


Figure 51 Comparison between modelled and observed back of oriented strand board temperatures

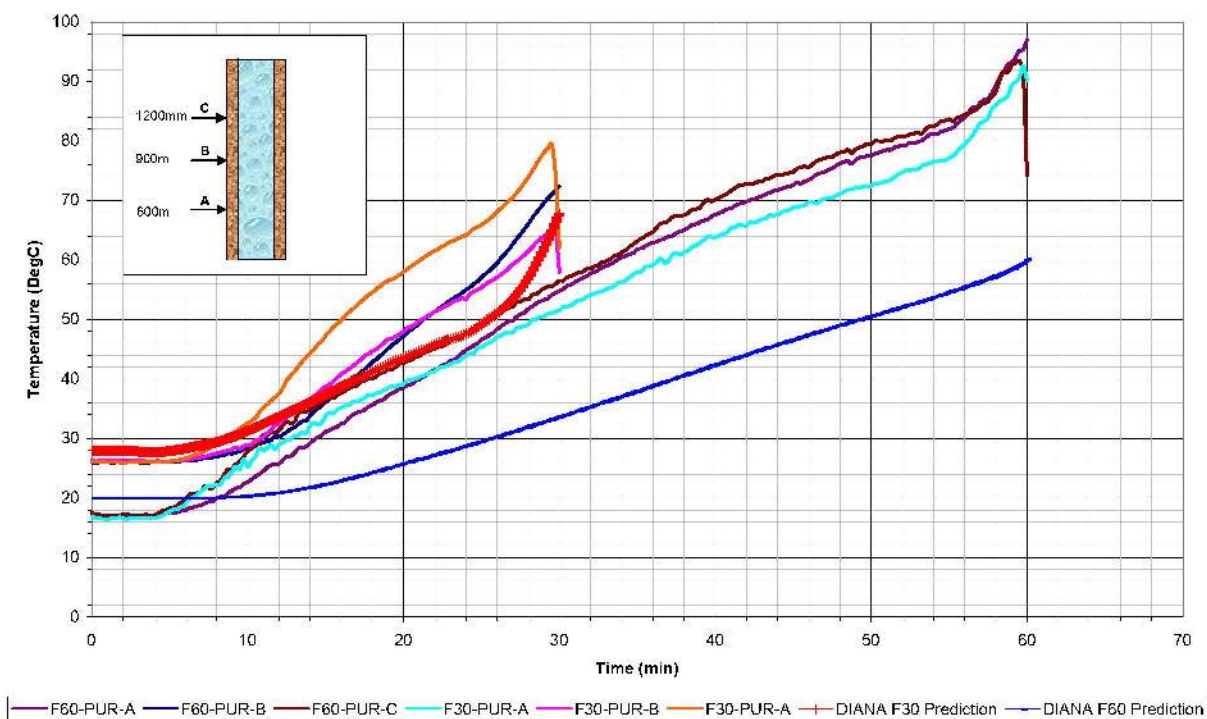
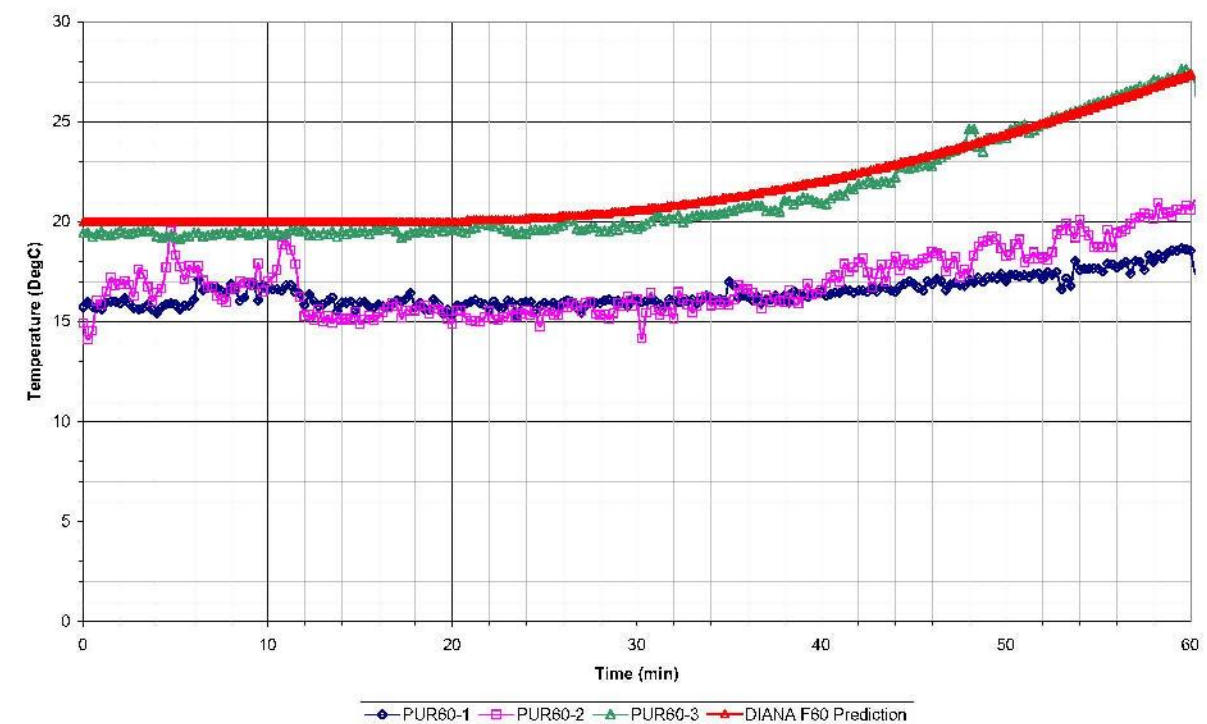


Figure 52 Comparison between modelled and observed centre of core temperatures



Generally, the figures indicate that the two dimensional heat transfer model is capable of predicting peak temperatures within a structural insulated panel for both 30 minute and 60 minute exposure conditions. The plasterboard thermo-physical relationship is clearly of critical importance to the temperatures that develop in the panel and hence modelling the processes that occur in the dry lining is key to accurately predicting the entire transient behaviour and temperature history. Like many works in this area, the temperatures predicted behind the plasterboard are much lower than those measured in the first ten minutes. It is hypothesised that this is possibly a test phenomenon which could arise due to the passage of hot gases through small joints between the plasterboard and timber battens at either the sides or bottom of the sample. Alternatively, it could be due to inaccuracies in the thermo-physical model for plasterboard presented in the literature at temperatures below which the first portion of chemically bound water is released. Beyond this period, as temperatures increase, the model becomes more accurate and in both instances successfully predicts the correct magnitude of temperature at the end of the fire resistance period. It must be noted that the sudden measured decrease in temperatures in the experimental data at the end of each test are due to the rapid shut down of the furnace and the speedy removal of the thermocouples so that the panel could be extinguished. Had the test continued beyond the design fire resistance period then inevitably the panel would have ignited and the temperatures would have increased exponentially, as predicted by the model. This has been supported by observations post test presented earlier.

Some discrepancies between the predicted and measured back of oriented strand board temperatures exist, particularly in the 60 minute case, where the measured and predicted differ by some 30°C. This is not particularly significant as the temperatures observed are very low. These errors could arise due to a number of factors. The thermo-physical model adopted for oriented strand board could be inaccurate. If this is the case, then either the mean conductivity is higher than that of solid timber or the temperature dependent specific heat is more than 30 per cent lower than that of MDF, as specified by Thoemen¹⁹. Alternatively, the proportion of radiative to convective fluxes calculated in the battened void is incorrect. If this is the case, then it is likely that the model is under-predicting the magnitude of the radiative portion of heat transfer in the battened void. This issue could be further investigated by performing a number of tests on panels with the dry-lining fixed directly to the oriented strand board skin. This would eliminate the need to model the battened void, turning the problem into a simple case of one dimensional conduction. This would indicate if the oriented strand board thermo-physical model implemented is accurate or if the calculated re-radiated and re-convected fluxes in the void are inaccurate.

2.6.5 HEAT TRANSFER PARAMETRIC STUDY

Once satisfied that the numerical model is predicting realistic temperatures within satisfactory tolerances, it can then be adopted in a numerical parametric study to investigate the heat transfer characteristics of structural insulated panels. Firstly, it must be noted that in the small-scale test programme, the panel depth and skin thickness were consistent and all dry-lining boards were fixed via solid timber battens. In addition, only one option for achieving 30 and 60 minutes fire resistance was assessed. It has become apparent that it is rare for a structural insulated panel to be dry-lined with 15mm and 30mm of type 5 fire rated plasterboard for 30 and 60 minutes fire resistance, respectively.

In reality, lower thicknesses of type 5 plasterboard are adopted, i.e. 12.5mm for 30 minutes fire resistance and 25mm for 60mm fire resistance. In some instances, a single layer of 15mm type 1 standard plasterboard is utilised for 30 minutes fire resistance and a combination of type 1 and type 5 plasterboards are a common means of achieving a fire resistance rating of 60 minutes. Further to this, not all linings are fixed via timber battens due to an increased likelihood of workmanship defects and therefore, it is not uncommon to mechanically fix the internal dry lining directly to the oriented strand board veneer of the panel. This is likely to be less onerous from a workmanship defect perspective as this process is often incorporated as part of the off-site manufacturing procedure. Variations to establish the influence of all of the above are costly to assess experimentally and hence modelling provides an avenue by which the effects of some of the above variables can be determined.

The remainder of this section presents the findings of the numerical parametric study. In all instances, only the polyurethane core material has been modelled due to the quality of datasets established in the literature. It is anticipated that the model could be applied to polystyrene cored panels using ambient temperature thermo-physical properties, which are commonly available. This approach however is only likely to be valid whilst the core material remains relatively cool, i.e. less than 100°C. At temperatures beyond this point the polystyrene changes state from a solid to a viscous flowing fluid and hence conduction is no longer the principal mode of heat transfer through the core material. This temperature is often referred to as the glass temperature and indicates a change of state from a solid to a plastic liquid.

2.6.5.1 Influence of lining fixing method and type

This aspect of the study focuses on the difference between fixing the dry-lining via timber battens, which introduces an air void, and fixing directly to the oriented strand board veneer. In addition to this the consequences of adopting a downgraded dry-lining compared with those tested is also determined. The modelling study matrix is shown in Table 14.

Table 14 Modelling matrix for study 1 and study 2

	Lining	30 minute passive fire protection		60 minute passive fire protection	
Study 1	Battened	12.5mm Type 5	15mm Type 5	25mm Type 5	30mm Type 5
Study 2	Fixed	12.5mm Type 5	15mm Type 5	25mm Type 5	30mm Type 5

The modelling study has been performed using the material properties specified previously. The study has been limited to fire rated type 5 plasterboard as this is more dimensionally stable than type 1 board and does not suffer as significantly from breakdown phenomena such as ablation. Regular type 1 plasterboard could be assessed as part of the numerical study. However, more small-scale tests would need to be performed on samples protected with type 1 plasterboard. The resulting back of

plasterboard (type 5), back of oriented strand board and centre of core temperatures versus time are shown in Figures 53 to 55.

Figure 53 Predicted back of plasterboard temperatures versus time for fixed and battened systems

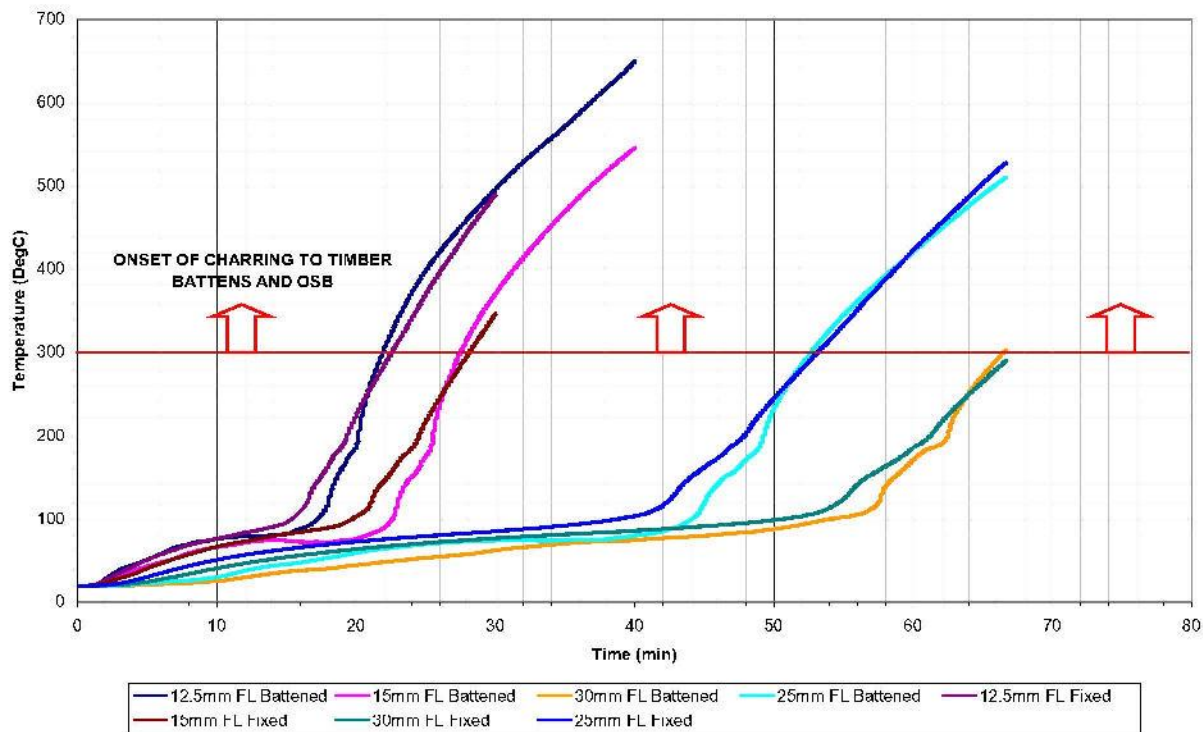


Figure 54 Predicted back of oriented strand board temperatures versus time for fixed and battened systems

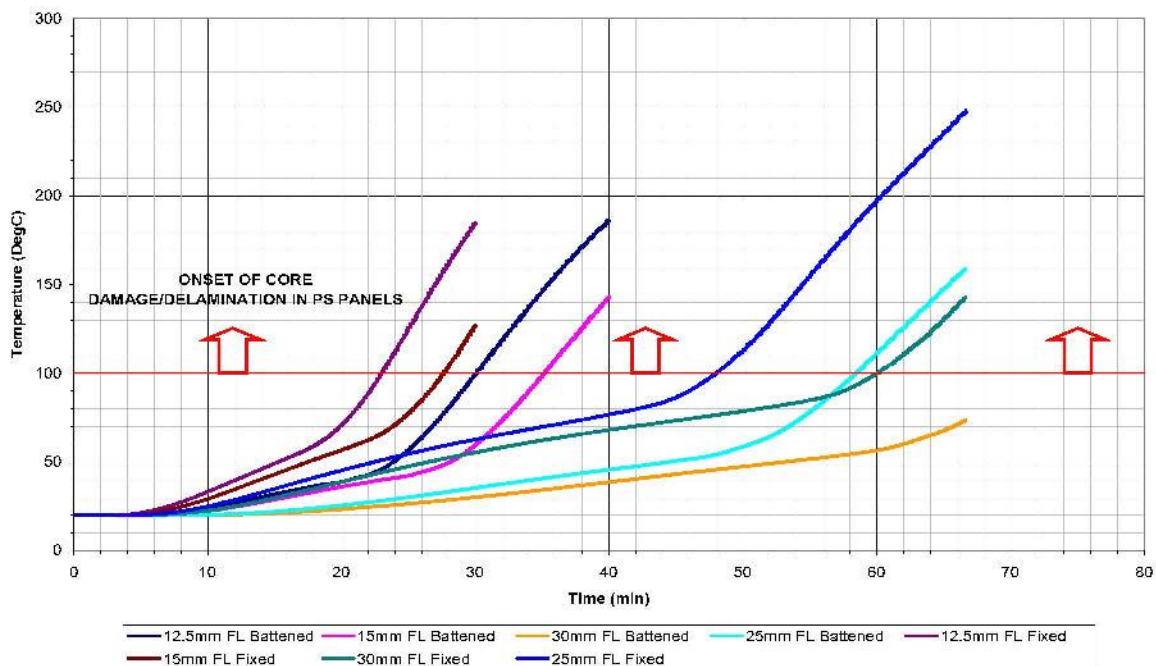
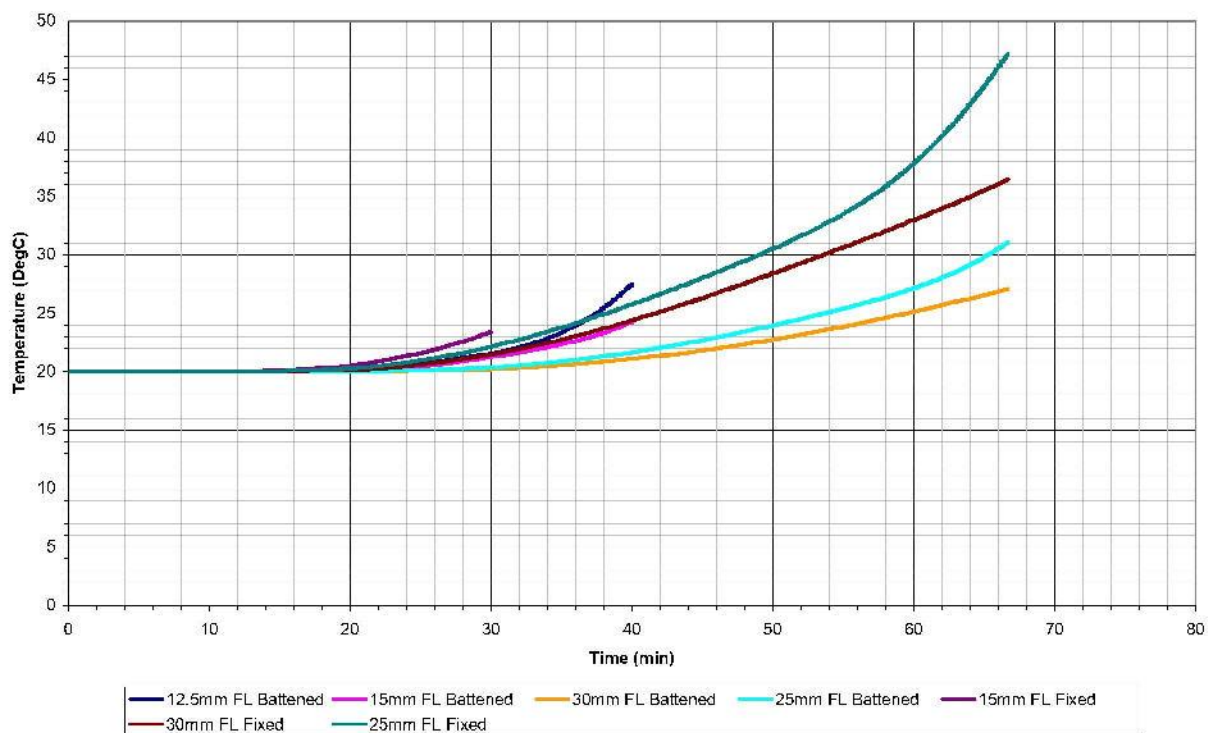


Figure 55 Predicted centre of core temperatures versus time for fixed and battened systems



The results presented in Figures 53 to 55 are predictable. Downgrading the specification of the internal dry-lining increases panel temperatures, which in some instances could have serious consequences for the load bearing capacity of the panel. Although polyurethane cores were studied numerically, the temperature difference between polyurethane and PS cored panels has been shown experimentally to be nominal for core temperatures below the glass temperature of PS (approximately 100°C). Therefore, it could be reasonably assumed that the temperature increases with time, up until the glass temperature of PS is almost identical for the two most common core materials. As a result the study has shown that before the design fire resistance period of the panel is reached, some breakdown of a polystyrene core would occur in almost all instances. This could cause de-lamination of the bond between the oriented strand board veneer and core material and result in a loss of composite action. Under pure compression, as is the case for most walls at the fire limit state, this is likely to result in localised buckling of the veneer most severely exposed to the fire.

Perhaps even more critical to the above, the study has shown that fixing directly to the oriented strand board veneer results in significantly higher temperatures in the panel when compared to a battened lining (assuming no workmanship defects in the latter case). This is due to the additional air medium through which the heat must pass where some energy is lost due to convection as the air slowly begins to increase in temperature. This difference is particularly pronounced after 60 minutes of exposure where, for the same passive fire protection (principally plasterboard), the difference between a battened and fixed lining can be as much as 85°C.

2.7 Large scale experimental programme

A series of four large-scale fire tests has been undertaken at BRE's fire test facility in Middlesbrough.

2.7.1 METHODOLOGY

Four large-scale fire tests were undertaken on structures built from structural insulated panel systems and protected from the effects of fire by fire resistant plasterboard linings. The order and configuration of the tests is as shown in Table 15. The two most common types of insulation material used by the UK structural insulated panels industry, expanded polystyrene and polyurethane, have been tested. In each case, the response of both a 30 minute and a 60 minute fire resistance design solution has been evaluated. The 60 minute solution is representative of a medium rise, multi-occupancy block comprising a compartment floor and a party wall each requiring 60 minutes fire resistance. The 30 minute solution is representative of a semi-detached dwelling where the party wall requires 60 minutes fire resistance but the remaining walls and floor require 30 minutes.

Table 15 Large-scale fire tests programme

Test	Fire resistance time (designed to achieve)	Core material	Height to underside of first floor (m)	Floor area (m x m)	First floor loading (kN/m ²)	Second floor loading (kN/m ²)	Test date
F1	60	EPS	2.4	4 x 3	0.75	2.25	13/10/09
F2	30	EPS	2.4	4 x 3	0.75	0.75	14/10/09
F3	60	PUR	2.4	4 x 3	0.75	2.25	27/10/09
F4	30	PUR	2.4	4 x 3	0.75	0.75	28/10/09

The objective of the tests was to determine the performance of the various configurations subject to a design fire scenario equivalent to 60 minutes exposure to the standard fire curve and to evaluate the mode of failure of the building system subject to a realistic fire scenario and a realistic level of applied loading.

In each test, the termination criteria were identical and consisted of:

- A loadbearing failure of the floor leading to collapse into the compartment, excessive displacement (>100mm) or excessive rate of displacement indicating imminent structural collapse or
- A structural failure of the wall panels or
- An integrity failure of the wall panels.

If none of the above criteria was achieved, the fire was allowed to continue until the fire had reached the cooling stage. Once the flames had died down to the extent that they were no longer impinging directly on the ceiling and the temperatures within the

compartment had reduced to below 600°C, the test was terminated and fire and rescue service personnel asked to extinguish the fire.

2.7.2 DESIGN, CONSTRUCTION AND DETAILING

Figure 56 (a) and (b) show the buildings at different stages of construction. The design and detailing of the two systems have much in common but there are also some significant differences. A detailed specification for the linings with other relevant details for each test compartment is provided in Tables 16 to 17.

Figure 56 Expanded polystyrene building (a) during construction and (b) prior to fire test



Table 16 Specification for expanded polystyrene fire tests

	Test F2 (EPS 30)	Test F1 (EPS 60)
Battens	50mm x 25mm softwood battens fixed vertically at 600mm centres to the SIP with 51mm high thread screws. Extra battens around edges of all openings.	
Resilient bars	Resilient bars 45mm wide by 17mm deep fixed to each joist at 400 centres with 38mm high thread screws.	
Wall lining	15mm Megadeco plasterboard fixed with longest edge parallel to timber battens with 38mm high thread screws at 300mm centres	15mm Firecheck plasterboard fixed with longest edge parallel to timber battens with 38mm high thread screws at 400mm centres. Second layer of 15mm Megadeco plasterboard fixed with 51mm high thread screws at 300mm centres.
Party wall	See specification for EPS 60 minute wall linings.	See above.
Ceiling lining	15mm Firecheck plasterboard fixed with longest edge perpendicular to resilient bars with 32mm self tapping screws. Fixed at 150mm centres along sheet edges and 230mm centres elsewhere. Screws staggered of the joint line.	15mm Firecheck plasterboard fixed with longest edge perpendicular to resilient bars with 32mm self tapping screws at 400 centres. Second layer of 15mm Megadeco plasterboard fixed with 44mm screws at 230mm centres in the field of the board and 150mm at cut edges. All joints staggered.
Masonry wall	100mm lightweight blocks. BTS4 SCR wall ties screwed to SIP with 32mm high thread screws. Spaced 225mm vertically and 600mm horizontally.	
Cavity barriers	65mm x 65mm mineral wool cavity barrier (in plastic sock) compression fitted between leaves of wall. Flanges stapled to timber wall prior to construction of masonry wall.	
SIP construction	11mm OSB either side of 89mm EPS core.	11mm OSB either side of 89mm EPS core apart from the two load bearing walls which have a 140mm core due to the increased load level.
First floor timber	220mm x 58mm engineered floor joists (I section) @ 600mm centres – span in long direction	
Second floor timber	220x58mm engineered floor joists (I section) @ 600mm centres – span in long direction	220x89mm engineered floor joists (I section) @ 400mm centres – span in long direction

Table 17 Specification for polyurethane fire tests

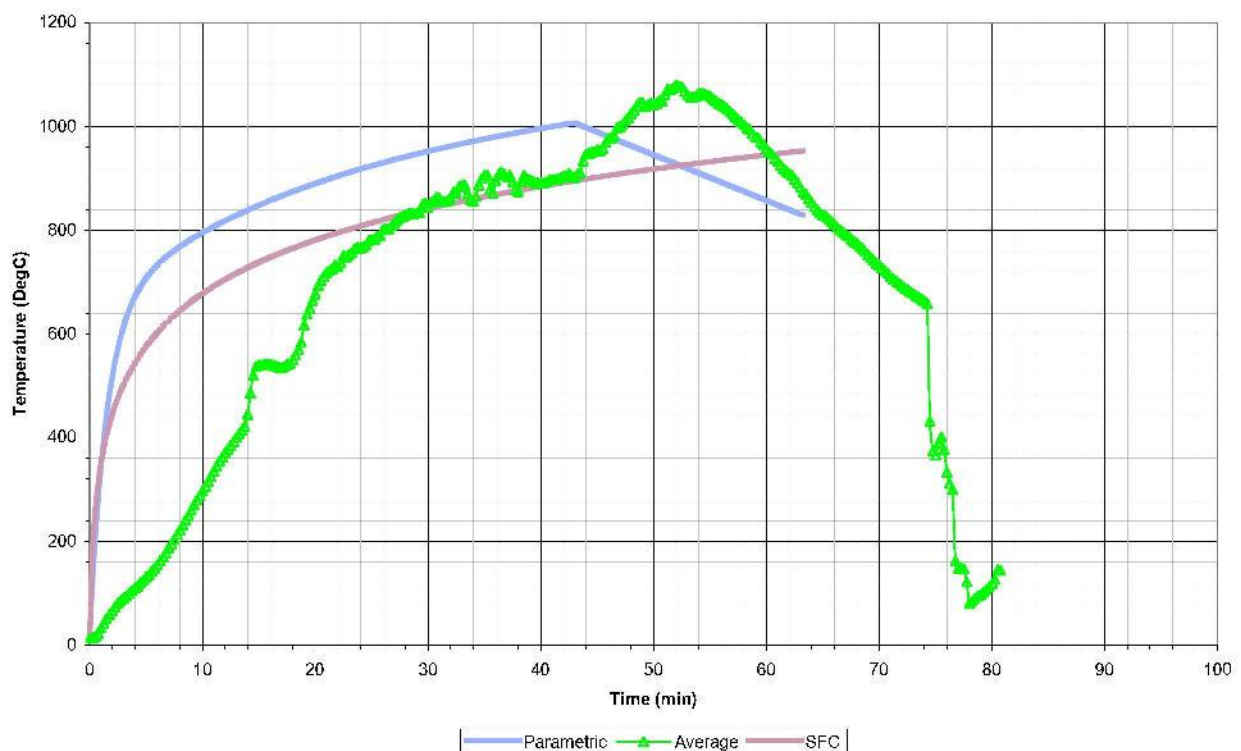
	Test F4 (PUR 30)	Test F3 (PUR 60)
Battens	50mm x 25mm softwood battens fixed vertically at 600mm centres to the SIP with 51mm high thread screws. Extra battens around edges of all openings.	
Resilient bars	Resilient bars 45mm wide by 17mm deep fixed to each joist at 400 centres with 38mm high thread screws.	
Wall lining	15mm Megadeco plasterboard fixed with longest edge parallel to timber battens with 38mm high thread screws at 300mm centres	15mm Firecheck plasterboard fixed with longest edge parallel to timber battens with 38mm high thread screws at 400mm centres. Second layer of 15mm Megadeco plasterboard fixed with 51mm high thread screws at 300mm centres.
Party wall	See specification for polyurethane 60 minute wall linings.	See above.
Ceiling lining	15mm Firecheck plasterboard fixed with longest edge perpendicular to resilient bars with 32mm self tapping screws. Fixed at 150mm centres along sheet edges and 230mm centres elsewhere. Screws staggered of the joint line.	15mm Firecheck plasterboard fixed with longest edge perpendicular to resilient bars with 32mm self tapping screws at 400 centres. Second layer of 15mm Megadeco plasterboard fixed with 44mm screws at 230mm centres in the field of the board and 150mm at cut edges. All joints staggered.
Masonry wall	100mm lightweight blocks. BTS4 SCR wall ties screwed to SIP with 32mm high thread screws. Spaced 225mm vertically and 600mm horizontally.	
Cavity barriers	65mm x 65mm mineral wool cavity barrier (in plastic sock) compression fitted between leaves of wall. Flanges stapled to timber wall prior to construction of masonry wall.	
SIP construction	15mm OSB either side of 114mm PUR core	
First floor timber	245mm x 45mm engineered floor joists (I section) @ 600mm centres – span in long direction	
Second floor timber	245x45mm engineered floor joists (I section) @ 400mm centres – span in short direction	
Service penetrations	Double electrical socket in rear and party walls	

2.7.3 RESULTS OF THE LARGE SCALE TESTS

2.7.4 TEST F1 – EXPANDED POLYSTYRENE 60

Test F1, the first of the large-scale fire tests, was conducted on an expanded polystyrene structure lined with two layers of plasterboard to achieve a notional fire resistance rating of 60 minutes. The fire was designed in accordance with the parametric approach set out in annex A to BS EN 1991-1-2¹⁴ and the concept of time equivalence set out in annex F of the same document to give a fire severity equivalent to 60 minutes exposure to the standard fire curve. The parameters in terms of fire load, thermal properties of compartment linings and ventilation have been set out in detail previously. The average measured time-temperature development and the calculated parametric prediction and the standard fire curve time-temperature response are shown in Figure 57.

Figure 57 Time-temperature development – Test F1 (expanded polystyrene 60)



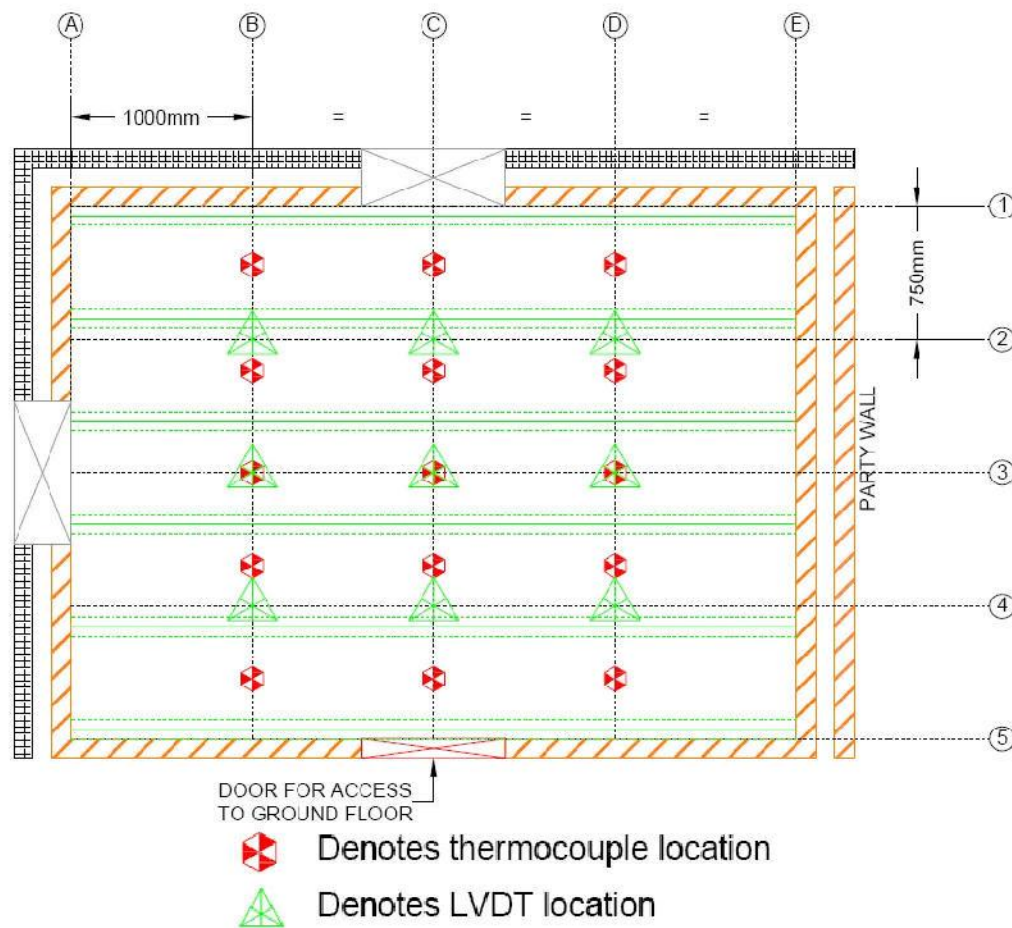
Although the peak temperature and time to peak temperature is underestimated by the parametric approach, the total heat release (or area under the curves) is very similar for the measured atmosphere temperature and the standard curve, confirming the equivalent severity.

The fire was allowed to continue until it entered its decay phase. At this stage, none of the pre-determined failure criteria had been reached. Once the temperature inside the compartment had reached approximately 600°C, fire and rescue service personnel were asked to extinguish the remaining cribs.

During the course of the Test F1, temperatures were recorded at various locations within the walls and through the depth of the floor void to evaluate the thermal response of the

building to the fire. The position of the instrumentation was related to the gridline identification illustrated in Figure 58.

Figure 58 Plan view of fire compartment showing layout of gridlines



Party wall (Gridline E)

Temperatures were measured through the party wall in the positions shown in Figure 59, all at a height of 1.6m above ground level. The instrumented locations coincided with gridlines 2 and 4 in Figure 58. The measured response is shown in Figures 60 and 61.

Figure 59 Thermocouple locations through party wall

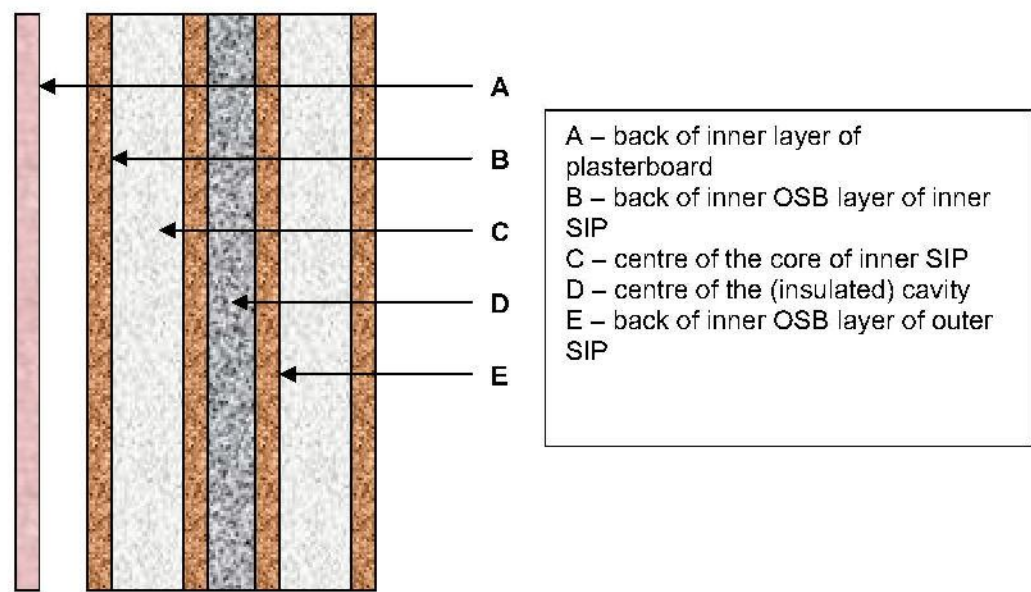


Figure 60 Temperature readings through party wall at gridline 2 – Test F1

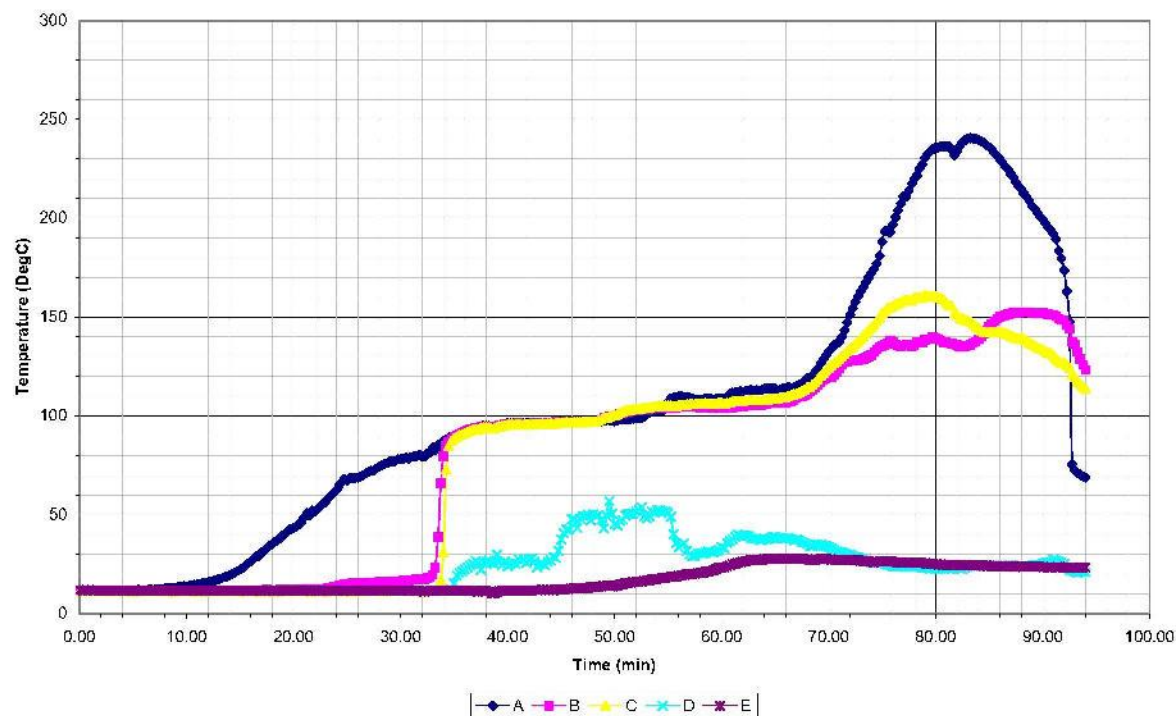
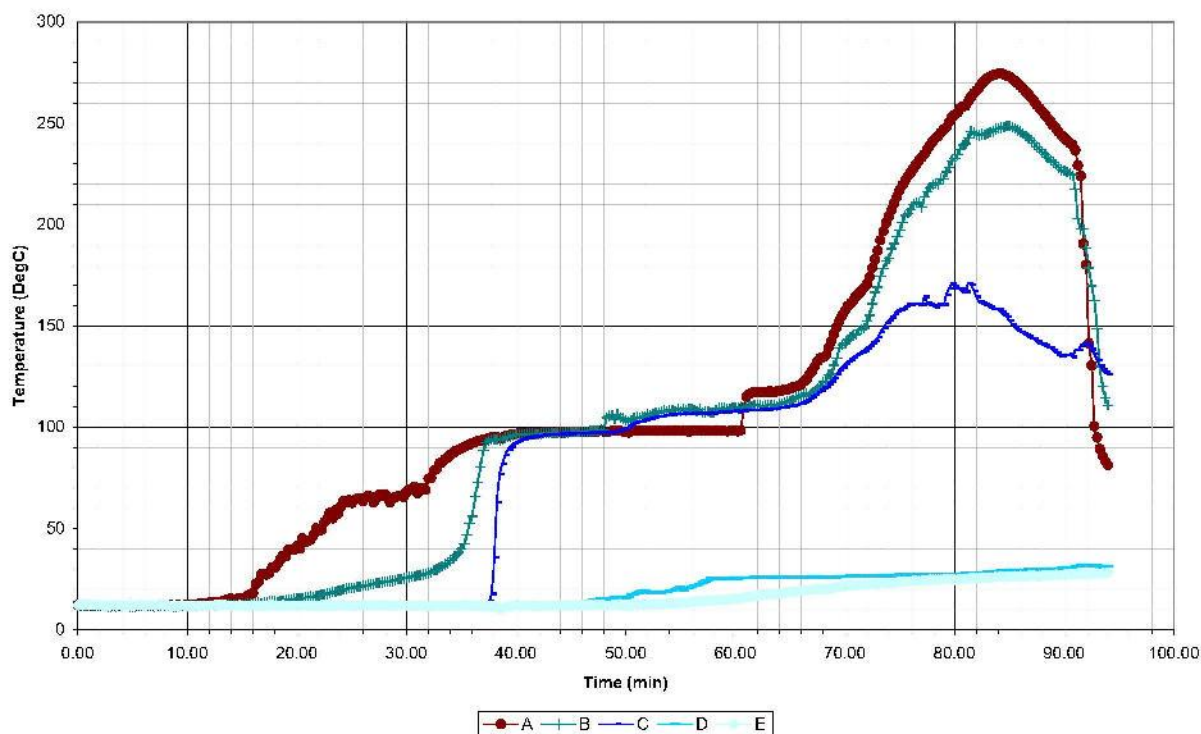


Figure 61 Temperature readings through party wall at gridline 4 – Test F1



Figures 60 and 61 show a gradual increase in the temperature behind the plasterboard as the moisture is driven off. The rapid temperature rise of the oriented strand board and the core after 30 minutes is likely to be due to migration of steam through the section via the holes used to fix the thermocouple positions. This rapid increase in temperature reaches the boiling point of water where the temperature is maintained at around 100°C for the duration of the moisture plateau. Once the plasterboard has completely dried out, the temperature of the inner layer of the oriented strand board and the temperature within the panel where the expanded polystyrene has melted can increase. The temperature of the party wall remained below the notional ignition temperature of timber (250 to 300°C) for the duration of the test.

Rear wall (Gridline 5)

Temperatures were measured through the structural insulated panel forming the rear wall in the positions shown in Figure 62 at a height of 1.6m above ground level. The measured values are shown in Figures 63 and 64.

Figure 62 Thermocouple locations through structural insulated panel forming the rear wall

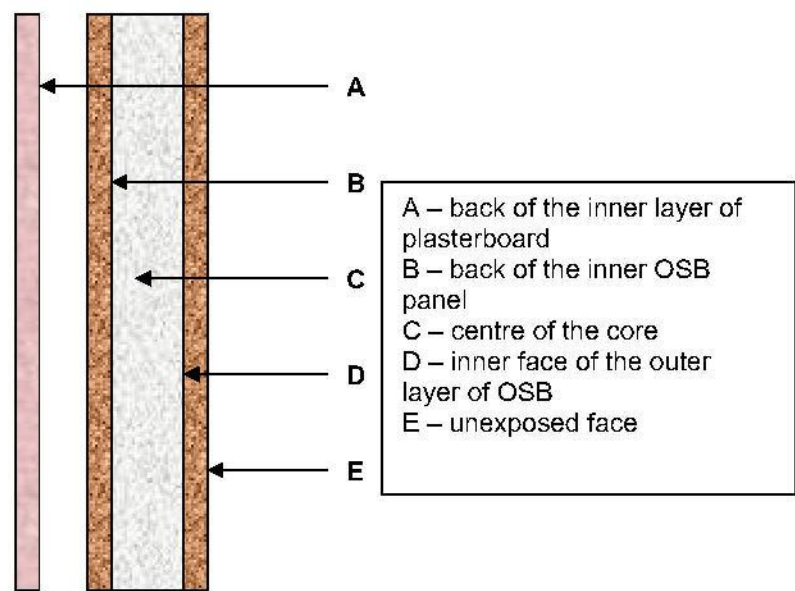


Figure 63 Temperature readings through rear wall on gridline D – Test F1

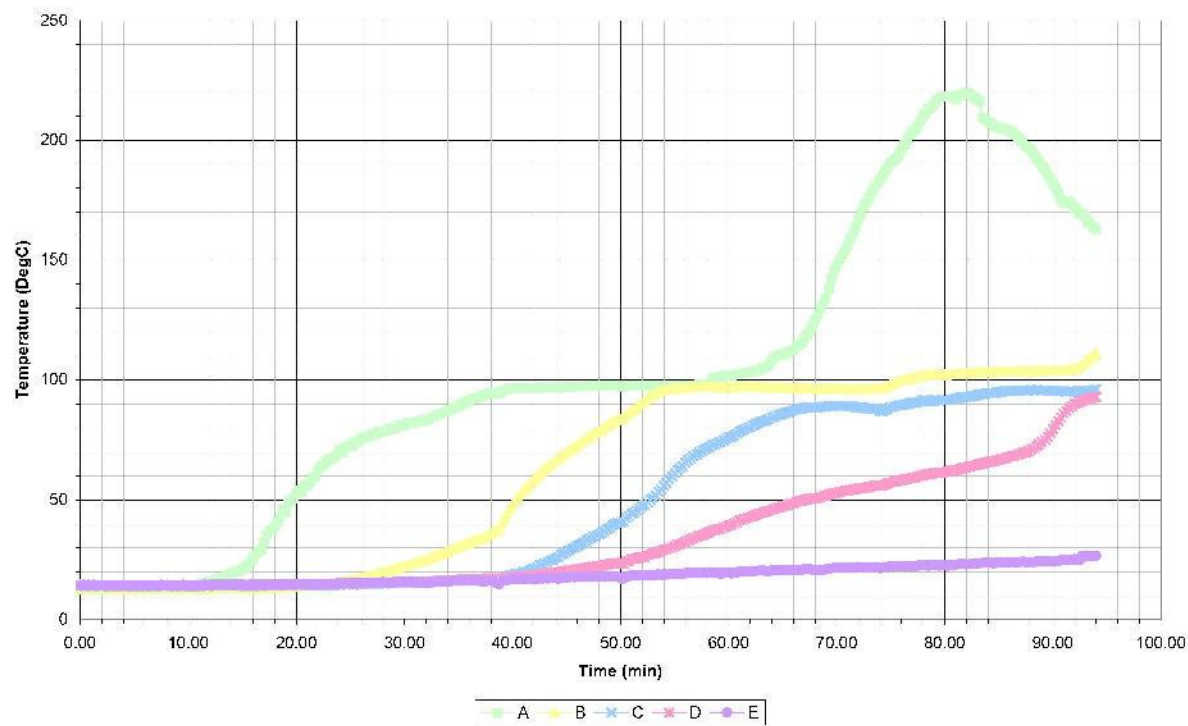
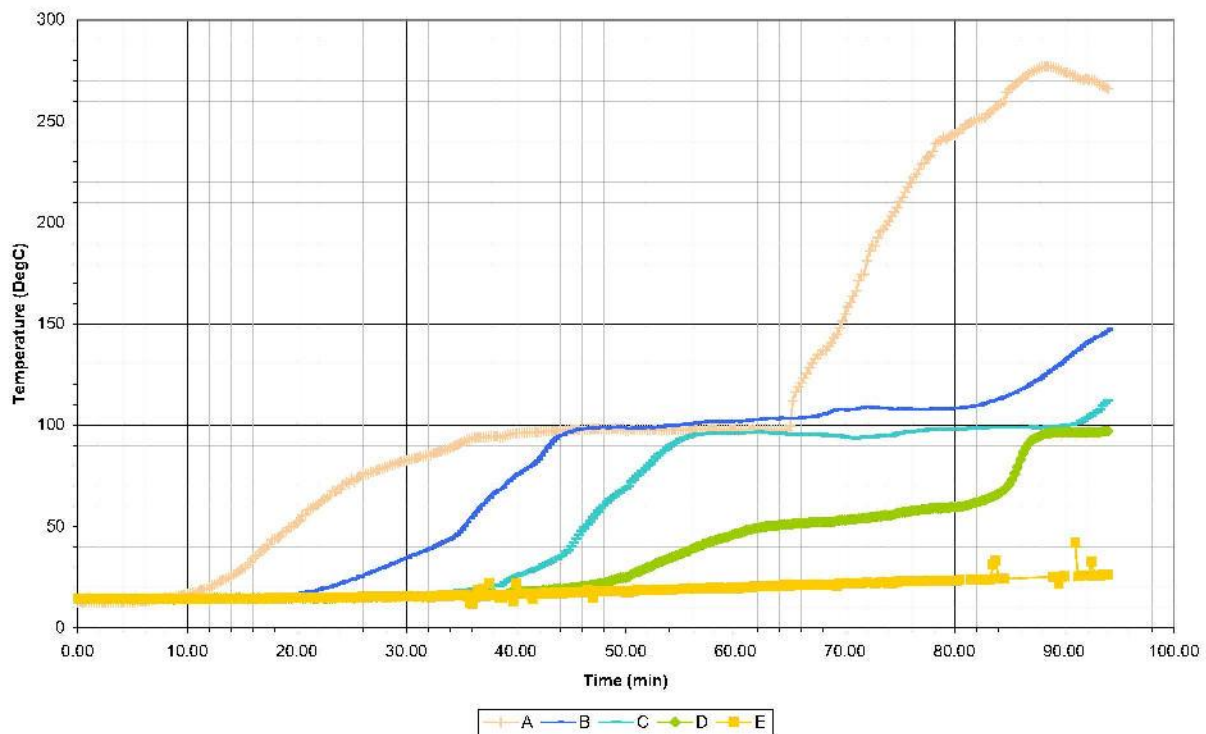


Figure 64 Temperature readings through rear wall on gridline B – Test F1

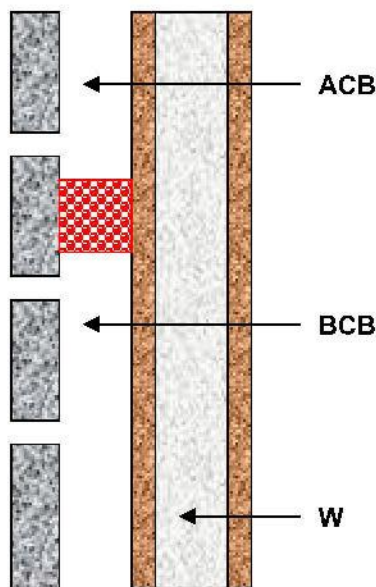


Figures 63 and 64 show a similar pattern to that for the party wall with a long moisture plateau and temperatures maintained below 300°C for the duration of the test. What is particularly noteworthy is that the temperatures within the structural insulated panel show no sign of reducing even at the end of the recording period when the temperatures behind the plasterboard are rapidly decreasing.

Cavity barrier

The effectiveness of the cavity barrier in providing a barrier to the spread of flame and smoke was evaluated by placing thermocouples in the cavity above and below the barrier in the locations shown in Figure 65. The measured values are shown in Figures 66 and 67.

Figure 65 Location of thermocouples around cavity barriers and window openings



ACB and BCB are temperature measurements above and below the cavity barrier, respectively and are recorded on gridlines B, C and D on the front wall and gridlines 2, 3 and 4 on the side wall with the window opening.

W is measured in the centre of the insulation core either side of both the front window and the side window.

Figure 66 Temperatures in cavity on front wall (GL1) and in insulated core adjacent to window opening

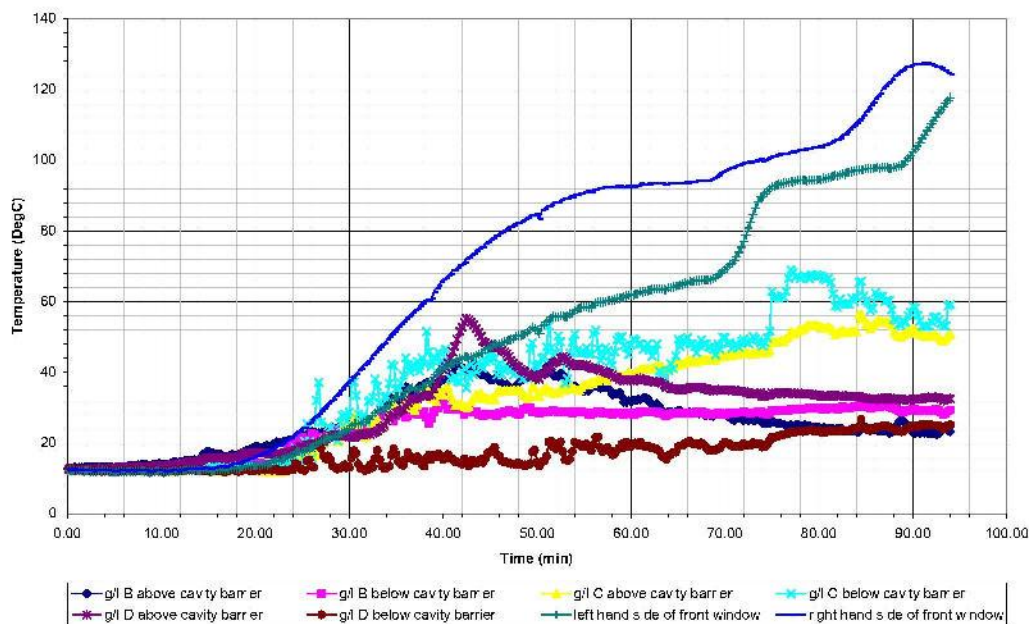
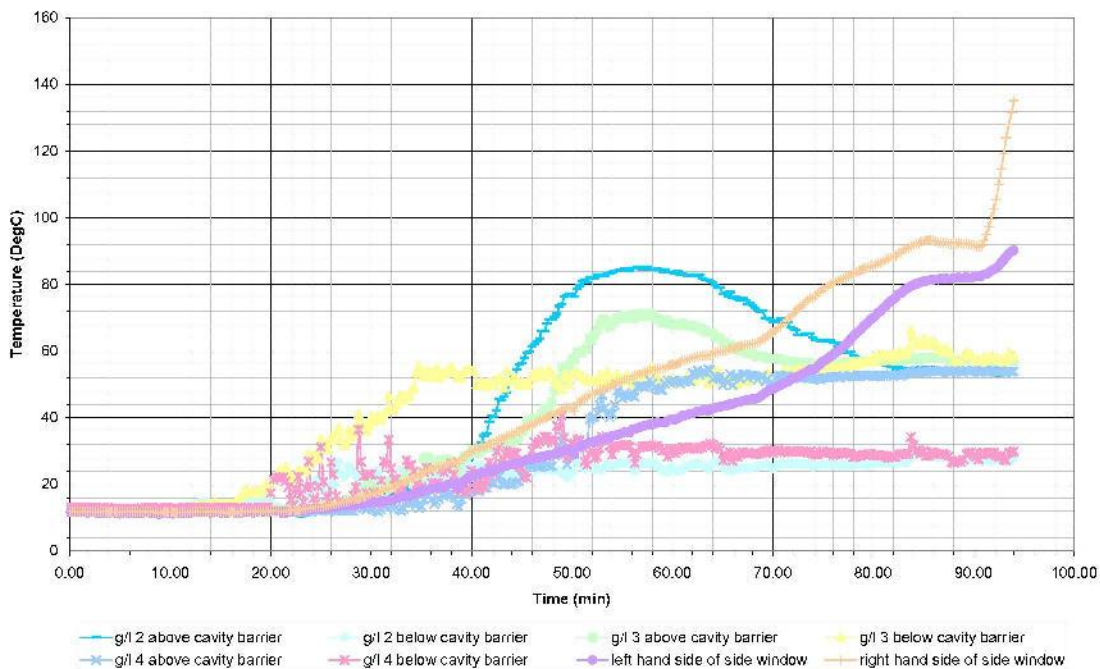


Figure 67 Temperatures in cavity on side wall (GLA) and insulated core adjacent to window opening



Figures 66 and 67 show that there was no appreciable temperature rise in the cavity between the structural insulated panel panels and the masonry for the duration of the test. In many cases the temperature above the cavity barrier is higher than that below. This can be accounted for by the ceramic fibre seal at the top of the wall. What is particularly noticeable in the figures is the temperature rise in the insulated core adjacent to the window opening. The temperatures continue to increase at the end of the test indicating a break through either from the window itself or from a breakdown of the internal linings in the latter stages of the test.

Floor void

The temperatures within the first floor void at mid-depth between the upper surface of the chipboard flooring and the underside of the plasterboard ceiling were recorded in the positions indicated in Figure 58. Each thermocouple was placed 120mm below finished floor level.

The measured temperatures are shown in Figure 68 for the gridline positions identified.

Figure 68 Temperatures in the first floor void – Test F1

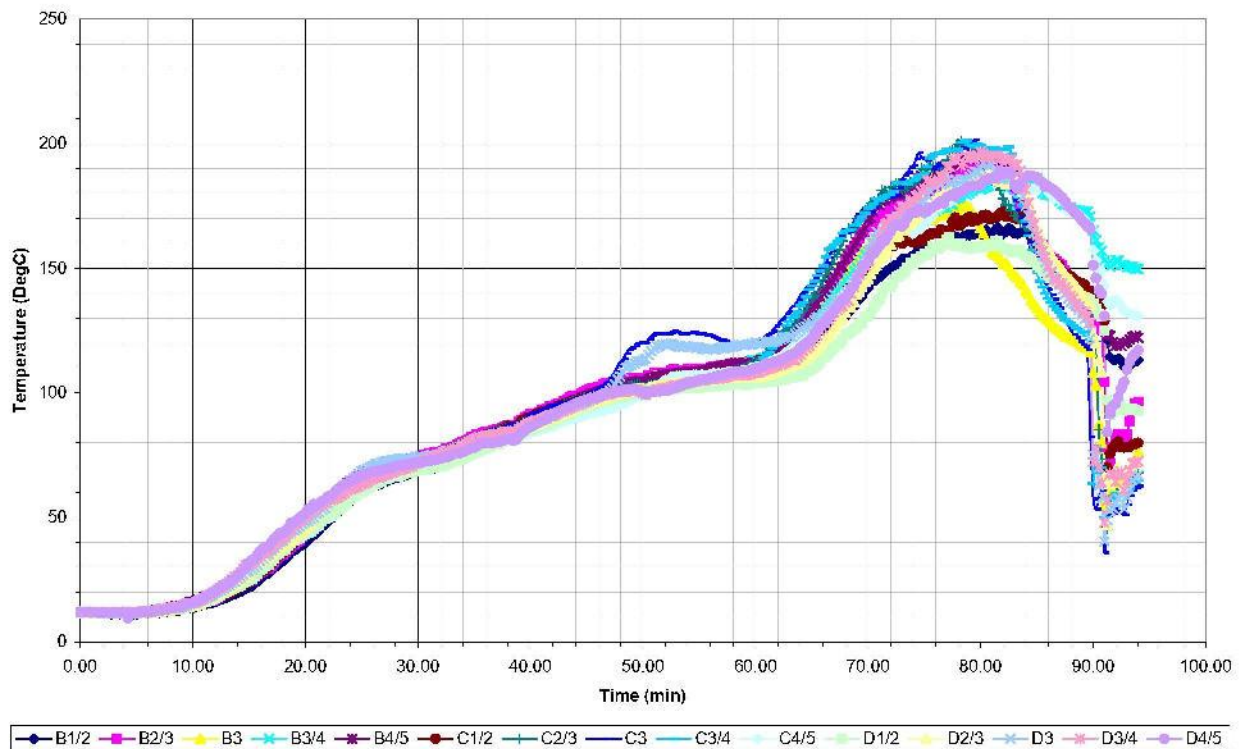


Figure 68 shows that the temperatures in the floor void did not exceed 200°C for the duration of the test and all areas had cooled down appreciably by the time the fire was suppressed.

2.7.4.1 Structural performance of building system

The deflection of the first floor (relative to the second floor) was recorded in the positions shown by the green triangles in Figure 58. The measured values of deflection are shown in Figure 69 with the identification relating to the gridline position. It was assumed and later validated that the top floor would remain at a constant level and hence the ceiling of the top floor could be utilised as a fixed datum against which first floor deflection could be measured.

Figure 69 Displacement of first floor relative to second floor – Test F1

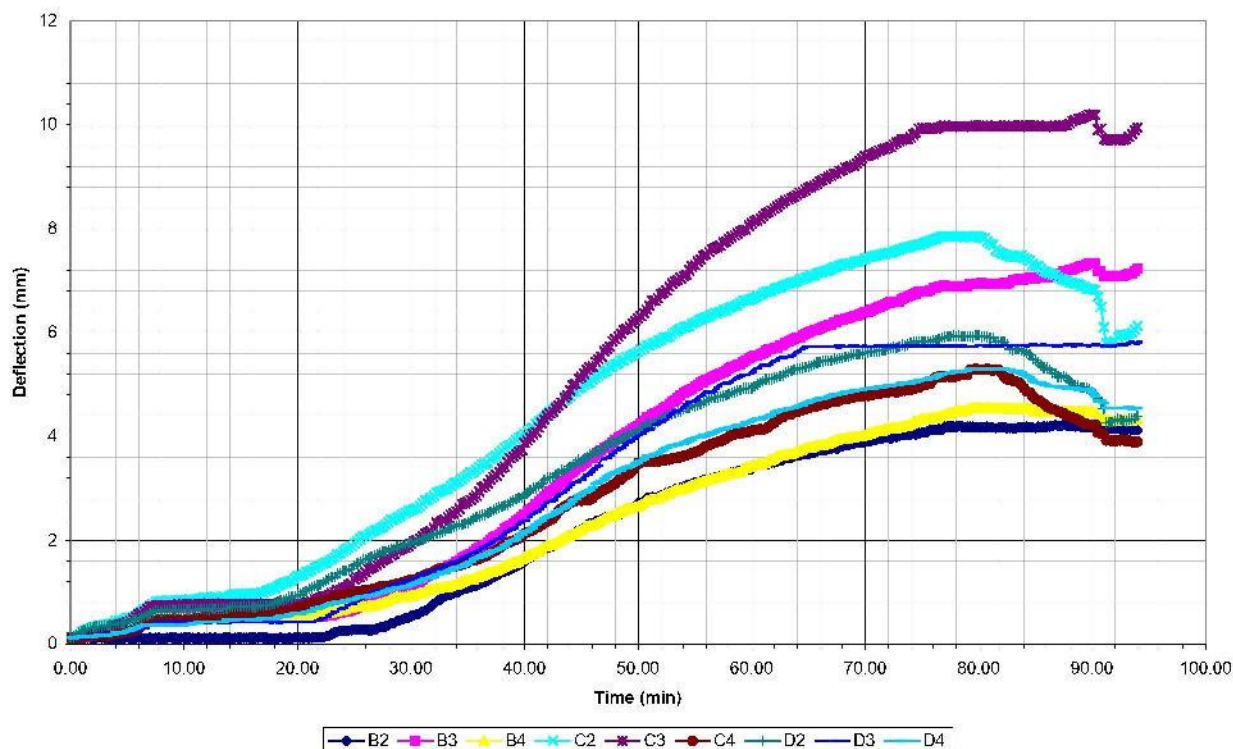


Figure 69 shows a maximum deflection of just over 10mm in the centre of the floor. Although the deflections have peaked and started to recover the graph shows some evidence that the deflections had started to increase again after the test was completed and the fire extinguished.

2.7.4.2 Post-test observations

As indicated by Figures 60 to 69, the building survived the fire test without reaching any of the planned termination criteria. Therefore, fire and rescue service personnel were asked to terminate the test and extinguish the residual fire load.

There was very little damage either to the engineered floor joists or the party wall, see Figures 70 and 71.

Figure 70 Engineered floor joists at end of Test F1



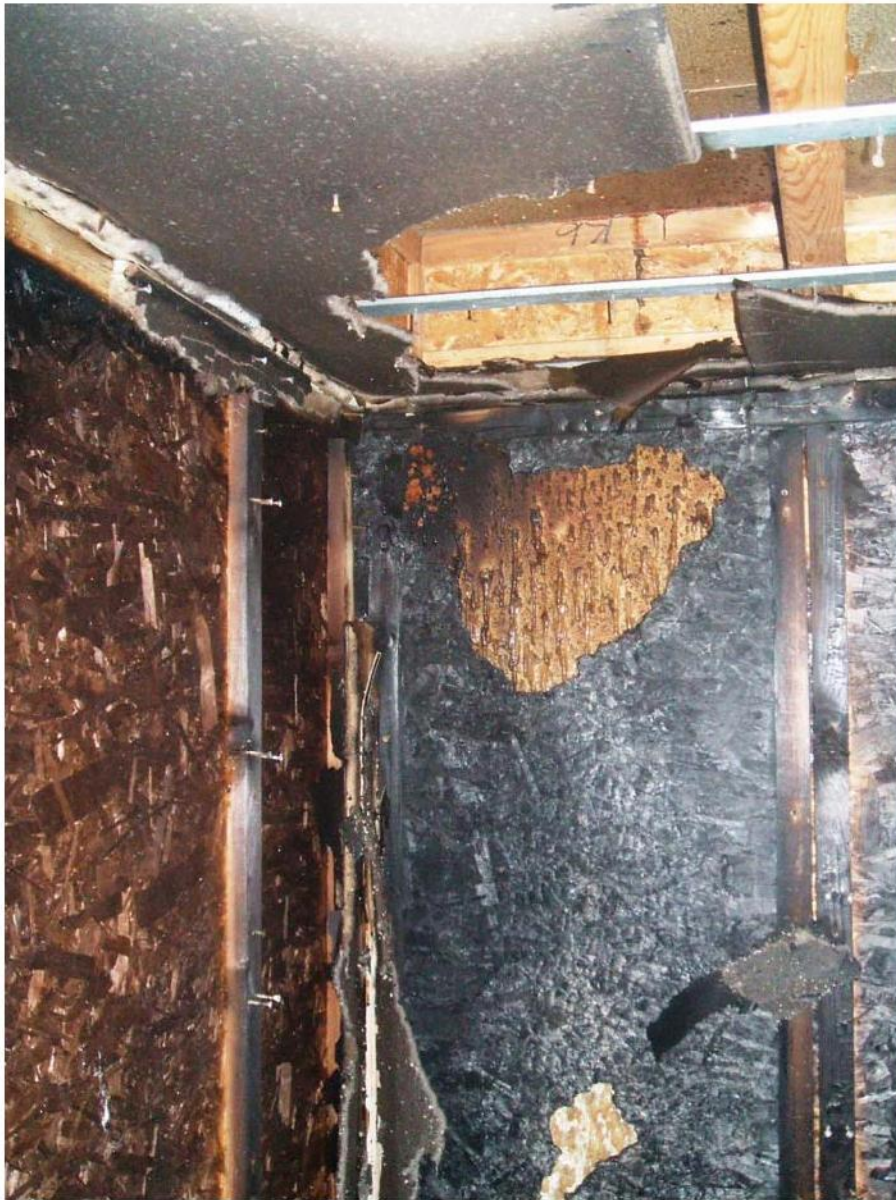
Figure 71 Condition of party wall (gridline E) – post-Test F1



Although the inner layer of oriented strand board appeared to be intact in most areas, there was some significant damage to the panels comprising the front, side and rear walls. In many areas, the core material had melted away and the inner layer of oriented

strand board had a significant amount of charring. This was particularly noticeable in the corner between the rear wall (grid line 5) and the side wall (grid line A). Once the fire and rescue service had left the facility, smoke was noticed emanating from the cavity space in this area. On removal of all the remaining plasterboard, it could be seen that the inner layer of the oriented strand board was severely damaged. As the damaged layer was removed, it became apparent that there was no insulation in this area, see Figure 72.

Figure 72 Damage to wall panel between side and rear wall – Test F1



The insulation had melted within this area to the extent that there was no insulation between the corner studs and the timber boxing out the window. The extent of the damage can clearly be seen in Figure 73.

Figure 73 is a view looking into the structural insulated panel towards the window frame. Figure 74 is a view looking down the same panel towards the sole plate and shows how far the insulation has melted away.

Figure 73 View through damaged structural insulated panel to window – Test F1



Figure 74 View down damaged structural insulated panel to the floor – Test F1



Once the extent of core damage was ascertained, other areas were inspected by drilling holes through the oriented strand board either from the inside or outside of the compartment. The expanded polystyrene insulation had melted from the panels in the rear wall between the door and the damaged corner shown above even though the inner layer of oriented strand board did not appear to be badly damaged, see Figure 72.

The fire in the cavity had started in the panel between the side window and the corner with the rear wall probably caused by smouldering of the battens used to fix the plasterboard or some movement of the joints in the dry lining at the ceiling to wall junction. The appearance of smoke and eventually flaming in the cavity between the masonry and the structural insulated panel coincided with the availability of an air supply. The panels come with prefabricated holes to facilitate lifting and erection. In a situation where there is a smouldering fire this has provided the oxygen necessary for combustion to take place. In order to extinguish the fire, it was necessary to remove the cavity barrier. In a fire test scenario with an open cavity, this only requires removing the ceramic fibre seal for access. In a real fire situation, access could be considerably more difficult. The area of combustion and the lifting hole is shown in Figure 75. Figure 76 shows the damage to the cavity barrier.

Figure 75 Location of post-test fire spread in cavity – Test F1



Figure 76 Damage to cavity barrier – Test F1



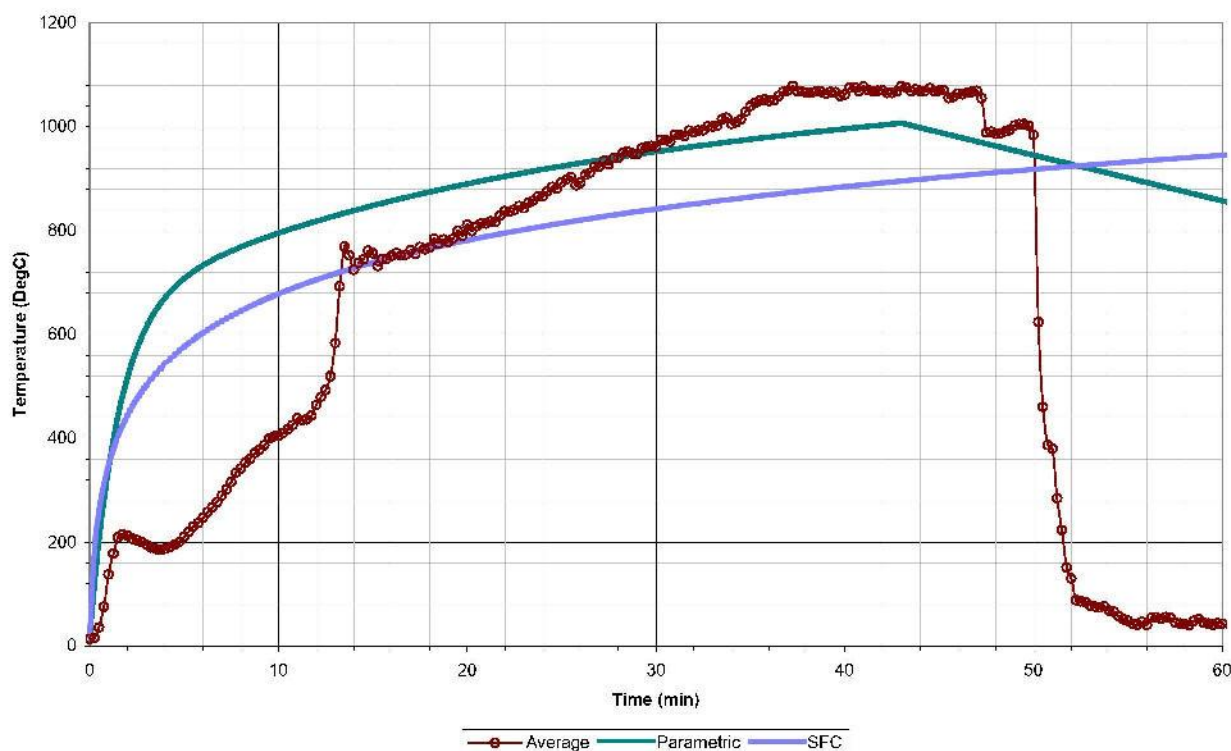
2.8 Test 2 – expanded polystyrene 30

Test F2, the second large-scale fire test, was conducted on an expanded polystyrene structure lined with a single layer of plasterboard to achieve a notional fire resistance rating of 30 minutes (apart from the party wall which was lined with two layers of plasterboard to achieve a notional fire resistance rating of 60 minutes).

2.8.1.1 Fire development

The fire design parameters were identical for all tests and are summarised in Table 10. The average measured time-temperature development, the calculated parametric prediction, and the standard time-temperature response are shown in Figure 77.

Figure 77 Time-temperature development – Test F2



The peak temperature and time to peak temperature is very similar to Test F1, confirming the repeatability of the fire design scenario. The fire was allowed to continue for approximately 50 minutes. At this stage, the deflection of the first floor and the rate of deflection had exceeded the planned termination criteria and the fire and rescue service personnel were asked to intervene and extinguish the fire.

2.8.1.2 Fire performance of building system

During the course of Test F2, temperatures were recorded at various locations within the walls and through the depth of the floor void to evaluate the thermal response of the building to the fire. The position of the instrumentation was similar to that used in the previous test.

Party wall (Gridline E)

Temperatures were measured through the party wall in the positions shown in Figure 59. The instrumented locations coincided with gridlines 2 and 4 in Figure 58. The measured response is shown in Figures 78 and 79.

Figure 78 Temperature readings through party wall at gridline 2 – Test F2

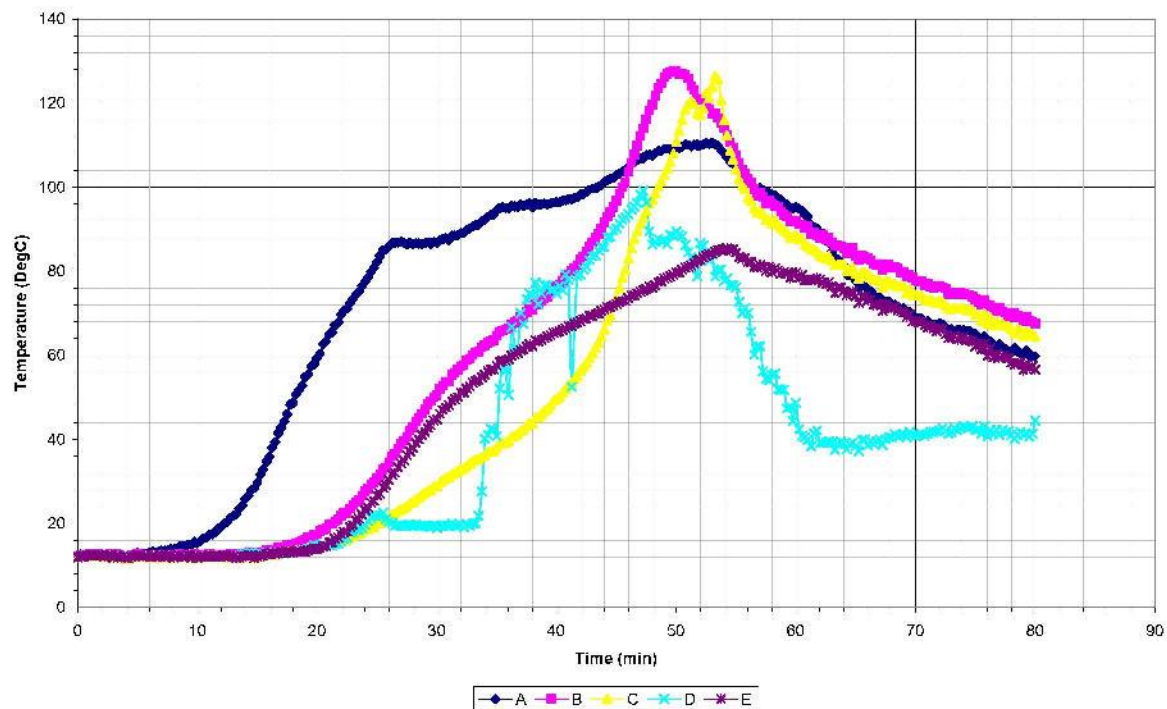
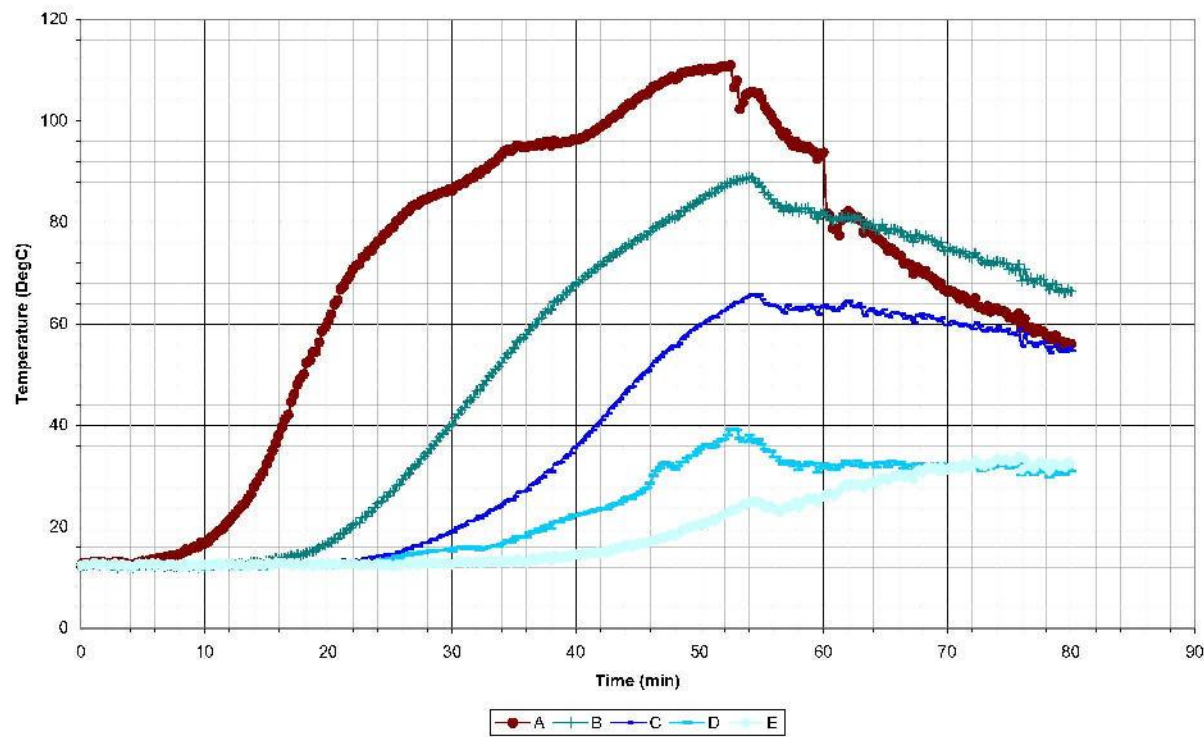


Figure 79 Temperature readings through party wall at gridline 4 – Test F2



Figures 78 and 79 show that the temperature of the party wall remained below the ignition temperature of timber for the duration of the test. Some anomalies exist in Figure 78 which can be explained by gas and steam migration through holes drilled for thermocouple placement.

Rear wall (Gridline 5)

Temperatures were measured through the structural insulated panel forming the rear wall in the positions shown in Figure 62. The measured values are shown in Figures 80 and 81.

Figure 80 Temperature readings through rear wall on gridline D – Test F2

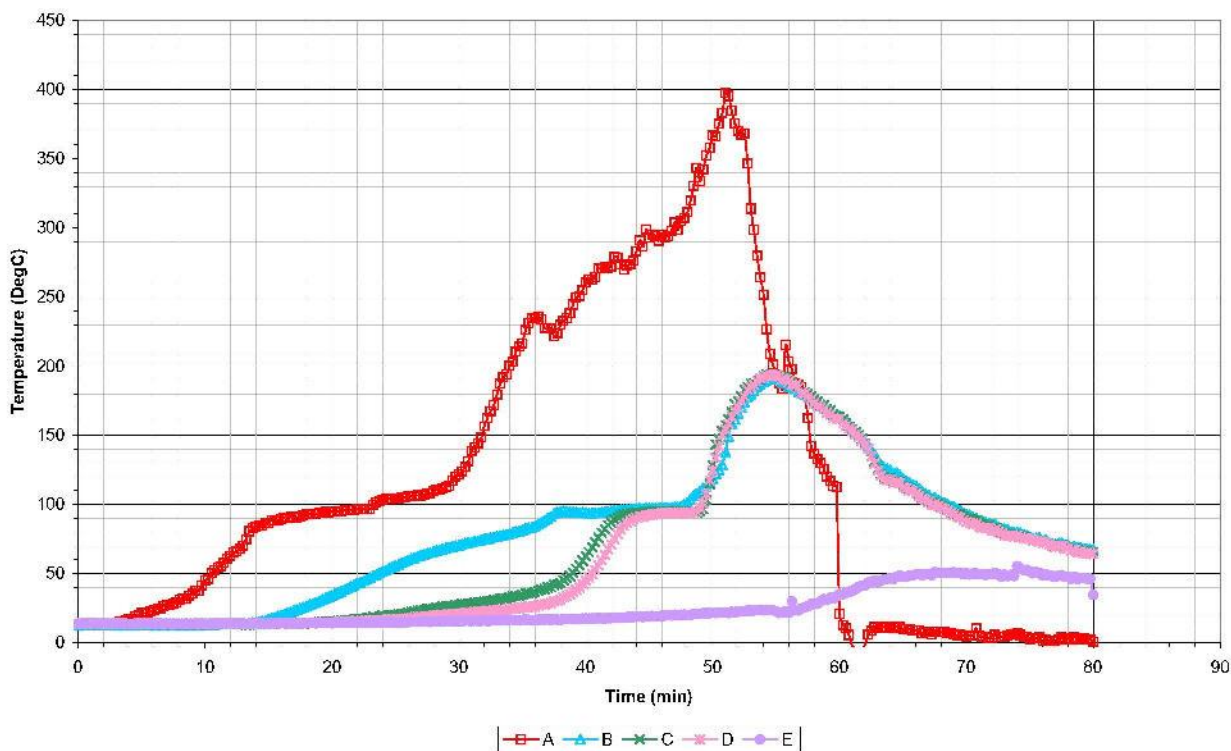
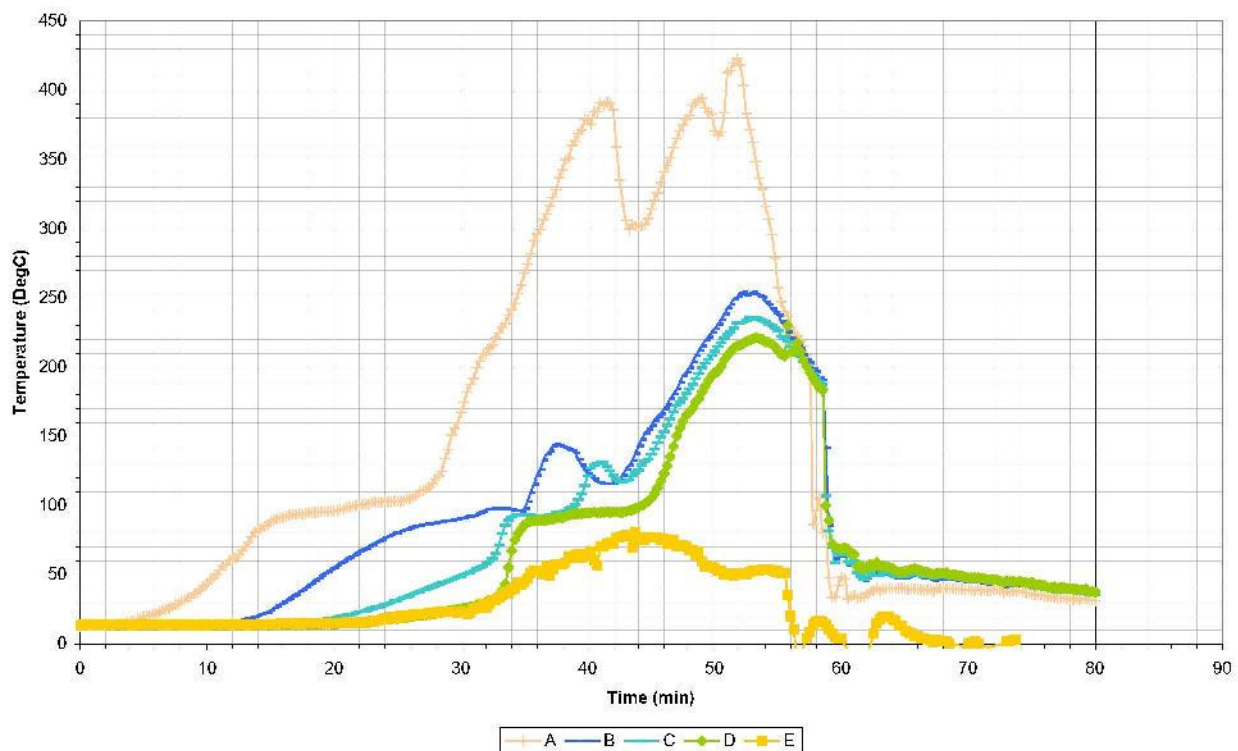


Figure 81 Temperature readings through rear wall on gridline B – Test F2



Figures 80 and 81 are consistent with a gradual breakdown of the plasterboard lining. In this case, there is evidence that the temperatures within the core continued to rise once fire-fighting operations had commenced. However, there is no evidence of an increase in temperature following fire-fighting operations.

Cavity barrier and window opening

The temperatures within the cavity below the level of the cavity barrier and the temperatures within the structural insulated panel core adjacent to the window opening are shown in Figures 82 and 83 for the front and side walls, respectively. The gridline of the measurement location is indicated.

Figure 82 Temperatures in cavity on front wall (GL1) and in insulated core adjacent to window opening – Test F2

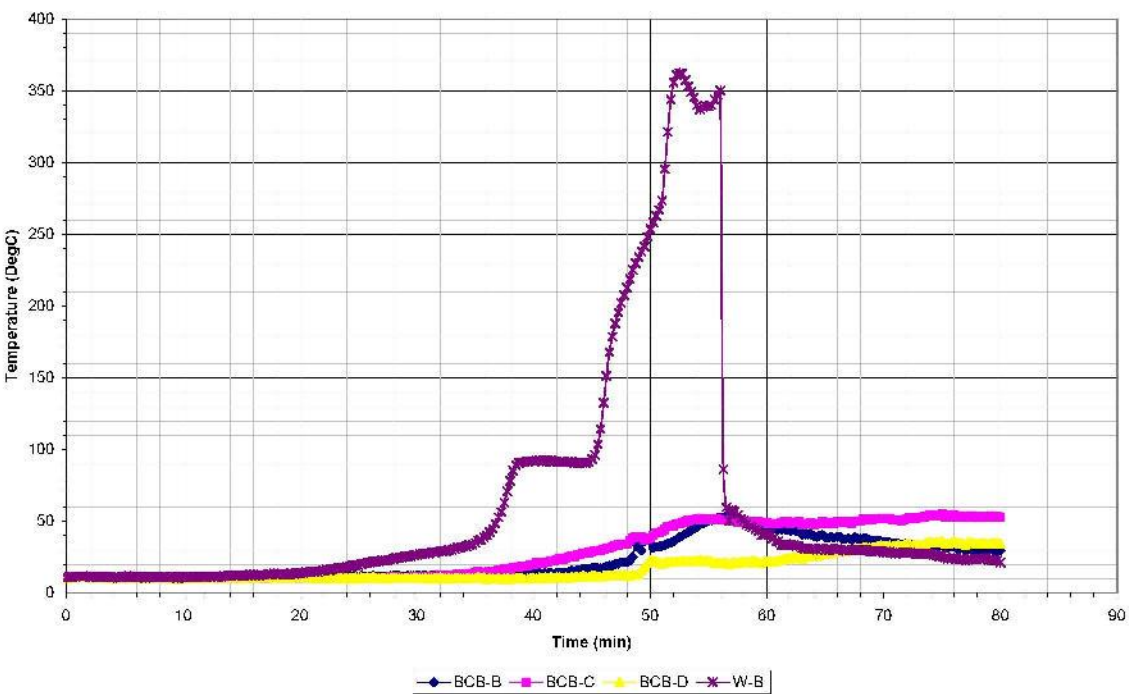
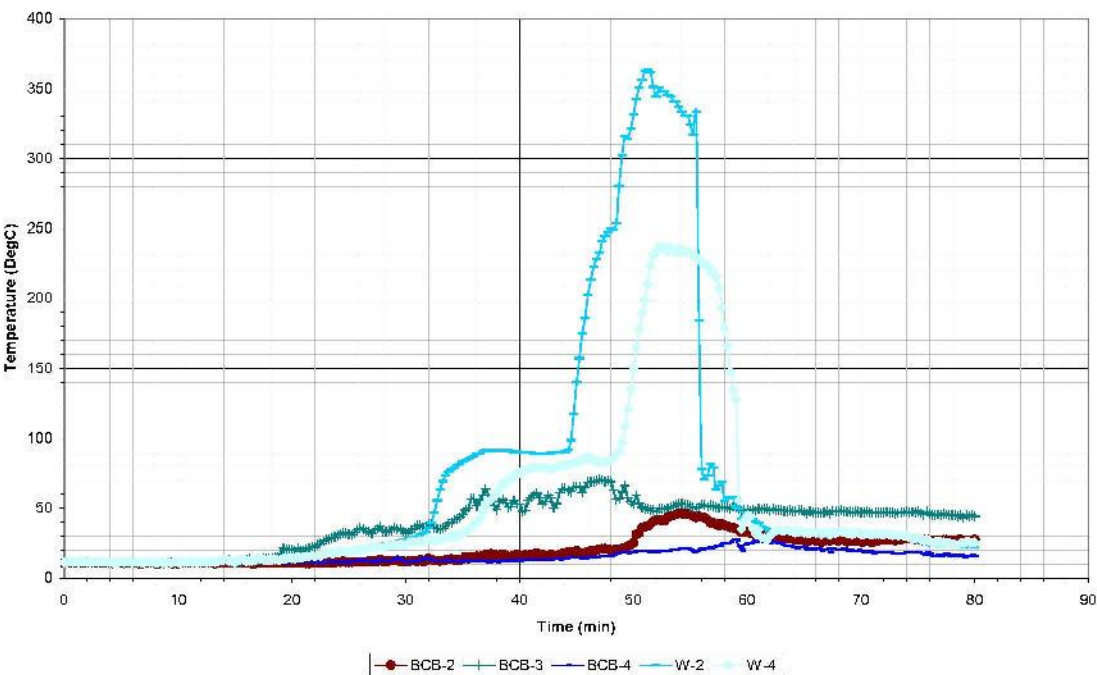


Figure 83 Temperatures in cavity on side wall (GLA) and insulated core adjacent to window opening – Test F2

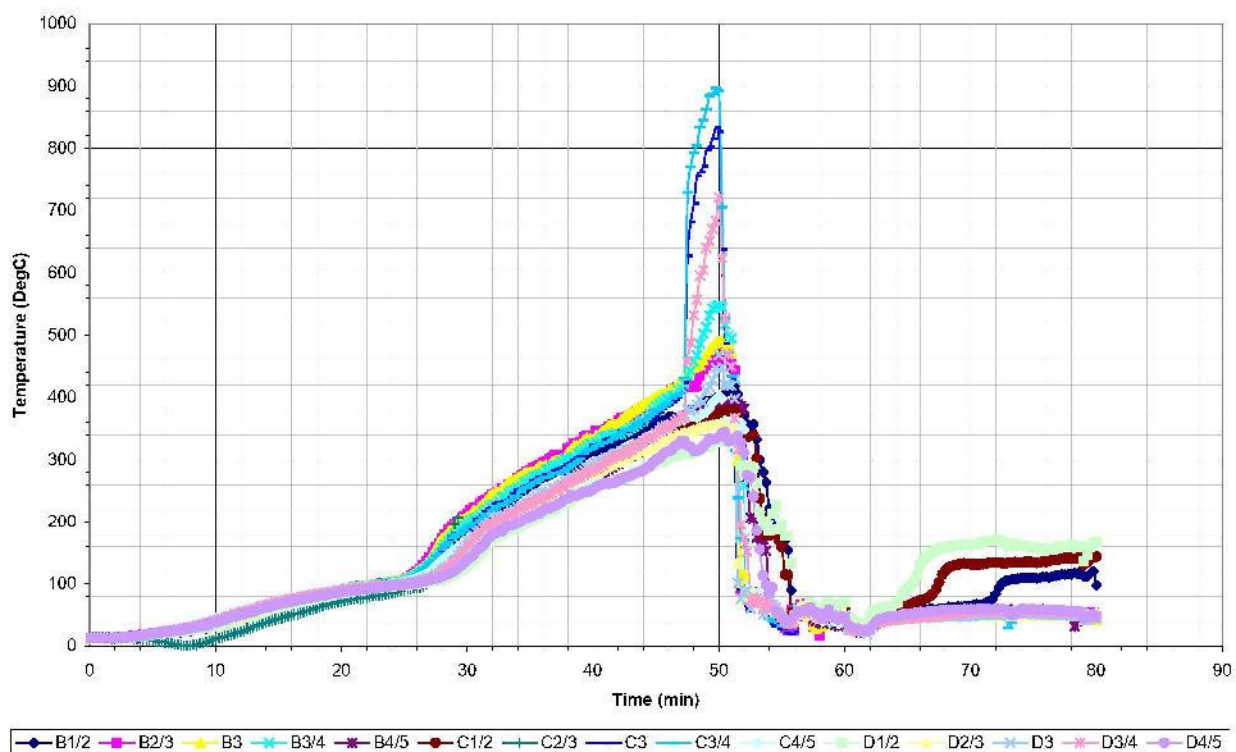


Figures 82 and 83 indicate combustion in the core during the latter stages of the fire. There was no evidence either from the measured temperatures or visual observation of any breakthrough into the cavity.

Floor void

The temperatures within the first floor void at mid-depth between the upper surface of the chipboard and the underside of the plasterboard ceiling were recorded in the positions indicated in Figure 58. The measured temperatures are shown in Figure 84.

Figure 84 Temperatures in the first floor void – Test F2



The temperatures are indicative of combustion in the floor void. At this stage (in conjunction with deflection readings – see Figure 85) a decision was taken to terminate the test on the basis that the floor was in imminent danger of collapse.

2.8.1.3 Structural performance of building system

The deflection of the first floor relative to the second floor was recorded. Because of the increased risk of structural collapse, only three displacement transducers were used corresponding to the three locations identified in Figure 60 on gridline C (centre of the compartment). The measured deflections are shown in Figure 85.

Figure 85 Displacement of first floor relative to second floor – Test F2

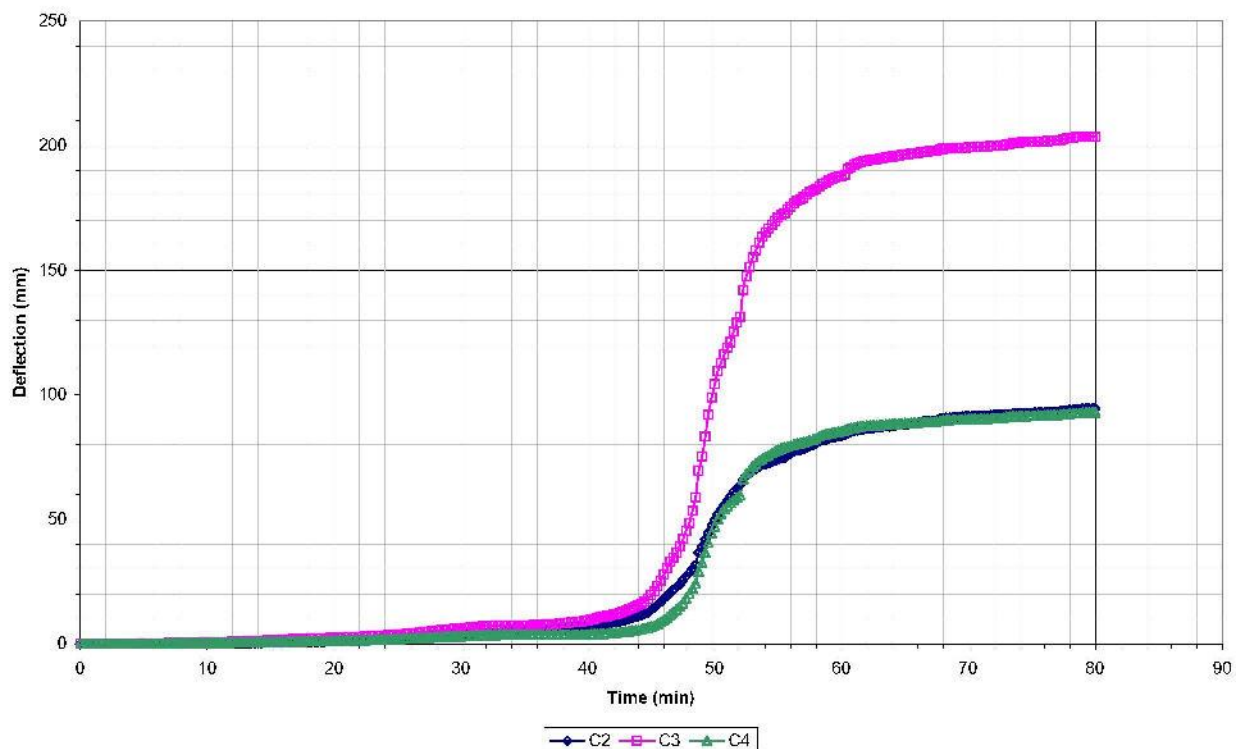


Figure 85 shows a rapid rate of deflection after approximately 45 minutes corresponding to the temperature rise shown in Figure 84 and the observed breakdown and fall off of the ceiling boards. The central deflection reached a value in excess of 200mm by the end of the test and showed no signs of recovery.

2.8.1.4 Post-test observations

As mentioned above, the test was terminated on the basis of the runaway deflection of the floor together with temperature measurements in the floor void. This indicated a break through of the fire into the floor void and direct flame impingement on the floor joists.

As this was effectively a 60 minute fire exposure in a structure designed to withstand 30 minutes (of the standard fire test), it was no surprise that one of the termination criteria was reached before the fire entered the cooling phase. The fire and rescue service personnel acted very quickly and prevented the collapse of the first floor by extinguishing the fire and suppressing flaming in the floor void. Most of the plasterboard lining to the walls (with the exception of the party wall) either fell away during the latter stages of the test or was removed during the fire-fighting operations.

Although there was no global collapse, it is clear from the test results and subsequent observations that the mode of failure for the building is the reduction in load carrying capacity of the floor caused by combustion of the oriented strand board web members of the engineered floor joists. Figures 86 to 88 show the condition of the floor joists after the test.

Figure 86 Engineered floor joists following Test F2



Figure 87 Close up of floor joist showing complete combustion of web following Test F2



Figure 88 Residual depth of engineered floor joist (original depth = 220mm) post Test F2



Other than the party wall, the plasterboard lining to the walls had either fallen off or disintegrated to the extent that the inner layer of oriented strand board had been involved and the insulation in the core had melted. Figure 89 provides a direct comparison between the condition of the party wall and the front wall at the end of the test.

Figure 89 Front and party wall (gridlines 1 and E) – Test F2



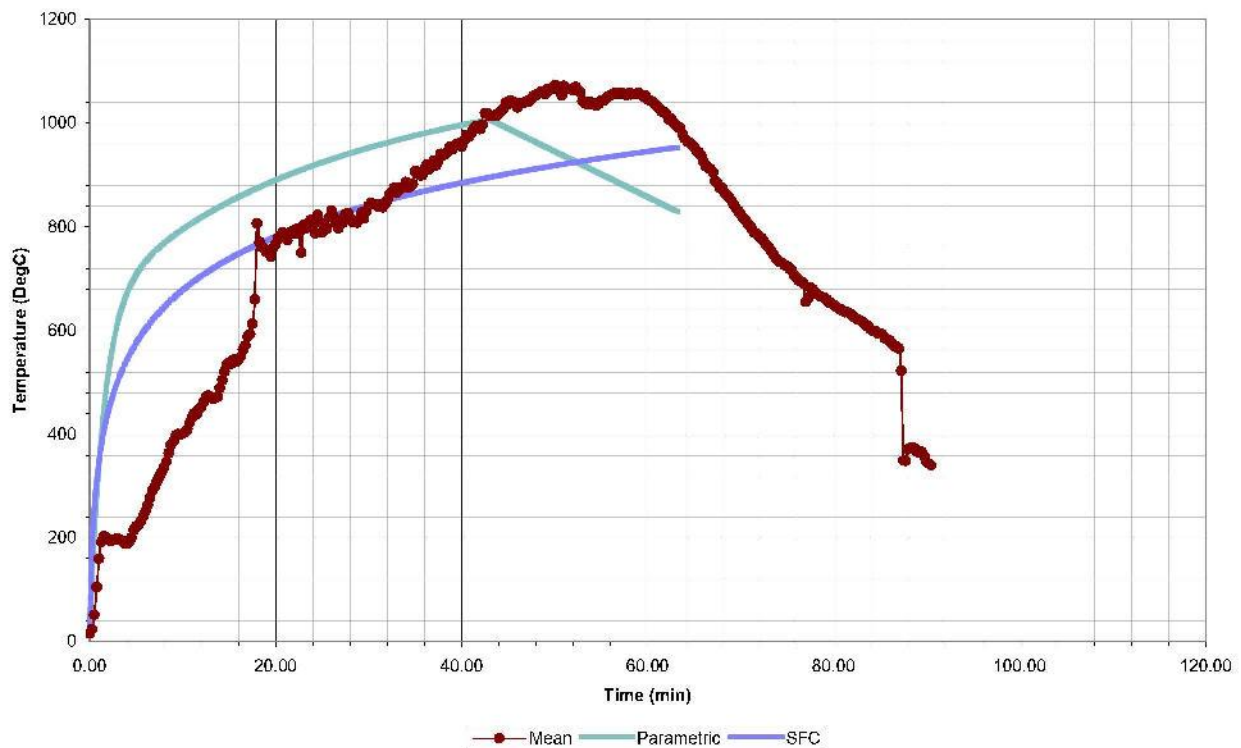
2.8.2 TEST 3 – POLYURETHANE 60

Test F3, the third test, involved a structural insulated panel structure with a polyurethane core lined with two layers of plasterboard to achieve a notional fire resistance rating of 60 minutes.

2.8.2.1 Fire development

The fire design parameters were identical for all tests and are summarised in Table 10. The average measured time-temperature development, the calculated parametric prediction, and the standard time-temperature response are shown in Figure 90.

Figure 90 Time-temperature response – Test F3



As with Test F1, the fire was allowed to continue until the cooling stage. At this stage, none of the pre-determined failure criteria had been reached. Once the temperature inside the compartment had reached approximately 600°C, the fire and rescue service personnel were asked to extinguish the remaining cribs.

2.8.2.2 Fire performance of building system

As with the previous tests, the temperature at various locations within the walls and first floor was recorded. The position of the instrumentation is related to the gridline identification shown in Figure 58.

Party wall (Gridline E)

Temperatures were measured through the party wall in the positions shown in Figure 61. The measured response is shown in Figures 91 and 92.

Figure 91 Temperature readings through party wall at gridline 2 – Test F3

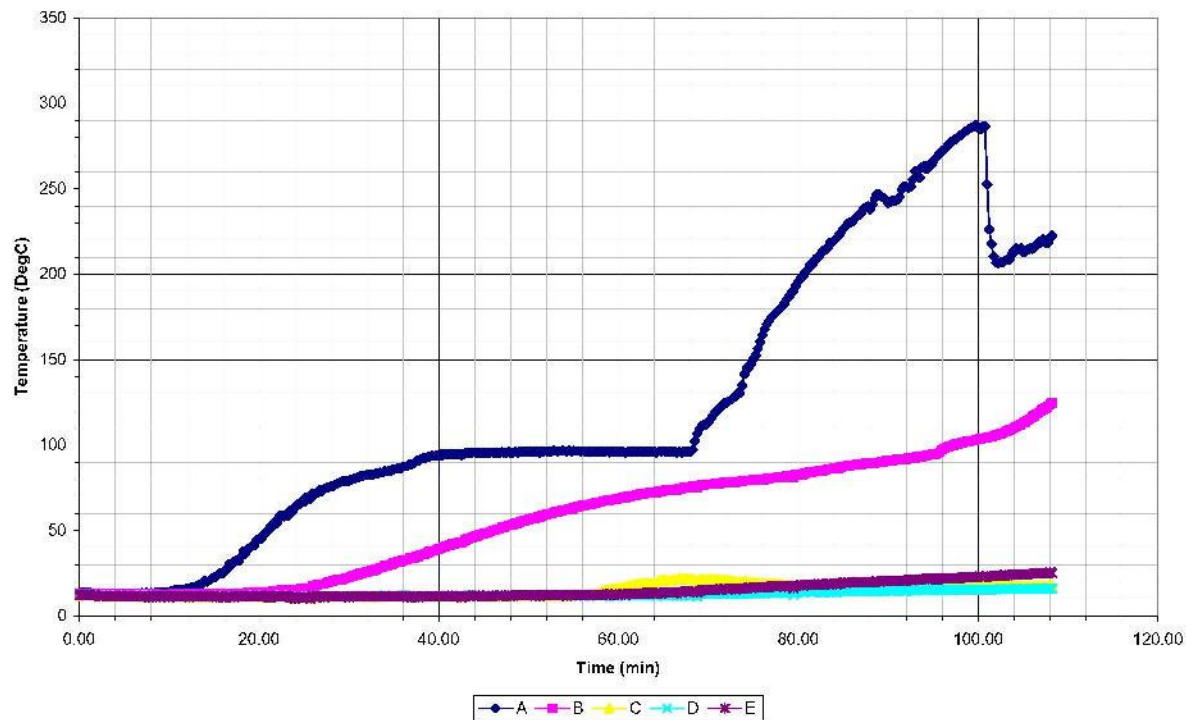
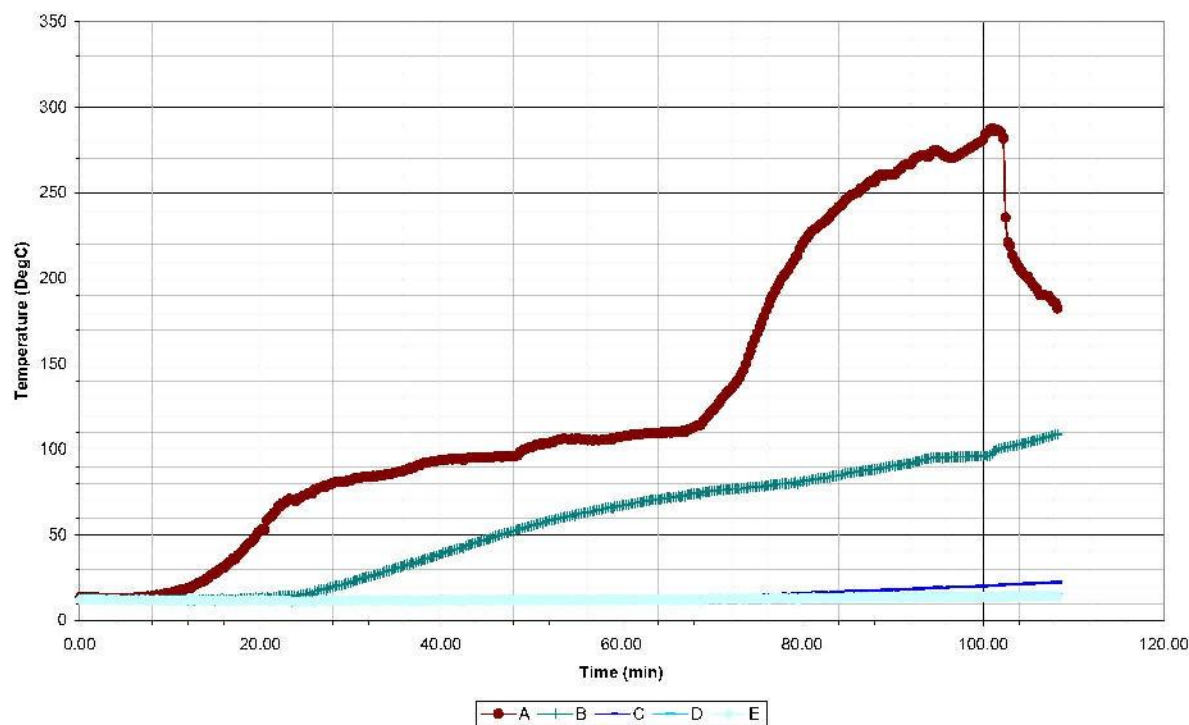


Figure 92 Temperature readings through party wall at gridline 4 – Test F3



Figures 91 and 92 show the temperatures within the core of the structural insulated panel forming the party wall were largely unaffected by the fire for the duration of the test. However, the inner layer of oriented strand board was subject to a 200°C temperature gradient through its depth based on temperatures measured near the front and rear face, respectively.

Rear wall (Gridline 5)

The temperatures were measured in the structural insulated panel forming the rear wall in the positions shown in Figure 62. The measured values are shown in Figures 93 and 94.

Figure 93 Temperature readings through rear wall on gridline D – Test F3

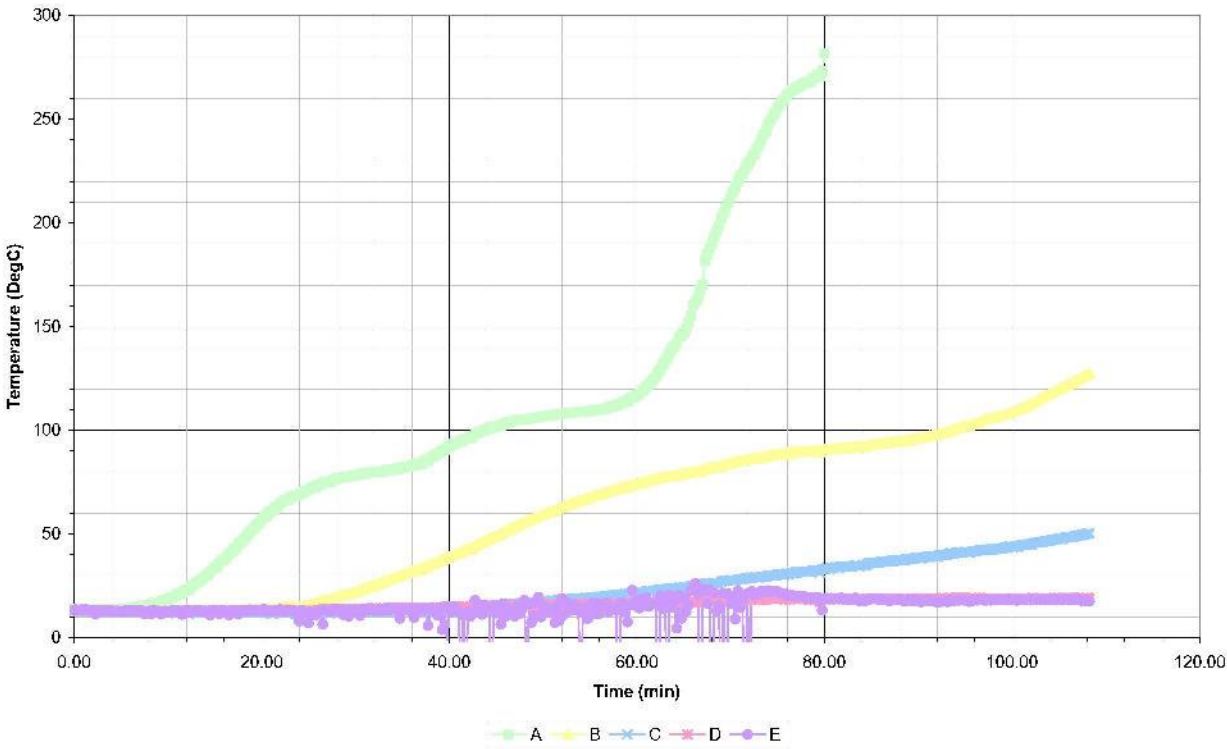
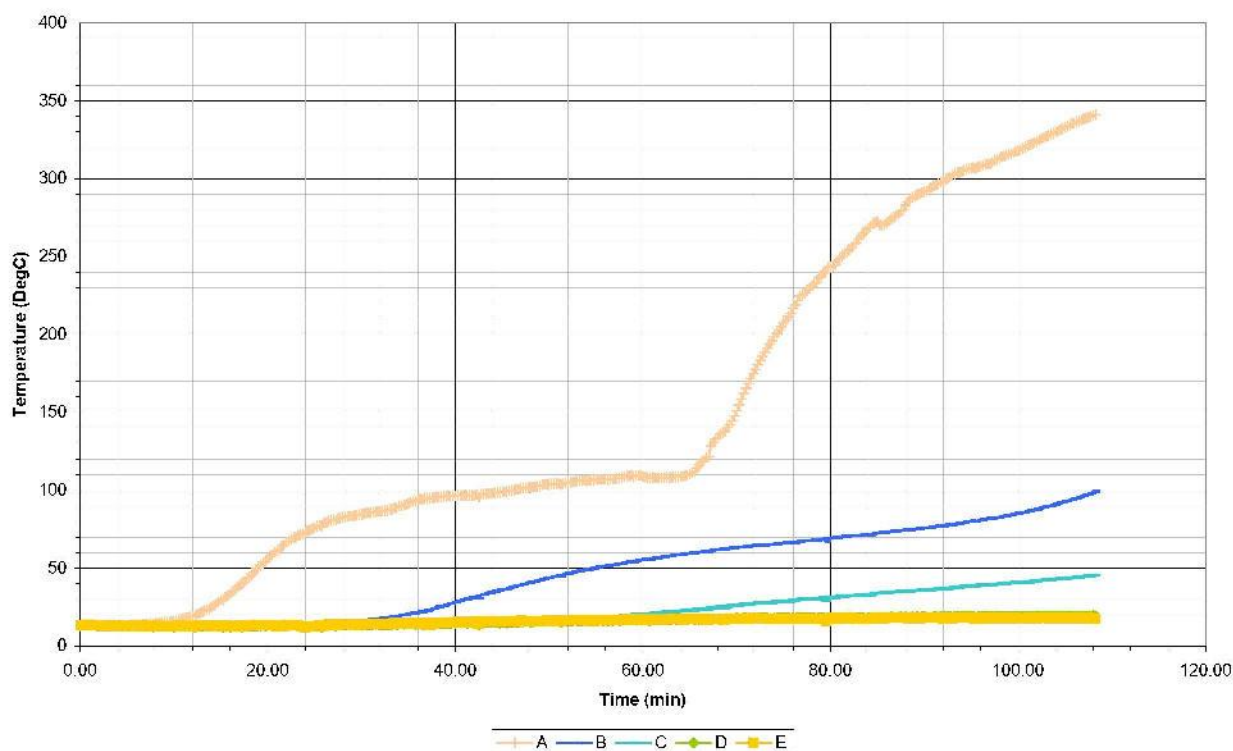


Figure 94 Temperature readings through rear wall on gridline B – Test F3



The measured temperatures again show that the fire had very little impact on the core temperatures of the structural insulated panel for the duration of the test. However, during the latter stages of the test when the atmosphere temperatures are reducing, the temperature within the core is continuing to increase despite the intervention of the fire and rescue service. Again, there is a significant temperature gradient apparent in the inner oriented strand board veneer which is also in the order of 200°C.

Cavity barrier

The effectiveness of the cavity barrier was evaluated by placing thermocouples in the cavity in the locations shown in Figure 65. Temperatures were also monitored in the centre of the insulation core either side of both the front and side window. The results are shown in Figures 95 and 96.

Figure 95 Temperatures in cavity on front wall (GL1) and in insulated core adjacent to window opening – Test F

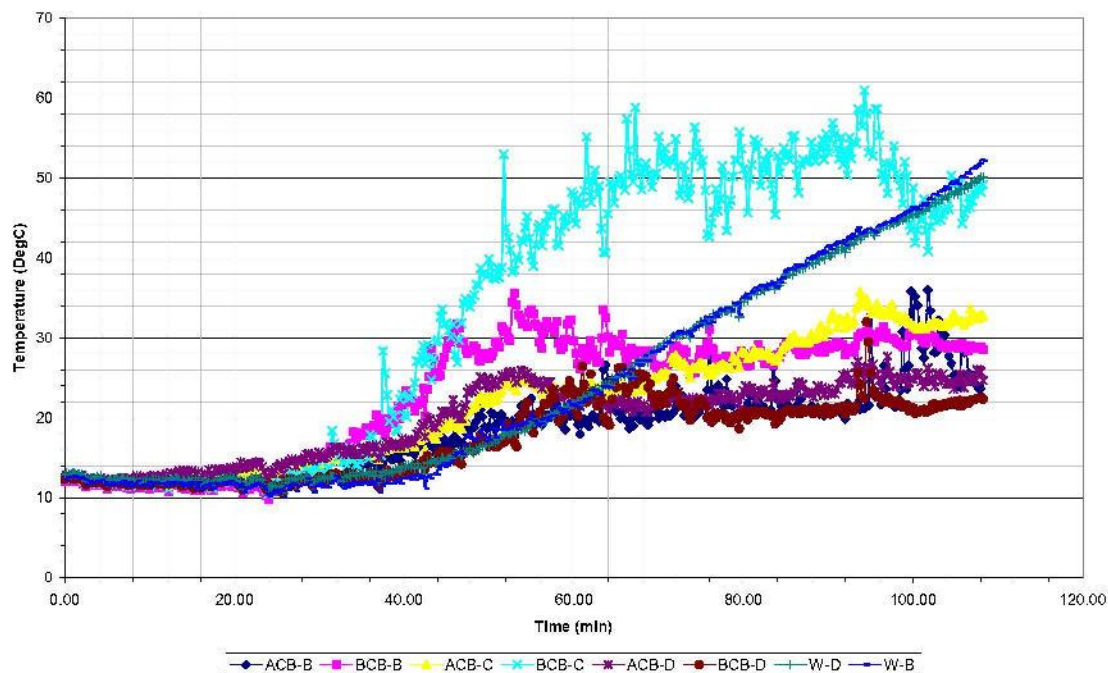
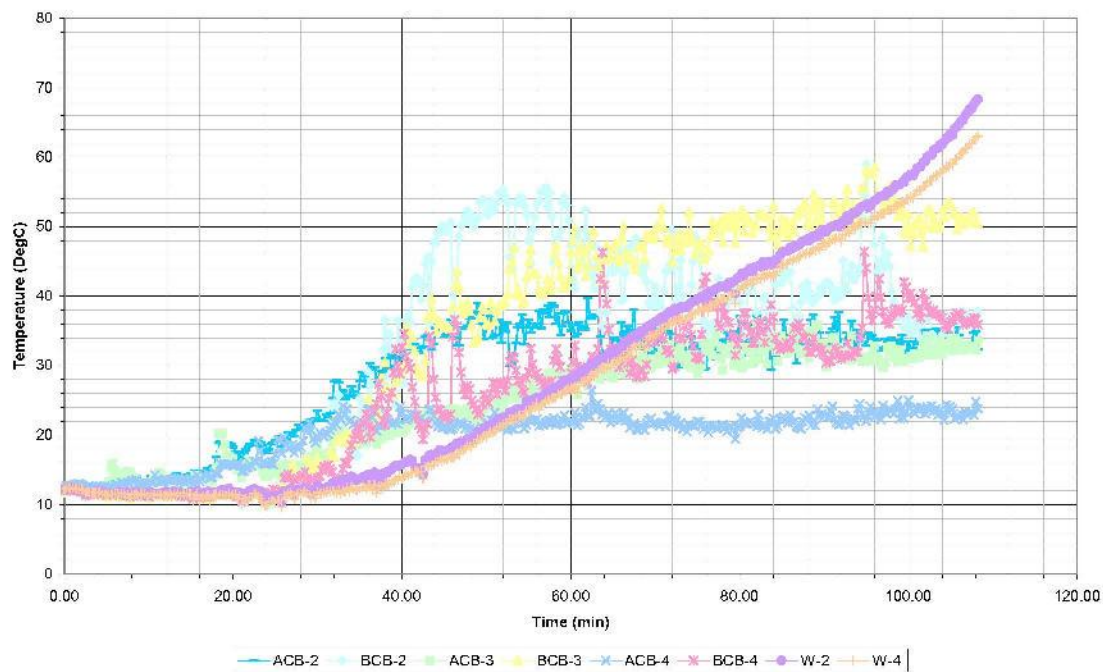


Figure 96 Temperatures in cavity on side wall (GLA) and insulated core adjacent to window opening – Test F3



Although the temperatures are below 70°C for the duration of the test, the core temperatures are increasing at a time that the fire has been suppressed.

Floor void

The temperatures within the first floor void at mid-depth between the upper surface of the chipboard flooring and the underside of the plasterboard ceiling were recorded in the positions indicated in Figure 58. The measured temperatures are shown in Figure 97.

Figure 97 Temperatures in the first floor void – Test F3

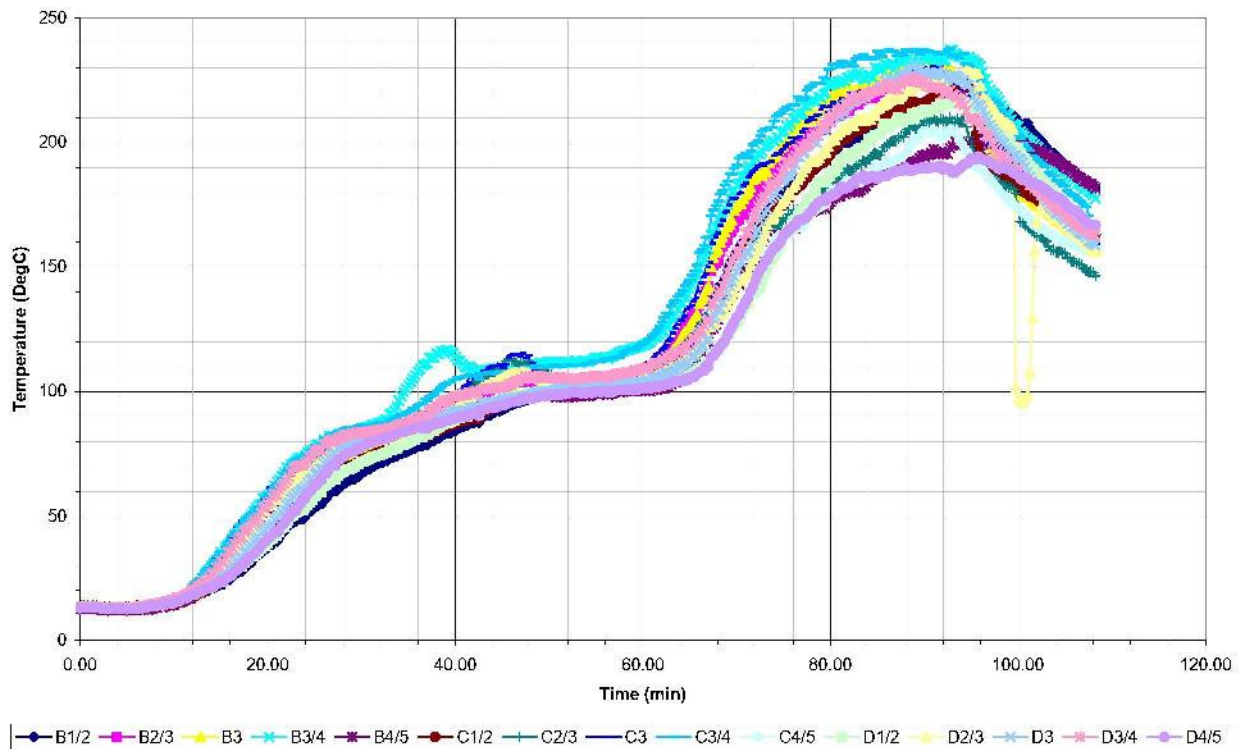


Figure 97 shows that the temperature in the floor void did not exceed 250°C for the duration of the test and that all areas (in contrast with the wall panels) had cooled down appreciably by the time the fire was suppressed.

2.8.2.3 Structural performance of the building system

The deflection of the first floor relative to the second floor was recorded in the positions shown in Figure 58. The measured values of deflection are shown in Figure 98.

Figure 98 Displacement of first floor relative to second floor – Test F3

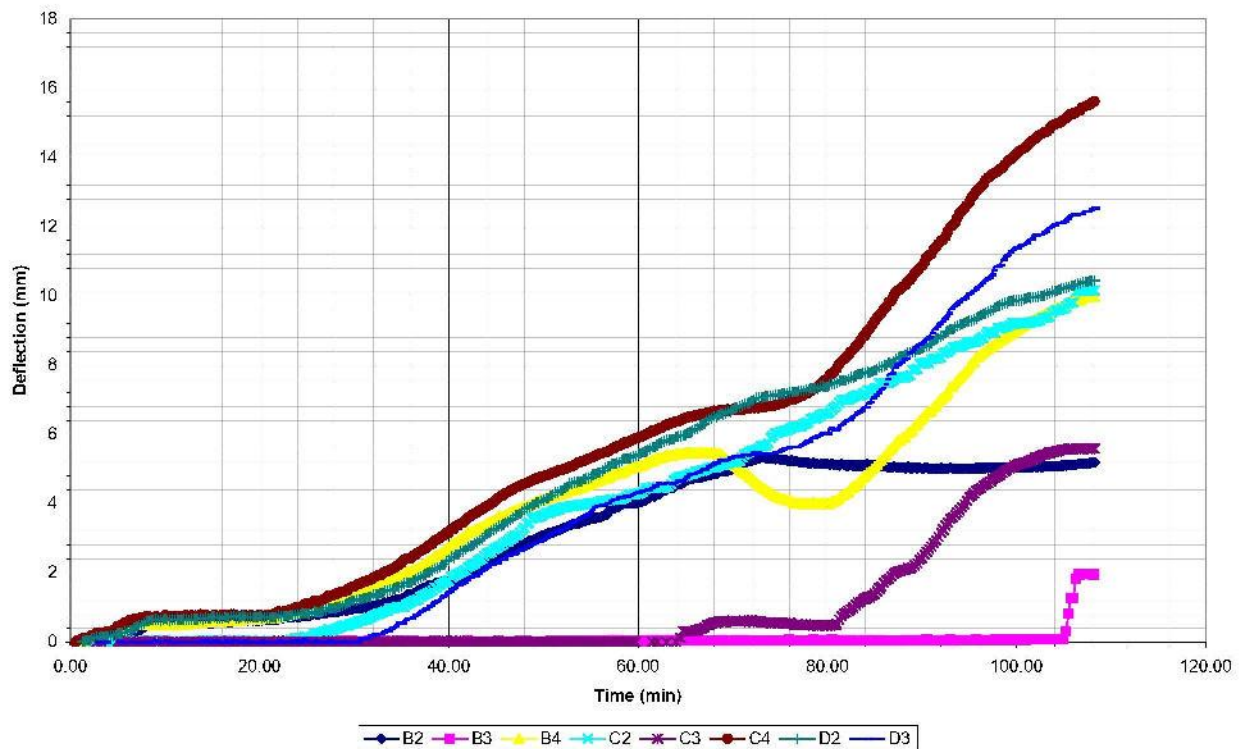


Figure 98 shows a maximum deflection of almost 16mm with an increasing rate of deflection towards the end of the test. The floor continued to deflect once the fire had been extinguished.

2.8.2.4 Post-test observations

On completion of the test, initial observations suggested there was very little damage as the linings were largely still in place, see Figure 99. There was no evidence of any significant damage to the floor joists and no indication that the fire had entered the first floor void, see Figure 100. However, once the fire load had been extinguished it was clear that the temperatures within the structural insulated panel panels were increasing and eventually the walls ignited in a number of different locations with the polyurethane involved in the combustion process. The small ignition sources were dealt with but it was unclear where the next outbreak would occur. All the remaining plasterboard was stripped away and the oriented strand board inspected.

Figure 99 Condition of internal wall and ceiling linings at end of Test F3 (Note location of service penetration)



Figure 100 Limited damage to floor system –Test F3



Damage to the core was extensive in certain areas, see Figure 101 and more localised in other areas, see Figures 102 and 103.

Figure 101 Damage to structural insulated panel on rear and side wall – Test F3



Figure 102 Localised damage to polyurethane core – Test F3



Figure 103 Localised damage to polyurethane core – Test F3



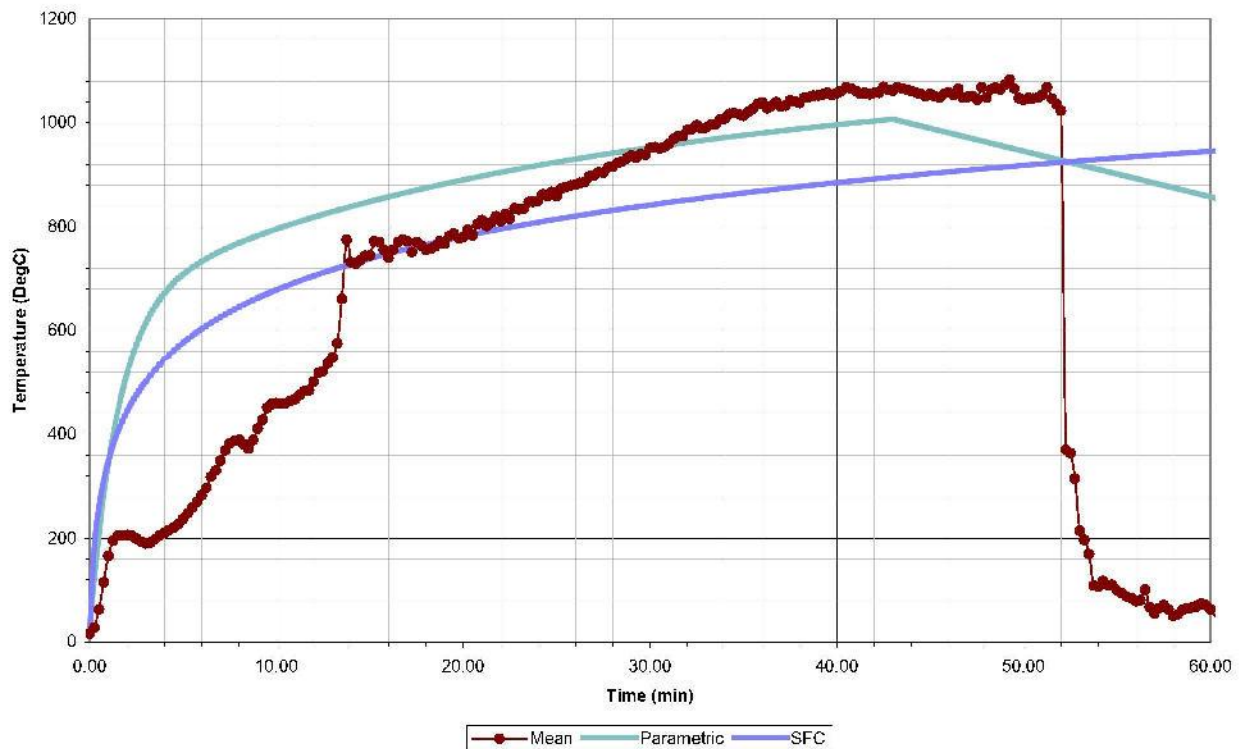
2.8.3 TEST 4 – POLYURETHANE 30

Test F4, the final large-scale fire test, involved the polyurethane structural insulated panel structure with a 60 minute party wall and the remaining linings to the ceiling and walls designed to achieve a notional fire resistance rating of 30 minutes.

2.8.3.1 *Fire development*

The fire design parameters were identical for all tests and are summarised in Table 10. The average time-temperature development, the calculated parametric prediction and the standard time-temperature response are shown in Figure 104.

Figure 104 Compartment time-temperature response – Test F4



In this case, a decision was made to terminate the test on the same basis as the expanded polystyrene 30 test, i.e. excessive deflection of the first floor together with an increased rate of deflection and temperatures in the floor void indicative of burning. The decision to extinguish the fire was also informed by evidence of flaming within the wall panels on the internal face of the front and side walls close to the window opening.

2.8.3.2 Fire performance of building system

Party wall (Gridline E)

Temperatures were measured in the party wall in the positions shown in Figure 61. The measured response is shown in Figures 105 and 106.

Figure 105 Temperature readings through party wall at gridline 2 –Test F4

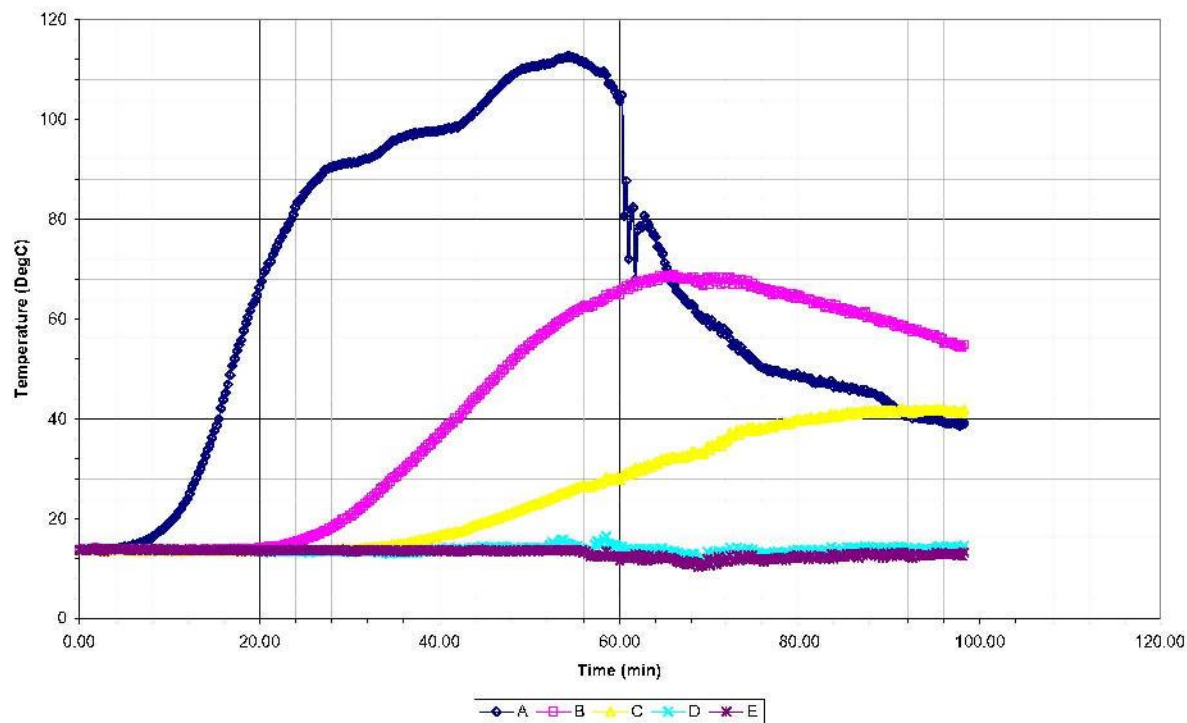
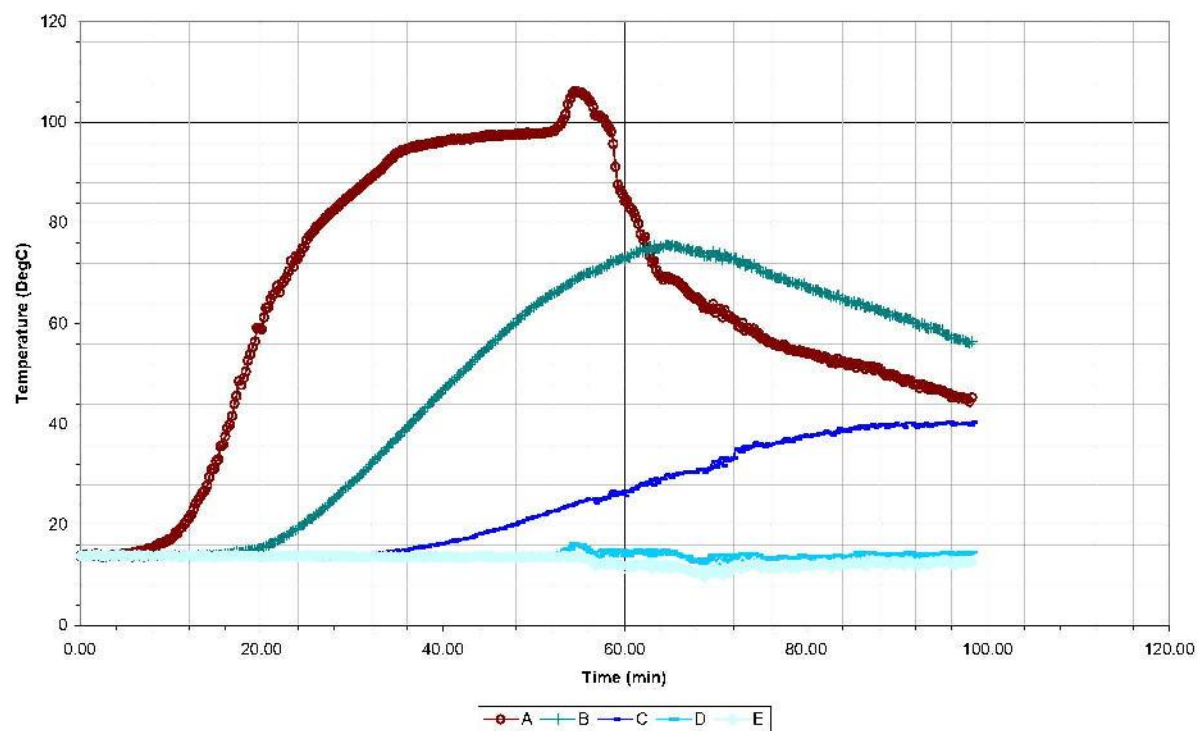


Figure 106 Temperature readings through party wall at gridline 4 – Test F4



The readings show that the temperature in the core of the structural insulated panel did not reach high temperatures and that the temperatures within the core had stabilised following fire-fighting operations. False readings arising from apparent steam migration were not present as the polyurethane core is generally less porous than the expanded polystyrene panels tested.

Rear wall (Gridline 5)

Temperatures were measured through the structural insulated panel forming the rear wall in the positions shown in Figure 62. The measured values are shown in Figures 107 and 108.

Figure 107 Temperature readings through rear wall on gridline D – Test F4

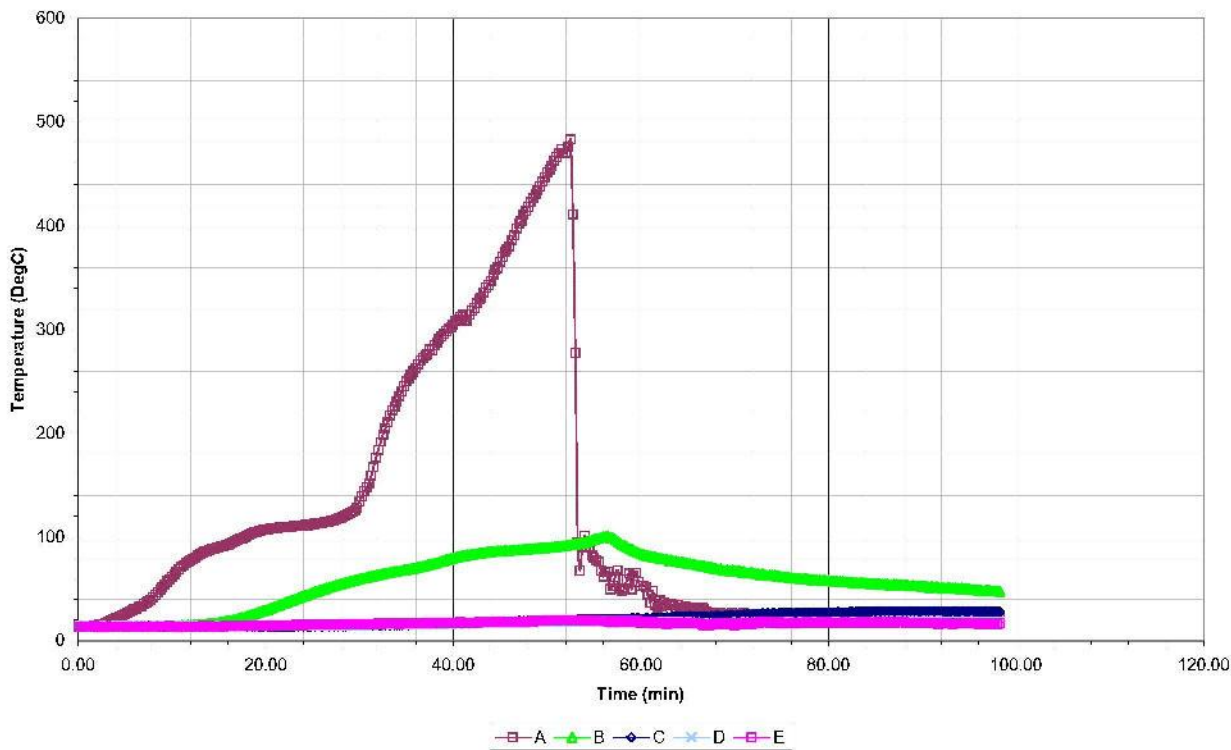
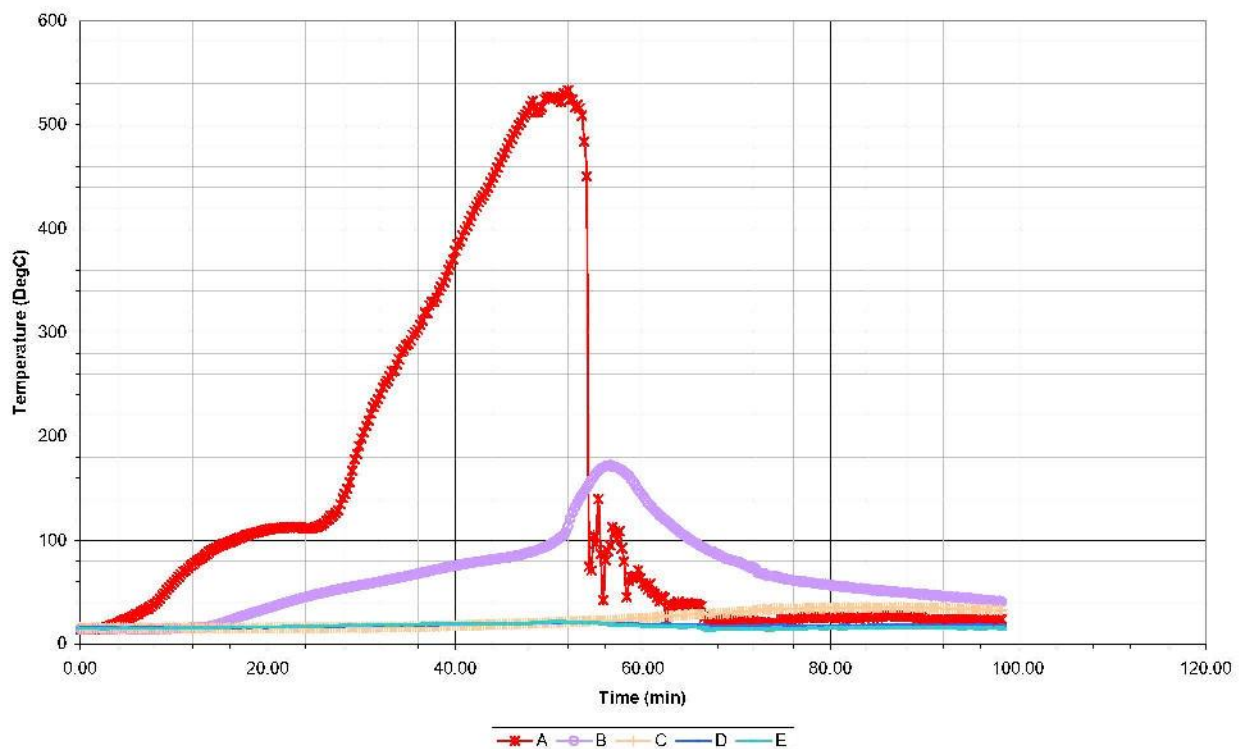


Figure 108 Temperature readings through rear wall on gridline B – Figure F4



Figures 107 and 108 show that the fire was brought under control shortly after fire-fighting operations commenced. In particular, Figure 108 shows the temperature behind the inner layer of oriented strand board initially increasing after the fire had been extinguished and then quickly reducing.

Cavity barrier

The temperatures in the cavity and in the core adjacent to the windows are shown in Figures 109 and 110.

Figure 109 Temperatures in cavity on front wall and in insulated core adjacent to window opening Test F4

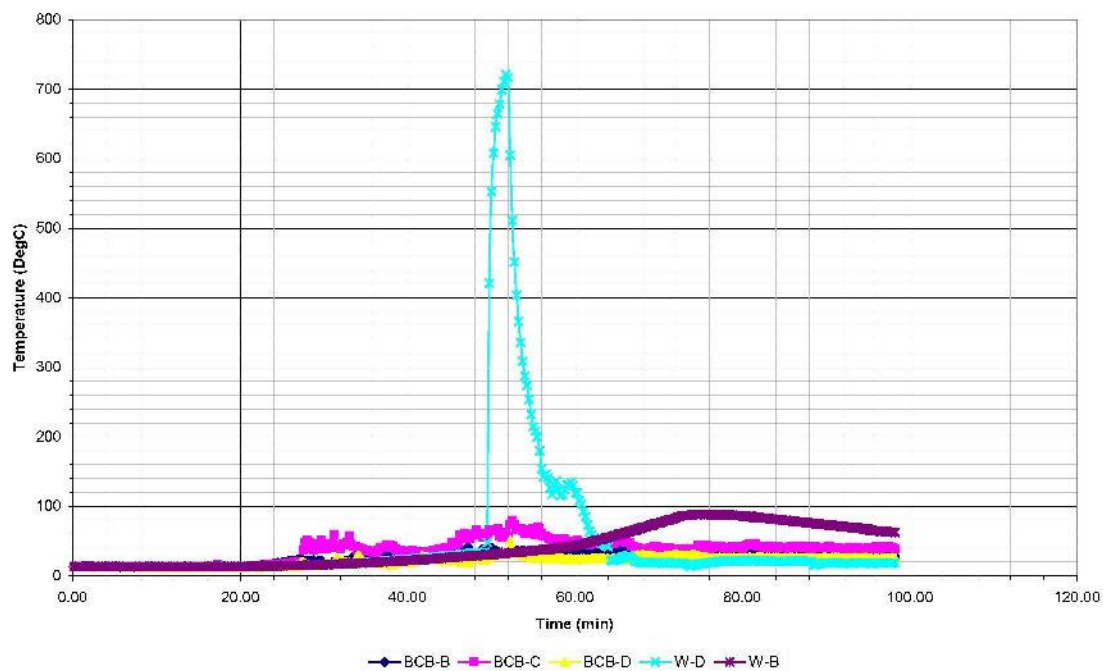
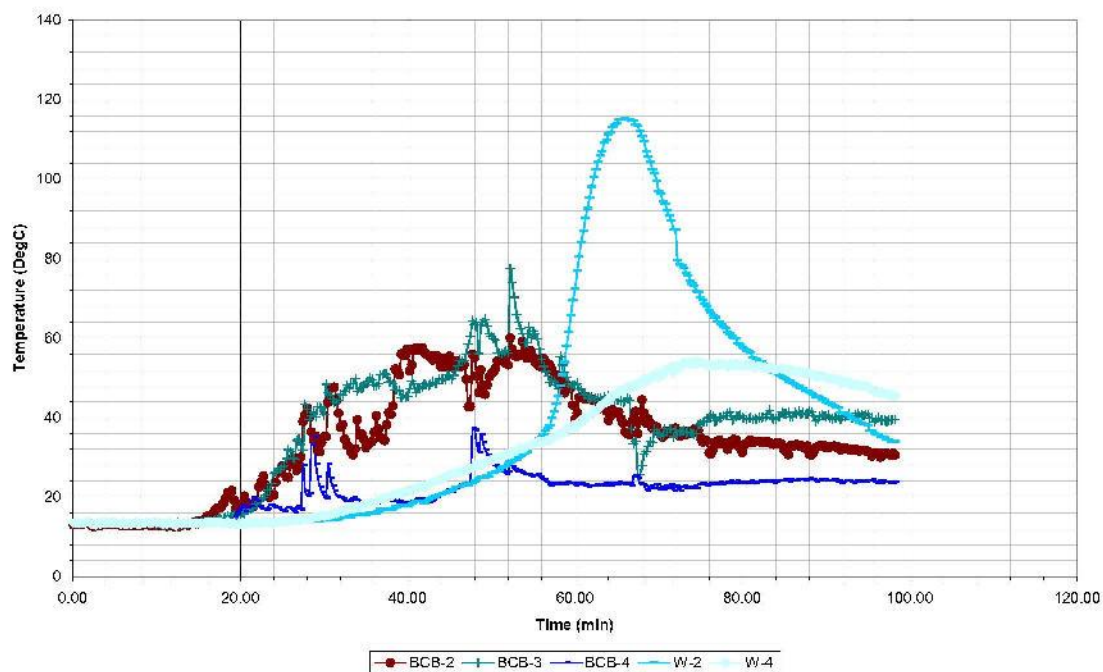


Figure 110 Temperatures in cavity on side wall and insulated core adjacent to window opening – Test F4



The figures confirm that all temperatures within the panels had either stabilised or were reducing at the end of fire-fighting operations. Figure 109 also confirms the observed behaviour of panel flaming close to the front window in the latter stages of the fire test.

Floor void

The temperatures in the floor void at mid-depth between the upper surface of the chipboard flooring and the underside of the plasterboard ceiling were recorded in the positions indicated in Figure 58. The measured temperatures are shown in Figure 111.

Figure 111 Temperatures in the first floor void – Test F4

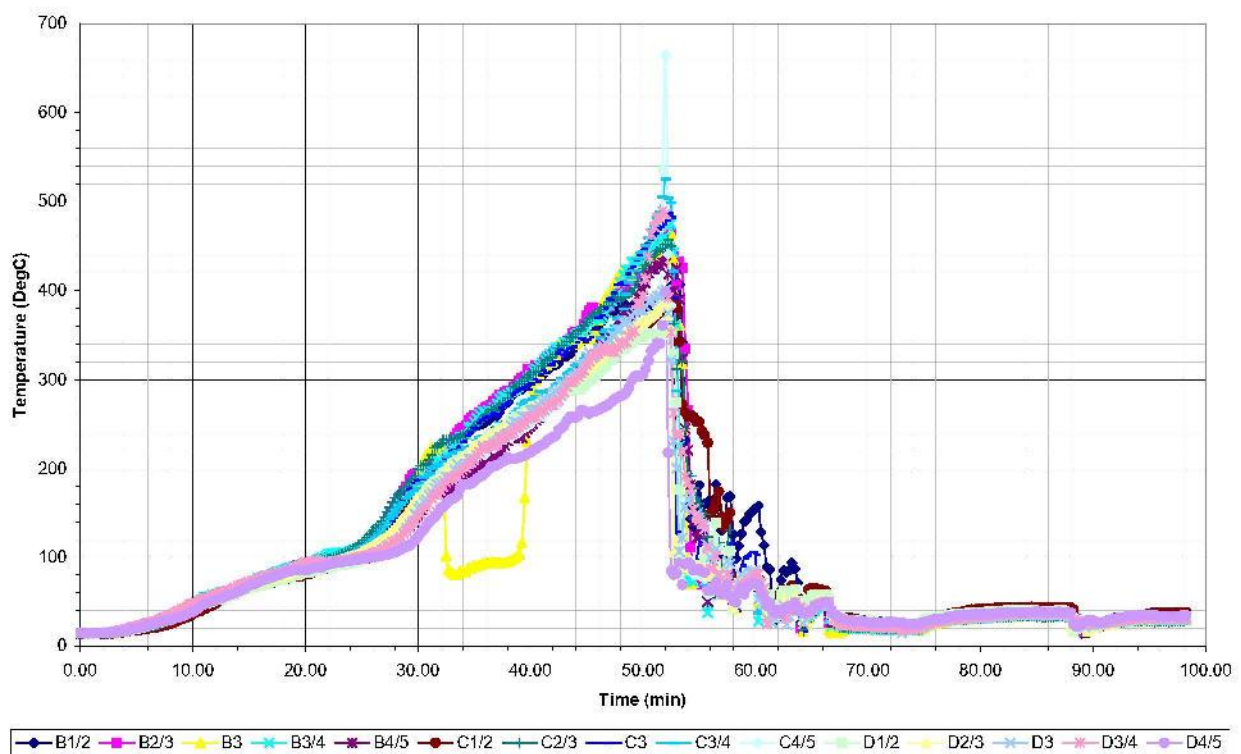


Figure 111 indicates a break through of the fire into the ceiling void and burning of the joists.

2.8.3.3 Structural performance of the building system

The deflection of the first floor relative to the second floor was recorded. Because of the increased risk of structural collapse, only three displacement transducers were used corresponding to the three locations identified in Figure 58 on gridline C (centre of the compartment). The measured deflections are shown in Figure 112.

Figure 112 Mid-span deflection of the first floor relative to second floor – Test F4

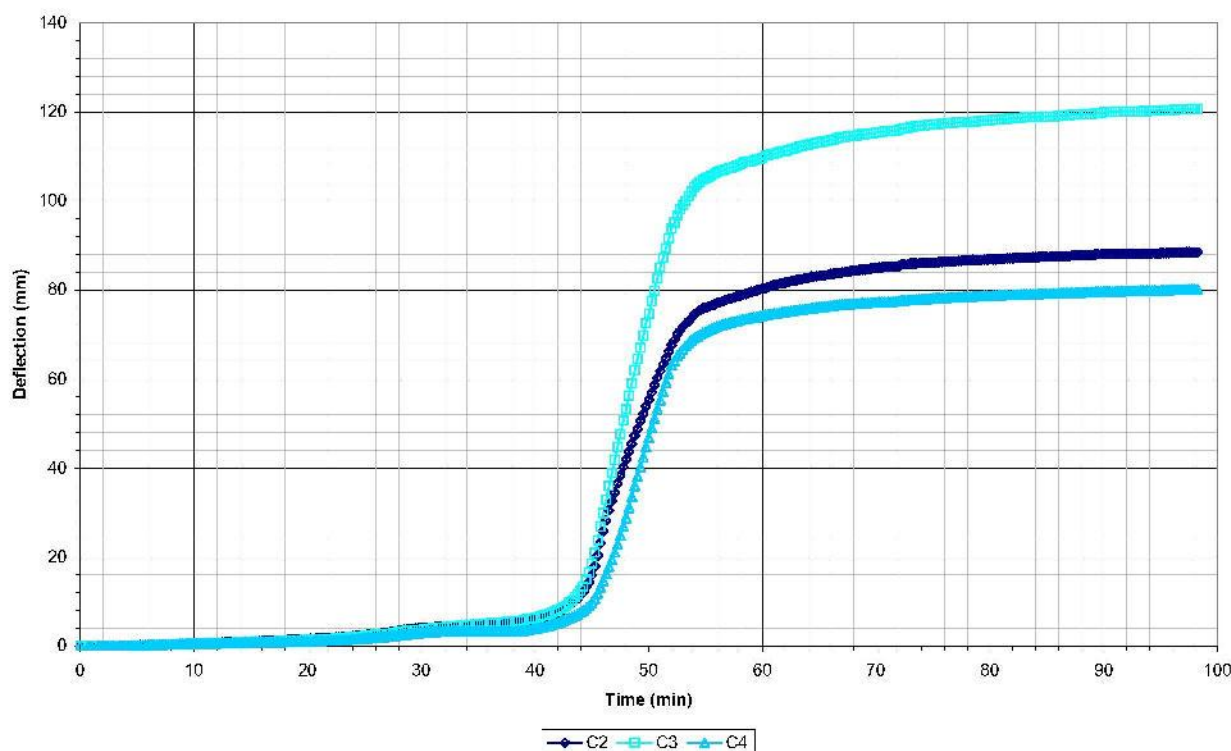


Figure 112 shows a maximum deflection of approximately 120mm with a very rapid rate of deflection just prior to termination of the test, giving little warning of impending collapse.

2.8.3.4 Post-test observations

As with the expanded polystyrene 30 minute test, the most significant damage was to the floor joists following spread of fire to the floor void once the integrity of the ceiling linings had been compromised. As in the previous case, a collapse of the floor has been shown to be the mode of failure for this form of structure. The degree of damage to the floor was less than the corresponding expanded polystyrene case but this was due to a slightly earlier instruction to terminate the test. The damage to the floor joists is shown in Figures 113 and 114.

Figure 113 Damage to engineered floor joist – Test F4



Figure 114 Damage to floor system – Test F4



There was little visible damage to the party wall with the lining remaining intact, see Figure 115. However, there was extensive damage to the remaining (30 minute) walls (Figure 116). During the test, the panels adjacent to the window openings were seen to be contributing to the fire development. At the end of the test, much of the plasterboard had fallen into the compartment. Fire-fighting operations removed all remaining boards making the identification and suppression of localised hot spots much easier.

Figure 115 Limited damage to party wall – Test F4



Figure 116 Damage to front wall – Test F4



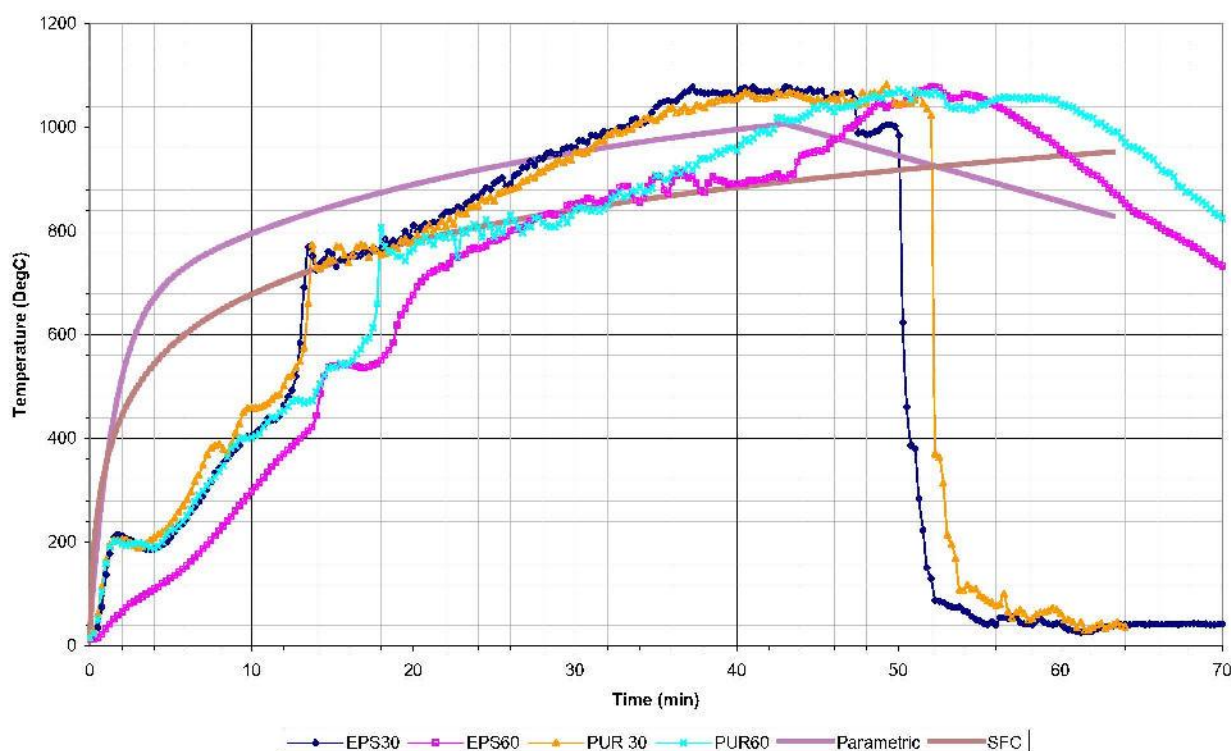
2.8.4 DISCUSSION

The large-scale tests have demonstrated the mode of failure in fire of modern structural insulated panel structures and have identified a number of areas of particular interest. The performance of the buildings has shown that the **system** is capable of achieving the required regulatory performance for the given natural fire exposure condition whilst highlighting a number of issues which require further consideration.

2.8.4.1 Fire development

The measured mean compartment time-temperature response at ceiling level for the four tests is shown in Figure 117.

Figure 117 Compartment time-temperature response for the four large-scale fire tests



Although there are some differences in the time to flashover between the 30 and 60 minute tests, the maximum temperature is almost identical for the four tests. The small differences are probably due to the relative location of the compartments within the BRE test building and the proximity to the nearest external opening. The tests have confirmed the repeatability of the test scenario. The total heat release (the area under the curve) is virtually identical in each case.

2.8.4.2 Fire performance of building system

The results from the tests clearly show a significant difference between the core temperatures for the two types of insulation. Figures 118 and 119 enable a comparison of the core temperature with the expanded polystyrene core showing much higher temperatures. Following the tests, the expanded polystyrene had melted away in many areas but did not contribute to fire development. The polyurethane core formed a char layer which, when sufficient oxygen was available, ignited and led to further fire spread within the core of the panel.

Figures 120 and 121 show similar results in relation to the measured temperature behind the inner layer of oriented strand board. The temperature behind the plasterboard is shown in Figures 122 and 123.

Figure 118 Central core temperatures for the 60 minute buildings

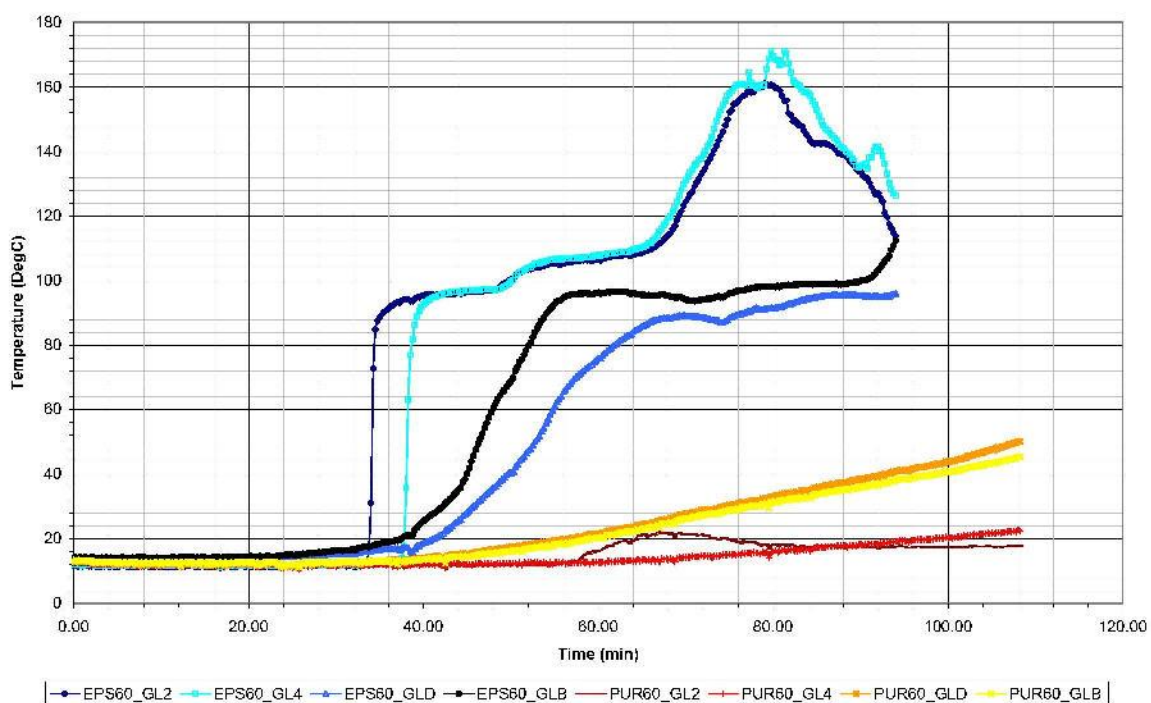


Figure 119 Central core temperatures for the 30 minute buildings

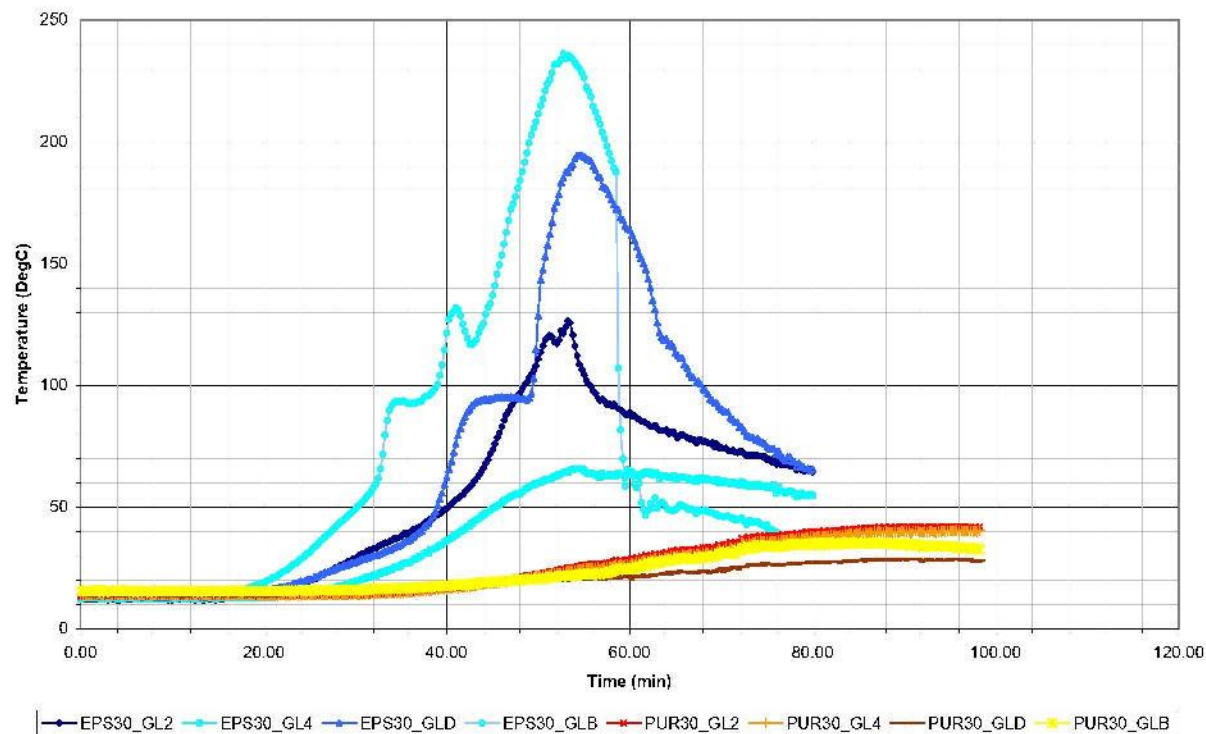


Figure 120 Oriented strand board temperatures for the 60 minute buildings

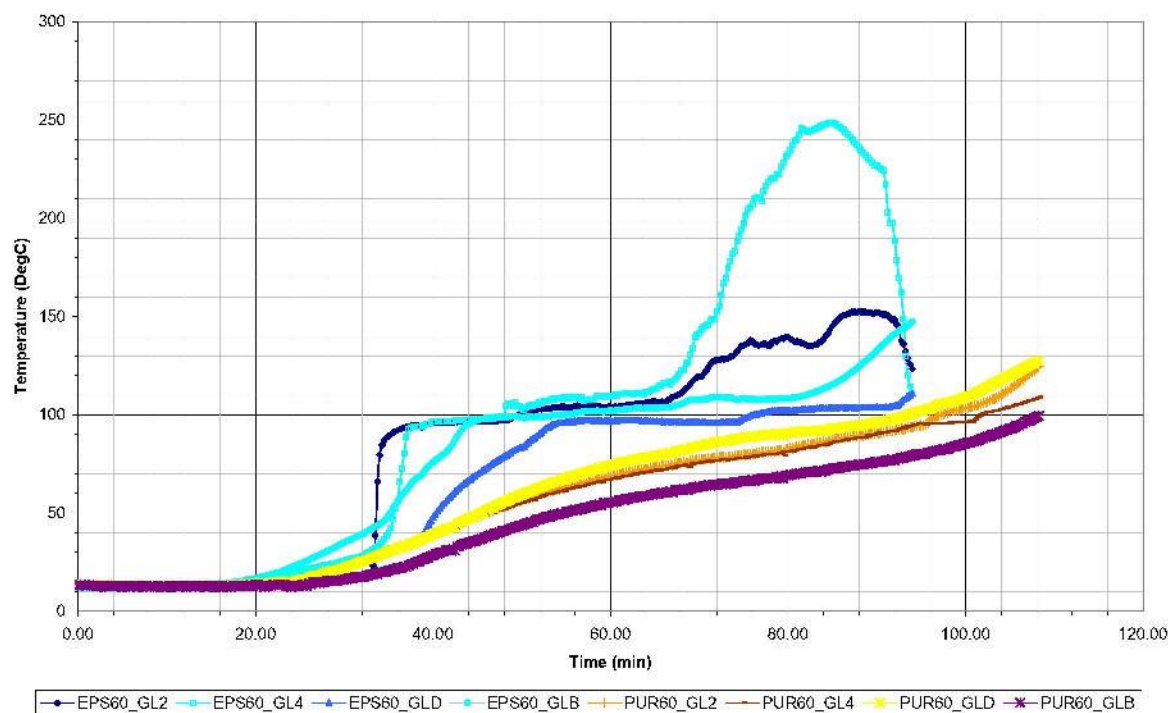


Figure 121 Oriented strand board temperatures for the 30 minute buildings

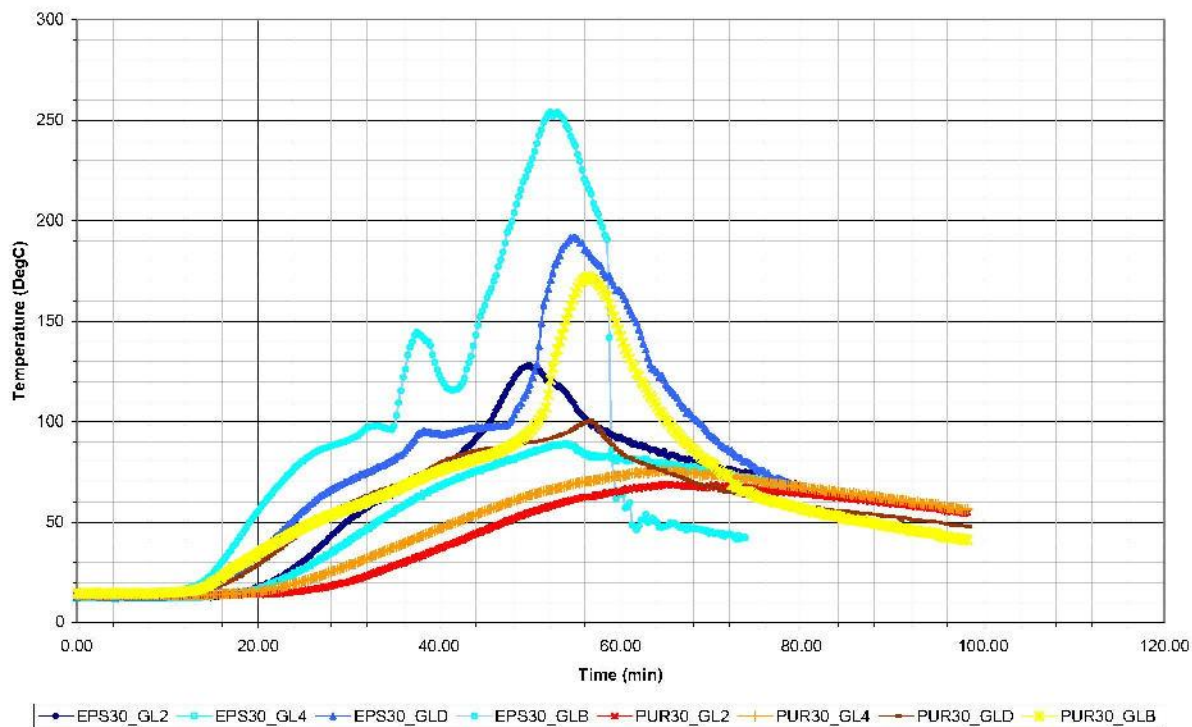


Figure 122 Temperature at rear of plasterboard for the 60 minute buildings

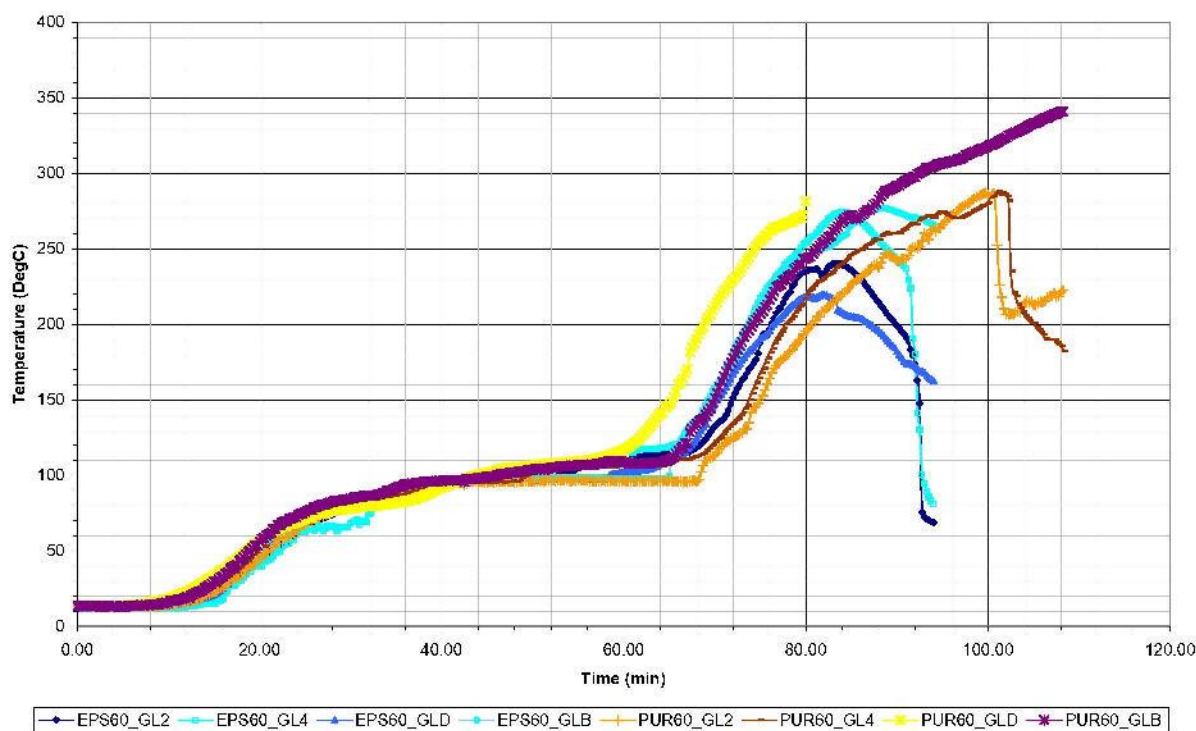
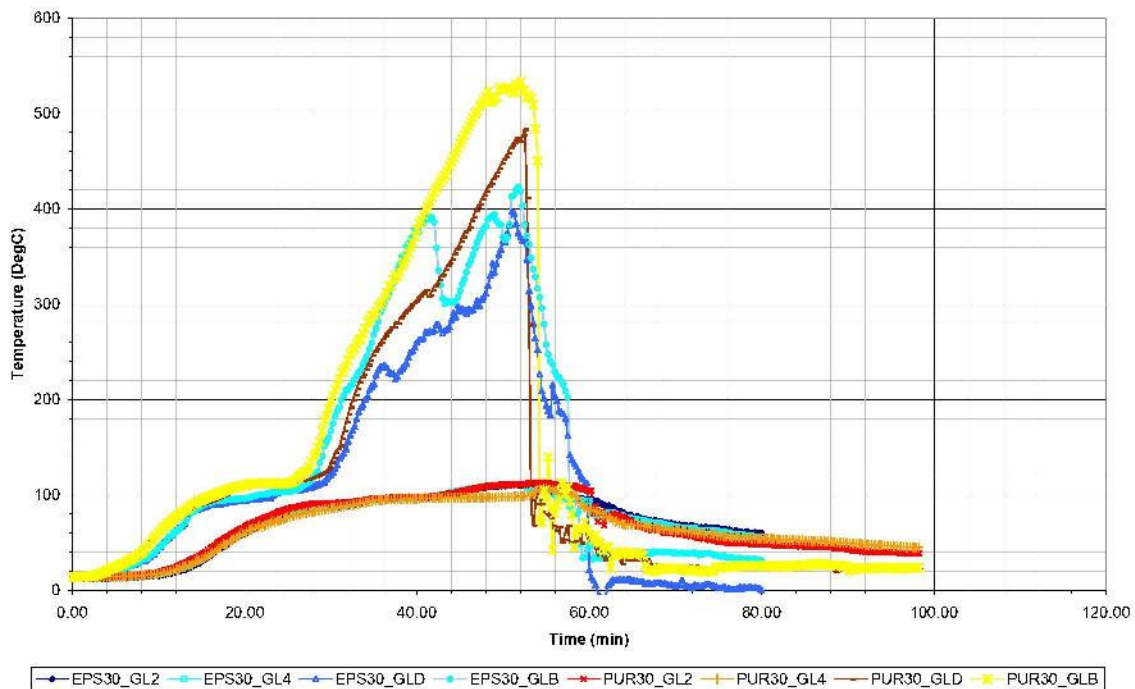


Figure 123 Temperatures at rear of plasterboard for the 30 minute buildings



Figures 122 and 123 show the temperature behind the plasterboard to be increasing for the polyurethane structure at the end of the test both for the 30 and 60 minute cases. This is due to the effectiveness of the insulation compared to the expanded polystyrene system where heat is effectively trapped between the fire side and the core of the insulation material.

2.8.4.3 Structural performance of building system

The relationship between floor void temperature and deflection is shown in Figure 124 for the two 60 minute structures.

Figure 124 Displacement-temperature for floor void for the 60 minute buildings

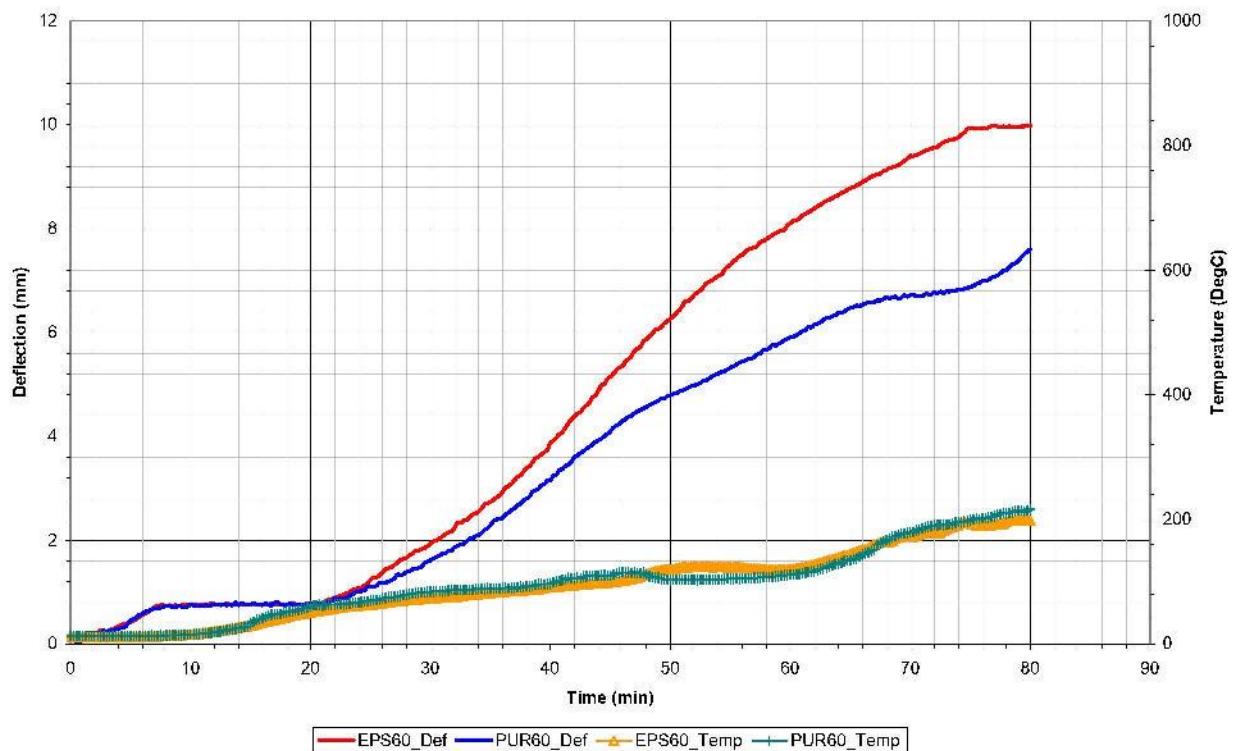
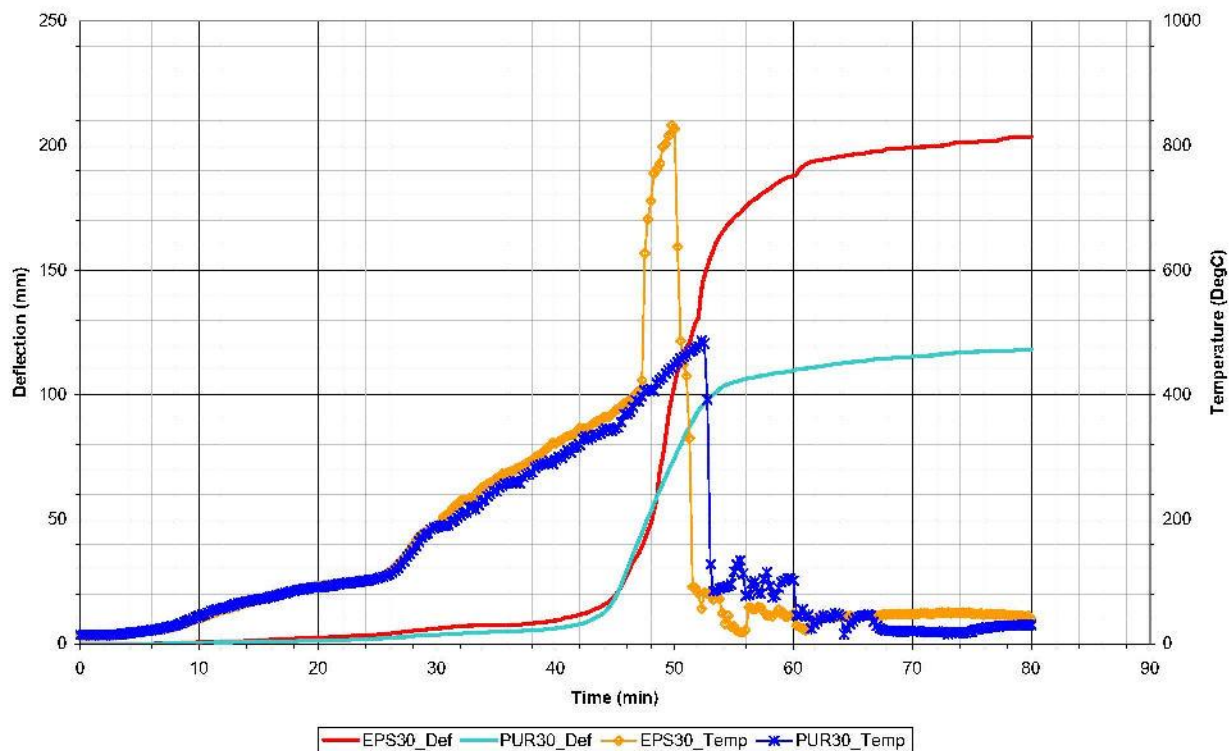


Figure 124 shows very similar behaviour between the two different types of structural insulated panel structure. The polyurethane 60 deflection shown refers to the off centre (grid line C2) displacement due to an error with mid-span (C3) displacement transducer. Hence, there is a slightly lower value for the polyurethane test.

The relationship between floor void temperature and deflection is shown in Figure 125 for the two 30 minute structures.

Figure 125 Displacement-temperature for floor void – 30 minute buildings



Both the temperature and the displacement plots show consistent behaviour. The larger deflections associated with the expanded polystyrene 30 minute test are a function of the higher temperatures in the floor void. There is little doubt that had the polyurethane test not been extinguished so rapidly that similar levels of displacement and temperature would have been reached within a matter of minutes.

2.8.4.4 Post-test observations

The test results and observations have highlighted a number of important issues in relation to the inherent fire resistance of the structural system and the role of the Fire and Rescue Services in dealing with fires in structural insulated panel buildings:

- The structural insulated panel systems tested in this project are capable of achieving the requirements of the Building Regulations in relation to B2 internal fire spread (linings) and B3 internal fire spread (structure).
- The mode of failure of the system is excessive deflection of the first floor caused by ignition and rapid combustion of the engineered floor joists. The rate of deflection increases very rapidly as the floor system approaches collapse. This behaviour is not influenced by the performance of the structural insulated panel system and would be the same for other panellised systems or traditionally built timber frame.
- There was no collapse of the floor in any of the tests despite the significant (>200mm or span/20) deflections. The chipboard flooring appears to have

contributed to the stability of the floor at large deflections. Inevitably, in the instance of both the polyurethane 30 and expanded polystyrene 30 compartments, the floors would have collapsed had the fire and rescue service not intervened. In addition, the introduction of a localised load, such as a person, would have almost certainly resulted in the collapse of the 30 minute floors at such large deflections.

- There was no collapse of the wall panels in any of the tests.
- There was no integrity failure of either the wall panels or the floor system with the exception of a very localised failure in the area of the unsealed lifting eyes (for the expanded polystyrene 60 test).
- At the end of the tests, the composite action assumed in design can no longer be relied on due to either degradation of the inner layer of oriented strand board and melting of the core (expanded polystyrene) or degradation of the oriented strand board and combustion of the core (polyurethane). As there was no collapse of the buildings, it is clear that an alternative load path was mobilised at the fire limit state. Load carrying capacity was maintained through the solid timber ring beams at first floor level and the presence of intermediate timber in the panels either at junctions between panels or around openings and the presence of timber studs in the corner.
- There was no significant damage to the ring beam in any of the tests.
- There was no evidence of any failures in the connections between the engineered floor joists and the timber ring beams.
- The inclusion of service penetrations, electrical sockets, in the polyurethane tests made no appreciable difference to the performance of the panel or of the structure.

Although the tests have demonstrated the ability of a structural system composed of structural insulated panels and engineered floor joists to meet the requirements of the Building Regulations in terms of performance in fire, there are a number of issues that need to be brought to the attention of the Fire and Rescue Services. In particular:

- The rapid rates of deflection (compared to a solid timber floor system) associated with breakthrough of fire into the floor void and potential for a sudden collapse of the floor system.
- The melting of the expanded polystyrene insulation before the plasterboard has fallen away, reducing the load bearing capacity of the composite panels in the latter stages of a fire. Where redundant timber studs do not exist, this could result in collapse of the wall panels.
- Smouldering combustion of the inner face of the polyurethane core leading to ignition once sufficient air is available. This may coincide with removal of the remaining plasterboard linings by the fire and rescue service.
- The results and observations from both the 30 minute tests show that it is possible to fully extinguish all hidden seats of combustion following a serious fire. However, it is necessary to remove all residual plasterboard and crews should be aware of the risks of floor and wall collapse.

- Consideration should be given to reviewing the current “defend in place” strategy for medium-rise occupancies where the structural frame is combustible.

The performance of the structural elements in fire is largely a function of the quality of the materials used to provide the linings to the walls, ceiling and around openings and the quality of workmanship used to install the linings. The specification summarised in Tables 37 to 40 could serve as a generic template for the type of plasterboard to be used for specific applications and the type and spacing of the fixings to be used. Clearly, such a generic specification needs to be independent of any particular supplier. One specific detail which can be identified immediately is that any pre-formed holes in the structural insulated panels used for lifting and erection are filled in with a fire resistant filler or foam prior to installation of the plasterboard linings or construction of the external façade.

2.9 Fire performance of engineered floor joists

As a result of a contract variation the project also incorporated a task to investigate the fire performance of engineered floor joists. Such floor systems are widely used within the construction industry and universally adopted within structural insulated panel buildings. The primary objective of this task was to establish the mode of failure for specific types of floor joist subject to a similar realistic fire scenario. This objective was achieved through an experimental programme consisting of three large-scale natural fire tests. Three individual flooring systems were investigated: a timber I beam floor (with oriented strand board web); a composite timber-steel floor system and a traditional solid timber floor. Each test was instrumented with thermocouples and deflection transducers to evaluate thermal and structural response.

2.9.1 INTRODUCTION

The primary objective of the work on the fire performance of engineered floor joists was to establish the mode of failure for specific types of floor joist subjected to a similar realistic fire scenario. This objective was achieved through an experimental programme consisting of three large-scale natural fire tests. Three individual flooring systems were investigated: a timber I beam floor (with oriented strand board web); a composite timber-steel floor system and a traditional solid timber floor. Each test was instrumented with thermocouples and deflection transducers to evaluate thermal and structural response.

This section provides details of the design of the fire compartment used for the three fire tests on timber floor joists and documents all relevant results and observations.

2.9.2 COMPARTMENT FIRE DESIGN

The compartment fire design was essentially the same as that used for the large scale fire tests and discussed in some detail in section 2.5.

2.9.3 COMPARTMENT CONSTRUCTION

The overall geometry of the fire compartment is the same as that used for the large scale fire tests discussed in section 2.5. However, in this case the walls were formed from load bearing concrete blocks rather than structural insulated panel panels. The floor joists were supported on proprietary masonry joist hangers. The joist hangers were fixed to the

wall and built into the mortar bed as work proceeded. According to manufacturer's instructions and published guidance, conventional masonry joist hangers will not develop their full design capacity until a minimum of 675mm of masonry has been installed and allowed to cure above the hanger. For this reason, the external walls were built up to a height of 3.2m, although the floor to ceiling height was only 2.4m.

Figures 126 and 127 show various details of the compartment during construction.

Figure 126 Rear elevation of compartment showing the access door (which will be sealed during tests)



Figure 127 Front elevation of test compartment showing ventilation opening



2.9.4 TEST 1 – SOLID FLOOR JOISTS

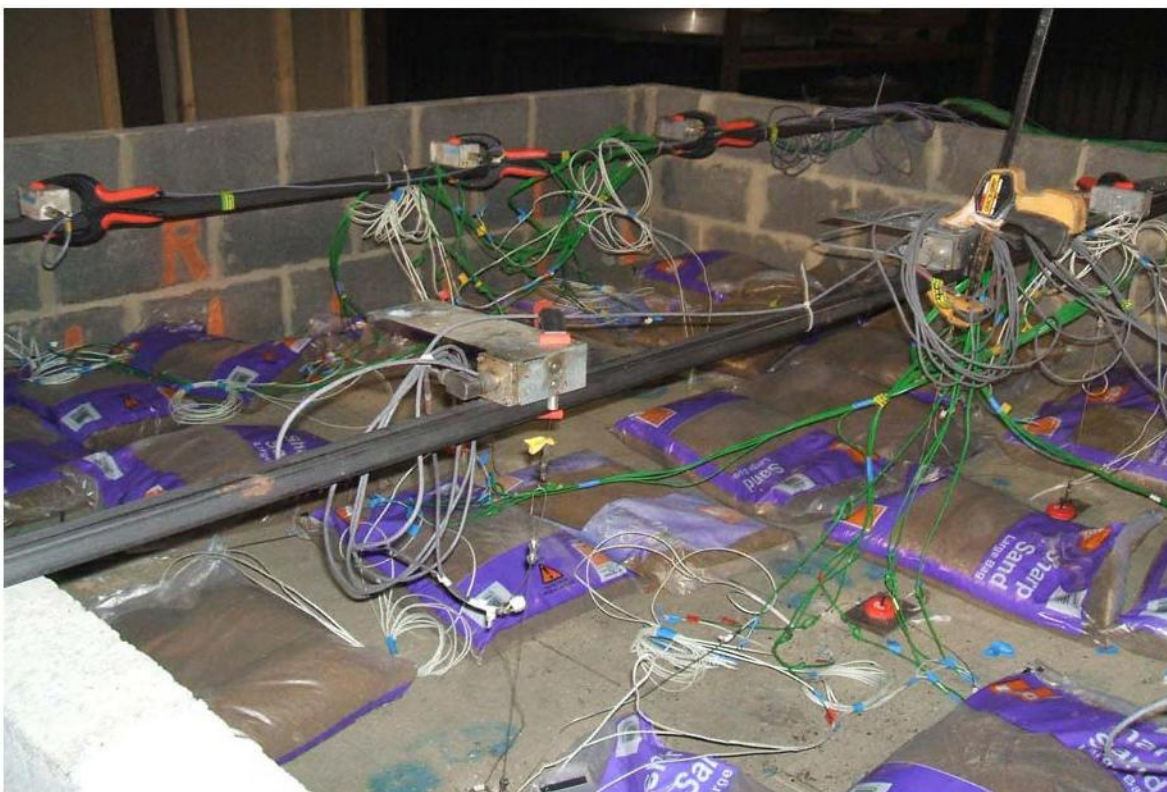
Test 1 investigated the response of “traditional” solid timber floor joists to a severe natural fire scenario and acted as a control specimen against which the performance of the more innovative engineered floor joists could be assessed following Tests 2 and 3.

The first floor system was made up from 45mm by 220mm solid floor joists spaced at 400mm centres. Resilient bars were fixed to the floor joists and used to support two layers of 12.5mm fire rated plasterboard in accordance with the manufacturer’s instructions. The upper surface was composed of 22mm P5 tongue and grooved chipboard fixed to the upper surface of the joists. Figure 128 shows the floor joists in location prior to the installation of the chipboard flooring. The load is transferred to the walls of the fire compartment via masonry joist hangers built into the walls as the work proceeded. Both the hangers and the resilient bars are clearly visible. Figure 129 shows the chipboard flooring in place, the instrumentation used to monitor the response of the floor and the sandbags used to provide the imposed loading.

Figure 128 Upper surface of floor prior to installation of chipboard



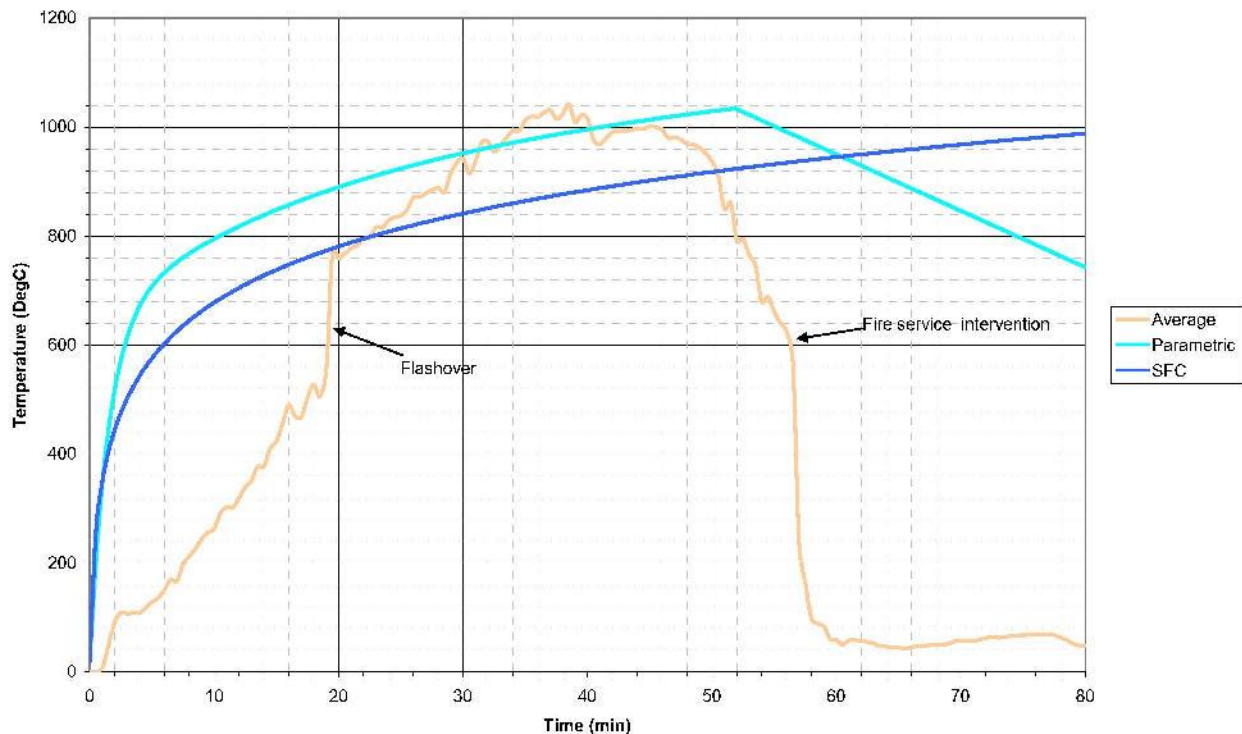
Figure 129 Upper surface of floor showing chipboard, instrumentation and imposed load



2.9.4.1 Fire development

Figure 130 shows graphs of the measured compartment temperature versus time, the standard fire curve and the predicted response using the parametric approach set out in the fire part of the Eurocode for Actions¹⁴.

Figure 130 Graph of compartment temperature versus time – Test 1



The fire severity, as indicated by the area under the curve, is equivalent to 60 minutes exposure to the standard curve. The parametric approach provides a reasonably accurate prediction of peak temperature and overall duration. The cooling phase for the test was curtailed due to fire and rescue service intervention. However, at this time the peak compartment temperatures had been attained and the fire was in the early stages of the cooling phase.

2.9.4.2 Fire performance of floor system

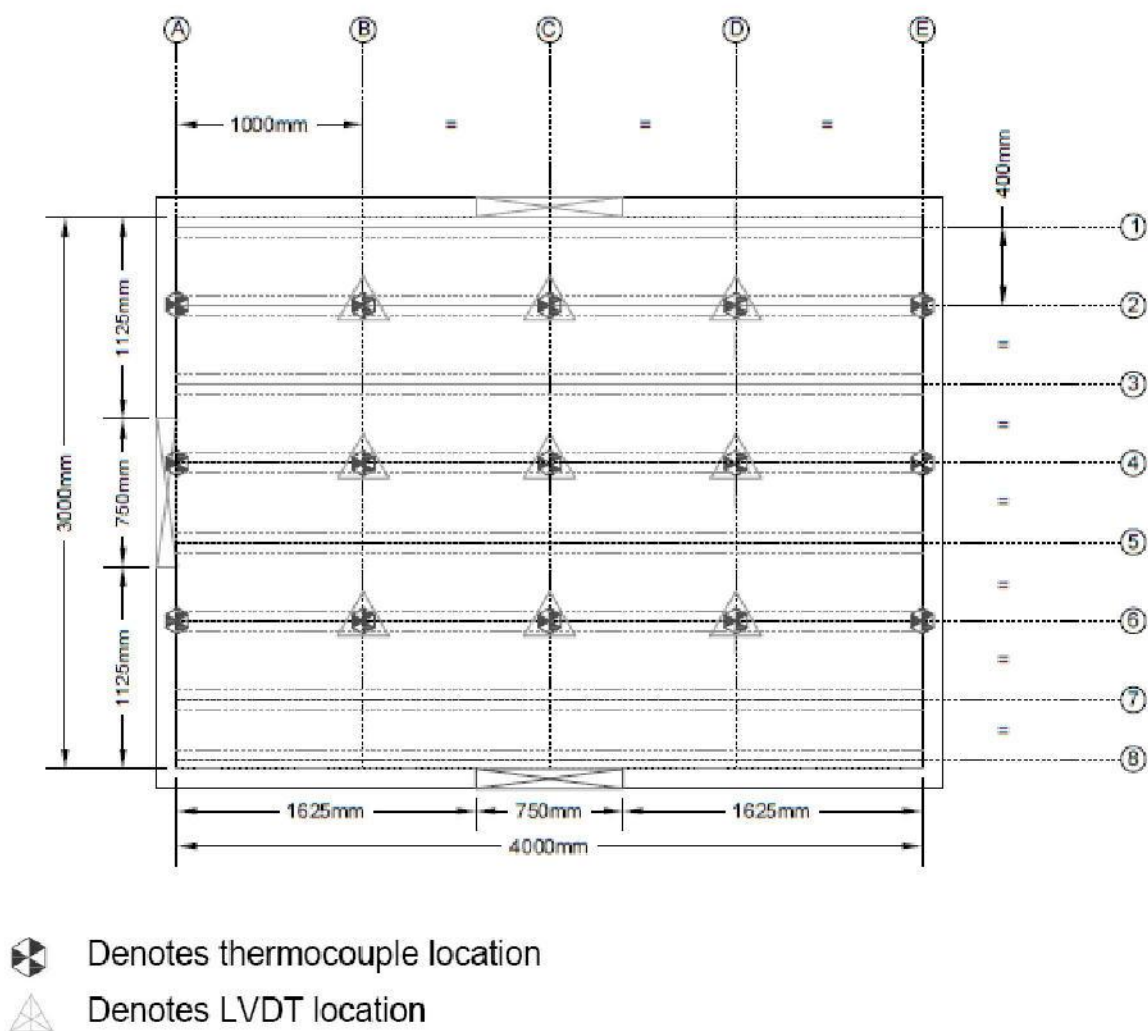
During the steady-state phase of fire development, with compartment temperatures around 1000°C, a number of the wall boards fell away from the masonry substrate. Towards the end of this phase of fire development, localised areas of the exposed layer of ceiling board fell into the compartment with gaps opening on the lower layer, allowing hot gases and sporadic flaming into the floor space between the joints. Figure 131 clearly illustrates this.

Figure 131 Damage to ceiling boards leading to localised flaming of floor joists



The extent of the damage to specific joists following localised failure of the ceiling linings can be assessed with reference to the temperature readings and visual observation. Thermocouple readings indicate temperatures on the surface of the joists in excess of 800°C which is well above the notional ignition temperature of the material. From visual observation, the most significant damage occurred in the north east corner of the compartment in the area around C2 and B2 (see Figure 132).

Figure 132 Plan of fire compartment showing gridlines for identification



Figures 133 and 134 show the measured temperatures with their associated local air temperature in locations B2 and C2, respectively.

Figure 133 Graphs of joist temperatures versus time at location B2

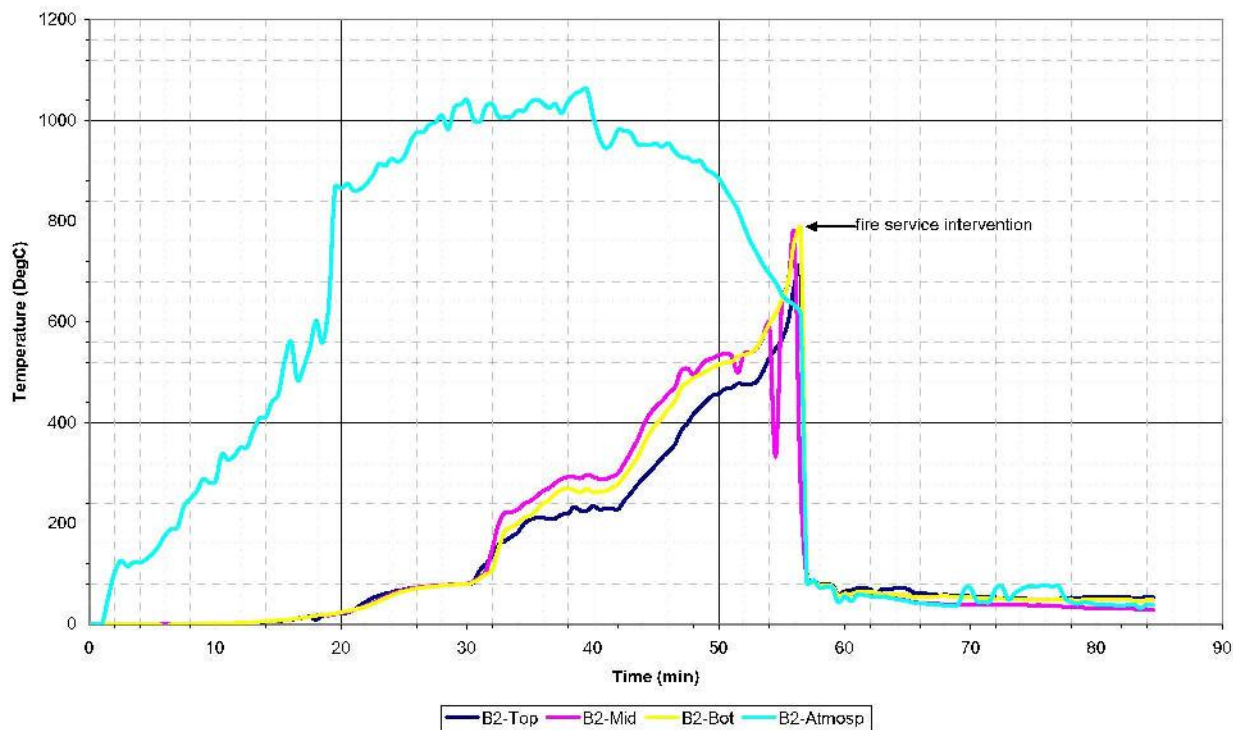
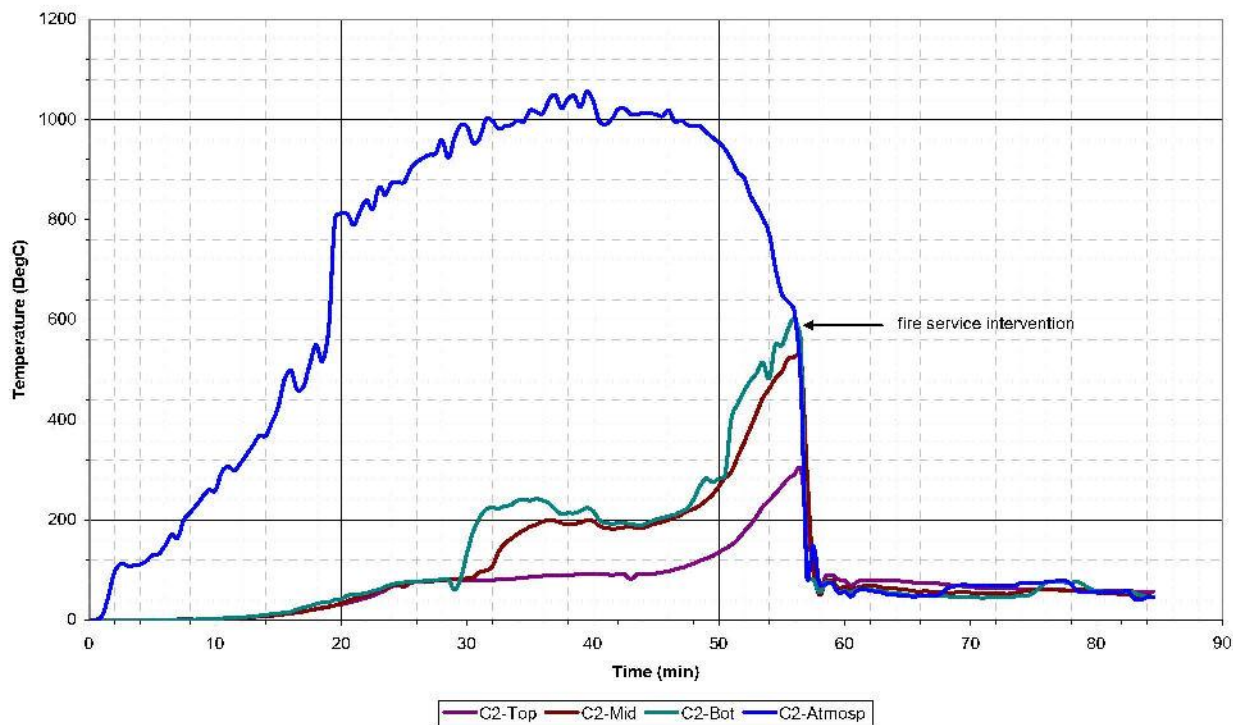


Figure 134 Graph of joist temperatures versus time at location C2



The results are confirmed by visual observation. Figure 133 shows the extensive charring towards the front of the compartment (joists 1 and 2) as well as localised charring of joist 5.

Figure 135 Charring of floor joists following test



Figure 136 shows the extent of charring, where the char layer has been scraped away back to the solid timber. The maximum depth of charring was approximately 15mm, leaving a residual core of approximately 15mm of solid timber.

Figure 136 Extent of charring to floor joist on gridline 1



Despite the extensive flaming in the ceiling void, there was no significant breakthrough of the fire through the chipboard flooring. The flooring itself provided some resistance to the spread of flame; see the visible charring in Figure 137.

Figure 137 Underside of floor joist on gridline 1 showing charring of chipboard flooring



2.9.4.3 Structural response of floor system

The floor was loaded with sandbags to provide an imposed load of 0.75kN/m^2 or $0.5 \times$ the design imposed loading. This was felt to be a realistic load level for a dwelling and also corresponds to the fire limit state partial factor for imposed loading from the Eurocode¹⁴. A reading was taken of the deflection of the floor slab under the applied loading, prior to ignition. The results are illustrated in Figure 138.

Figure 138 Deflection under load in all locations

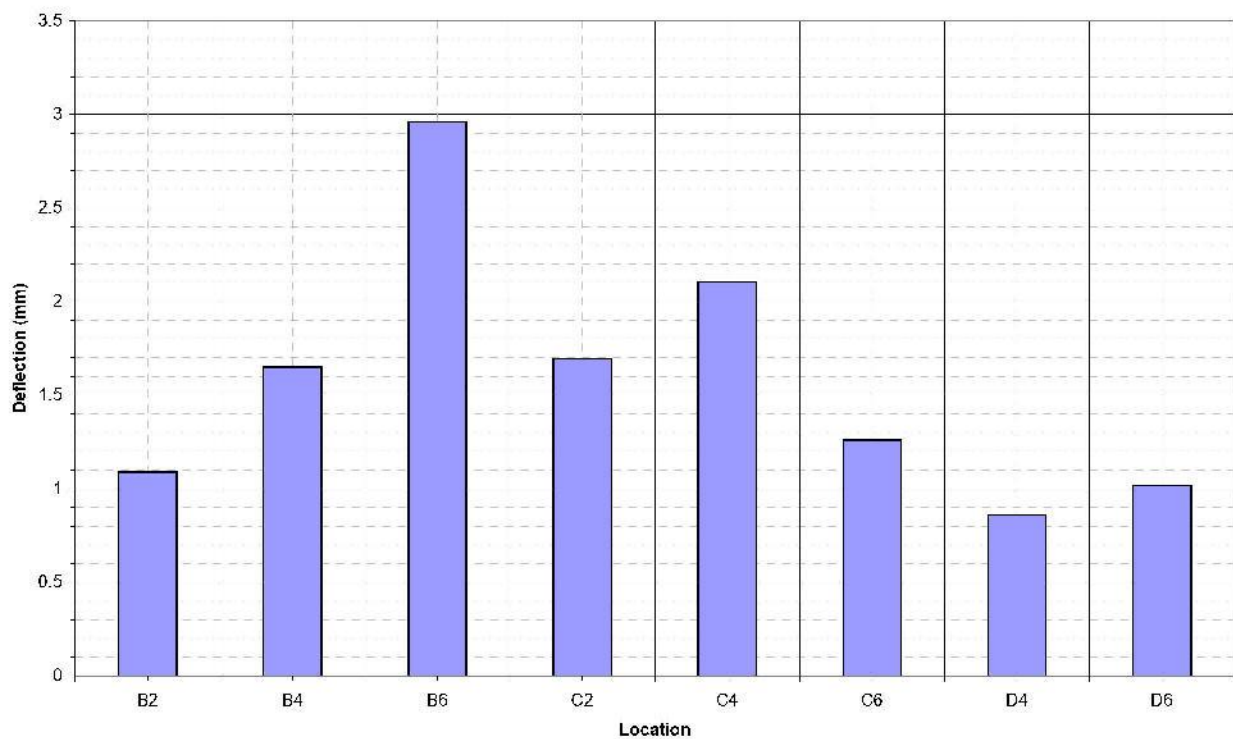


Figure 139 shows the load-deflection behaviour for the duration of the test. It shows little appreciable movement up to approximately 30 minutes, followed by a rapid increase in the rate of deflection up to the point where the test was terminated. It is unclear whether this point corresponds to the localised loss of the exposed layer of plasterboard or to a change in heat transfer characteristics due to moisture migration through the plasterboard or to some combination of the two.

As expected, the largest deflections occur in the area where the joist temperatures were highest and where flaming in the ceiling void was observed during the test.

Figure 139 Graph of deflection under load versus time in all locations

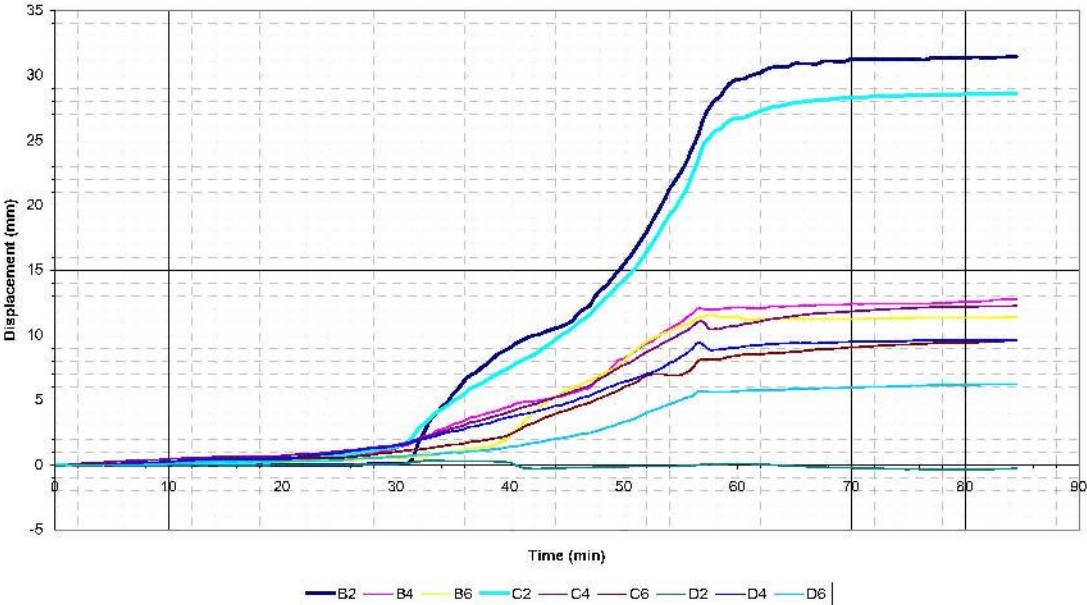
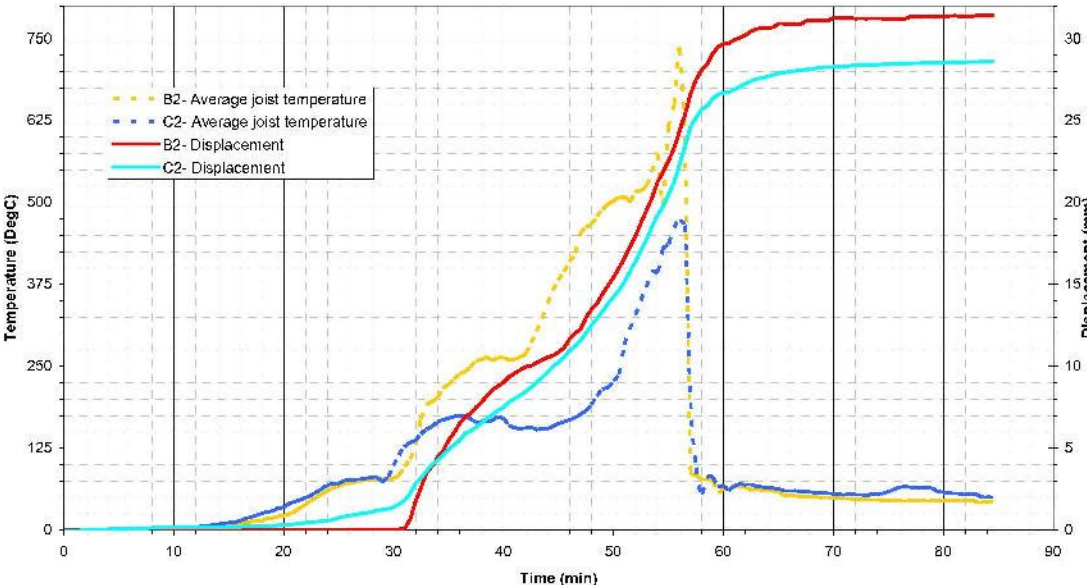


Figure 140 shows the relationship between joist temperature and deflection for the locations of most significant damage (B2 and C2).

Figure 140 Relationship between average joist temperature and displacement at locations B2 and C2



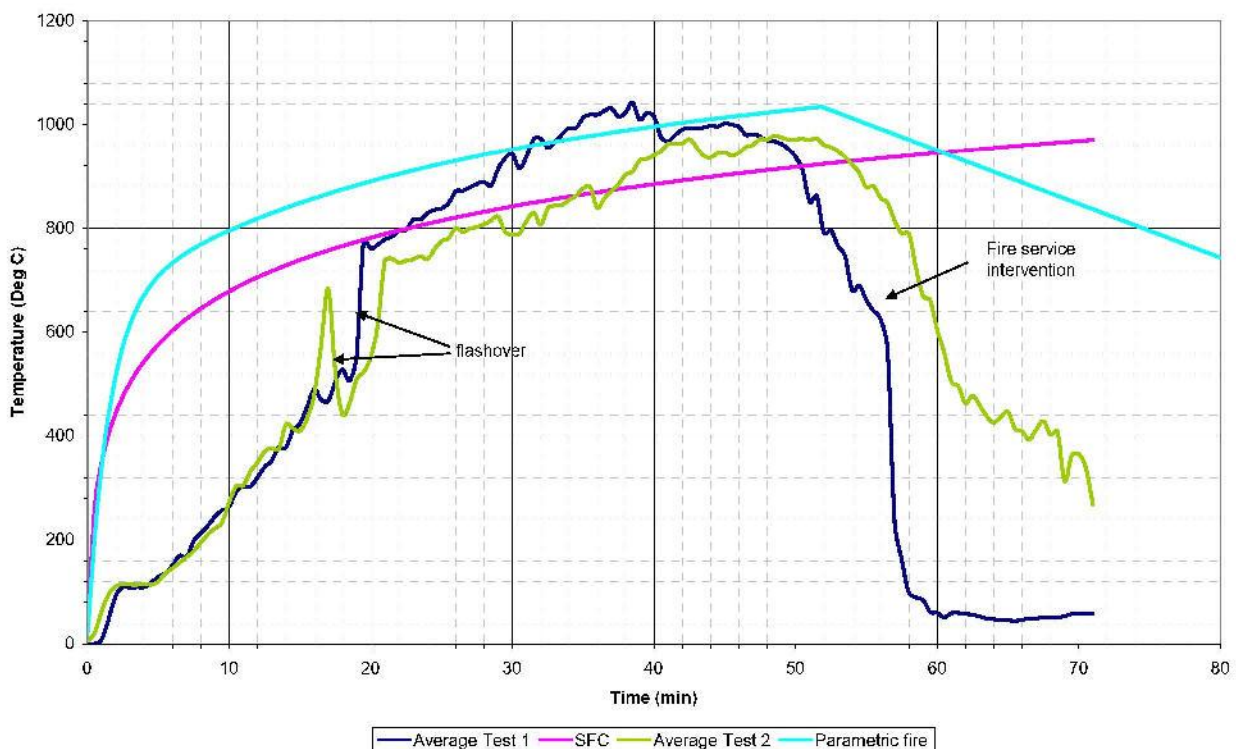
2.9.5 TEST 2 – TIMBER I JOISTS

Test 2 investigated the thermal and structural response of a typical engineered floor joist to an identical test scenario to Test 1. In this case, the floor joists consisted of 220mm deep I joists consisting of solid timber (45mm wide) top and bottom flanges to carry the flexural loads and a 9mm thick oriented strand board web to transfer the shear forces. In accordance with the manufacturer's instructions for a 60 minute separating floor, the joists were protected on the underside by a ceiling made up of two layers of 15mm fire rated plasterboard fixed to the lower flange via resilient bars. Note that this is a higher level of protection than the previous system which utilised two 12.5mm fire resistant boards. The top surface of the floor was formed from 22mm chipboard as in Test 1.

2.9.5.1 Fire development

Figure 141 compares the average compartment temperature versus time graphs for Tests 2 with Test 1 and the standard fire curve and the predicted response using the parametric approach in the fire part of the Eurocode for Actions¹⁴.

Figure 141 Graph of average compartment temperature versus time - Tests 1 and 2



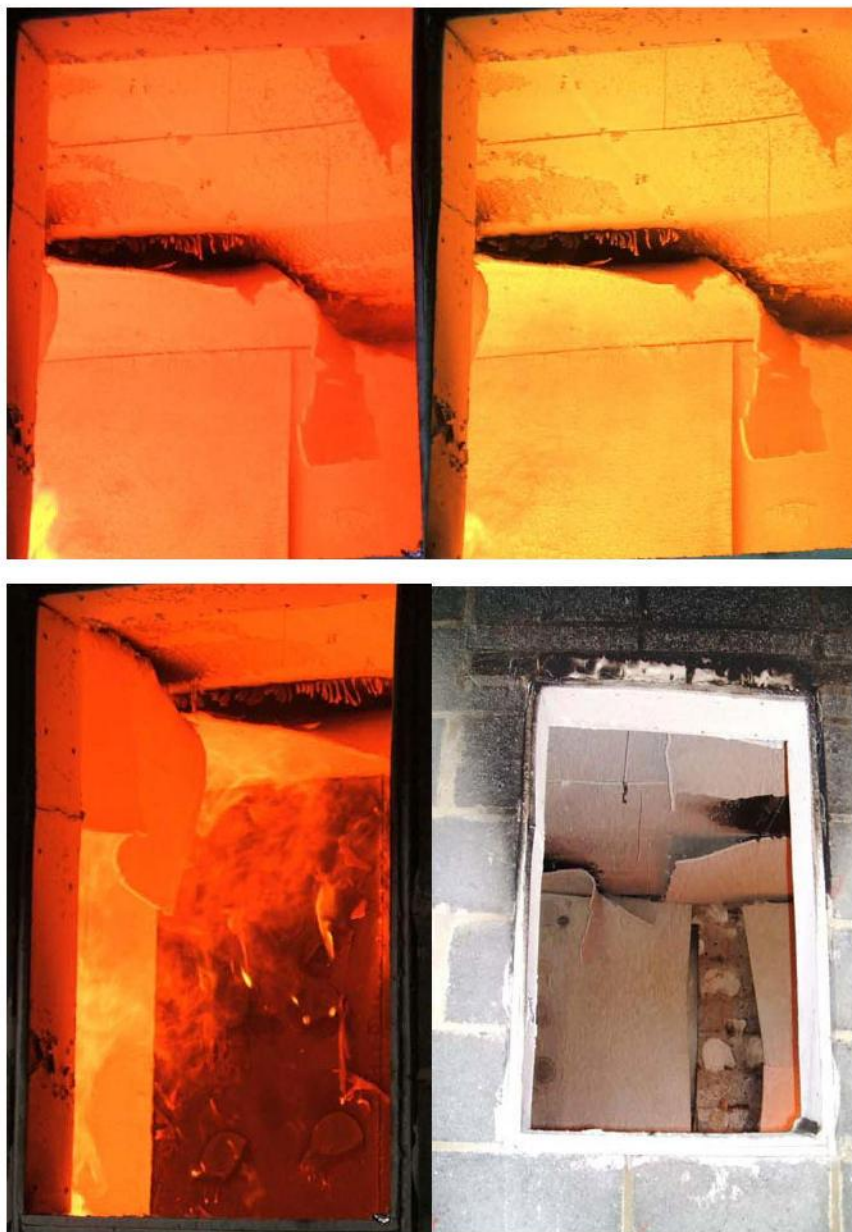
Both curves are similar in terms of overall severity. Problems with cross-draught led to an initial peak in atmosphere temperature in Test 2 followed by a reduction. This was overcome by restricting the ventilation prior to the advent of flashover and the full involvement of all combustibles within the compartment. There is good agreement with the parametric prediction in both cases.

2.9.5.2 Fire performance of floor system

Although the overall fire development was very similar for Test 1 and Test 2, with flashover occurring in a similar time frame the plasterboard appeared to survive for longer in Test 2 with the first observed loss of the exposed layer of ceiling board occurring approximately 49 minutes from ignition. At this point, temperatures within the compartment had effectively peaked.

Although damaged, the inner layer of boards remained relatively intact and provided protection to the floor joists for a period sufficient for external flaming to have died down to the extent that flames were no longer in contact with the ceiling. This is shown in the sequence of photographs in Figure 142.

Figure 142 Performance of plasterboard



Consequently, with one exception at location C4 close to the centre of the compartment, measured joist temperatures were below 175°C for the duration of the test. Unlike Test 1, it was therefore not necessary to extinguish the fire to prevent fire spread through the floor and subsequent damage to instrumentation. Figure 143 shows the measured joist temperatures at location B6. Figure 144 shows the average joist temperatures for all locations.

Figure 143 Graph of average joist temperatures versus time at location B6

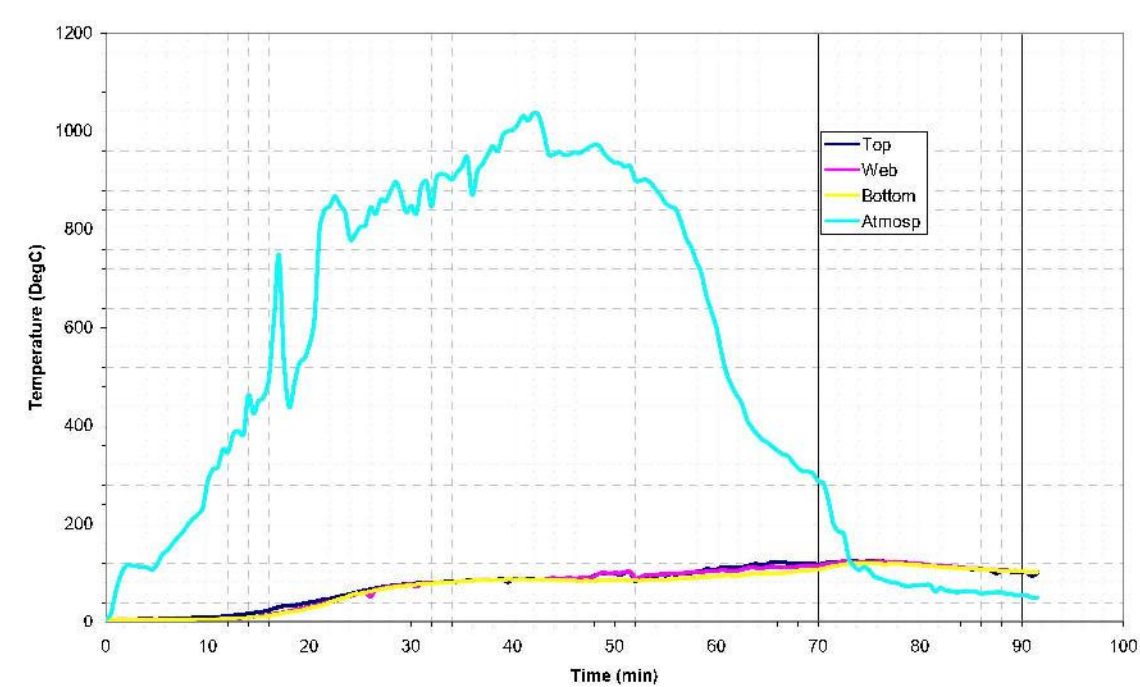
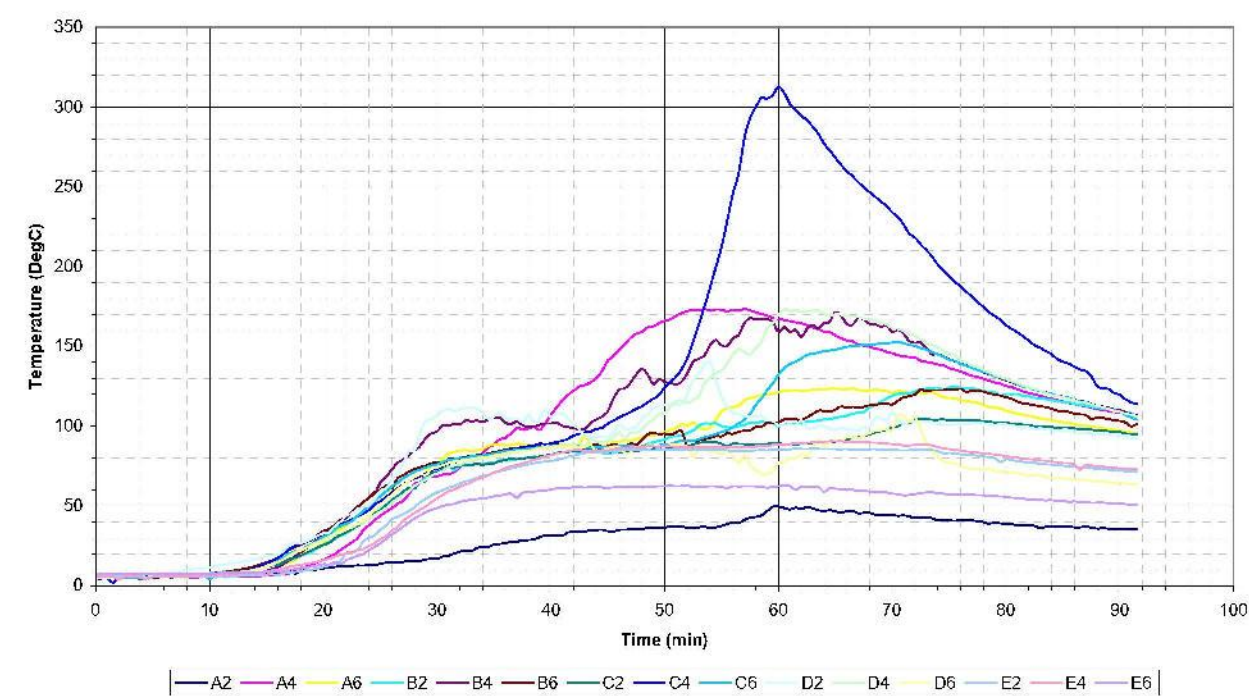


Figure 144 Graph of average joist temperatures versus time in all locations



The measured peak temperatures and observations following the test show that at least one of the joists must have been very close to the self-ignition temperature. Figure 145 illustrates the charring of the bottom flange, the oriented strand board web and, particularly the top flange.

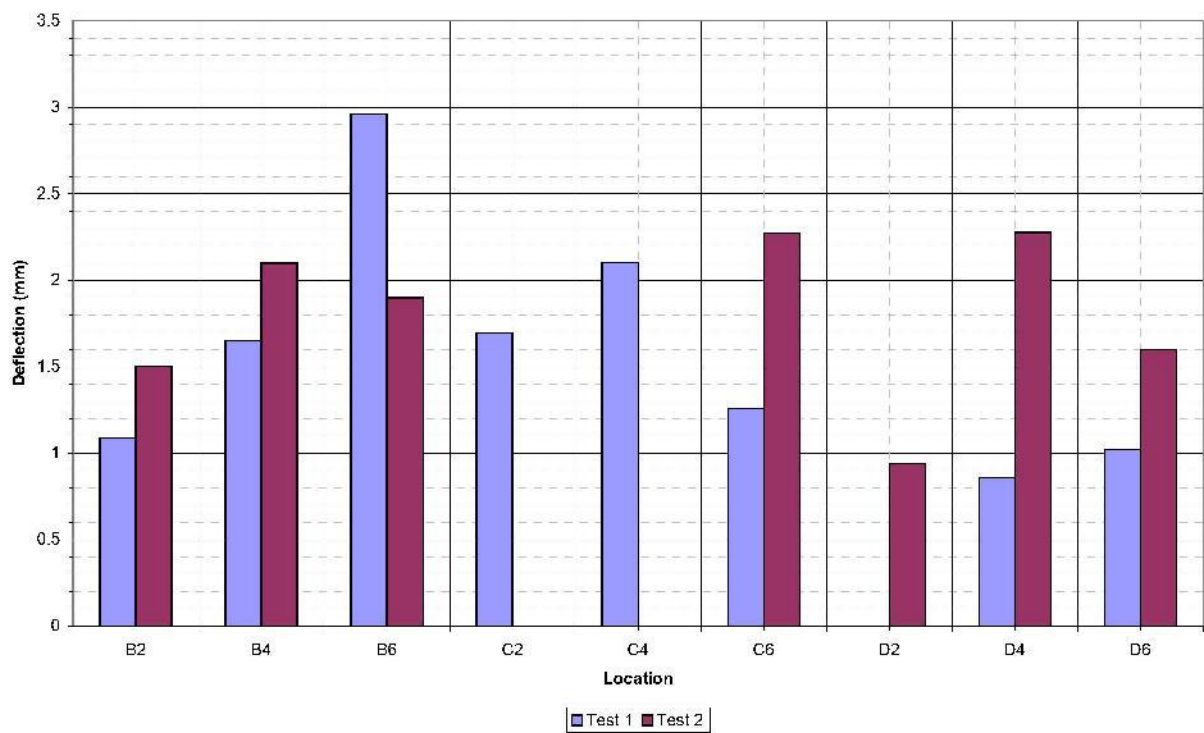
Figure 145 Charring of I joist close to the front opening



2.9.5.3 Structural performance of floor system

As with Test 1, an initial reading was taken of the deflection due to the applied loading. Figure 146 shows the results for Test 2 and compares them to the results for Test 1.

Figure 146 Comparison of deflection under load in all locations (see Figure 8) - Tests 1 and 2



The behaviours of the two floor systems are broadly similar. Any differences are most likely to be due to the random nature of applying the distributed load.

Figure 147 shows the load-deflection behaviour for the duration of the test for all the measured locations. Figure 148 illustrates the average joist deflection-temperature relationship.

Figure 147 Graph of deflection under load versus time in all locations – Test 2

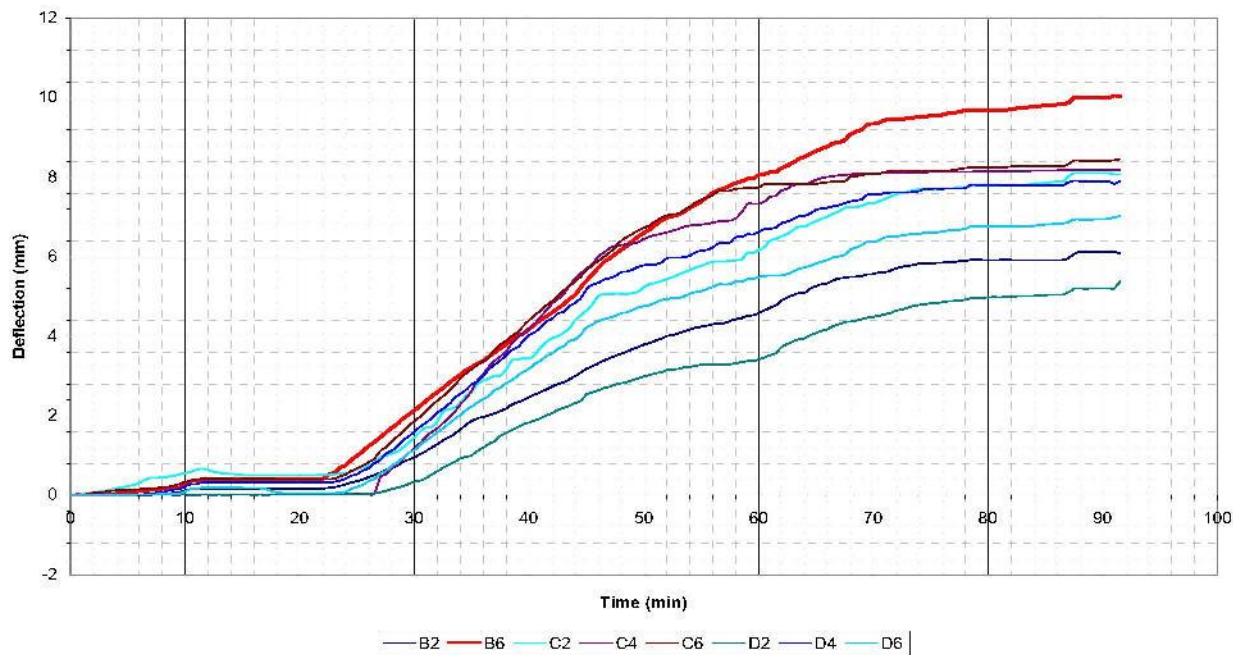


Figure 148 Relationship between average joist temperature and displacement relationship at location B6 –Test 2

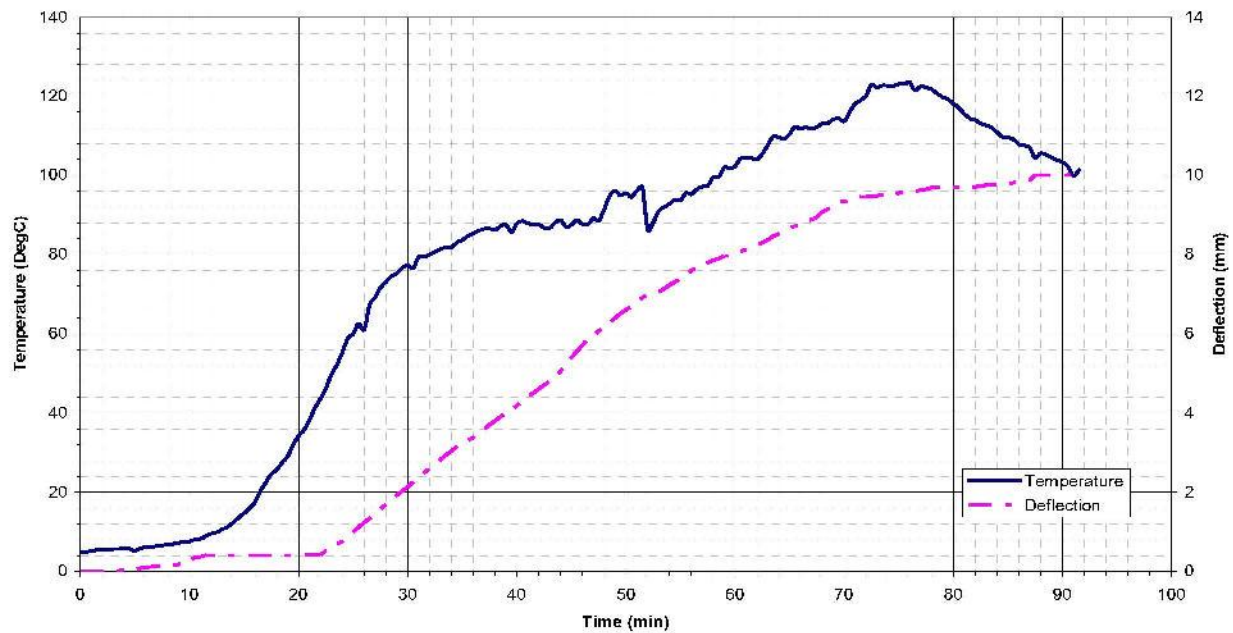
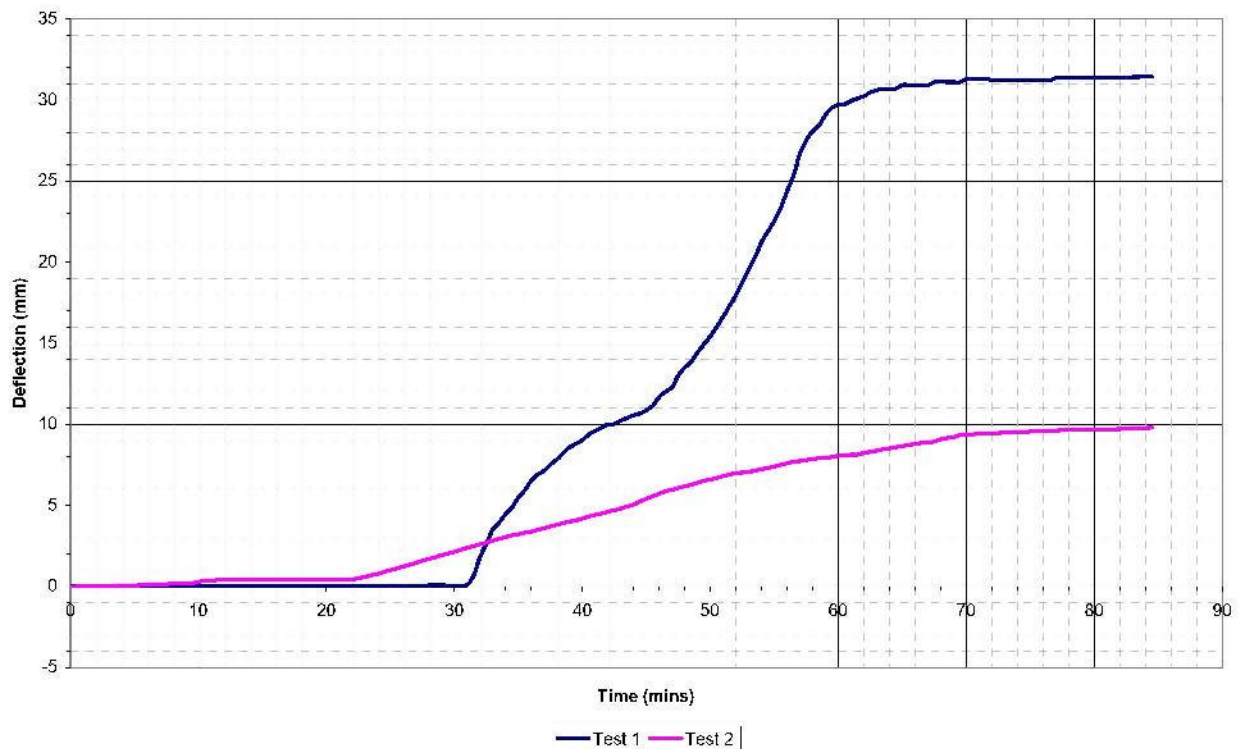


Figure 149 is a comparison between the maximum measured displacement for Test 1 and Test 2. In Test 1, the position of maximum deflection (B2) is located towards the front of the compartment in an area where the plasterboard had failed locally and allowed fire spread within the ceiling void. In Test 2, the maximum displacement was recorded towards the rear of the compartment. Clearly, the reason for the larger deflections for Test 1 is the loss of fire protection to the floor joists.

Figure 149 Comparison of maximum deflection versus time - Test 1 and 2



2.9.6 TEST 3 – STEEL WEB FLOOR JOISTS

Test 3 considered the performance of a floor composed of composite timber-steel joists. Figure 150 shows the joists prior to installation. They are made up from solid timber top and bottom chords 72mm wide by 47mm deep connected by v shaped steel webs. In accordance with the manufacturer's instructions for a 60 minute separating floor the joists were protected on the underside by a ceiling made up from two layers of 12.5mm fire rated plasterboard fixed to the lower timber chord via resilient bars. The top surface of the floor was again formed from 22mm chipboard as in Test 1 and Test 2.

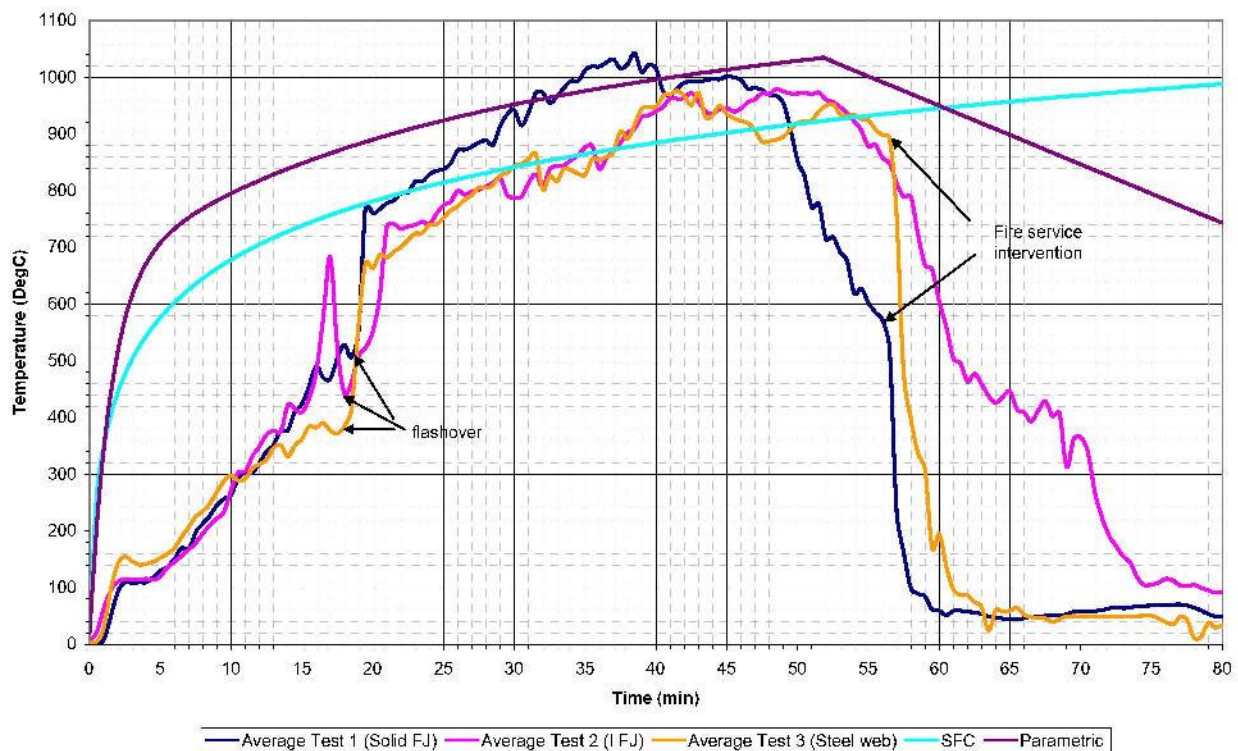
Figure 150 Steel web floor joist prior to installation



2.9.6.1 Fire development

Figure 151 shows the average compartment temperature for Test 3 compared to Test 1 and Test 2, the standard fire curve and the predicted time-temperature response according to the parametric approach in the fire part of the Eurocode for Actions¹⁴.

Figure 151 Graph of average compartment temperature versus time - Tests 1 to 3



The time-temperature response for Test 3 is almost identical to Test 2. Fire fighting was initiated at 56 minutes from ignition due to extensive fire spread in the ceiling void.

2.9.6.2 Fire performance of floor system

During Test 3, the boards were seen to bend downwards approximately 40 minutes from ignition. There is no clear delineation between loss of the first layer and the second layer. From the results and the observations it would appear that the boards opened up locally to allow flames to enter the ceiling void and impinge directly on the floor joists. Figure 152 shows this sequence of events.

Figure 153 shows the temperature of the joist at location C4 which, towards the end of Test 3 was approaching the atmosphere temperature within the compartment.

Figure 152 Ceiling boards opening up during test leading to flaming in void

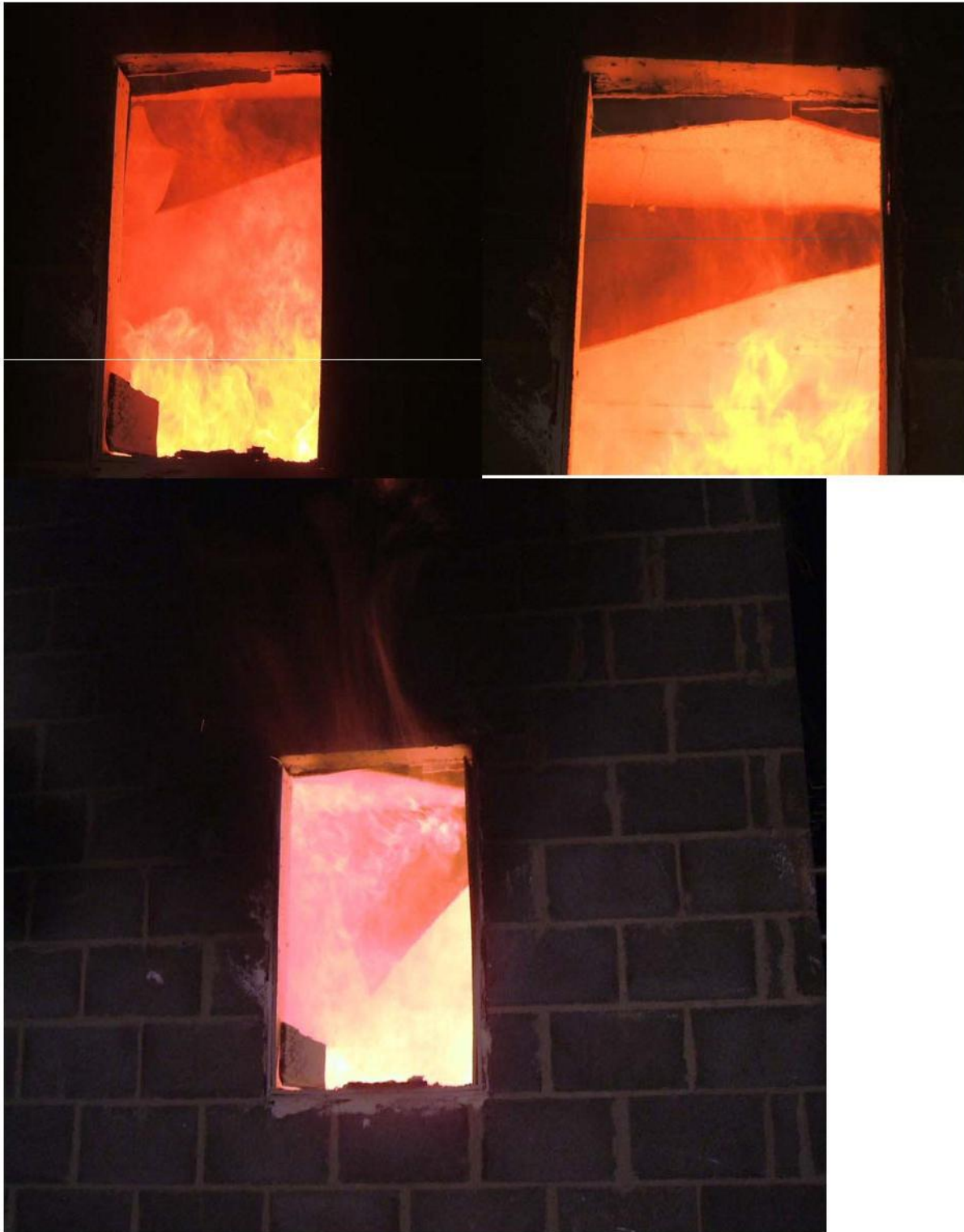
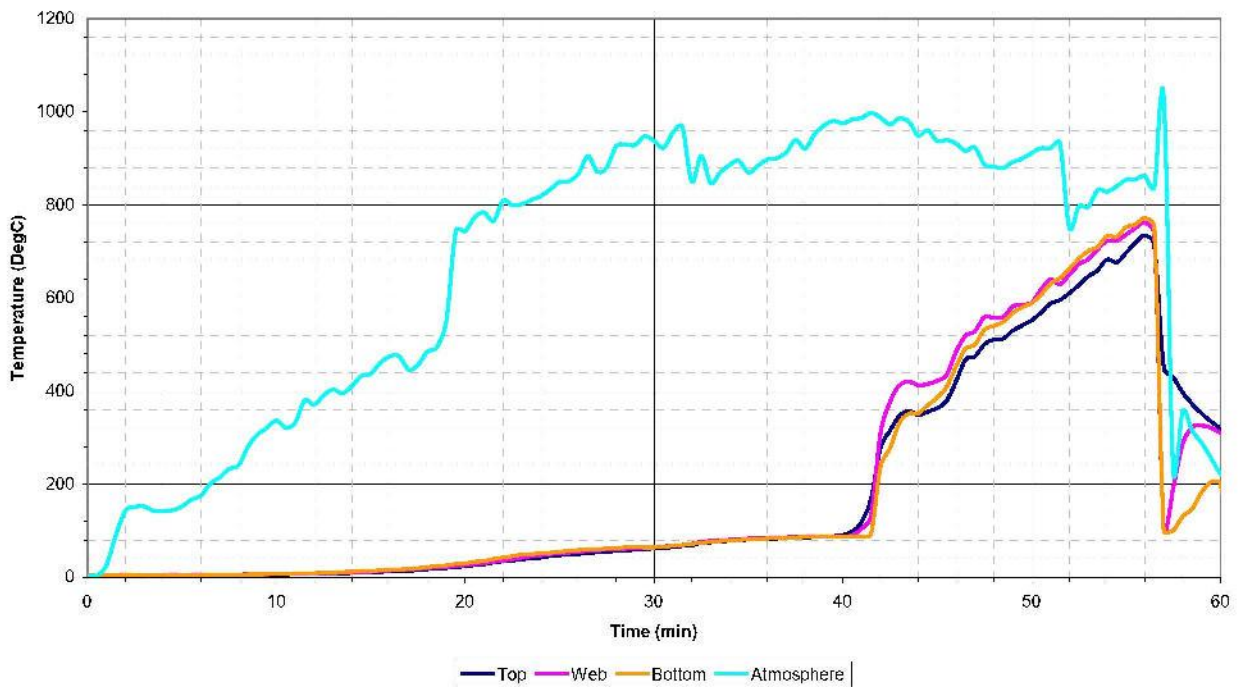


Figure 153 Graph of joist temperature versus time at location C4



Despite a rapid rise in temperature some forty minutes from ignition no attempt was made to extinguish the fire. Both temperature and deflection readings indicated that the fire had entered the ceiling void and the joists had become involved in the fire. Observations following Test 3 confirmed that there had been significant fire spread in the ceiling void. Figure 154 shows the floor joists immediately after the fire had been extinguished. Figure 155 shows the charring of floor joists.

Figure 154 Extensive charring to floor joists



Figure 155 Charring of floor joists and strongback noggin



Steel web pieces used in the fabrication of timber trusses with steel webs such as those tested are produced from galvanised sheet steel, shaped to provide rigidity with teeth punched into the plate and embedded in the timber. The charring of the timber has, in a number of places, led to the teeth coming away from the bottom chord, see Figure 156.

Figure 156 Loss of connection between steel web and solid timber chord



Figure 156 also shows the extent of charring to the timber. From measurements taken on site the maximum depth of charring recorded resulted in a residual timber section of 50mm x 20mm from an initial nominal section size of 72mm x 47mm. Figure 157 illustrates this.

Figure 157 Residual section indicating extent of charring



Although there was significant deformation of the floor, there was no appreciable damage to the joist hangers used to transfer the load from the joists to the load bearing blockwork wall. Figure 158 shows the joist hangers immediately following the test.

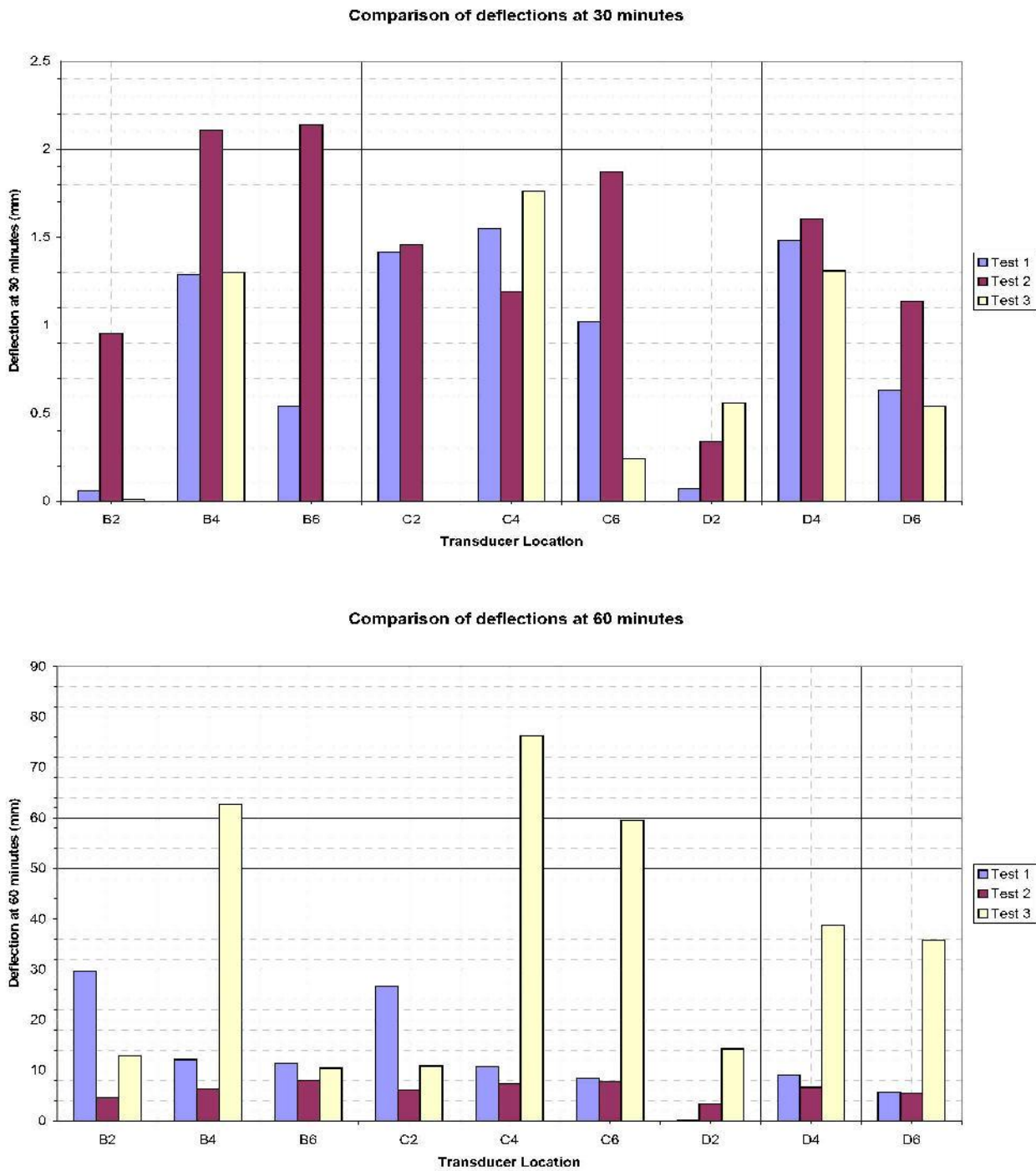
Figure 158 Joist hangers immediately after test



2.9.6.3 Structural performance of floor system

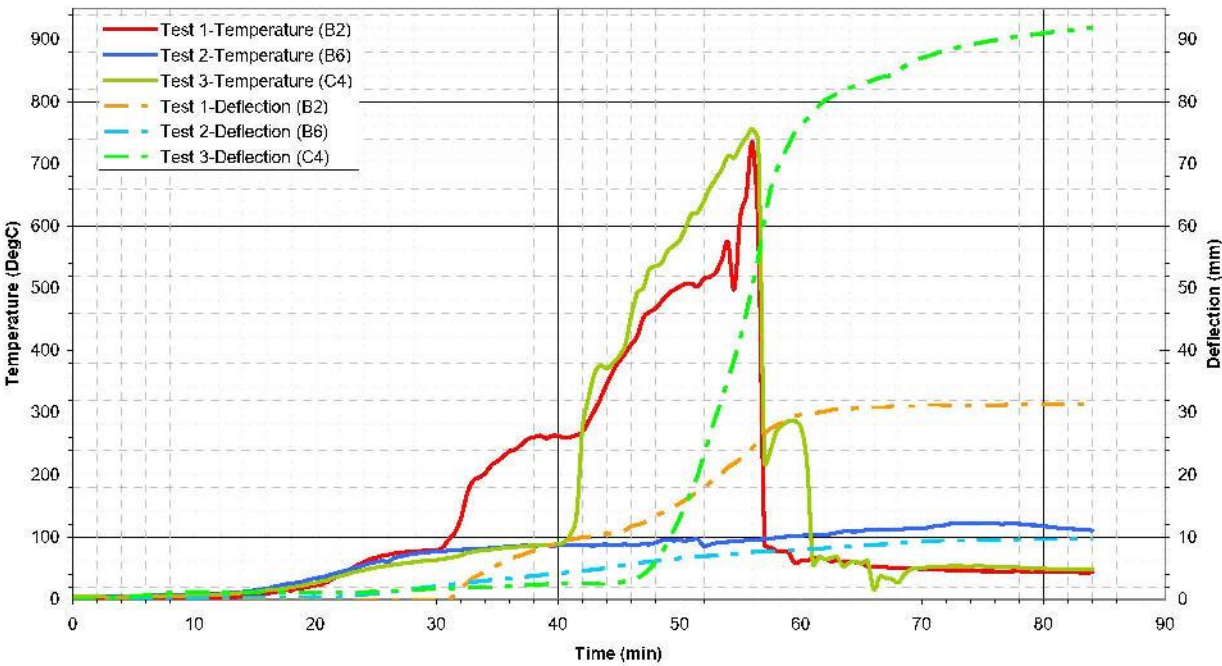
Figure 159 shows the measured values of vertical deflection at 30 minutes and at 60 minutes for Tests 1 to 3.

Figure 159 Comparison of deflection under load at all locations at 30 and 60 minutes



For Test 3 the floor continued to deflect under the applied load even after the fire had been extinguished. Figure 160 shows the relationship between temperature and deflection for the point of maximum deflection for Tests 1 to 3.

Figure 160 Relationship between temperature and deflection - Tests 1 to 3 at points of maximum deflection



3 Conclusion

The project has identified a mode of failure for the structural insulated panel building systems tested as part of this project in fire. The mode of failure was collapse of a floor system consisting of engineered floor joists as a result of fire breaking into the floor/ceiling void and burning through the oriented strand board webs of I section floor joists.

The project identified collapse of the floor as the predominant mode of failure of the building system based on fire penetration into the floor/ceiling void and combustion of the oriented strand board webs of the engineered floor joists leading to loss of load bearing capacity and runaway deflection.

The following conclusions can be drawn in relation to individual tasks.

3.1 Literature survey and review

The following conclusions can be drawn from the literature survey and review undertaken:

- It is apparent that the majority of manufacturers in the UK utilise oriented strand board as the face material and either expanded polystyrene, XPS, polyurethane or PIR, polymeric foams, as the insulating core. Alternative facing materials such as cement particle boards or similar, although not very common in the UK, are used globally.
- Structural insulated panels are principally used as load bearing wall members and roofs in the UK. They are also used as floor members and as a substitute for roof trusses. The main market sector in which they are being used is for residential buildings up to four storeys in height. However, when used as infill panels in framed structures, structural insulated panels are used for multi-storey applications. Additionally, structural insulated panels are more frequently being used for commercial applications such as hotels and schools.
- Structural insulated panels at ambient temperatures have been shown to act as a strong structural composite. They have significant compressive and racking resistance.
- The transfer of shear stresses via the insulating core has been shown to be critical to the loadbearing capability of the unit, when stressed under flexural loads. As a result it is critical that neither the core nor the bond between the core and the skin fail due to shear stresses. The evidence gathered indicates that, at ambient temperature, the strength of the glue bond is much greater than the shear strength of the core and hence the core typically fails. It is not however known how the bond between the skin and the core degrades as a result of high temperatures, such as those experienced in a fire. It would therefore be desirable to determine how the bond performs in a fire relative to the core as this is likely to determine the time and nature of the failure of a panel in a fire.
- Test data presented in the literature and gathered as part of this programme indicates that the introduction of intermediate stiffeners within a panel significantly increased the failure loads at ambient temperatures, particularly for compression

members. However, by introducing stiffeners the failure mode becomes less ductile. The introduction of stiffeners could potentially improve the fire performance of the panel as the load bearing mechanism would not wholly rely on shear transfer through the glue bond and insulating core. Stiffeners could introduce some redundancy in the ambient design of a panel which could provide essential additional capacity in a fire scenario. This needs to be further investigated through comparative tests on fire exposed panels with and without intermediate stiffeners.

- No formal design method exists for structural insulated panels. Equations have been derived based on simple linear elastic theory which may be used to predict typical deflections. In addition, failure mode equations have been developed for sandwich beams. However, these methods target flexural methods using either metal or GRP veneers. The application of the timber Eurocode (EC5) to structural insulated panels, using comparable assumptions to the above equations, is shown to over predict the failure loads of compressively loaded panels. This is largely because structural insulated panels are shear-weak and suffer large shear deformations. This results in both cross sectional deformation and partial shear interaction between the core and the skins. A design method needs to be derived for structural insulated panels which can then be adjusted for the fire scenario in a similar manner to those used for other structural materials.
- Evidence from the large-scale fire tests conducted in this project indicates that the failure of a panel is heavily dependent on the choice on lining material which ultimately governs the heat transfer rate into the panel. Panels tested with a combination of plasterboard and a fire rated lining board perform better than either unprotected panels or panels with a single layer of plasterboard. The failure modes experienced in standard tests are relatively evenly spread between load bearing and integrity failures. However the integrity failures derive from excessive deflections which are a function of the structural performance of the panel. No tests reviewed indicated an insulation failure. Although the majority passed the necessary requirements for the respective applications in the standard test, ultimately all panels suffered severe failures shortly after this period, either due to full ignition of the panel or through complete collapse. This is a significant concern for whole building performance in fires as this could result in complete collapse.
- Very limited research has been undertaken to date which addresses the fire performance of structural insulated panels. A plethora of data exists for cladding sandwich panels. However, these are fundamentally different in terms of both materials and their applications.
- Sufficient materials data for both oriented strand board and the core materials exist, which could be used for the development of a numerical model capable of predicting both the heat transfer and structural response. The accuracy of such models, based on the data currently available, will be limited and is unlikely to accurately reflect actual fire performance. Additional supporting data, derived from small scale testing, would be very beneficial for developing more accurate numerical models.
- In terms of material data there are a number of unknowns with regards to oriented strand board performance in fires. Limited work has been performed to determine

constitutive relationships for oriented strand board at ambient temperature. However, no work has addressed the strength retention rate of oriented strand board when exposed to elevated temperatures. Guidance exists for timber in EC5 which provides strength retention factors in compression, tension and shear for temperatures ranging from ambient to 300°C. Similar data are not available for oriented strand board and it would be crude to apply such factors to a composite timber product as the influence of the resin is likely to be significant, particularly in a fire.

- The use of the standard fire test (BS 476) brings about a number of uncertainties with regards to the assessment of structural insulated panels. Firstly, it is quite likely that the failure mode of a panel is a function of the restraint provided to the unit in the test procedure. This level of restraint at the boundaries is unlikely to represent the support conditions in a building as this is highly dependent on the joining details used by the manufacturer. The joining details have been shown to be highly variable between manufacturers. In addition, it is common to provide timber stiffeners at the unit ends in the test procedure to prevent flame spread into the core, via the discontinuous ends of the panel. These stiffeners are often not used in the building system on site. Hence, an additional level of redundancy exists in the test which may not be the case for the constructed building.
- The strength of the core is shown to be dependent on its density. The standard test procedure does not measure the density of the core and hence, there is no evidence that the tested core material reflects what is applied on site.

3.2 Small scale evaluation of performance of structural elements

The following conclusions can be drawn from the small-scale tests undertaken on individual panels:

- A single layer of 15mm Type F fire rated plasterboard has been shown to prevent significant damage to structural insulated panels exposed to 30 minutes ISO834 furnace conditions. As a result no loadbearing failures were apparent under combined heating and loading conditions (for load levels up to 108kN/m).
- The temperatures of the outer face of the oriented strand board skin immediately behind the plasterboard are very close to the ignition temperature of timber at the end of the 30 minute test.
- The difference in core material has a nominal impact on the core temperature during the 30 minute exposure time considered.
- Two layers of 15mm Type F fire rated plasterboard has been shown to prevent significant damage to structural insulated panels exposed to 60 minutes ISO834 furnace conditions. Similarly, as a result no loadbearing failures were apparent under combined heating and loading conditions (for load levels up to 108kN/m).
- The temperatures at 60 minutes of the outer face of the oriented strand board skin immediately behind the plasterboard are much lower than the corresponding value for the 30 minute case and significantly lower than the ignition temperature of timber.

- The core material does not have any impact on the core temperature during the 60 minute exposure period considered. However, where steam is allowed to enter the core the steam temperatures are sufficient to cause de-lamination of the polystyrene core.
- Ambient temperature load tests have determined the capacity of the polyurethane core structural insulated panels. For the 1.8m high samples the ultimate capacity is approximately 300 kN.
- Residual load tests on damaged specimens have shown that the fire test makes no appreciable difference to the ultimate load capacity of the panel.
- The inclusion of electrical sockets made no appreciable difference to the performance of the structural insulated panel panels during the fire tests when installed into the cavity between the plasterboard and the structural insulated panel. It is possible that other installation methods may yield different outcomes, but these were not considered as part of this project.
- Where a single layer of 12.5mm Type A plasterboard was used for a 30 minute fire exposure the test had to be terminated after approximately 20 minutes due to combustion of the oriented strand board skin.
- Where a single layer of Type F plasterboard was fixed directly to the structural insulated panel the results indicate a higher temperature increase behind the plasterboard lining compared to the corresponding case where the lining was fixed via softwood battens.

3.3 Parametric study

The following conclusions can be drawn from the numerical studies undertaken:

- The DIANA two dimensional heat transfer model, with the specified thermo-physical properties for the various structural insulated panel constituents, is capable of predicting peak temperatures within a panel for both 30 and 60 minutes of fire exposure.
- The numerical model could be further calibrated to improve accuracy in the early phases of heating through further testing of panels with the dry-lining fixed directly to the oriented strand board veneer. In addition the scope of application of the model to include type A plasterboard linings could be achieved through some additional tests on structural insulated panels protected with such a lining.
- The numerical model has shown that there is a significant difference in the temperatures that develop in panels when there is a variation in the specification of the PFP. In addition it has also shown that a battened approach to fixing the dry-lining is preferable assuming that there are no workmanship defects that arise as a result of this.

3.4 Large-scale fire tests

The following conclusions can be drawn from the four large-scale fire tests undertaken on building systems:

- Structural insulated panel systems tested as part of this project are capable of achieving the requirements of the Building Regulations in relation to B2 internal fire spread (linings) and B3 internal fire spread (structure).
- The mode of failure of the systems tested as part of this project was excessive deflection of the first floor caused by ignition and rapid combustion of the engineered floor joists. The rate of deflection increases very rapidly as the floor system approaches collapse. This behaviour is not influenced by the performance of the structural insulated panel system and would be the same for other panellised systems or traditionally built timber frame.
- There was no collapse of the floor in any of the tests despite the significant (>200mm or span/20) deflections. The chipboard flooring appears to have contributed to the stability of the floor at large deflections. Inevitably, in the instance of both the polyurethane 30 and expanded polystyrene 30 compartments, the floors would have collapsed had the fire and rescue service not intervened. In addition, the introduction of a localised load, such as a person, would have almost certainly resulted in the collapse of the 30 minute floors at such large deflections.
- There was no collapse of the wall panels in any of the tests.
- There was no integrity failure of either the wall panels or the floor system with the exception of a very localised failure in the area of the unsealed lifting eyes (for the expanded polystyrene 60 test).
- At the end of the tests, the composite action assumed in design can no longer be relied on due to either degradation of the inner layer of oriented strand board and melting of the core (EPS) or degradation of the oriented strand board and combustion of the core (PUR). As there was no collapse of the buildings, it is clear that an alternative load path was mobilised at the fire limit state. Load carrying capacity was maintained through the solid timber ring beams at first floor level and the presence of intermediate timber in the panels either at junctions between panels or around openings and the presence of timber studs in the corner.
- There was no significant damage to the ring beam in any of the tests.
- There was no evidence of any failures in the connections between the engineered floor joists and the timber ring beams.
- The inclusion of service penetrations, electrical sockets, installed in the cavity between the plasterboard and the structural insulated panel in the polyurethane tests made no appreciable difference to the performance of the panel or of the structure.

The fire tests have highlighted a number of issues of specific concern to the fire and rescue service. The information derived has been fed through to the fire and rescue service through representatives on the Stakeholder Group and include:

- The rapid rates of deflection (compared to a solid timber floor system) associated with breakthrough of fire into the floor void and potential for a sudden collapse of the floor system.
- The melting of the expanded polystyrene insulation before the plasterboard has fallen away, reducing the load bearing capacity of the composite panels in the latter stages of a fire. Where redundant timber studs do not exist, this could result in collapse of the wall panels.
- Smouldering combustion of the inner face of the polyurethane core leading to ignition once sufficient air is available. This may coincide with removal of the remaining plasterboard linings by the fire and rescue service.
- The results and observations from both the 30 minute tests show that it is possible to fully extinguish all hidden seats of combustion following a serious fire. However, it is necessary to remove all residual plasterboard and crews should be aware of the risks of floor and wall collapse.
- On the basis of the risk of secondary fire initiation involving the fabric of the building, consideration should be given to reviewing the current “defend in place” strategy for medium-rise occupancies where the structural frame is combustible.

3.5 Fire performance of engineered floor joists

The large-scale fire tests provided important information on the performance in fire of one type of engineered floor joist (I section beams with oriented strand board webs) used in conjunction with structural insulated panel wall panels. Additional fire tests were undertaken to evaluate the relative performance of different types of timber floor joist.

The following conclusions can be drawn from the fire tests undertaken on timber floor joists:

- Workmanship is of critical importance in providing the required fire resistance. Any gaps, fissures, missing fixings or poorly overlapped or sealed joints will significantly impair the performance of the floor system.
- The connections (joist hangers) performed in a consistent and reliable manner showed no signs of weakness or deformation.
- Clearly the specification of the linings has a crucial role to play in providing the required fire resistance period. Once the plasterboard has been breached and the floor joists have become involved in the fire none of the systems tested has any significant fire resistance. It is therefore not surprising that the system that suffered the least damage was that where the specification for 60 minutes fire resistance consisted of two layers of 15mm fire resistant plasterboard.
- The composite section utilising a steel web performed in a ductile manner once the fire had penetrated the ceiling void. Charring of the timber led to a number of the steel plates coming away from the timber chords.

- The chipboard flooring provides a contribution to the overall fire resistance of the floor system by delaying the spread of fire through the surface once the ceiling void has been breached.
- The performance of the timber I joists in one of the tests shows that engineered floor joists are capable of surviving complete burn out of all combustibles for a given fire scenario provided the fire protection is adequately specified and installed.

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Appendix A – Summary of the research

Sustainable Buildings Division of Communities and Local Government (DCLG) commissioned BRE to carry out a project titled 'The Performance in Fire of Structural Insulated Panel Systems'.

There was a need to undertake a research project in collaboration with manufacturers to establish the relationship between the results from standard fire tests and performance under realistic conditions.

The overall aim of the project was to undertake an experimental programme to determine the performance of a typical structural insulated panel system in response to a realistic fire scenario and to compare the results with the outcome from standard fire tests. The project was intended to identify modes of failure associated with system performance in fire.

This report describes the project, the findings and conclusions based on the work programme undertaken.

The project started with the formation of a Stakeholder Group, who represented a range of stakeholder interests. This Stakeholder Group provided invaluable input throughout the duration of the project. The programme of work has also included the following tasks: a literature survey and review; selection and identification of potential design solutions; small-scale fire tests; developing a large-scale test methodology; numerical modelling and large-scale fire tests. Additionally, three large-scale fire tests were carried out on engineered floor joists.

The project has identified a mode of failure for the structural insulated panel building systems tested as part of this project in fire. This was collapse of the floor as the predominant mode of failure of the building system based on fire penetration into the floor/ceiling void and combustion of the oriented strand board webs of the engineered floor joists leading to loss of load bearing capacity and runaway deflection. Other significant conclusions are reported from the individual tasks.

This report will be of interest to key stakeholders including the fire and rescue service, regulators, national and local authority building control bodies, insurers, manufacturers and clients.

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