Fire performance of new residential buildings

NHBC FOUNDATION
Housing research in partnership with BRE Trust

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FOREWORD

In recent decades there has been an increase in the number of homes built using non-traditional forms of construction. This has been driven by a wish to achieve greater construction efficiency and in general enhanced energy performance standards. But one of the consequences has been an increased use of combustible materials, with potential consequences for life safety and property protection in the event of fire.

This project involved a stakeholder group, which included representatives from across the house-building industry, DCLG, the London Fire Brigade and the Fire Protection Association to review the issues in detail, taking account of data from real fire incidents. This report provides a summary of the data and presents a number of case studies, from which useful lessons can be drawn.

Although the evidence currently available does not allow for conclusions to be reached as to whether non-traditional forms of construction add to the fire risk, it does reinforce the vital importance of care and attention in the design and construction of all buildings. Regardless of construction type, there is a clear risk of the spread of fire through cavities within the fabric and externally via the façade.

In light of some recent high profile fire events, this report provides a balanced review, which I trust will help inform further debate and lead to improved practice across the industry.

Rt. Hon. Nick Raynsford MP
Chairman, NHBC Foundation

ABOUT THE NHBC FOUNDATION

The NHBC Foundation was established in 2006 by the NHBC in partnership with the BRE Trust. Its purpose is to deliver high-quality research and practical guidance to help the industry meet its considerable challenges.

Since its inception, the NHBC Foundation's work has focused primarily on the sustainability agenda and the challenges of the government's 2016 zero carbon homes target. Research has included a review of microgeneration and renewable energy techniques and the groundbreaking research on zero carbon and what it means to homeowners and housebuilders.

The NHBC Foundation is also involved in a programme of positive engagement with government, development agencies, academics and other key stakeholders, focusing on current and pressing issues relevant to the industry.

Further details on the latest output from the NHBC Foundation can be found at www.nhbcfoundation.org.

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Professor Steve Wilcox, Centre for Housing Policy, University of York

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1 Introduction

This report describes a study into the fire performance of residential buildings commissioned by the NHBC Foundation and carried out by BRE Global Ltd.

The report presents the results of the study, identifies the issues that need to be considered with regard to fire safety of modern residential buildings, and provides guidance and sources of information that should benefit a number of key stakeholders within the construction industry.

The greatest risk from fire both in terms of life safety and property protection arises in medium rise multi-occupancy residential buildings. Therefore this sector of the market has provided the primary focus for this study.

The available statistical evidence has been analysed to investigate the hypotheses that current methods and forms of construction are contributing toward an increase in the level of damage following a fire and that such damage may be instigated from a relatively small ignition source. The evidence does not provide conclusive results. In large part, this is a function of the method of collating information from real fire incidents where traditionally there has been no requirement to identify specific forms of construction. However, recent data provided by both the insurance industry and the Fire and Rescue Service has provided more detailed information on issues such as type of construction and failure of compartmentation. Over time the changes to the way data is collected will provide a robust database relating to fires in modern forms of construction. Initial implications suggest that certain forms of construction may contribute towards the extent of fire spread and may help to explain the continuing increase in large claims when the overall trend currently indicates a decline in the number of fires and a decline in injuries and fatalities due to fire.

The regulatory requirements for elements of construction and construction materials have been explained in the context of current regulatory guidance documents and standard methods of test and assessment. Where appropriate, consideration should be given to means of test and assessment that more closely reflect the end use condition of the structural components and the interaction between individual elements such as walls and floors.

The use of combustible materials either as principal framing elements or within the fabric of the building may provide a route for either internal fire spread through cavities or external fire spread via the façade. It has been shown that the potential increased fire load, should the fabric or structure of the building become involved, is significant.

In terms of internal fire spread the importance of specifying and installing the correct passive fire protection has been highlighted. Compartmentation may be prematurely breached in the event of a fire either by incorrect specification of linings, poor workmanship or inadequate supervision. It is essential that cavity barriers are installed and located correctly. Any discontinuities will provide a route for fire spread through cavities bypassing all other passive fire protection systems.

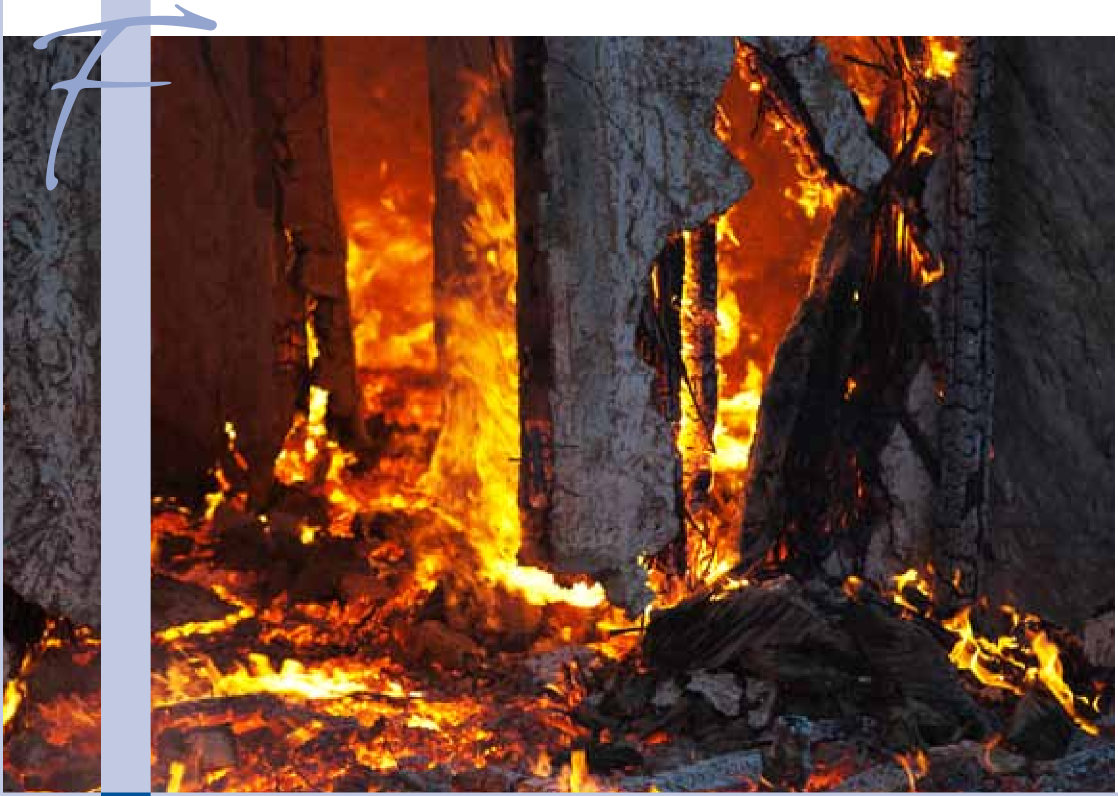
The specific issue of compartmentation in roof voids has been addressed in a recent government funded research study. A review of planning submissions and real fire incidents has shown that there is often insufficient detail provided to demonstrate compliance with the requirements of the Building Regulations throughout the UK.

Combustible material used within external façades may contribute to external fire spread and may allow fire to break back into the building at a level above the initial incident. For buildings over 18 m high where combustible materials are used in external non-loadbearing walls, performance can be assessed against the performance criteria in BRE Report BR 135[1] using full-scale test data from the appropriate part of BS 8414[2].

Guidance is now available to reduce the risks of accidental or deliberate ignition sources on construction sites containing large quantities of combustible material. A number of different solutions have been proposed to address this issue. They include:

- the use of closed panel solutions where wall and floor panels are prepared off site with the linings already installed
- rescheduling the work to install linings as work proceeds
- the use of fire retardant products to limit the rate of heat release and extend escape time for site staff
- the use of non-combustible board to form the sheathing/racking layer
- non-combustible screens tied back to the scaffold to reduce the potential for ignition of adjacent buildings due to external fire spread
- sprinkler/deluge systems.

Within the UK, separate legislation exists for the construction of new buildings and for the control of fire precautions in occupied premises. The information within this report only relates to the Building Regulations which cover England and Wales.



2 Background

Modern Methods of Construction (MMC) ranging from factory-built systems through to innovative site-built systems are increasingly being used in the UK residential sector. This change from traditional building techniques and materials is being driven by a number of factors including:

- the Energy Performance of Buildings Directive[3], the need to reduce CO_2 emissions, the challenge to achieve zero carbon homes, the Code for Sustainable Homes and changes to The Building Regulations 2000 (Part E – Resistance to sound[4], Part L – Conservation of fuel and power)[5]. These initiatives have resulted in an increasing amount of (generally combustible) thermal insulation materials being used within dwellings
- a shortage of skilled labour in the construction industry
- a drive to improve the quality of construction and minimise the impact of poor workmanship on site
- a drive to improve the efficiency of the construction process by adopting techniques previously associated with the manufacturing sector.

These factors will have an impact on the fire performance of many modern residential buildings. To date, strict compliance with the requirements of the prescriptive guidance to the Building Regulations has been assumed to provide adequate levels of safety. Consideration should be given to what effect these changes will have on both life safety and property protection.

The increasing use of thermal insulation products, many of which are combustible, means that the (potential) combustible fire load within dwellings is increased. Due to the innovative nature of many of the products used for modern dwellings, they have a limited track record of service in the UK. However, based on emerging evidence (see Section 3), there is some concern that these types of buildings may be susceptible to disproportionate damage in a fire with consequential implications in terms of life safety and property protection. This project has investigated fire-related issues and provided the industry with factual information and guidance to assist in addressing these concerns.

2.1 Stakeholder group

The study was guided by a stakeholder group which was established at the start of the study and met twice during the work programme. The organisations represented on the stakeholder group are listed below:

- Department for Communities and Local Government (DCLG)
- Fire Protection Association (FPA)
- Health and Safety Executive (HSE)
- Insulating Concrete Formwork Association (ICFA)
- London Fire Brigade (LFB)
- National House-Building Council (NHBC)
- NHBC Building Control Services Ltd
- NHBC Foundation
- Royal Institution of British Architects (RIBA)
- Steel Construction Institute (SCI)
- UK Structural Insulated Panel Association (UK SIP Association)
- UK Timber Frame Association (UKTFA)

The stakeholder group reviewed and provided general advice on all aspects of the methodology of the study.

2.2 Construction types

The generic terms MMC or Innovative Construction Products and Techniques (ICPT) are used to describe a wide variety of different products, techniques and practices that have little in common with each other. In terms of the current project, the types of construction specifically considered as having a potential impact on the fire performance of highly insulated residential buildings are listed below together with a brief description of the form of construction. For more general information on the classification of modern forms of construction, the reader should consult the available literature[6]. Previous studies related to modern forms of construction have adopted classifications related either to whether the system or technique is site-based or pre-fabricated, or the nature of the structural form (panellised, modular, etc). For current purposes, material behaviour is at least as important as structural form or the level of pre-fabrication. It is important to appreciate that, for many modern forms of construction, identifying the material forming the load-carrying frame is not necessarily straightforward. Many modern structural framing systems mimic traditional forms of construction, by utilising non-loadbearing masonry cladding systems for instance.

Figure 1 'Mock' chimney breast on a timber frame building (photo courtesy of London Fire Brigade)

Figure 1 shows a brick chimney stack on top of a timber frame building. From the outside, the completed building would look like a traditional masonry structure. The 'chimney' is clearly there purely for aesthetic reasons to mimic traditional forms of construction. For those bodies responsible for enforcement of fire safety legislation in relation to multi-occupancy residential buildings, it is important that they are aware of the form of construction at an early stage in the design process. The sections below provide a brief description of some of the principal MMCs used for domestic dwellings.

2.2.1 Insulated concrete formwork

Insulated concrete formwork (ICF) (Figure 2) is a building system that provides formwork for in situ concrete structures. The formwork is then left in place permanently as thermal insulation. Used in continental Europe and in the USA for many years, ICF has proved to be a robust, cost-effective method of constructing a variety of building types from houses to multi-storey cinemas and commercial buildings. In essence, ICF consists of twin-walled expanded polystyrene (EPS) panels or blocks that are built up to create the walls of a house or other building. This formwork system is then filled with ready-mixed concrete to create a structure ready to accept the roof or floor construction. Many ICF systems also incorporate their own flooring system. The EPS remains in place to provide thermal insulation for the walls of the finished building, and provides a uniform surface ready for the direct application of most finishes and proprietary cladding systems[7].

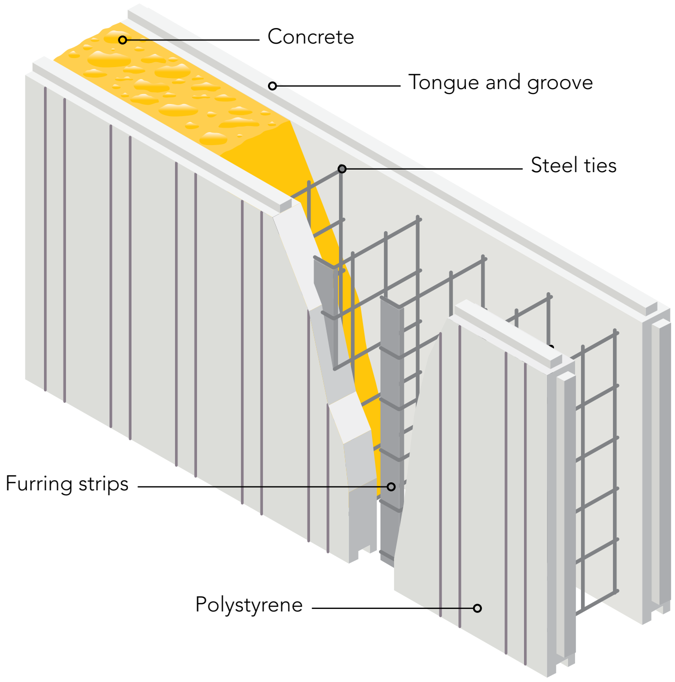


Figure 2 Insulated concrete formwork[7]

The fire performance of concrete structures has been widely researched. From such research, the design code Eurocode 2 part 1.2[8] was developed for the fire design of concrete structures. Like traditional concrete construction, the fire resistance of ICF is largely governed by the behaviour of the concrete core. The introduction of insulation formwork will undoubtedly increase fire loads in buildings. However, from a robustness and integrity viewpoint, providing there is sufficient cover to the reinforcement in ICF buildings, then there should be minimal risk of collapse. Issues associated with spalling would essentially be mitigated as the foam and internal finish layers would, for a short duration, protect the concrete from unduly high heating rates.

2.2.2 Light timber frame

Light timber frame generally refers to walls and floor systems formed from relatively small section timber members protected by gypsum plasterboard. It is almost exclusively adopted in residential applications in buildings ranging from one to four storeys in height. It is widely accepted that the fire resistance of such forms of construction is almost wholly reliant on the performance of the gypsum plasterboard system which exhibits high levels of inherent fire resistance. The behaviour of solid timber in the post-protection phase of a fire (ie after the plasterboard has failed) is fairly consistent and predictable. Ultimately, failure will occur when the residual charred cross-section is no longer sufficiently large to support the applied loadings imposed on the structure.

The structural design for light timber frame exposed to fire is covered in the European standard Eurocode 5 part 1.2[9]. This contains guidance on the design of timber structural elements exposed to standard fire conditions and to a lesser extent, non-standard fire conditions. Much research underpins this code which was largely validated in Scandinavia through a number of tests undertaken on a range of timber structural assemblies.

The failure of traditional solid timber floors is characterised by a gradual, almost linear increase in deflection, with increasing depth of char[10, 11]. The exact nature of such behaviour will depend largely on whether the floor is initially protected or not. If left unprotected, the floor will gradually deflect from the point of fire ignition until failure occurs. If the floor is initially protected, then little or no deflection occurs until the passive fire protection fails. After this period, charring begins and occurs at an accelerated rate until either the joist is consumed or the residual cross-section is insufficient to sustain the applied loads.

In the case of light timber stud walls, failure typically occurs as a result of buckling. At ambient temperature, the plasterboard lining is often assumed to restrain the studs, resulting in a reduced effective length and thus increased buckling resistance. In the case of a fire, the plasterboard layer will eventually degrade, crack and ultimately fall off. This, coupled with charring, results in firstly an eccentricity in the applied axial load, in conjunction with a diminished buckling capacity due to a lack of restraint. Failure is characterised by a gradual increase in lateral deflection before buckling and the development of irrecoverable lateral and axial displacements. A number of issues concerned with fire spread in light timber frame residential buildings are covered in Section 8 dealing with case studies.

2.2.3 Structural insulated panels

Structural insulated panels (SIPs) are formed from the lamination of two structural grade boards separated by a polymer foam insulation core. These members are then used to form a building's primary structure. Typically, SIPs are used as compression members in walls, however, examples exist where SIPs are adopted as either roof, or occasionally floor, members. More information on the background to SIP technology including generic information on thermal insulation and structural performance may be found in BRE IP 13/04[12]. An example of a SIP wall panel is shown in Figure 3.

Figure 3 Structural insulated panel showing oriented strand board (OSB) skins and insulated core (photo courtesy UK SIP Association)

The performance in fire of SIPs, has, until recently, not been widely researched. In relation to fire performance, BRE Global, in conjunction with the Department for Communities and Local Government (DCLG), has recently completed an extensive study into the fire performance of SIPs. The project comprised elements of numerical modelling, laboratory-scale furnace experiments and full-scale natural fire experiments. Information from the project is included in the case studies in Section 8. Further information is available[13, 14].

2.2.4 Engineered floor joists

Solid timber floor joists are increasingly being replaced by engineered products such as timber 'I' beams and steel web joists which are lighter and stiffer than solid timber. These systems find widespread use across a range of construction systems including traditional forms of construction. Deep joists up to 12 m long can be produced allowing much larger distances to be spanned without the need for intermediate structural support. Examples of engineered floor joists are illustrated in Figure 4.

Figure 4 Engineered floor joists (photo courtesy of UK SIP Association)

A number of studies have been performed in the USA and Canada to investigate the fire performance of light engineered floor systems. These studies, however, are of limited use as they predominantly investigated unprotected floors as these are allowed under the US and Canadian regulatory frameworks. Indications from such research suggest that the failure of engineered timber can occur in as little as 6 minutes when left unprotected, as is the case in many US and Canadian basements. Comparatively solid timber (traditional) floors have been shown to fail in 19 minutes for approximately the same fire load conditions. Similar conclusions were found in research undertaken in Canada.

The most comprehensive studies on engineered floor performance in fire, for UK applications, have been completed by BRE Global as part of government funded projects on floor systems[11] and SIPs[12]. A number of issues concerning the performance in fire of engineered floor joists are covered in the case studies in Section 8. Further information is available[14, 15].

2.2.5 Light steel framing

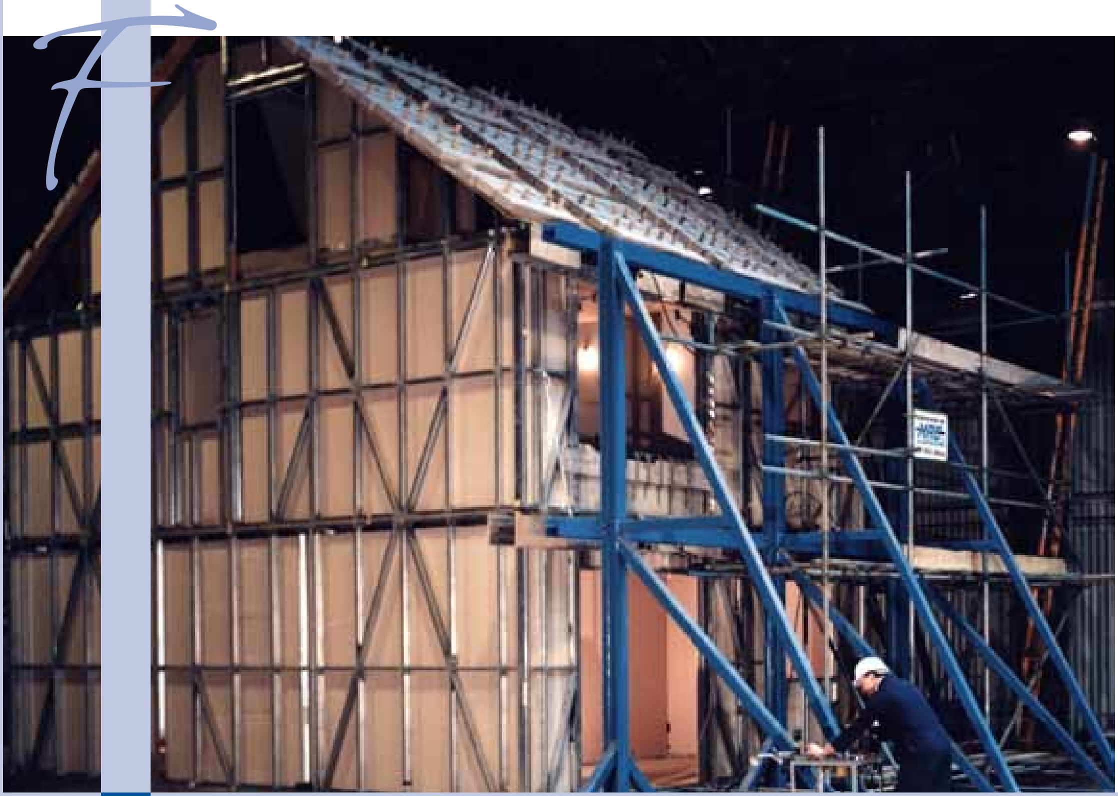
Modern light steel framing techniques are based on technology transfer from the manufacturing sector using innovative jointing techniques associated with mass-production assembly lines. Light gauge cold formed steel framed modular and panellised systems have played an important role in meeting targets for new housing in recent years and it is expected that the market will continue to grow in the foreseeable future. As with other innovative forms of construction, the development of such systems has been driven by the need to achieve higher standards in relation to energy use and acoustic and thermal performance. There is little evidence that performance in fire has been considered explicitly other than ensuring that elements meet the minimum regulatory requirements in respect of life safety.

Such innovative forms of construction are ideally suited to provide repeatable units such as apartment blocks, student accommodation and hotels. A number of steel frame building systems replicate light timber frame design using standard stud centres to accommodate available plasterboard sheet sizes. The potential for fire spread in cavities, the performance of plasterboard linings and issues of workmanship and quality control on site are common concerns for both the timber and light steel frame industries. The small section sizes associated with light steel frames mean that deformation due to thermal gradients, together with a reduction in properties at elevated temperature, may lead to instability.

Cold formed steel differs substantially from the hot rolled sections used in multi-storey construction. The sections are shaped at ambient temperature using bending and pressing and the resulting cross-sections are very slender. It is common for cold formed members to be formed from steel sheet that is no more than a few millimetres thick whilst hot rolled sections would, at their most slender, be in excess of 4 mm thickness. Examples of light steel frame construction are shown in Figure 5. A number of issues concerning the performance in fire of light steel framed construction are covered in the case studies in Section 8.

Courtesy of SCI

Figure 5 Light steel frame showing floor cassette and wall frames



3 Real fire data

Data related to real fire incidents are collected by the Fire and Rescue Services and collated and analysed centrally by the DCLG. Information is also collected by individual insurance companies and by bodies representing the insurance industry as a whole (based on returns provided by individual companies). Historically, there has been a different emphasis in relation to the information recorded, with the Fire and Rescue Service focused very much on initial causes and on subsequent injury or loss of life reflecting their primary area of responsibility. The insurance industry figures relate more closely to the financial costs of fire including consequential losses and business disruption. In recent years, there has been a growing awareness of the need to gather information in relation to specific forms of construction to ensure that accurate information is available to identify specific areas for future research. This issue was highlighted in the DCLG funded scoping study, Innovative Construction Products and Techniques[16]. During this study, all of the available sources of statistical information have been studied to try to identify trends related to modern forms of construction. Due to deficiencies in the way the data are collected, small sample sizes and missing contextual information with regard to market share, it is very difficult to come to any firm conclusions.

3.1 Insurance industry data

There is a growing concern in the fire safety community and particularly in the insurance sector, that fires in modern buildings result in larger financial losses when compared to 'traditional' forms of construction[17]. In order to investigate this concern, it is necessary to interrogate the available data. World fire statistics are published annually by the Geneva Association representing leading insurers in each participating country. The data indicate a general increase in the direct cost of UK losses due to fire over the period from 1998 to 2006 and a corresponding increase in the costs of providing fire protection. However, over the same period, the number of fatalities has decreased.

3.1.1 RISCAuthority large loss fire statistics

Any attempt to analyse the data in terms of specific forms of construction or the nature of innovation within buildings is generally hampered by the amount of information which is not of direct relevance to the subject. To date, it has been very difficult to analyse statistics on fire losses by construction type. A new initiative by RISCAuthority, a group of UK insurers who actively support a number of expert working groups developing and promulgating best practice for the protection of people, property, business and the environment from loss due to fire and other risks, has attempted to publish data on large losses in a manner which provides quality evidence to influence those in a position to effect beneficial change. The first release of data on large losses has been published by the Fire Protection Association[18] covering returns submitted between 1/4/2009 and 31/3/2010. Large losses are defined as those where the value exceeds £100,000 or involves loss of life. As this is the first publication from a new system, it is inevitable that the data set will be deficient in some areas. However, the aim is to improve on the overall quality of the data.

With respect to the current project, this information is particularly relevant as it is broken down not only by the usual categories of occupancy type, causation, etc, but includes information on fires related to innovative forms of construction and construction type. From the data, a number of salient points can be drawn with regard to dwellings and innovative forms of construction:

- Fires in dwellings account for some 18% of all large losses reported during the period. This is the largest single category.
- Approximately 50% of dwelling fires are started deliberately where the cause is known.
- The most common ignition sources are smoking related (12.9%) and electricity supply (9.1%). The corresponding figures are 24% and 17%, respectively, when those ignition sources classified as either unknown or unassigned are removed from the data set.
- Problems with access and, to a lesser extent, inadequate water supply are the chief impedances to firefighting in dwellings.
- Approximately 40% of fires in dwellings are reported between midnight and 6 am.
- Timber frame accounts for the highest reported type of innovative construction. This is not particularly surprising as there are a large number of timber dwellings in existence. However, the highest single category is reported as ‘other’ where construction type has been reported. This suggests that loss adjusters may require additional training on identification of particular forms of construction.

Even given the deficiencies within the data, dealing as it does with a limited data set and a limited time frame, the RISCAuthority/FPA initiative is an important development and will provide data that can be used to identify real issues in the construction sector rather than issues based on anecdotal evidence.

3.2 Fire and Rescue Service data

Information is collected by individual fire authorities based on returns from all incidents, and collated and analysed centrally through DCLG[19]. The data confirm a number of the conclusions drawn from the information supplied by the insurance industry notably that fires in dwellings account for the largest single category of fires and exceed those within all other categories of buildings combined. At the same time, the figures reflect the general trend of a decrease in the number of fires.

3.2.1 London Fire Brigade real fires database

London Fire Brigade (LFB), the largest fire authority in the UK, maintains a database of real fire incidents where data are collected and analysed in relation to a number of categories. The information shows that fires in dwellings account for some 65% of all building fires. Through querying the database, trends relating to fires in modern buildings can be analysed. Due to changes in how fires are reported by LFB, only fire events occurring after April 2005 are included in this report. Much of the analysis focuses on occupied purpose-built flats or maisonettes of four to nine storeys in height. This group represents the most likely market for alternative forms of construction.

The database was first interrogated to establish in which type of multiple occupancy structures the largest amount of 'damage' was observed (measured in m^2). The information is summarised in Figure 6. The data set was limited to residential or residential type (ie hotels and motels) multi-storey buildings. Generally, it can be seen that most damage in such buildings is relatively small. However, where there is a large amount of damage, such events are more apparent in hotels than residential apartment buildings.

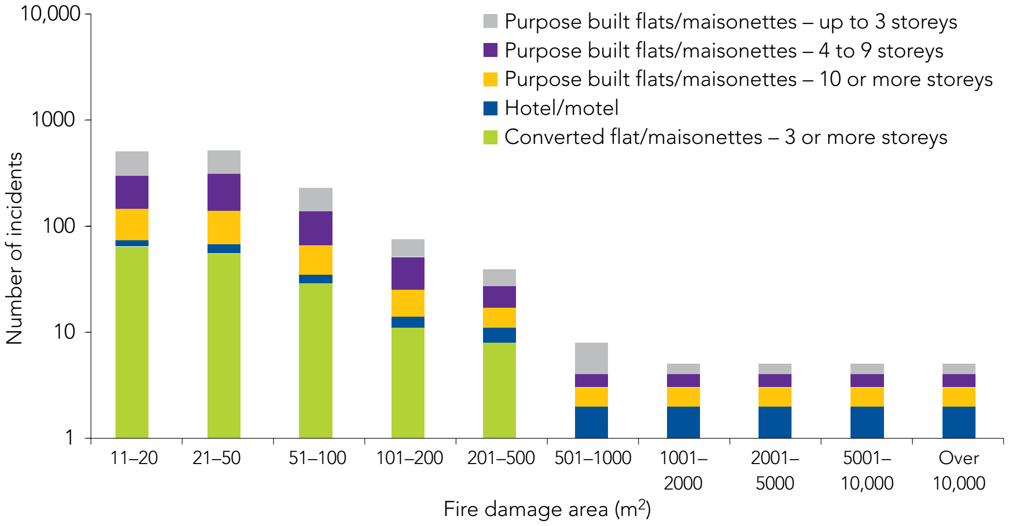


Figure 6 Fire damage area by building use for multiple occupancy structures

If the search is focused upon occupied apartment buildings ranging from four to nine storeys in height, which was deemed to be the most likely instance where modern forms of construction may be adopted, then the amount of damage suffered due to fire can be correlated with the year in which it was constructed. This is shown in Figure 7.

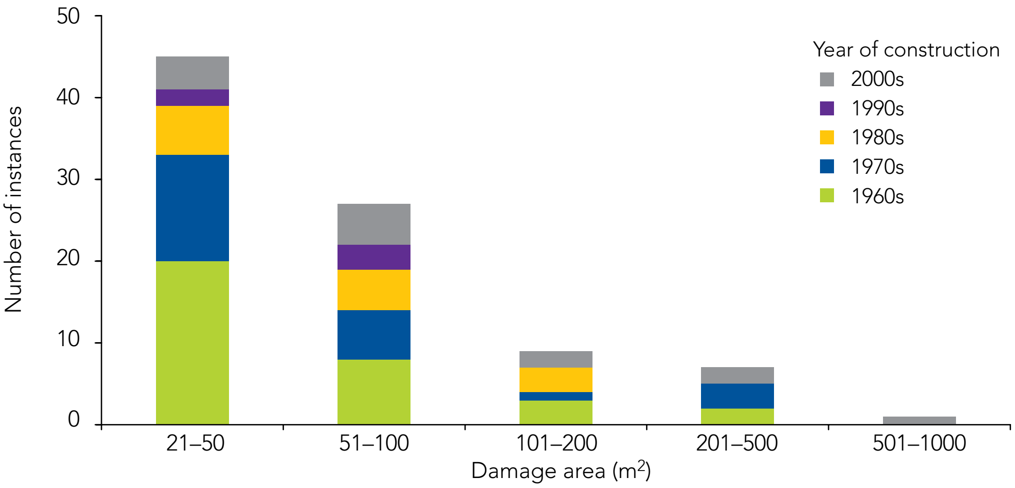


Figure 7 Approximate year of construction versus fire damaged area for occupied flats and maisonettes ranging from four to nine storeys in height

The trend is a little inconclusive and appears to indicate that, although the largest volume of damage occurred in a building constructed after the year 2000, buildings constructed circa 1960 to 1970 are equally as susceptible to high levels of damage as modern buildings. This is, however, based on a relatively small sample size. Similarly, if the extent of fire spread is focused upon rather than the 'extent of damage', the results are shown in Figure 8.

Figure 8 indicates that, in the instances where fire engulfed the entire four to nine storey block of flats, the year of construction was post-2000. This however represents a single event in the period 2005 to 2010. The statistics relating to fires which affected more than a single storey are more interesting. These suggest that buildings constructed in the 1960s are equally as susceptible to breaches of compartmentation as more modern buildings.

One of the many criticisms levelled at modern highly insulated buildings is that they suffer disproportionate damage in fires relative to more traditional construction. This refers to the concept that a very small fire may lead to the level of damage corresponding to that of a much larger severe fire. Supporting this concept with statistical evidence is difficult, however, if year of construction is plotted versus item of first ignition, for fires that have breached the compartment of origin in occupied four to nine storey flats, the results are seen in Figure 9.

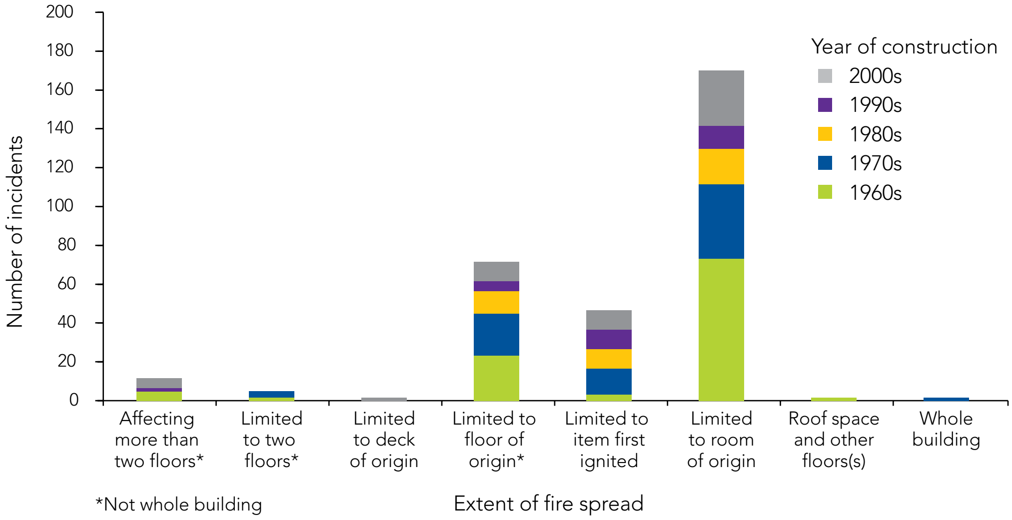


Figure 8 Extent of fire spread versus year of construction for occupied flats and maisonettes ranging from four to nine storeys in height

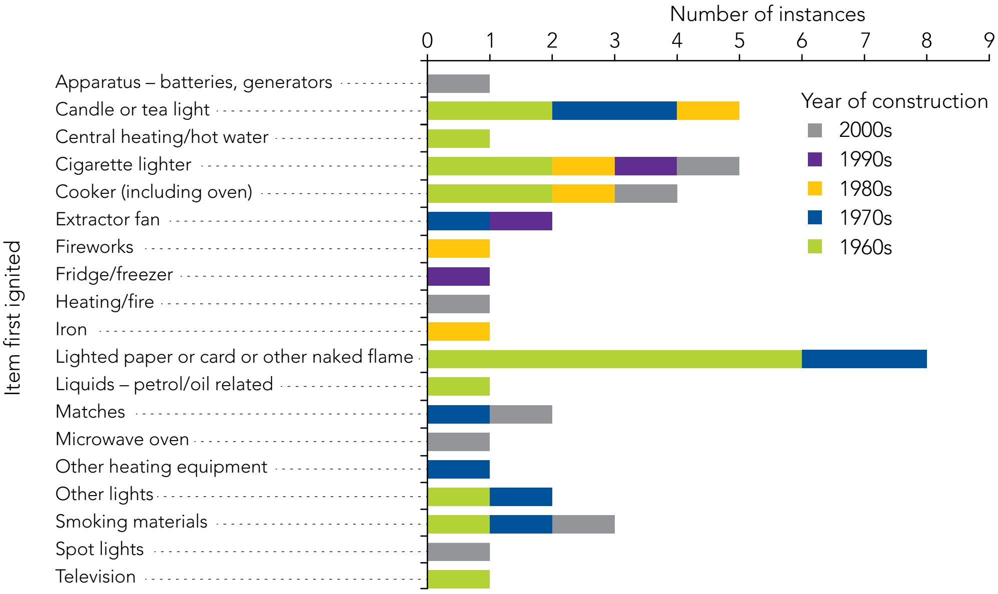


Figure 9 Item first ignited versus year of construction, for occupied flats four to nine storeys in height, where the compartment of origin was breached

Similar to previous figures, the evidence to support the criticisms levelled at highly insulated buildings is lacking. Figure 9 suggests that, in the last five years (2005 to 2010), more fires in traditional building structures have breached the compartment of origin compared to more modern buildings.

The analysed statistics from LFB shown above are inconclusive. There appears to be no trends indicating that modern buildings are more susceptible to higher levels of damage than traditional building stock. These statistics must however be put into reasonable perspective. Firstly, particularly in historic London, the proportion of new buildings constructed post-2000 is small relative to traditional building stock constructed before 2000. As a result, the probability of a fire occurring in a newer building is small and thus the statistics are skewed by this factor. If the database is queried in a more considered manner, and the number of fires breaching compartmentation are presented as a proportion of the number of fires for any given decade of construction, then Figure 10 to Figure 12 emerge. Figure 10 presents data for flats below four storeys, Figure 11 indicates trends for flats four to nine storeys in height whilst Figure 12 presents data for flats over 10 storeys in height.

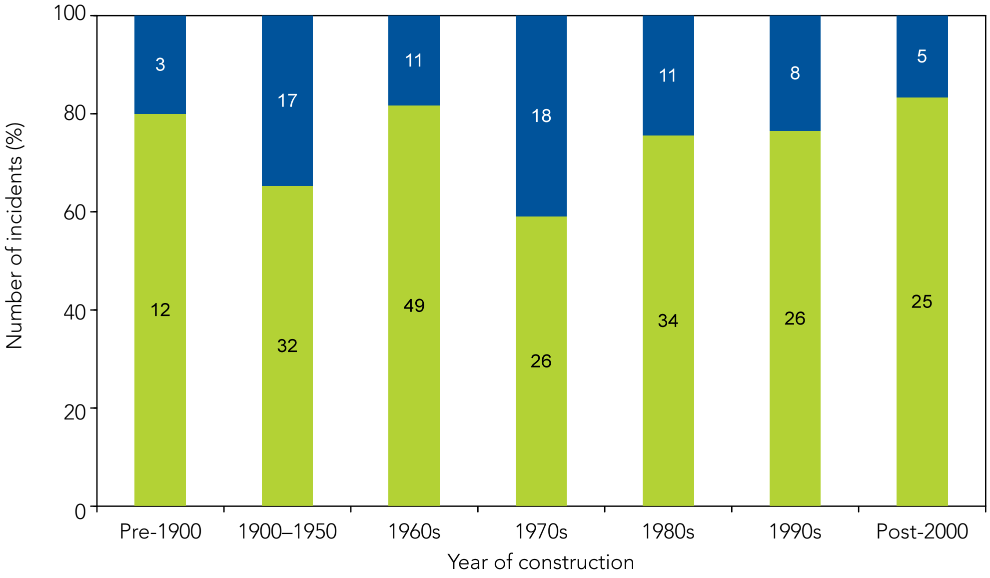


Figure 10 Count of fires by year of construction, for occupied flats below four storeys in height. Percentage of fires which have breached the compartment of origin shown in blue.

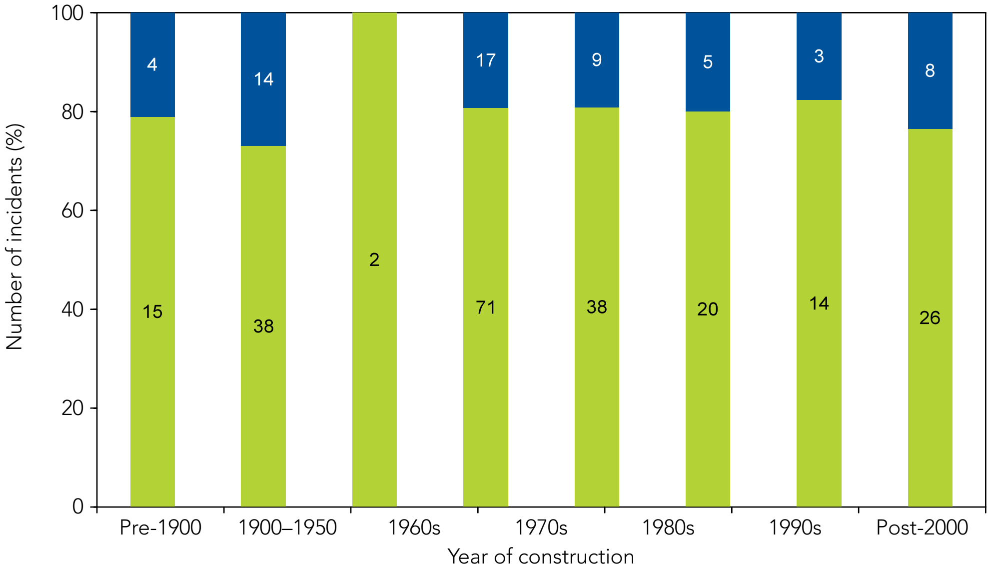


Figure 11 Count of fires by year of construction, for occupied flats four to nine storeys in height. Percentage of fires which have breached the compartment of origin shown in blue.

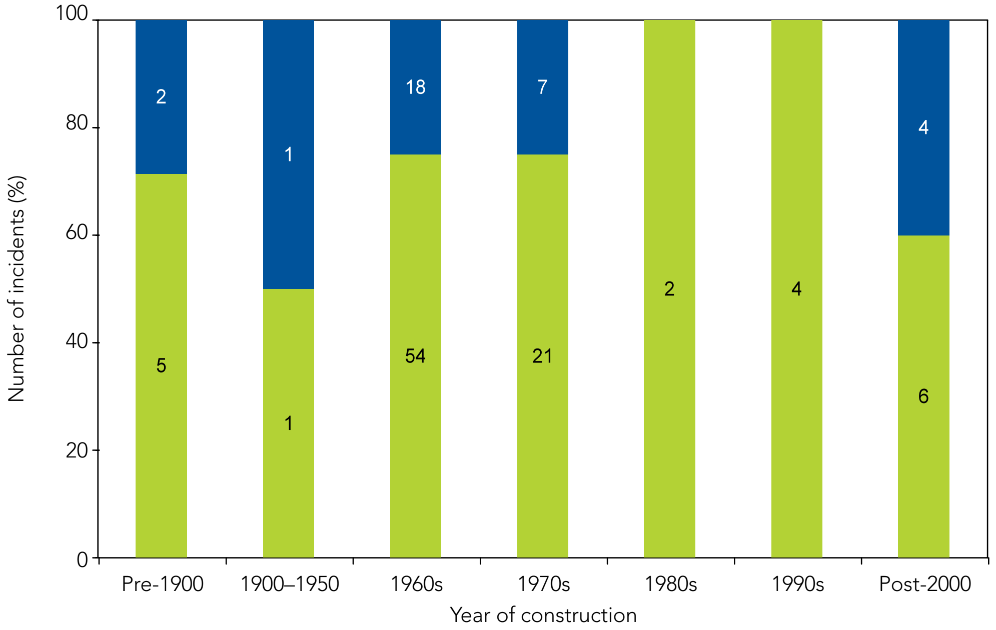


Figure 12 Count of fires by year of construction, for occupied flats 10 storeys or above in height. Percentage of fires which have breached the compartment of origin shown in blue.

For occupied high rise flats of four floors or more, the statistics indicate that the proportion of fires breaching compartmentation are higher for more modern buildings compared to older stock. This conclusion appears to be valid for all events in buildings constructed post-1960. However, the statistics relating to low rise flats, ie less than four storeys, suggest a decreasing trend of fire spread for more modern buildings. This appears to occur year upon year for all incidents in buildings constructed post-1950.

The presented statistics, however, are subject to caveats. Firstly, the LFB database, although an excellent resource, is not intended for queries like those that are presented in this report. Any conclusions from these data are drawn from incidents where data, such as year of construction, are recorded. There are however a plethora of instances where such data were not recorded and thus the trends identified may be skewed by this factor. Secondly, the accuracy of the data depends upon the expertise of the reporting officer. More conclusive trends could be derived through minor changes in the data collected by LFB. The addition of fields such as ‘type of construction’ and more thorough completion of the field relating to breach of compartmentation and year of construction would improve the ability to identify trends.

3.2.2 UK fire statistics, April 2009 to April 2010

The DCLG has recently published fire statistics for the period April 2009 to March 2010[20]. For the first time, these statistics have been analysed such that fire events in timber frame construction can be critically evaluated. The DCLG statistics includes data for domestic, non-domestic and construction site fires. Given the theme of this report, the domestic data have been focused upon. Figure 13 gives relationships between damage area (measured in m^2) and the number of instances presented as a proportion of the total number of fires occurring. The data have been split such that differences between timber frame and ‘non-special’ forms of construction can be reviewed.

The data led the DCLG to the general conclusion:

> *‘The appropriate statistical test (Pearson’s chi-squared test) indicates that fires in timber-framed dwellings do tend to have a greater area of fire and heat damage than fires in dwellings of no special construction.’*[20]

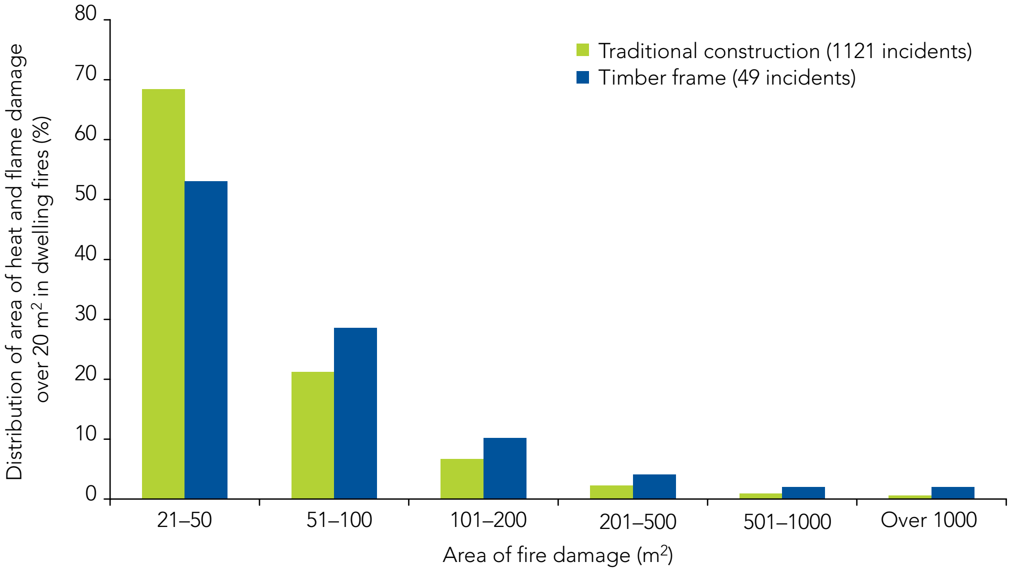


Figure 13 Distribution of area of heat and flame damage over 20 m^2 in dwelling fires[20]

However, the differences are not particularly significant and further data are required. Attempts to relate information from fire incidents to specific forms of construction will, once sufficient data have been collated, enable informed decisions to be made. At present, the data are limited and the contextual information with regard to relative market share is missing. It is therefore very difficult to draw any firm conclusions with regard to the relationship between fire damage and modern forms of construction.

4 Regulatory framework

The requirements discussed in this report relate specifically to the regulatory requirements for England and Wales. It should be noted that there are separate building standards in Scotland and Northern Ireland. Within the UK, separate legislation exists for the construction of new buildings and for the control of fire precautions in occupied premises. The information within this report is only concerned with The Building Regulations 2000 (England and Wales).

In the UK, the primary aim of Building Regulations is to ensure the safety and health of those in and around buildings. In the event of a fire, the primary objective is the life safety of those in and around the building including fire fighters. Property protection is only considered to the extent required to ensure that the primary life safety objective is achieved.

The method of specifying legislative requirements depends upon the method adopted by, or permissible under, the rules which specify control and the legal status of the documents so produced. According to Read and Morris[21], three methods are available:

- In a *functional* system, the aims or objectives are specified and the designer or architect can, by reference to explanatory notes and guides or codes, provide evidence that the objectives are being achieved.
- In a *performance*-based system, the objectives are translated into specific performance levels to be achieved in appropriate tests or evaluation techniques.
- In a *prescriptive* system, the precise details of construction or permissible systems are given, which may possibly be specified on a deemed-to-satisfy basis.

The various UK Building Regulations are functionally based although the most common route to demonstrating compliance with the functional requirements is to rely on either performance-based or prescriptive rules. This has important implications as it opens the way for fire engineering design solutions specifically tailored to the needs of the project.

Broadly speaking, the requirements of the Building Regulations with regard to material properties can be sub-divided into two main categories – those dealing with the reaction to fire properties and those dealing with resistance to fire. The former is covered under requirement B2 of the Building Regulations (England and Wales) Approved Document B[22] dealing with internal fire spread (linings) while the latter is covered under requirement B3 dealing with internal fire spread (structure). There are also some issues that cover both areas related to external fire exposure under requirement B4. When considering fire resistance, it is important to distinguish between specified fire resistance periods and performance in a real fire. Thirty, 60, 90 or 120 minutes fire resistance for elements of structure means that they have achieved that specified performance in a standard fire test subject to the specific parameters of the standard test regime. It does not mean that the elements are capable of achieving this level of performance in relation to time in a real fire. Actual performance is dependent on the severity of the fire exposure (which may be more or less severe than the standard fire curve) and the specific structural parameters in relation to loading and boundary conditions.

4.1 Reaction to fire

The functional requirement B2 covering the internal fire spread within a building through control of wall and ceiling linings states that:

> *'To inhibit the spread of fire within the building, the internal linings shall:*
>
> *(a) adequately resist the spread of flame over their surfaces; and*
>
> *(b) have, if ignited, either a rate of heat release or a rate of fire growth, which is reasonable in the circumstances.'*

Where internal linings refer to the materials or products used in lining any partition, wall, ceiling or other internal structure.

The provisions of the regulations do not apply to the upper surfaces of floors and stairs although reference should be made to the provisions covering common means of escape. External flame spread is dealt with separately (see below).

In terms of performance requirements, the classifications depend on the size of the room considered and the purpose (occupancy) class of the building. Table 1 summarises the recommended performance.

Table 1

Classification of linings (from Approved Document B[22])

Location	National class	European class
Small rooms of area not more than: a) 4 m² in residential accommodation b) 30 m² in non-residential accommodation	3	D-s3,d2
Domestic garages of area not more than 40 m²		
Other rooms (including garages)	1	C-s3,d2
Circulation spaces within dwellings		
Other circulation spaces, including the common areas of flats and maisonettes	0	B-s3,d2

Notes:
1 The term 'room' includes large spaces such as warehouses and auditoria
2 The national classifications do not automatically equate with the equivalent European classifications. It is important to realise that it is only possible to obtain a national classification by carrying out the national tests or to obtain a European classification by carrying out European tests.

4.1.1 UK reaction to fire tests

In the UK, the fire performance of products is assessed according to procedures set out in the BS 476 series. These include test methods for both reaction to fire and fire resistance. The original series ran from Part 3 to Part 8. The intention was that these would be replaced by new standards with Parts 11 to 19 dealing with the response to fire of building products and parts 20[23] to 29 dealing with elements of building construction. However, the process of adopting this new system has been superseded by the development of European fire test standards (see Section 4.1.2 and 4.2.2). The scope of each of the current UK standards in relation to the reaction to fire properties is summarised in Appendix A. Table 2 provides typical performance ratings for generic materials and products according to the national classification.

Table 2

Typical performance ratings for some generic materials and products[23]

Rating	Material or product
Class 0 (national)	Non-combustible material or material of limited combustibility Brickwork, concrete, blockwork, ceramic tiles Plasterboard Woodwool cement slabs Mineral fibre tiles or sheets with cement or resin binding
Class 3 (national)	Timber or plywood with a density more than 400 kg/m³ Wood particle board or hardboard Standard glass reinforced polyesters

4.1.2 European reaction to fire tests

In July 2013, European reaction to fire tests and classifications will replace the existing methods of testing and classification of building products in all member states within the European Union. For all products excluding flooring products, a set of four test standards will be used together with a supporting standard detailing the conditioning requirements for test specimens and the use of substrates. The relevant standards are detailed in Appendix A.

4.2 Resistance to fire

The functional requirement B3 covering internal fire spread in relation to the structure states that:

> *'The building shall be designed and constructed so that, in the event of a fire, its stability will be maintained for a reasonable period.'*

This is achieved through effective sub-division using fire-resistant construction depending on the size and intended use of the building and through adequate fire stopping around openings or cavities.

The fire resistance of an element of construction is a measure of its ability (in terms of time) to withstand the effects of fire in one or more of the following ways:

- resistance to collapse, ie the ability to maintain *loadbearing* capacity
- resistance to fire penetration, ie an ability to maintain the *integrity* of the element
- resistance to the transfer of excessive heat, ie an ability to provide *insulation* from high temperatures.

Although the designer is free to demonstrate compliance with the functional requirement in whatever way he or she chooses, the most common means of meeting the requirement is with reference to the results from standard fire tests. Recommended performance requirements are presented in the guidance to the Building Regulations. For example, The Building Regulations 2000 Approved Document B[22] provides recommended values in relation to height (or depth) of the structure and purpose group as summarised in Table 3.

Table 3

Minimum periods of fire resistance (after Table A2 Approved Document B Volume 2[22] – see Approved Document B for variations and additions to those shown in this table)

Purpose group of building	Minimum periods of fire resistance (minutes) in a:					
	Basement storey		Ground or upper storey			
	Depth (m) of lowest basement		Height (m) of top floor above ground, in a building or separated part of a building			
	More than 10	Not more than 10	Not more than 5	Not more than 18	Not more than 30	More than 30
1. Residential						
a. Block of flats						
– not sprinklered	90	60	30*	60**	90**	Not permitted
– sprinklered	90	60	30*	60**	90**	120**
b. Institutional	90	60	30*	60	90	120#
c. Other residential	90	60	30*	60	90	120#
2. Office						
– not sprinklered	90	60	30*	60	90	Not permitted
– sprinklered	60	60	30*	30*	60	120#
3. Shop and commercial						
– not sprinklered	90	60	60	60	90	Not permitted
– sprinklered	60	60	30*	60	60	120#
4. Assembly and recreation						
– not sprinklered	90	60	60	60	90	Not permitted
– sprinklered	60	60	30*	60	60	120#
5. Industrial						
– not sprinklered	120	90	60	90	120	Not permitted
– sprinklered	90	60	30*	60	90	120#
6. Storage and other non-residential						
a. any building or part not described elsewhere						
– not sprinklered	120	90	60	90	120	Not permitted
– sprinklered	90	60	30*	60	90	120#
b. car park for light vehicles						
– open sided car park	NA	NA	15*+	15*+	15*+	60
– any other car park	90	60	30*	60	90	120#

* increased to a minimum of 60 min for compartment walls separating buildings
** reduced to 30 min for any floor within a flat with more than one storey, but not if the floor contributes to the support of the building
\# reduced to 90 min for elements not forming part of the structural frame
\+ increased to 30 min for elements protecting means of escape.

4.2.1 UK fire resistance tests

The most common route to ensure compliance with the regulatory requirements is through performance under standard fire test conditions whereby an element of structure (beam, column, wall, floor) is subject to a standard fire exposure as defined in BS 476: Part 20[23] under conditions representative of its end use in the building. The specific requirements of the standard test, in terms of fire exposure, loading and support conditions are set out in the relevant standards. Those standards dealing with fire resistance are included in Appendix B.

4.2.2 European fire resistance tests

In July 2013, the European fire resistance tests and classifications will replace the existing national methods of testing in all member states within the European Union. The corresponding European document to BS 476: Part 20 is BS EN 1363 Part 1[24]. This sets out the general principles for determining fire resistance for elements of construction subject to standard fire exposure conditions. Generally, the conditions and criteria for failure are the same as in BS 476: Part 20, as is the standard time/temperature curve specified. However, the most significant difference between the national and European test methods is in the means of controlling the specified furnace temperature.

Control of furnace temperature in the European test is achieved through the use of plate thermometers rather than the traditional bead thermocouples used in the BS 476: Part 20 test. The 'plate' was introduced in an attempt to harmonise furnace performance across Europe. The plate has a higher thermal inertia and therefore in the early stages of the fire, it requires more energy to achieve a given temperature. For this reason the European test is often seen as being more severe and has an adverse effect on the fire resistance ratings of materials with a high thermal conductivity – such as unprotected structural steel. The relevant European test standards for the assessment of fire resistance are summarised in Appendix B. Information on principles and applications of fire testing is available[25].

In addition to regulatory controls with regard to reaction to fire characteristics and fire resistance summarised in Tables 1 and 2, Section B4 of The Building Regulations 2000 Approved Document B[22] also imposes restrictions on the use of materials to reduce the risk of external fire spread. This issue is covered in Section 6.2.

5 Post-flashover fire development

This section considers the impact of increased levels of thermal insulation on the post-flashover stage of fire development. Fire growth leading to flashover is the most relevant stage for life safety but this has not been considered in this study. The post-flashover phase is relevant for structural stability and property protection and may impact on life safety where a 'defend in place' strategy is adopted by the Fire and Rescue Service. Such an approach is generally adopted for medium-rise residential accommodation.

Over the years, a great deal of work has been carried out, both here in the UK and abroad, on fire growth and development. The principal parameters which influence fire severity and duration are well established. They are:

- fire load – quantity, type, distribution
- geometry – size and structural form of the fire compartment
- ventilation – size, location and geometry of openings (vertical and horizontal)
- insulation – the thermal properties of the compartment linings assessed in terms of the density, thermal conductivity and specific heat of the materials which form the compartment boundaries
- detection and suppression.

A consideration of the above parameters for a specific design scenario, together with the influence of measures used for detection and suppression, should form the first step in an overall fire safety engineering approach.

Fire load

The existing regulations consider the occupancy type and the size of the structure to define a fire resistance requirement in terms of a time to survival in a standard furnace test. Indirectly this is related to the amount of combustible material likely to be found in such a building and the consequences of a fire occurring. In terms of defining a fire load for design calculations, the usual method is to choose a value which is only exceeded in a limited number of cases.

This probabilistic method is only as good as the statistical database used to provide the source data. A commonly used value is the 80% fractile, which is that value of fire load, not exceeded in 80% of the buildings surveyed. However, in the UK, the data come from survey data which is many years old[26, 27]. The *Design Guide: Structural Fire Safety* produced by CIB committee W14[28] presents more up-to-date data from the 1970s and 1980s although there is no reference to a UK source. The quantity, distribution and type of fire load found in modern office buildings is likely to differ greatly from the figures in this report.

Any estimate of the gas temperatures is specific to the particular conditions of the design fire. There is some evidence to suggest that the standard time/temperature response is a reasonable estimation of the atmosphere temperature within a specific compartment construction and geometry given a specific quantity of cellulosic (wood-based) fire load. This is the basis of the parametric approach in EN 1991-1-2[29]. The standard fire is then modified to take into account the particular characteristics (in terms of compartment construction and ventilation) for the given design scenario. This does not however take into account the influence of commonly used furnishing materials such as plastics on fire growth. The effect of such materials is to increase the rate of growth of compartment fires. It is important that information on the combustion of modern materials (in the form of calorific values) continues to be collated to take account of innovations and allow for their influence on fire severity and duration.

The distribution of fire load is an important factor in the early stages of fire development. However, this is a factor beyond the control of the designer. Such factors as the distribution and accessibility of fire load in real buildings can only be addressed through a reduction in the combustion efficiency of the design fire load resulting in reduced temperatures. Otherwise a worst case scenario is envisaged.

Geometry

Given the growth of open plan flats in recent years[30], future design procedures may have to take into account the existence of simultaneous growing and decaying fires in different areas of very large compartments.

Ventilation

Openings such as windows and doors perform an important function in allowing cold air into the compartment and providing for the escape of flames and hot gases to the open air. The behaviour of glazing systems in real fires is not yet fully understood. The general assumption is that all windows are immediately broken so that the area of openings is the maximum available. In reality, the open area will vary with time and according to the performance of the glazing. When carrying out fire engineering design calculations, a sensitivity analysis should be carried out to determine the worst case to be used for design purposes. The influence of smoke control and mechanical ventilation systems also needs to be considered.

Insulation

Tests such as those carried out in support of the Natural Fire Safety Concept[31] have demonstrated the important influence of compartment linings on fire development. Current design methods require knowledge of the thermal inertia of modern construction materials. This information is not generally available. The fire engineering community would benefit from collating and documenting generic information on the thermal properties of commonly used construction materials.

Detection and suppression

The use of active measures can improve life safety and property protection and may have a significant influence on fire development, particularly in the important pre-flashover phase. Their use should be considered at the design stage as part of an overall fire safety risk assessment.

The following sections consider fire development in terms of the potential impact of combustible materials within the structural frame and fabric of the building and the influence of the thermal inertia of compartment linings on fully developed post-flashover fire behaviour.

5.1 Fire loading

One of the major concerns of stakeholders, in the consideration of the fire performance of MMCs, is the consequences of introducing large volumes of combustible materials into the construction of a building in addition to the contents which typically are not regulated. Unlike what we term 'traditional' forms of construction, either the structure itself may be formed from a combustible material, such as timber, or the structure may be surrounded by highly insulating polymers or foams. The issue is not restricted to innovative forms of construction as the use of insulation backed plasterboards in masonry constructions would also increase the potential fire load. Regulatory compliance for such systems, including light timber frame, SIPs and light gauge steel constructions, is typically achieved through specification of plasterboard or other similar 'fire-resistant' linings. As such, the additional fire load associated with the combustibles outside of the fire compartment is generally not considered.

Some studies have investigated the additional fire loading that should be considered where the construction itself is combustible. Data from the CIB W14 Workshop on structural fire safety[28] give total fire loads, including the construction, for buildings which would be considered as traditional. Some of these are summarised in Table 4. However, it should be noted that this data set was published in 1986 and the nature of the contents of buildings has changed significantly since then which will have an impact on the value of fire loads. It is probable that these fire loads are now in the lower quartile of what might be found in modern buildings, although this has not been substantiated due to the lack of any more recent fire load surveys.

Table 4

Fire load densities of typical construction including variable and permanent loads

Occupancy	Variable fire load (MJ/m^2)	Total (including permanent load) (MJ/m^2)	Increase due to permanent load (%)
Residence	320 (average)	730–1270	128–297
Hospital	230–330 (average)	270–1990	17–765
Technical office	250 (average)	540	116
Offices	580 (average)	635–3900	9.5–572
Department store	420 (average)	935	123

Similar calculations can be performed for modern buildings formed from combustible materials such as timber and insulation. Thomas[32] has shown that, for a 6.0 × 6.0 m office compartment formed from heavy timber construction, the increased fuel load due to the permanent fire load (the structure) can be as low as 17%.

For a simple compartment, similar to those used in research by BRE Global[11], of overall dimensions 4 m × 3 m × 2.4 m, the additional fire loading attributed to the permanent structure can be determined. An average fire load density for residential occupancy is adopted and all of the combustible structure is assumed to be consumed. This is reasonable where the structure is formed from light timber construction or similar as the timber will burn rather than gradually char. Calorific values are taken from published data. The calculations do not consider the external envelope (ie façades and roof).

The effect of incorporating permanent fire load can be seen in Table 5.

Table 5

Impact of incorporating permanent fire load

1. **Light timber frame construction – studs at 400 mm centres, joists at 600 mm centres, non-combustible insulation between studs:**

Variable fire load: 450 MJ/m^2 × 12 m^2 = 5400 MJ

Permanent fire load: 35 studs each 2.4 m × 0.045 m × 0.15 m gives a fire load of:
35 × 0.0162 m^3 × 450 kg/m^3 × 18 MJ/kg = 4592.7 MJ

5 joists each 4 m × 0.045 m × 0.22 m gives a fire load of:
5 × 0.0396 m^3 × 450 kg/m^3 × 18 MJ/kg = 1603.8 MJ

Total fire load = 5400 + 4592.7 + 1603.8 = 11,596.5 MJ

Percentage increase due to permanent fire load = 115%.

2. **SIP construction – 150 mm deep panel with PUR insulation and 15 mm OSB skins, joists at 600 mm centres:**

Variable fire load: 450 MJ/m^2 × 12 m^2 = 5400 MJ

Permanent fire load:
Volume of OSB – (4 × 2.4 m × 4 m × 0.015 m) + (4 × 2.4 m × 3 m × 0.015 m) = 1 m^3
Volume of PUR – (2 × 4 m × 2.4 m × 0.13 m) + (2 × 3 m × 2.4 m × 0.13 m) = 4.368 m^3

Fire load due to SIPs =
(1 m^3 × 450 kg/m^3 × 18 MJ/kg) + (4.368 m^3 × 40 kg/m^3 × 25 MJ/kg) = 12,468 MJ

5 joists each 4 m × 0.045 m × 0.22 m gives a fire load of:
5 × 0.0396 m^3 × 450 kg/m^3 × 18 MJ/kg = 1603.8 MJ

Total fire load = 5400 + 12,468 + 1603.8 = 19,472 MJ

Percentage increase due to permanent fire load = 261%.

3. **Light steel frame construction – non-combustible frame, insulated with PUR foam:**

Variable fire load: 450 MJ/m^2 × 12 m^2 = 5400 MJ

Notional volume of PUR – (2 × 4 m × 2.4 m × 0.13 m) + (2 × 3 m × 2.4 m × 0.13 m) = 4.368 m^3

Fire load due to insulation – 4.368 m^3 × 40 kg/m^3 × 25 MJ/kg = 4368 MJ.

Total fire load = 5400 + 4368 = 9768 MJ

Percentage increase due to permanent fire load = 81%.

The increased fire load density (%) due to consideration of the permanent (structure) fire loads is in the bounds of those noted by research published in the 1980s for similar occupancy types.

If, however, the light timber frame structure is considered in isolation without consideration of the variable fire load (approximately 6200 MJ for the given geometry), then the damage associated with construction site fires becomes understandable. In reality, on a large timber frame development site, the volume of timber could be in excess of 100 times what has been considered in this simple study. This gives potential fire loads in excess of 620,000 MJ.

Consideration of the potential permanent fire loads in a modern building highlights the importance of passive fire protection as it is this alone which limits the fire loading to that contained within a building or compartment.

5.2 Influence of boundary thermal inertia

The thermal inertia of a fire compartment heavily influences fire development. The thermal inertia can be simply defined as the product of thermal conductivity, density and specific heat. For compartment boundaries, the innermost layer, typically plasterboard or plaster in most homes, governs the thermal inertia of the compartment. However, the supporting substrate, typically masonry or timber frame and the presence of insulation, also has some influence on fire development. The thermal inertia of the 'construction' is normally taken as some form of weighted average of the properties making up an element of construction and hence substrate properties carry some importance. There is a perception that the increased use of insulation in buildings may result in more severe (higher temperatures and faster fire growth rates) compartment fires as the compartment boundaries are more heavily insulated and thus have lower thermal inertias. The impact of thermal inertia (*b*) on peak temperature (Θ_{max}) can be shown with reference to Table 6 (and Figure 14) which is based upon the parametric design fire in EN1991-1-2[29].

Table 6

Impact of thermal inertia on peak fire temperature

$b\ \sqrt{k\rho c}$ ($J/m^2s^{1/2}K$)	700	800	900	1000	1100	1200	1300	1400	1500
Θ_{max} (°C)	1122	1083	1052	1027	1007	994	979	968	960

This indicates that when compartment thermal inertia (*b*) increases fires become cooler for a fixed level of ventilation and fire loading.

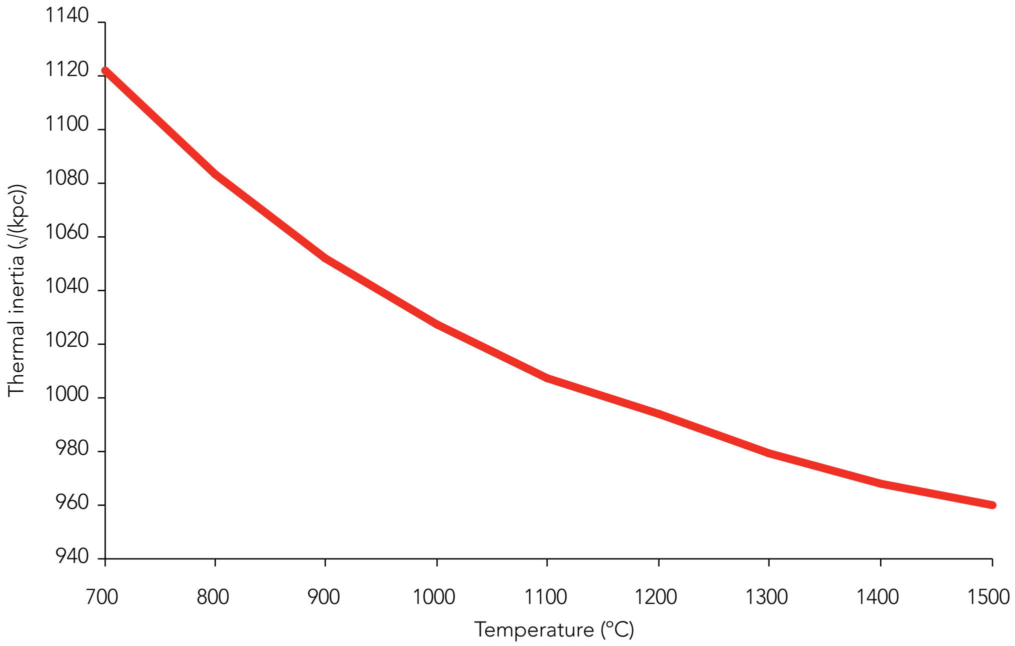


Figure 14 Impact of thermal inertia on peak compartment temperature, from BS EN 1991-1-2[29]

To investigate the influence of insulation on fire development, due to boundary thermal inertia effects, a simple parametric study has been completed using the zone model OZONE, developed by the University of Liege and validated against test data from BRE. The purpose of this study is to investigate the impact of different types of wall construction (and thus variations in thermal inertia) on fire development.

For a given constant fire design scenario, in this instance the natural fire safety concept residential fire and a constant compartment geometry (4 × 3 × 2.5 m with two openings of 0.75 m²), the influence of low thermal inertia boundaries (as a result of highly insulated walls) can be assessed by inspecting resulting hot gas layer temperatures. These transient temperatures are benchmarked against a traditional unlined blockwork compartment. The key parameters for the parametric study are summarised in Tables 7 and 8.

Table 7

Run identification with wall layers (abbreviations defined in Table 8)

Run	Construction	Layer 1	Layer 2	Layer 3	Layer 4
1	Blockwork compartment	LWCB	N/A	N/A	N/A
2	Gypsum lined (15 mm) blockwork compartment	PLBD	LWCB	N/A	N/A
3	Gypsum lined (30 mm) blockwork compartment	PLBD	LWCB	N/A	N/A
4	Open panel timber frame	PLBD	RCKW	OSB	N/A
5	Closed panel timber frame	PLBD	OSB	RCKW	OSB
6	SIP low density core	PLBD	OSB	PUR-LD	OSB
7	SIP medium density core	PLBD	OSB	PUR-MD	OSB
8	SIP high density core	PLBD	OSB	PUR-HD	OSB
9	Approximated adiabatic compartment	ρ = 1.0 kg/m^3; k=0.001 W/m.K; c= 500 J/kg/K			
10	High thermal inertia compartment	ρ = 500 kg/m^3; k=1.0 W/m.K; c= 2000 J/kg/K			

Table 8

Material identification and thermal properties

ID	Material	Thickness (mm)	Density (kg/m³)	Conductivity (W/m.K)	Specific heat (J/kg.K)
LWCB	Light weight concrete block	100	550	0.14	840
PLBD	Plasterboard	Varies	900	0.25	1000
RCKW	Rock wool insulation	140	60	0.037	1030
OSB	Oriented strand board	15	450	0.1	1113
PUR-LD	Low density polyurethane foam	140	35	0.0238	1268
PUR-MD	Medium density polyurethane foam	140	70	0.0238	1268
PUR-HD	High density polyurethane foam	140	100	0.0238	1268

In each instance, the ceiling boundary was assumed to be a 30 mm thick layer of plasterboard whilst the floor boundary was 100 mm of normal weight concrete. The properties of the wall, constructed from up to four discrete layers, were varied in accordance with Table 7.

5.2.1 Modelling approach and results

Ozone[33] is a zone model developed by the University of Liege as part of the natural fire safety concept programme[31]. As a result of the experiments against which it was benchmarked, the model is designed to simulate fire behaviour in small compartments. Fires are initially simulated as a localised fire with a pre-defined heat release and growth rate. This results in the formation of two layers defined as the hot (or upper) layer, formed from smoke and ceiling jets, and a cool (or lower) layer which forms below the upper layer. By default, flashover is assumed to occur in Ozone when the hot layer temperature reaches a pre-defined value. For the purpose of this investigation, 550°C is assumed. Once this temperature is reached, the fire behaviour in the compartment is characterised by a single zone at a uniform temperature. Factors, such as boundary thermal inertia, ultimately influence both the time taken to switch from a two-zone to a single zone model (ie flashover) and the overall severity of the fire. Severity for the purposes of this study is defined as peak compartment temperature and overall fire duration.

The consequences of variations in wall construction for fire development can be noted with reference to Figure 15 which shows the transient development of hot layer temperature for the properties defined in Tables 7 and 8. For completeness, a fictitious highly insulated compartment (adiabatic – run 9) and poorly insulated compartment (run 10) are modelled. These exist to show upper and lower bounds in relation to the range of fires that could be expected in the compartment defined. Interestingly, the adiabatic case points to an upper temperature boundary that can be developed in an Ozone simulation (1400°C). This is the limit imposed by the developers which points to a temperature at which compartment fires would become non-physical and realistic. As all of the simulations performed (runs 1 to 8) are well below this boundary, it gives confidence in the results obtained.

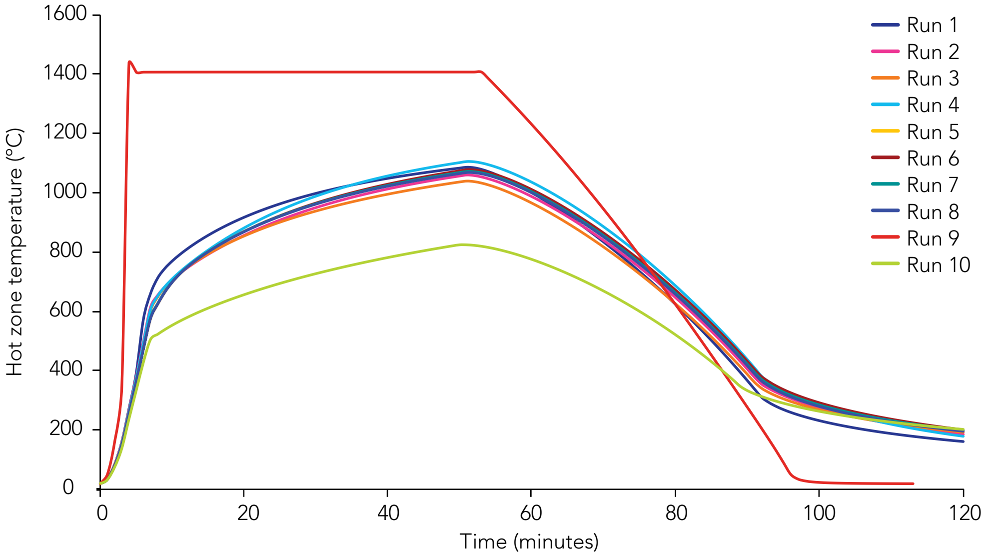


Figure 15 Hot layer temperatures for a range of wall thermal inertias

Based on the results of this study, it is apparent that highly insulated walls, such as a SIP or closed panel timber frame, have little significant influence on fire development considering boundary thermal inertia effects only. This appears to be because the benchmark lightweight blockwork compartment is itself a very good insulator and hence more highly insulated walls such as SIPs result in only relatively minor improvements in insulation performance. However, this study does not consider the consequences of the additional air tightness associated with SIPs and other similar systems which would also influence fire behaviour. The temperature development in the runs performed is highly sensitive and almost entirely dependent on the lining to the compartment and not the substrate to which it is connected. This is because the plasterboard is the foremost layer of the construction relative to the position of the fire and contributes the largest proportion of the construction's overall thermal inertia. Should the plasterboard fail during the burning phase, then this of course would influence fire behaviour as additional fire loading would be introduced. This however is not considered in this parametric study.

Peak temperatures from Figure 14 have been summarised in Table 9.

Table 9

Peak temperatures for different wall constructions

Run	Construction	Peak temperature (°C)
1	Blockwork compartment	1086.86
2	Gypsum lined (15 mm) blockwork compartment	1060.64
3	Gypsum lined (30 mm) blockwork compartment	1040.08
4	Open panel timber frame	1106.13
5	Closed panel timber frame	1075.75
6	SIP low density core	1078.57
7	SIP medium density core	1072.6
8	SIP high density core	1068.91

The time to reach flashover in all cases is very similar and seems unaffected by the minor changes in thermal inertia associated with adopting a blockwork compartment, relative to a highly insulated compartment. This finding is eluded to by Thomas and Bullen[34] in their early research which notes that a weaker relationship than expected exists between time to flashover and boundary thermal inertia. The study has presented a primitive investigation of the impacts of changes in thermal inertia, associated with adopting high levels of wall insulation, on post-flashover fire severity. This study is, however, subject to caveats as many post-flashover behaviours which may also be influenced by wall construction are not considered. Factors related to escape from a fire during the pre-flashover stage, such as heat release rate and smoke and toxic species production rates, have not been investigated in this study.

6 Fire spread

Fire spread within buildings can occur through a number of different mechanisms. The regulatory framework and associated fire testing regime exist, in large part, to prevent fire from spreading from the compartment of origin to adjacent compartments within the same building or to other buildings within the vicinity of the initial incident.

The requirements are independent of the structural form. However, it must be recognised that certain forms of construction represent a greater risk than others. The risk may arise as a function of the finished form, the inherent risk associated with the materials used for construction or the manner in which it has been constructed. For example, a cavity within a masonry brick and block wall, whether filled with insulation or not, does not represent as great a risk as a fire within the cavity between a timber frame wall and an external rainscreen cladding. This issue is considered further in Section 8 with reference to the post-test cavity fire incident which occurred on the TF2000 test building at Cardington.

Broadly speaking, there are two principal mechanisms for fire spread, internal and external. Internal fire spread is covered by regulations relating to compartmentation (including provisions to inhibit the unseen spread of fire and smoke in voids and cavities) through requirement B2[22] Approved Document B, and external fire spread is dealt with principally through restrictions on the use of combustible materials and controls on separation distances between buildings through requirement B4.

6.1 Internal fire spread (including fire spread in cavities and voids)

Dwellings, and specifically multi-occupancy dwellings, are characterised by high levels of compartmentation. Each individual occupancy is classed as an individual compartment and separated using fire-resistant construction from neighbouring apartments and from common areas such as lobbies and staircases used as a means of escape. For many modern forms of construction and some more traditional techniques, the principal means of ensuring compartmentation is through the use of plasterboard linings. In addition to providing the required levels of fire resistance, the linings also provide significant levels of thermal insulation and may provide moisture resistance and a surface suitable for direct application of decorative finishes. There are a bewildering number of different types of plasterboard available from a range of different suppliers. Guidance on classification of plasterboards is available in national and European standards[35, 36]. It is important that the correct board is specified for the specific application required. For the present purposes, the most significant difference is between those boards designated as type F and other boards. Type F boards have improved core adhesion at high temperatures from the inclusion of mineral fibres and/or other additives in the gypsum core.

Plasterboard performance in terms of fire protection to structural frames has been well established over a number of years. A large number of fire tests have been undertaken to demonstrate compliance with the regulatory requirements and in support of third party accreditation schemes. However, the vast majority of the data from these tests is commercial, in confidence, and cannot be referenced or disseminated. Standard fire tests tend to be undertaken under strictly controlled conditions with special care and attention paid to detailing around joints and to ensuring the correct fixings are adopted at the centres specified by the manufacturer. Plasterboard manufacturers, through their technical departments, have produced extensive guidance for installers. *The White Book* produced by British Gypsum[37] is an example of information made available by manufacturers to support installation of their products. Similar guidance is available from the other manufacturers. Workmanship and site supervision are of crucial importance in ensuring that the boards are capable of providing the level of protection assumed in design and based on performance in standard fire tests. This is particularly important where multi-layer systems are adopted and the inner layer is not visible once the work has been completed. Guidance in this regard is provided in a BRE Report[38]. Further generic guidance is available through industry best practice[39,40].

One means by which the integrity of compartmentation can be compromised is a breakdown in the performance of the wall and ceiling linings. The other potential route for internal fire spread is through voids within the building. Approved Document B[22] states that:

> *'The building shall be designed and constructed so that the unseen spread of fire and smoke within concealed spaces in its structure and fabric is inhibited.'*[22]

The requirements will be met if:

> *'any hidden voids in the construction are sealed and sub-divided to inhibit the unseen spread of fire and products of combustion, in order to reduce the risk of structural failure and the spread of fire, in so far as they pose a threat to the safety of people in and around the building.'*[22]

There is a recognition of the specific risk associated with cavities and voids:

> *'Concealed spaces or cavities in the construction of a building provide a ready route for smoke and fire spread' and 'As any spread is concealed, it presents a greater danger than would a more obvious weakness in the fabric of the building'.*[22]

It is known from fires in relatively modern apartment buildings that compartmentation between dwellings can be compromised by inadequate detailing between compartment walls and the underside of pitched roofs resulting in extensive fire spread in roof voids. This situation has been addressed in a recent DCLG funded research study[41]. The study provided examples of good and bad practice in relation to detailing of fire stopping within roof voids and included a number of examples of planning submissions where inadequate detail was presented to confirm whether the proposed method of construction complies with the guidance to Approved Document B. The study included information from real fire incidents involving fires in roof voids of residential buildings.

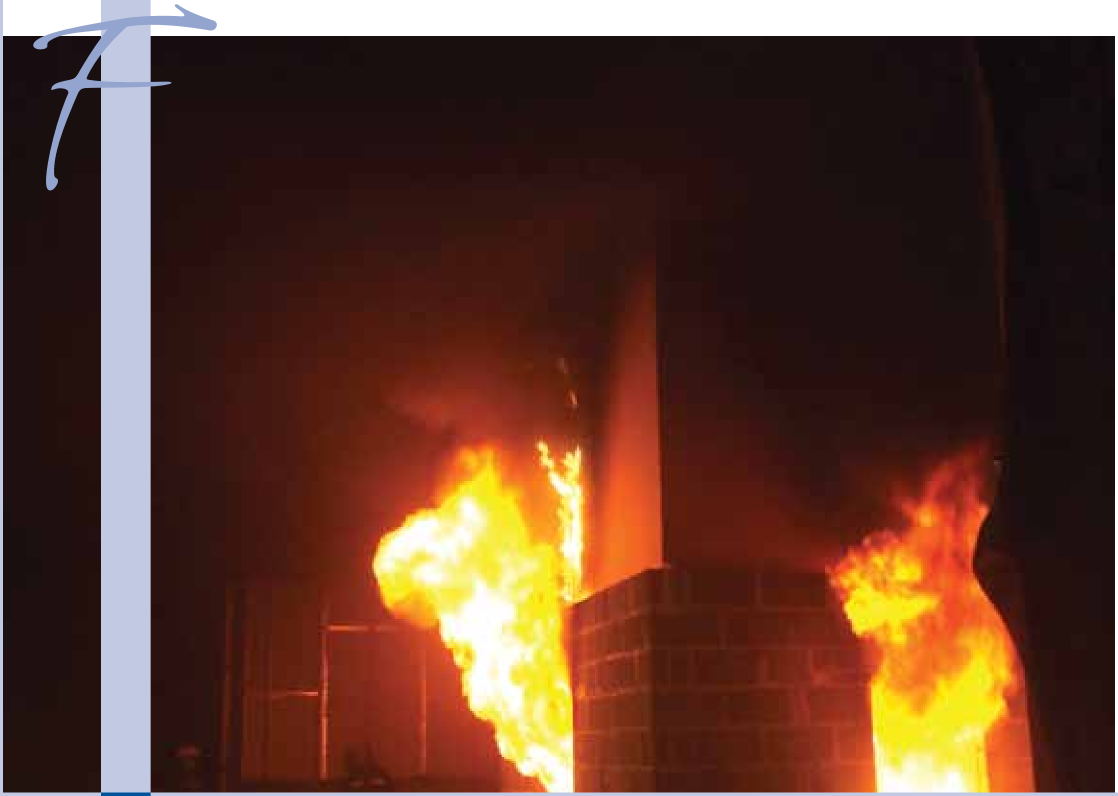
A number of the issues relating to fire spread within cavities and the particular situation where the internal face of the cavity is made up of combustible material are described in some detail in the case studies in Section 8.

6.2 External fire spread

There are three main potential ignition sources in relation to external fire spread. They are:

- Radiated heat from an external source such as a fire in an adjacent building.
- External fire source in direct contact with the building. This could be initiated through careless storage of materials adjacent to the structure or could arise as a consequence of a deliberate arson event.
- Fire breaking out of one of the compartments within the structure with flames emerging from window openings igniting the external surface of the cladding, breaking back in through windows or igniting combustible window frames.

Controls are imposed due to restrictions on the amount of combustible material present on the external façade of the building. The extent of the restrictions is determined by the occupancy class, height and distance from the boundary of adjacent buildings. Traditionally, compliance with the regulations has been achieved through reaction to fire tests (see Section 5.1). Such tests consider issues such as ignitability, flame spread and heat release rate. However, they are generally applicable to external surfaces. Many of the cladding systems now on the market are complex composite or built-up systems where an assessment of the characteristics of the exposed surface with respect to flame spread may not provide an accurate picture of performance in a realistic fire scenario. For this reason and due to some high profile fires involving vertical flame spread, particularly the fire at Irvine in 1999[42], a large scale test method was developed by BRE and this eventually became the basis of a British Standard[2] fire test for cladding systems. The test method looks at performance due to a realistic fire scenario corresponding to a fully developed fire within a compartment with external flaming from a window opening impinging directly on the external façade. The test considers system performance rather than surface spread of flame properties in isolation. The original standard covered non-loadbearing external rainscreen overcladding systems or external wall insulation systems applied to the face of a building. An additional part to the standard[43] was developed to cover the testing of non-loadbearing external cladding systems such as curtain walling, glazed elements, infill panels and insulated composite panels fixed to, and supported by, a structural steel frame.



7 Life cycle issues

7.1 Construction phase

In general, fire safety on construction sites comes under the authority of the HSE. In recent years, a number of high profile fires have occurred on large timber frame construction sites which have brought this issue into sharp focus and resulted in a number of articles in construction related publications. Timber frame and other modern forms of construction represent a particular risk during the construction phase before any fire protection has been installed. Incidents such as that which occurred at Colindale in North London in 2006 raised a number of issues which are pertinent to those bodies with regulatory responsibilities for completed buildings. In particular, the issue of partial occupation of buildings under construction tends to blur the lines of responsibility. Similarly, for large developments, the regulatory requirements with regard to distances to the nearest boundary are not designed to take into account the high levels of radiative heat flux emanating from an unprotected timber frame.

In part, the frequency and extent of the damage associated with recent incidents on timber frame construction sites are functions of the growth of the timber frame industry. Timber frame now accounts for 30 to 40% of medium rise apartment construction in the UK. Clearly with a larger market share, there will be more incidents involving timber frame buildings. However, there are certain specific characteristics of timber frame construction that make it particularly vulnerable to fire damage during the construction phase.

The majority of timber frame projects, particularly medium-rise buildings, are constructed using open panel platform frame construction where the timber structural frame is built floor by floor with the preceding floor forming the 'platform' for subsequent construction. This technique produces fast construction times and minimises the amount of time following trades have to be on site. However, such a system means that the internal linings and associated insulation are not generally installed until the structural frame is complete. At this stage, the frame is particularly vulnerable to damage by fire. The studs and floor joists used in modern UK timber frame construction are generally formed from small section timber with typical stud sizes for external wall frames of 140 × 38 mm. Such small section timber has negligible fire resistance based on standard charring rates. It is understood that European practice is to use larger section timbers for the structural frame although US practice utilises section sizes closer to those used in the UK.

The probability of fire occurrence can be minimised through rigorous site management and enhanced security measures. Effective detection or perhaps suppression may be used in tandem with preventative measures to reduce the severity of any fire that does occur. Whilst it is important to concentrate on site safety and security and to minimise the possibility of accidental or deliberate ignition sources this, in itself, is not a solution. There are many potential solutions that could contribute towards reducing the risks.

One potential option is to move towards closed panel construction where the linings are installed off site. This would also potentially deal with issues concerning quality of construction and workmanship. An alternative option is to reschedule the construction process to include installation of linings as work proceeds. Other options which could be considered are the use of fire retardant treatment processes and the use of non-combustible board forming the sheathing layer in place of the more commonly used OSB. However, it is important to ensure that any applied coatings or other fire retardant systems do not adversely affect durability. Any of the above measures would potentially reduce the damage due to a fire during the construction phase by limiting fire spread and delaying the time to ignition of the main structural components. However, there are potential cost implications which may well have an adverse effect on the market position of timber frame for residential buildings.

The latest release of information on fire statistics produced by DCLG[20] and discussed in Section 3.2.2 includes information on construction site fires. Figure 16 shows the area of fire damage versus number of instances. This has been normalised against the relative proportions of fires in timber and traditional constructions. The data presented are for domestic type properties. In a similar manner to the completed building statistics, the trends indicate that, proportionally, timber frame construction site fires produce more damage area than traditional forms of construction.

The UK timber frame industry has responded to concerns through the publication of guidance related to fire safety on construction sites[44]. Publications covering similar areas have been produced by the Fire Protection Association and the HSE[45, 46]. Both of these documents have recently been reissued to incorporate lessons learned from recent large construction site fires involving timber frame buildings. Information from the Colindale fire is included in the case studies in Section 8.

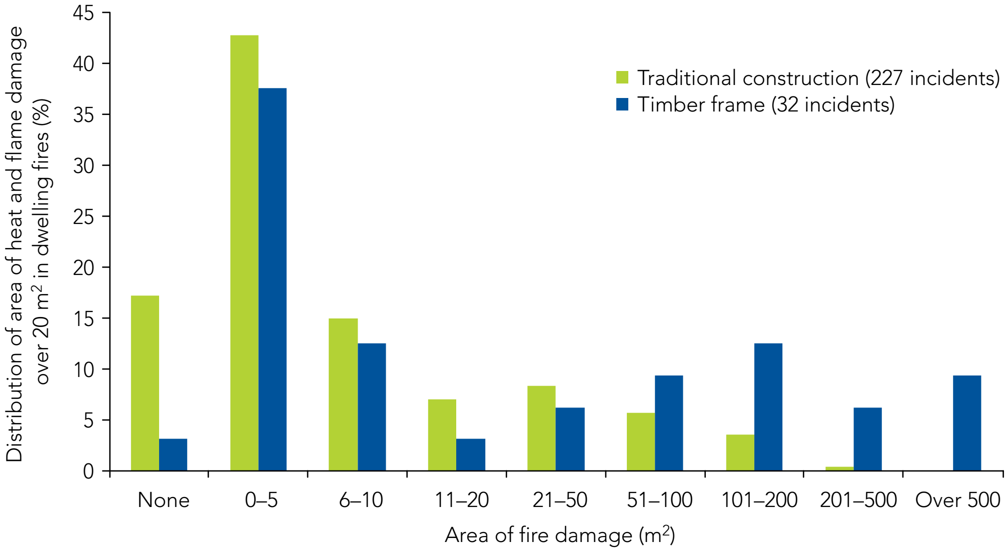


Figure 16 Distribution of area of heat and flame damage for construction site fires[20]

7.2 Post-construction phase

This issue has been considered in some detail in a previous study[16] with a particular emphasis on workmanship issues and the potential for misinformed alterations and modifications to have an adverse effect on the performance of the building in a fire.

On completion, responsibility for ongoing compliance with the regulatory requirements in relation to fire safety reverts to the building control authority and the local fire authority as far as general fire precautions are concerned. One particular concern is the extent to which the building will be subject to modifications/alterations over the course of its design life and what impact these modifications may have in terms of fire performance. The concerns apply to all forms of construction. However, there is little doubt that many modern forms of construction, particularly lightweight framing systems such as timber frame, SIPs or light gauge steel, make it easier to produce inappropriate modifications. Useful information is available in an NHBC guide[47] for home owners on potential issues arising from misinformed alterations. The guide also identifies the significant differences between masonry and timber frame construction and gives guidance related to internal walls, external walls and separating (party) walls.

Requirement 16B of The Building Regulations (Requirement 38 as of 2010) deals with provision of fire safety information to the responsible person (as defined in the Regulatory Reform Order) to help them meet their statutory duties under the fire safety order. This could include information on the importance of maintaining adequate separation and the possible impact of misinformed alterations. Further guidance is available in Appendix G of Approved Document B[22].

The issue of getting important information to the right people is best dealt with through the building owners' manual which is a document provided by the manufacturer containing fundamental details and thermal performance characteristics, and which clearly identifies the 'Dos and Don'ts' that need to be understood before any maintenance, or adaptation, of the system is undertaken. Should further evidence be required of the ability of a particular system to perform in a satisfactory manner in the event of a fire, then testing and assessment to LPS 1501[48] could be specified. This loss prevention standard has been developed to provide a fire test, performance and classification system for innovative building systems. Alternative fire testing procedures are also specified in national standards[49]. Issues concerning modifications or alterations to existing buildings are dealt with below.

Concern has been expressed over the impact of 'misinformed' alterations to buildings constructed using innovative forms of construction in terms of robustness and fire spread. Many of the issues that impact on the long-term integrity of MMC buildings have been addressed during various discussions with stakeholders and include:

- availability of specialist components or materials
- adaptability of systems/components
- availability of specialist staff for repair/modification of existing construction
- 'buildability' of systems to ensure they are built as planned.

Residential buildings are particularly at risk from misinformed alterations as there is a higher possibility of residents undertaking unapproved alterations without the involvement of experienced professional advisers. Guidance should be provided in the home owners' manual or building owners' manual as appropriate. Specific areas which should be addressed include:

- modifications to sheathing/racking/internal lining boards. Sheathing boards may provide both fire protection and racking resistance. It is important to ensure that replacement is undertaken on a 'like for like' basis as the performance of different boards varies considerably. Cutting holes in sheathing/lining boards will significantly affect the structural performance of the panel and could compromise compartmentation in relation to fire performance

- modifications to bracing members either through cutting or removal could have a serious impact on the overall structural stability of the system
- using noggins to provide lateral restraint (through a reduction in the slenderness ratio) to studs. They should not be removed without seeking specialist advice.

7.3 Robustness

The idea of disproportionate damage and disproportionate collapse in relation to innovative forms of construction used to provide dwellings is nothing new. Figure 17 shows the aftermath of a gas explosion within a large panel system (LPS) residential block in Newham, East London, in 1968. This incident and the subsequent public enquiry prompted the provisions on disproportionate collapse in the current Building Regulations. Approved Document A of the Building Regulations[50] classifies buildings according to categories based on occupancy type and height of structure. Of particular concern in terms of this current project are those buildings falling into Class 2A or 2B, particularly in relation to medium-rise residential buildings.

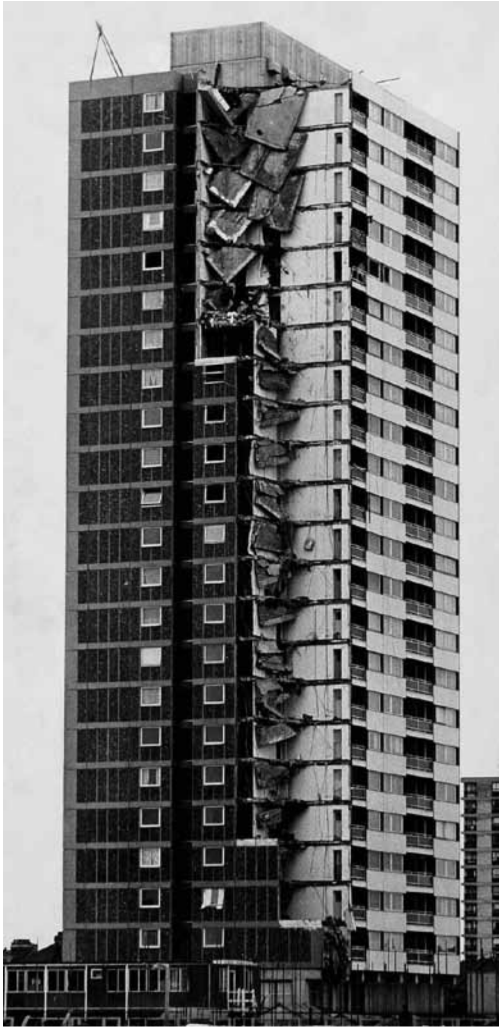


Figure 17 Damage to Ronan Point following a gas explosion in 1968

The requirement in the Building Regulations with respect to disproportionate collapse is particularly relevant in relation to some of the concerns expressed by key stakeholders. Requirement A3 states that:

> *'The building shall be constructed so that in the event of an accident the building will not suffer collapse to an extent disproportionate to the cause.'*[50]

In terms of MMC, work undertaken by the Steel Construction Institute[51] (Figure 18) and BRE[38] (Figure 19) in conjunction with the UK timber frame industry have shown that typical examples of light gauge steel and timber frame construction provide high levels of robustness in relation to scenarios where key elements have been removed.

Figure 18 Steel framed house used to demonstrate robustness

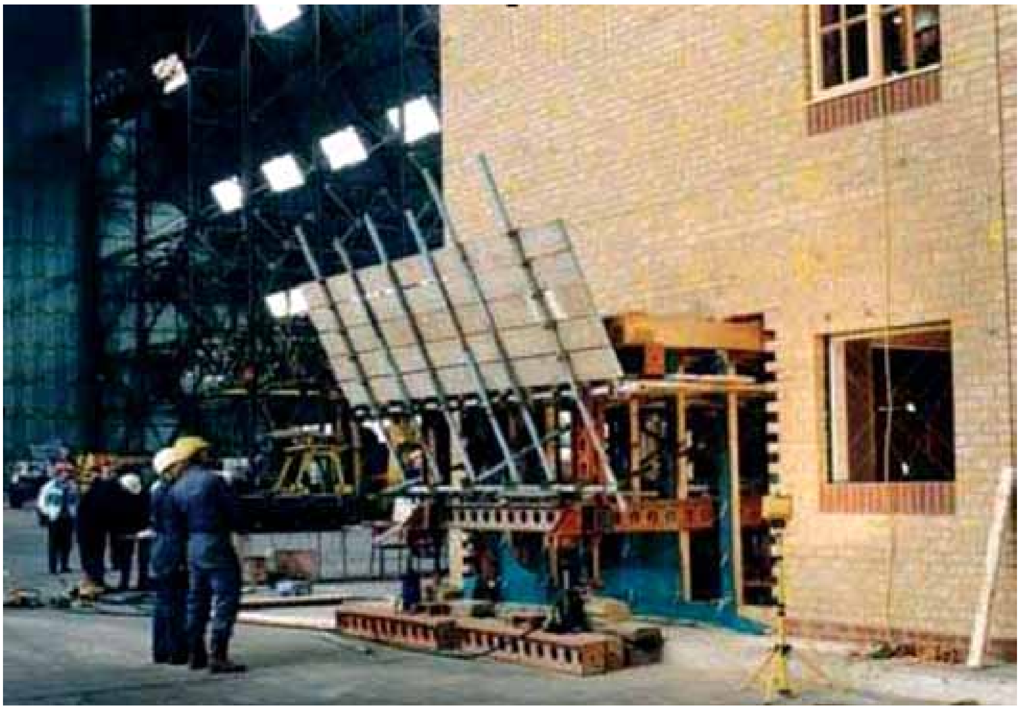
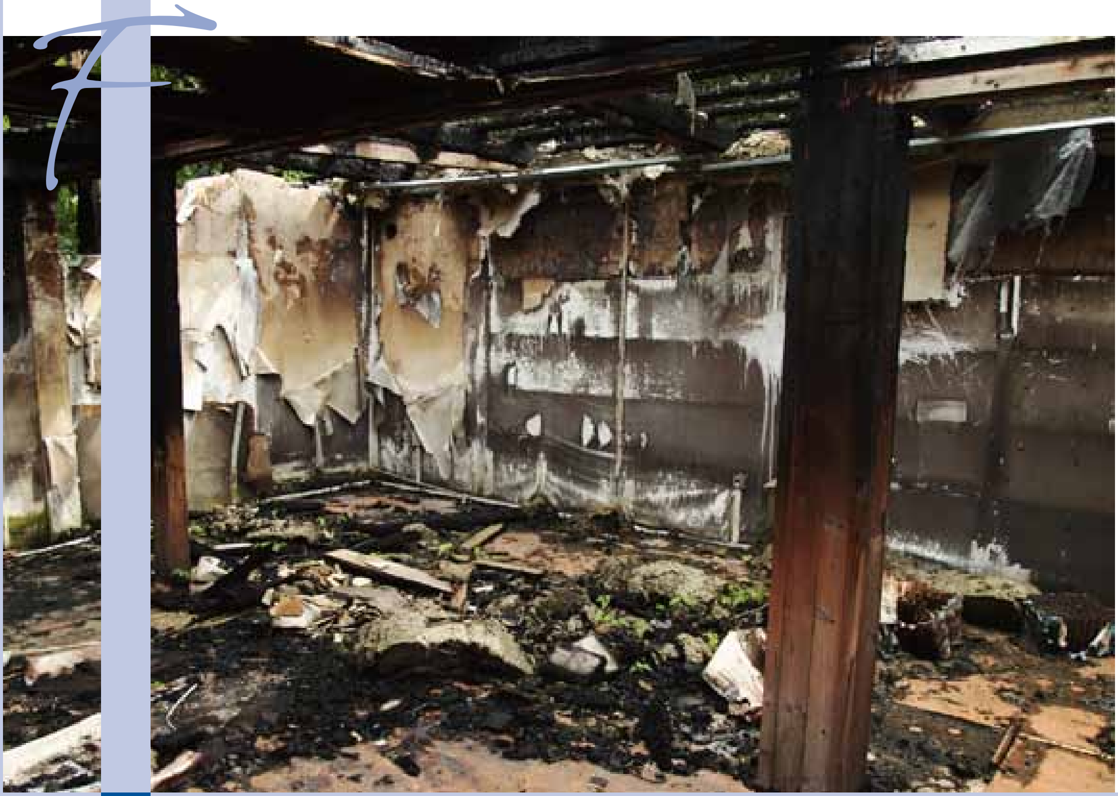


Figure 19 Disproportionate collapse test on TF2000 timber frame building

7.4 Demolition

Demolition is covered under the same CDM regulations that govern the construction phase. Therefore, much of the guidance referenced in Section 7.1 will apply equally to demolition sites. Guidance on the demarcation of responsibilities between HSE and local authority inspectors and the Fire and Rescue Authorities has been produced by the HSE[52] to ensure there is no confusion over who has overall responsibility for enforcement of General Fire Precautions and Process Fire Precautions in specific circumstances.



8 Case studies

In order to investigate many of the issues discussed above in relation to fire spread in cavities, the performance of key components in relation to overall stability and the issues surrounding fires on construction sites, information is provided from five examples related to large-scale fire research projects or real fire incidents.

8.1 Case study 1: TF2000 cavity fire incident – understanding fire risks in combustible cavities

The risk of unseen fire spread in association with combustible cavities was brought into sharp focus following the compartment fire test on the TF2000 building at Cardington. After suppression of a fire test within one of the dwellings on the second floor of the building, a seat of smouldering combustion remained in the corner of the living area. Over a number of hours, this small ignition source burnt through the OSB panelling and entered the cavity between the timber frame and the external masonry cladding. This particular area was open to the elements at the bottom of the cavity due to a previous structural test to investigate disproportionate collapse (see Figure 19). Once the smouldering timber came into contact with the ventilated cavity, the fire quickly developed with initially the OSB sheathing board providing the main source of fuel. The horizontal barriers at compartment floor level proved ineffective in preventing vertical fire spread. Over the course of the evening, the fire spread from the second to the fifth floor. The initial fire test before the cavity fire incident is illustrated in Figure 20. Figure 21 shows the damage to the external wall at a level above the initial fire compartment and clearly shows that, not just the sheathing board but the entire loadbearing stud wall and sections of the loadbearing ring beam have been consumed by the fire. Some minor clearing away of debris and removal of existing boards had taken place. The extent of vertical fire spread is illustrated in Figure 22 showing the front elevation of the TF2000 building after the cavity fire event.

Figure 20 Compartment fire test on 2nd floor of the TF2000 building

Figure 21 Loadbearing wall completely consumed by the cavity fire (3rd floor) of the TF2000 building

Following the TF2000 cavity fire, a collaborative research project was undertaken funded jointly by the UK government and the UK timber frame industry. The project, Understanding Fire Risks in Combustible Cavities, was led by Chiltern International Fire with BRE as project partners. The research investigated the cause of the cavity fire incident on the TF2000 project, initiated a number of small-scale cavity fires on the building using a small ignition source and a representative ventilation condition corresponding to air flow rates recommended for drained and ventilated cavities, developed a test methodology for assessment of cavity barriers used in timber frame construction and undertook training exercises for the Fire and Rescue Service to help identify and access the seat of the fire in the most effective manner possible.

Figure 22 Front elevation of TF2000 building showing extent of vertical fire spread

Findings from the research included:

- When properly installed, current commonly specified cavity barrier types meet the functional requirements of Building Regulations. The workmanship involved with the installation of cavity barriers has the greatest impact on the performance of the cavity barrier in the event of a fire.
- Irrespective of construction type and ignition scenario, cavity fires may be difficult to locate and extinguish.
- The Fire and Rescue Service possesses tools to locate the seat of a cavity fire within a short time of arriving at an incident. However, information and training material on the correct method for locating and accessing the seat of the fire needs to be disseminated for all construction types.
- The project highlighted a number of methods that can be employed by design/project teams to ensure that the functional objectives of the Building Regulations

with respect to performance of cavity barriers can be met and that the risk of fire spread within the cavity is reduced. These are as follows:

- The option of designing the cavity so that it is lined with non-combustible materials or materials of limited combustibility.
- Use of tested and approved proprietary cavity barriers fitted in accordance with manufacturers' recommendations and used within the limits of the stated field of application of the product.
- Clarification of responsibility within the construction team in respect of workmanship issues relating to the installation of fire protection measures such as cavity barriers.
- Instruction of contractors by approved bodies and appropriate supervision at key stages to ensure that cavity barriers are being installed correctly and the installation is not compromised by follow-on trades.

For further information, see the report produced[53].

8.2 Case study 2: Light gauge steel – robustness of connections

As part of the research project commissioned by the UK government to investigate the fire performance of light steel frame housing, two large-scale fire tests were undertaken on two different light gauge steel residential systems.

The first test (Figure 23) had to be terminated due to fire breaking through the end wall before any significant damage had occurred to the separating floor or wall. In the test, there was no external gable wall present. In a realistic scenario, the observed behaviour would have led to the fire breaking into the cavity between the structural frame and the brickwork forming the gable end. The performance of the cavity barrier between the frame and the brickwork would then become critical. However, once the plasterboard has fallen away, the fire is then in contact with the thermal sheathing, in this case a rigid polystyrene board. As the board melts, a new cavity is created between the structural frame and the moisture-resistant plasterboard. In this instance, there was no provision for fire stopping in this area. For multi-occupancy dwellings, it is recommended that the plasterboard specification to the external walls is at least equivalent to that used for the ceiling to the compartment floor and the party walls. Although all elements may meet the requirements of the Building Regulations, care should be taken to ensure that system performance is not compromised by failure of the weakest element. In this instance, the specification was for 60 minutes' fire resistance for the party wall, 60 minutes for the floor and 30 minutes for the external wall.

Figure 23 Light steel frame fire test (before and after)

For the second test (Figure 24), the specification for the external wall was increased to 60 minutes resulting in a very different mode of failure. Once the plasterboard had fallen from the ceiling, the strength of the floor joists was reduced leading to significant vertical deflection. Ultimately, the dead weight of the floor system, together with the imposed load on the floor above, caused a partial collapse of the floor followed soon after by complete collapse. The boards on the walls were still intact at the time the floor collapsed. The boards were removed to assist staff in fighting the fire following collapse. In some cases, the screws fixing the floor joists to the top rail through Zed hangers had sheared off. Immediately before collapse of the floor, flames could be seen inside the cavity between the floor joists. This can only have been caused through ignition of combustible material used in the construction of the floor. It is likely that the OSB sheeting, resilient layer and polythene sheet all contributed to this localised fire development.

Figure 24 Fire test on light steel frame building

8.3 Case study 3: Fire performance of structural insulated panel systems (SIPs)

As with all other forms of construction, the fire performance of SIPs is assessed through standard fire tests to ensure compliance with the mandatory requirements of the Building Regulations. Standard fire resistance tests provide a good indication of the relative performance of elements of building construction subject to a specific scenario, which is based on idealised loading and support conditions and a single thermal exposure according to the standard fire curve. However, such a system of test and assessment provides little information on the likely behaviour of the building system when subject to a realistic fire scenario.

A scoping study[16] funded by DCLG and involving a number of key stakeholders including insurers and the Fire and Rescue Service, identified the fire performance of SIP buildings as a priority for research. To this end, DCLG commissioned BRE to undertake a research project, The Performance in Fire of Structural Insulated Panel Systems. The overall aim was to undertake an experimental programme to determine performance subject to a realistic fire scenario and to compare the results with the outcome from standard fire tests. More detailed information from the project may be found in a BRE Information Paper[14]. As part of the project, BRE conducted four large-scale fire tests on SIP structures incorporating engineered floor joists and protected from the effects of fire by plasterboard linings to the ceilings and walls. The order and configuration of the tests are shown in Table 10. In each case, the overall dimensions of the test compartment were the same, with a floor area of 4 × 3 m and a height from floor to ceiling of 2.4 m. The first floor loading was identical in all cases with an imposed load of 0.75 kN/m^2 spread uniformly over the first floor. The second floor was varied as in Table 10 to represent either a two (0.75 kN/m^2) or four (2.25 kN/m^2) storey building.

Table 10

Summary of large-scale fire tests

Test	Design fire resistance period (min)	Core material	2nd floor loading (kN/m²)
F1	60	EPS	2.25
F2	30	EPS	0.75
F3	60	PUR	2.25
F4	30	PUR	0.75
Key: EPS, expanded polystyrene; PUR, polyurethane foam.			

The 30 and 60 minute design solutions were effectively representing a two storey house and a multi-occupancy apartment dwelling, respectively. In all cases, the fire loading and ventilation conditions were the same with the fire designed to provide an equivalent severity to a 60 minute exposure in a standard fire test[23]. The results from the large-scale fire tests are summarised in Table 11. The scale of the fire testing is illustrated in Figure 25.

Figure 25 Large-scale fire test programme

The numerical modelling and laboratory-scale elements of the project indicated that current specifications for passive fire protection may be insufficient. The largest factor influencing the fire resistance performance of SIPs is the specification of the plasterboard lining with the SIP offering only nominal inherent fire resistance. The modelling studies undertaken also indicated that the means of fixing passive fire protection to the panels significantly influenced performance. Fixing of the lining via softwood battens was shown to decrease temperature development in SIPs when compared to passive fire protection fixed directly to the OSB sheathing, thus increasing fire resistance performance.

Table 11

Summary of large-scale tests

Test	Results and comments
F1	Maximum atmosphere temperature 1075°C after 52 minutes. Test continued up to cooling phase. Peak temperature in floor void approximately 200°C with a corresponding maximum deflection of approximately 10 mm. Floor joists, resilient bars and the party wall remained intact (Figure 26). The polystyrene core material had melted away in localised areas within the external walls. The location of the most significant damage coincided with an unsealed hole used for erection purposes which allowed sufficient air into the system to maintain combustion during the latter stages of the fire.
F2	Maximum atmosphere temperature 1078°C after 43 minutes. Test terminated 50 minutes from ignition due to runaway deflection of the floor caused by combustion of the OSB web of the engineered floor joists (Figure 27) once the integrity of the plasterboard linings had been compromised. Peak temperatures in the floor void approximately 900°C with a corresponding maximum deflection of 203 mm. Large areas of the insulated core had melted away at the end of the test. However, there was no indication of any integrity failure of the wall panels.
F3	Maximum atmosphere temperature 1071°C after 51 minutes. Test continued up to cooling phase. Peak temperatures in floor void approximately 200°C with a corresponding maximum deflection of approximately 15 mm. Core temperatures largely unaffected by the fire for the duration of the test but continued to rise in the cooling phase. Some time after the initial fire had been extinguished, localised combustion continued within the wall panels with the inner surface of the PUR involved. Although initially there was no evidence of any damage to the wall panels, the post-test damage was significant (Figure 28). The inclusion of electrical sockets did not influence the temperature of the panels.
F4	Maximum atmosphere temperature 1083°C after 49 minutes. Test terminated 50 minutes from ignition due to runaway deflection of the floor caused by combustion of the OSB web of the engineered floor joists once the integrity of the ceiling plasterboard had been compromised. Peak temperatures in the floor void 664°C with a corresponding maximum deflection of 120 mm. Although the temperature within the external wall panels continued to increase towards the end of the test, any combustion of the PUR insulation was quickly dealt with by the Fire and Rescue Service. Temperatures within the core of the party wall remained low throughout the test. The inclusion of electrical sockets did not influence the temperature of the panels.

Figure 26 Limited damage to floor joists and party wall. Test F1.

The correct specification and installation of the internal linings to both the ceiling and the floor are critical to the performance of the system in a real fire situation. Based on the results and the observations from the research project, recommendations for achieving design fire resistance periods of 30 minutes and 60 minutes are given in Table 12. These recommendations have been adopted by the UK SIPS Association.

Installation of linings should comply with the instructions and detailed guidance produced by the supplier. Compliance with recommendations for minimum lengths of fixings and minimum centres between fixings is particularly important.

Figure 27 Damage to engineered floor joists. Test F2.

Figure 28 Damage to PUR wall panels. Test F3.

Table 12

Specification for specific periods of fire resistance

	Recommended specification for fire resistance period of:	
	30 min	60 min
Wall lining	15 mm Type F plasterboard fixed to softwood battens All joints taped and sealed	30 mm Type F plasterboard fixed to softwood battens All joints between layers staggered Exposed joints taped and sealed
Ceiling lining	15 mm Type F plasterboard fixed to resilient bars All joints taped and sealed	30 mm Type F plasterboard fixed to softwood battens All joints between layers staggered Exposed joints taped and sealed
Services	Incorporated within service void formed by battens	Incorporated within service void formed by battens
Penetrations in SIPs	All penetrations to be adequately fire stopped Lifting holes to be sealed following erection of panels	All penetrations to be adequately fire stopped Lifting holes to be sealed following erection of panels

8.4 Case study 4: Engineered floor joists

The work undertaken by BRE Global on SIPs highlighted the crucial role that lightweight engineered floor joists play in relation to the global structural behaviour of SIP buildings. In particular, runaway deflection of 'I'-section floor joists was identified as the predominant mode of failure for such buildings. Further work has been conducted to look specifically at the performance of engineered floor joists in fire[11]. The project consisted of three fire tests on floor systems as shown in Table 13. Previous work undertaken in the USA on unprotected floor systems had shown that engineered systems failed much earlier than similar floor assemblies constructed from traditional solid timber joists.

Table 13

Joist details

	Overall dimensions (mm)	Flange dimensions (mm)	Web	Web to flange fixing
Solid timber joist	45 × 220	N/A	N/A	N/A
Engineered 'I'-section joist	45 × 220	45 × 45	9 mm OSB (structural grade)	Phenol-formaldehyde adhesive
Engineered truss joist	72 × 220	72 × 45	Cold formed steel pressed web (1 mm gauge)	Mechanical nailing plates with 7 mm protruding teeth

The compartment design and the fire design were, in each case, very similar to that described in relation to the large-scale fire tests on SIP structures discussed in Section 8.3 above. The principal difference is that for these tests, the walls were formed from loadbearing blockwork lined internally with plasterboard. For each joist type, a passive fire protection system for 60 minutes' fire resistance was adopted based on guidance provided by manufacturers and the results from standard fire resistance testing. For the solid timber joists and steel truss web joists, 25 mm of Type F plasterboard was specified while for the 'I'-section joists, the corresponding specification was for 30 mm of Type F plasterboard. A typical section through the floor is shown in Figure 29.

The results from the fire tests are summarised in Table 14.

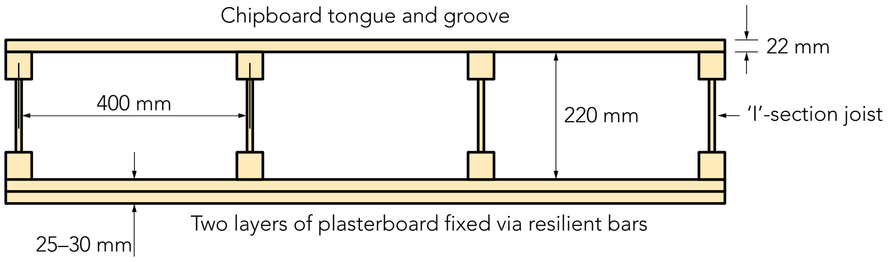


Figure 29 Typical section through floor.

Although at first sight the results indicate that the timber 'I'-joists performed better than the solid joists, this is a result of the enhanced (30 mm rather than 25 mm) plasterboard specification to achieve 60 minutes' fire resistance. What is of crucial significance, and of particular concern to fire fighters, is the rate of deflection approaching failure. In the tests, for approximately the same joist temperature, the engineered truss joists deflected almost three times more than the traditional floor joists and continued to deflect once the fire had been extinguished.

Table 14

Summary of results from tests on engineered floor joists

Test	Solid floor joists	OSB web 'I'-joist	Steel truss web joist
Test termination time (min)	56	N/A	56.5
Peak gas temperature (°C)	1084	1034	1036
Time to peak gas temperature (min)	44	42.5	41
Peak joist temperature (°C)	773	312	756
Time to peak joist temperature (min)	52	60	56
Peak deflection (mm)	31	10	92
Peak rate of deflection (mm/min)	1.0	0.2	6.4
Breach of passive fire protection (min)	30	50	40
Nature of breach	Fall off of ceiling boards	Minor gaps at board joints	Fall off of ceiling boards

The work alongside the SIPs research discussed previously has shown that engineered floors may be able to provide the same levels of fire resistance as that of solid timber floors provided that the engineered joists are properly protected from fire by adequate boarding and that a good quality of installation is provided during construction. When exposed to fire, some engineered floor joists may fail in a more rapid manner when compared to solid timber joists.

When exposed to fire directly, the behaviour of engineered truss joists, similar to the one tested, results in a more rapid, less ductile, mode of failure. The test showed that this type of floor system exhibits large deflections and continues to deflect at a high rate over a short period of time leading to a sudden failure of the floor system. In this case, the steel modules forming the web of the section were detached due to charring of the timber chords (Figure 30) which caused the connecting plate to lose its bond with the chord members.

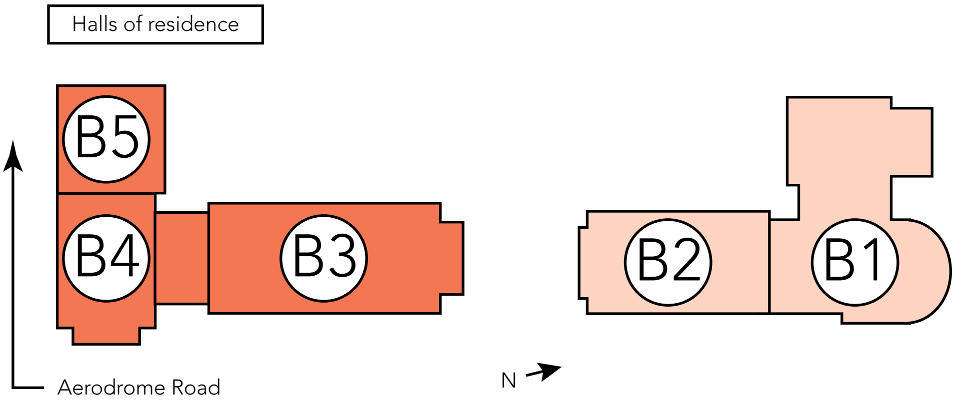
Figure 30 Loss of fixity between steel web elements and lower timber chord

8.5 Case study 5: Construction site fires – Beaufort Park, Colindale

A number of high profile fires have occurred during the construction phase in recent years (see Section 7.1). Of these, many have involved multi-occupancy residential projects where the primary frame has been constructed using light timber framing. This section focuses on one such project where a great deal of information has been provided through the project stakeholder group and one which highlights a number of important issues in relation to fires in construction sites in general with specific reference to large timber frame sites.

A serious fire occurred on the Beaufort Park development in Colindale, North London on the afternoon of 12 July 2006. The site was a mixed use development comprising retail units on the ground floor and residential accommodation above. The first phase of the development involved the construction of two structures forming five separate accommodation units each comprising either five or six storeys with the ground to first floor built of concrete and the remaining structure comprising light timber framing.

A schematic of the site plan is shown in Figure 31 which illustrates the relationship between blocks B1 to B5. At the time of the fire, B1 was virtually complete and ready for hand over, B2 was partially completed with the rainscreen cladding (a combination of masonry and rendered cement particle board) under construction. Blocks B3 to B5 consisted of the bare timber frame only without any cladding or sheathing. Effectively, B3 to B5 formed one structure separated by a distance of some 18 m from the adjacent building housing blocks B1 and B2.



Block B1 – Ground + six storeys
Block B2 – Ground + five storeys
Block B3 – Ground + five storeys
Block B4 – Ground + six storeys
Block B5 – Ground + five storeys

Figure 31 Site plan for Beaufort Park development

The fire was first noted by a worker who saw smoke emanating from the west elevation of B3. A timeline of significant events based on information provided by LFB is shown in Table 15.

Table 15

Timeline of significant events

Time (min)	Event	Comments
0.0	First call to LFB	Smoke seen from west side of B3
3.0	Whole of B4 east elevation in flames	
4.0	First pump in attendance	
9.0	Whole of B4 alight	Collapse of B3, B4 and B5 very shortly after
47.0	Fire spread to B2 noted	Soffit/gutter alight (Figure 32 and Figure 33)
91.0	Whole of B2 alight and spread to B1	Figure 34 and Figure 35

Figure 32 B3 (east elevation) collapse and fire spread to B2 (reproduced by courtesy of the London Fire Brigade)

Figure 33 Fire spread to block B2 (reproduced by courtesy of the London Fire Brigade)

Figure 34 Block B2 fully involved (reproduced by courtesy of the London Fire Brigade)

The fire developed extremely rapidly. Blocks B3, B4 and B5 collapsed just 2 to 3 minutes after the LFB arrived or approximately 9 minutes from the first call. Firefighting was initially hampered by a shortage of available water, the presence of acetylene cylinders and the intense levels of radiated heat.

Figure 35 Fire spread to block B1 (reproduced by courtesy of the London Fire Brigade)

For completed buildings, the guidance to the Building Regulations sets out limitations on unprotected areas defined as those which will not provide adequate protection from external spread of fire from one building to another. The concept of space separation is based on a balance between separation distance and the amount of unprotected area allowed and is governed in large part by the degree of compartmentation within the building.

The boundary distance is based on the assumption that the more openings or other unprotected areas in the external enclosure of the building, the further the building (or side of the building) should be from the boundary[54]. In this case, the separation distances between buildings both within the site boundary and outside the site were well in excess of the minimum values required for compliance with the regulations. It has been calculated that the distance between blocks B3, B4 and B5 and blocks B1 and 2 was approximately 18 m and that the distance to the nearest habitable occupancy (University of Middlesex student accommodation) was approximately 30 m.

However, the extremely high levels of radiated heat produced during combustion of a large unprotected timber frame were sufficient not only to ignite the partially completed block B2 but also to cause significant damage to the student accommodation located opposite the western elevation of blocks B4 and B3 and diagonally opposite block B5. The severity of the fully developed fire is illustrated in Figure 36. Fire spread to the adjacent properties could have been caused by radiant heat or burning brands carried by the wind or some combination of the two. The university accommodation was separated from the construction site by a line of trees which may have provided some protection at low levels. However, the fire ignited the soffit to the underside of the roof and subsequently spread to destroy the whole of the roof of the building (Figure 37) and much of the glazing (Figure 38). Figure 37 shows the concrete slab forming the first floor of the development to have remained intact supported on concrete and masonry piers.

Figure 36 Fully developed fire (reproduced by courtesy of the London Fire Brigade)

Figure 37 Extent of damage to roof structure of student accommodation opposite blocks B4 and B3

Figure 38 Damage to eastern elevation of student accommodation

The incident raised a number of issues which apply to other timber frame construction site fires, notably:

- the potential for large fires during the construction phase to spread to adjacent buildings outside the site boundary
- control and management of large timber frame construction sites commensurate with the risk associated with the project
- provision of adequate means of warning and adequate means of escape for workers in the event of such an incident occurring

- the issue of the partial occupation of dwellings where construction work is ongoing either within the same building or an adjacent structure on the same site
- the need for dialogue and continued liaison with local fire fighters to ensure that the Fire Brigade Integrated Risk Management Plan reflects the risks associated with large timber frame construction sites.

Guidance on these issues has been published and updated where appropriate. Those responsible for the planning, design, construction and ongoing control of such projects should consult the documentation referenced in Section 7.1 of this report.

It is important to note that many of these issues could apply equally to other forms of construction which rely on following trades to provide the required regulatory levels of fire resistance.

9 Conclusions

This report has investigated a number of issues in relation to the fire performance of modern forms of construction with a particular emphasis on projects where combustible material is used to provide enhanced thermal performance.

The available evidence base has been analysed to investigate the hypotheses that current methods and forms of construction are contributing towards an increase in the level of damage following a fire and that such damage may be instigated from a relatively small ignition source. The available sources of statistical evidence do not provide conclusive results either way. The trends are difficult to identify and often provide contradictory conclusions. In large part, this is a function of the method of collating information from real fire incidents where traditionally there has been no requirement to identify specific forms of construction. The inclusion of such information in reports, filed either by fire fighters or insurers, is far from straightforward given the nature of many modern systems and the continuing tendency to use brickwork as an external façade making identification of the structural frame difficult unless the fire damage is so extensive as to expose the structural members. It is clear that all sectors of the construction industry and fire safety community would benefit from improved communication between building control authorities and the Fire and Rescue Service.

However, recent data provided by the insurance industry and the Fire and Rescue Service both nationally and locally have been modified to provide more detailed information on issues such as type of construction and failure of compartmentation which, given time, will provide a robust database to assist with decisions such as allocation of resources for research and development. Initial implications from the most recent data sets suggest that certain forms of construction may contribute towards the extent of fire spread and may help to explain the continuing increase in large claims when the overall trend currently indicates a decline in the number of fires and a decline in injuries and fatalities due to fire.

The regulatory requirements for elements of construction and construction materials have been explained in the context of regulatory guidance documents and standard methods of test and assessment. Questions have been raised about the suitability of such an approach which encourages design to meet the minimum regulatory requirement rather than design for fire safety. Means of assessment that more closely reflect the end use condition and interaction between individual elements are now available.

Two specific issues identified through consultation with the stakeholder group have been addressed, namely, the impact of combustible materials within the fabric of the structure in terms of potential increase in fire severity and fire spread either internally through cavities or externally via the façade. It has been shown that the potential for increased fire load can be significant should the fabric or structure of the building become involved, and may provide a source of fuel in excess of that generally considered as the variable fire load in fire engineering design procedures.

Internal fire spread, including fire spread in cavities as a result of either inadequate fire stopping or combustion of thermal insulation material, has been discussed. The importance of specifying the correct passive fire protection for each application has been highlighted. Compartmentation may be prematurely breached in the event of a fire either by incorrect specification of linings (use of a Type A board rather than a Type F board, for example), poor workmanship (eg gaps between boards, joints not staggered, use of incorrect fixings, etc) or poor supervision. In terms of holistic buildability issues, it is important that all parties are aware of the importance of following the design and manufacturer's recommendations in relation to the specification and installation of all passive fire protection products. Guidance is available through industry bodies[44]. The specific issue of compartmentation in roof voids has been addressed in a recent government-funded research study. A review of planning submissions and real fire incidents has shown that there is often insufficient detail provided to demonstrate compliance with the requirements of the Building Regulations.

The risk due to external fire spread is limited by regulatory controls of the materials used to provide the external surface related to the height, occupancy class and distance from neighbouring buildings. Where the distance to the boundary is less than 1 m, external walls may require fire resistance from both inside and outside the building. Where the façade is not loadbearing, there are restrictions on the reaction to fire properties of the material used to provide the external surface and, for buildings over 18 m in height, there are restrictions on the use of insulation materials not having the required reaction to fire properties. As described in Section 4, such tests are undertaken on small samples not representative of the actual condition on site. An alternative approach for external walls is to meet the performance criteria given in the BRE Report BR 135[1] using full-scale test data from the appropriate part of BS 8414[2, 43].

Whilst guidance is available to reduce the risks of accidental or deliberate ignition sources on construction sites containing large quantities of combustible material this, in itself, is not a solution. There are a number of potential solutions that could contribute towards reducing the risks. One potential option is to move towards closed panel solutions where the linings are installed off site. This would also potentially deal with issues concerning quality of construction and workmanship. An alternative option is to reschedule the construction process to include installation of linings as work proceeds. Other options which could be considered are the use of fire retardant treatment processes and the use of non-combustible board forming the sheathing layer in place of the more commonly used OSB. Any of the above measures would potentially reduce the damage due to a fire in the construction phase by limiting fire spread and delaying the time to ignition of the main structural components. However, there could be potential cost implications which may well have an adverse effect on the market position of frames containing large amounts of combustible material.

Many of the issues raised within Sections 3 to 7 are illustrated with respect to specific incidents in Section 8 dealing with case studies. The important aspects arising are:

- importance of workmanship issues in relation to installation of cavity barriers (TF2000)
- robustness of connections for light steel frame buildings

- buildability issues, particularly in relation to unauthorised modifications and alterations
- importance of specification and installation of passive fire protection in achieving design fire resistance (SIPs and EFJs)
- mitigation of risks associated with fires in construction sites in accordance with the requirements of new and revised guidance documents. Range of alternative options available to reduce risk of fire initiation and spread during the construction phase.

APPENDIX A

Reaction to fire tests

Table A1

British Standards: reaction to fire test standards

Standard reference	Title/scope
BS 476-3: 2004	Fire tests on building materials and structures. Classification and method of test for external fire exposure to roofs
BS 476-4: 1970	Fire tests on building materials and structures. Non-combustibility test for materials
BS 476-6: 1989	Fire tests on building materials and structures. Method of test for fire propagation of products
BS 476-7: 1997	Fire tests on building materials and structures. Method of test to determine the classification of the surface spread of flame of products
BS 476-11: 1982	Fire tests on building materials and structures. Method for assessing the heat emission from building products
BS 476-12: 1991	Fire tests on building materials and structures. Method of test for ignitability of products by direct flame impingement
BS 476-13: 1987, ISO 5657: 1986	Fire tests on building materials and structures. Method of measuring the ignitability of products subject to thermal irradiance
BS 476-15: 1993, ISO 5660-1: 1993	Fire tests on building materials and structures. Method for measuring the rate of heat release for products

Table A2

European standards: reaction to fire tests and fire classification methods

Standard reference	Title/scope
BS EN ISO 1716: 2010	Reaction to fire tests for building products – Determination of the gross heat of combustion (calorific value)
BS EN ISO 1182: 2010	Reaction to fire tests for products – Non-combustibility test
BS EN 13823: 2002	Reaction to fire tests on building products – Building products excluding floorings exposed to the thermal attack by a single burning item
BS EN ISO 11925-2: 2002	Reaction to fire tests – Ignitability of building products subjected to direct impingement of flame – Part 2: Single-flame source test
BS EN 13238: 2010	Reaction to fire tests for building products – Conditioning procedures and general rules for selection of substrates
BS EN 13501-1: 2007 + A1 2009	Fire classification of construction products and building elements Part 1: Classification using test data from reaction to fire tests

APPENDIX B

Fire resistance tests

Table B1

UK fire resistance test standards

Standard reference	Title/scope
BS 476-20: 1987	Fire tests on building materials and structures. Method for the determination of the fire resistance of elements of construction (general principles)
BS 476-21: 1987	Fire tests on building materials and structures. Methods for the determination of the fire resistance of loadbearing elements of construction
BS 476-22: 1987	Fire tests on building materials and structures. Methods for the determination of the fire resistance of non-loadbearing elements of construction
BS 476-23: 1987	Fire tests on building materials and structures. Method for the determination of the contribution of components to the fire resistance of a structure
BS 476-24: 1987, ISO 6944: 1985	Fire tests on building materials and structures. Method for the determination of the fire resistance of ventilation ducts

Table B2

European fire resistance tests and classification standards for elements of construction

Standard reference	Title/scope
BS EN 1363-1:1999	Fire resistance tests – Part 1: General requirements
BS EN 1363-2: 1999	Fire resistance tests – Part 2: Alternative and additional procedures
BS EN 1364-1: 1999	Fire resistance tests for non-loadbearing elements – Part 1: Walls
BS EN 1364-2: 1999	Fire resistance tests for non-loadbearing elements – Part 2: Ceilings
BS EN 1365-1: 1999	Fire resistance tests for loadbearing elements – Part 1: Walls
BS EN 1365-2: 2000	Fire resistance tests for loadbearing elements – Part 2: Floors and roofs
BS EN 1365-3: 2000	Fire resistance tests for loadbearing elements – Part 3: Beams
BS EN 1365-4: 1999	Fire resistance tests for loadbearing elements – Part 4: Columns
BS EN 1365-5: 2004	Fire resistance tests for loadbearing elements – Part 5: Balconies and walkways
BS EN 1365-6: 2004	Fire resistance tests for loadbearing elements – Part 6: Stairs
BS EN 13501-2: 2007 + A1 2009	Fire classification of construction products and building elements – Part 2: Classification using data from fire resistance tests, excluding ventilation services

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