



BSI Standards Publication

## **Application of fire safety engineering principles to the design of buildings**

Part 3: Structural response to fire and fire spread beyond the enclosure of origin (Sub-system 3)

**Publishing and copyright information**

The BSI copyright notice displayed in this document indicates when the document was last issued.

© The British Standards Institution 2019

Published by BSI Standards Limited 2019

ISBN 978 0 580 97727 5

ICS 13.220.20; 91.040.01

The following BSI references relate to the work on this document:

Committee reference FSH/24

Draft for comment 18/30373550 DC

**Amendments/corrigenda issued since publication**

| Date  | Text affected |
|-------|---------------|
| <hr/> |               |

# Contents

|                                                                                                                                                  | Page      |
|--------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
| <b>Foreword</b>                                                                                                                                  | <b>iv</b> |
| 1 Scope                                                                                                                                          | 1         |
| 2 Normative references                                                                                                                           | 1         |
| 3 Terms and definitions                                                                                                                          | 1         |
| 4 Symbols                                                                                                                                        | 4         |
| 5 Design approach to PD 7974-3                                                                                                                   | 7         |
| 5.1 General                                                                                                                                      | 7         |
| 5.2 Interaction with BS 7974 framework                                                                                                           | 7         |
| <i>Figure 1 — Interaction between the various professions and the design team in addressing PD 7974-3 factors</i>                                | 7         |
| 5.3 Functional objectives                                                                                                                        | 7         |
| 5.4 Identification of fire hazards and possible consequences                                                                                     | 8         |
| 5.5 Identification of acceptance criteria and appropriate methods of analysis                                                                    | 8         |
| 5.6 Establishing trial fire safety designs                                                                                                       | 9         |
| 5.7 Establish fire scenarios for analysis                                                                                                        | 9         |
| 5.8 Analysis                                                                                                                                     | 10        |
| <i>Figure 2 — Procedure for analysis within PD 7974-3</i>                                                                                        | 10        |
| 6 Analysis methods                                                                                                                               | 11        |
| 6.1 General                                                                                                                                      | 11        |
| 6.2 Basis of analysis                                                                                                                            | 11        |
| 6.3 Accuracy                                                                                                                                     | 12        |
| 6.4 Means                                                                                                                                        | 12        |
| 6.5 Measures                                                                                                                                     | 13        |
| 7 Evaluation of fire conditions                                                                                                                  | 13        |
| 7.1 Design fire characterization                                                                                                                 | 13        |
| 7.2 Selection of design fires                                                                                                                    | 13        |
| <i>Figure 3 — Gas temperature in non-combustible and combustible compartments [8]</i>                                                            | 15        |
| 8 Evaluation of thermal response                                                                                                                 | 15        |
| 8.1 Thermal response of elements within enclosure                                                                                                | 15        |
| 8.2 Empirical data                                                                                                                               | 15        |
| 8.3 Simplistic calculations                                                                                                                      | 16        |
| 8.4 Advanced calculations                                                                                                                        | 17        |
| 8.5 Quantitative analysis of heat flow by conduction                                                                                             | 17        |
| 8.6 Quantitative analysis of heat flow by convection                                                                                             | 19        |
| 8.7 Quantitative analysis of heat flow by radiation                                                                                              | 19        |
| 8.8 Characterizing the condition of fires spreading from openings in enclosures                                                                  | 20        |
| 9 Behaviour of separating elements in fire                                                                                                       | 21        |
| 9.1 Behaviour of fire-resisting separating elements                                                                                              | 21        |
| 9.2 Maintaining the separating capability of elements or constructions                                                                           | 33        |
| <i>Figure 4 — Typical detail showing protection to a floor beam with a service penetration</i>                                                   | 35        |
| 9.3 Behaviour of non-fire-resisting separating elements                                                                                          | 36        |
| <i>Table 1 — Notional period of fire endurance for which imperforate condition can be assumed for unproven elements subject to fire exposure</i> | 36        |
| 10 Analysis of structural response of loadbearing structural elements and frames                                                                 | 37        |
| 10.1 Concepts                                                                                                                                    | 37        |
| <i>Table 2 — Partial safety factors for loads (PD 6688-1-2:2007, Table 1)</i>                                                                    | 38        |
| 10.2 Acceptance criteria                                                                                                                         | 39        |
| 10.3 Methods for determining structural response                                                                                                 | 40        |

|                |                                                                                                                                                                   |           |
|----------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
|                | <i>Figure 5 — Maximum steel temperature concept</i>                                                                                                               | 42        |
|                | <i>Table 3 — Values of <math>k_b</math></i>                                                                                                                       | 42        |
|                | <i>Figure 6 — General approach to structural fire safety design</i>                                                                                               | 45        |
| <b>Annex A</b> | <b>(informative) Fire spread mechanisms</b>                                                                                                                       | <b>49</b> |
|                | <i>Figure A.1 — Routes for fire transmission</i>                                                                                                                  | 51        |
| <b>Annex B</b> | <b>(informative) Design fires</b>                                                                                                                                 | <b>53</b> |
| <b>Annex C</b> | <b>(informative) Heat transfer (and thermal response) of specific materials</b>                                                                                   | <b>54</b> |
|                | <i>Table C.1 — Guidance on the material surface emissivity of construction materials</i>                                                                          | 54        |
|                | <i>Figure C.1 — Configuration factors for typical scenarios</i>                                                                                                   | 55        |
|                | <i>Figure C.2 — Calculation of section factors</i>                                                                                                                | 60        |
|                | <i>Table C.2 — Calculation of element factors (EF)</i>                                                                                                            | 61        |
|                | <i>Figure C.3 — Calculation of element factors</i>                                                                                                                | 62        |
|                | <i>Table C.3 — Typical set of coating thicknesses for a profile non-reactive spray-applied protection system</i>                                                  | 63        |
|                | <i>Figure C.4 — Typical set of board thicknesses for a box encasement fire protection system</i>                                                                  | 64        |
|                | <i>Figure C.5 — Compartment parameters</i>                                                                                                                        | 67        |
|                | <i>Table C.4 — Location of columns between windows to avoid direct flame impingement</i>                                                                          | 67        |
|                | <i>Figure C.6 — Spandrel beam with shielded flanges</i>                                                                                                           | 68        |
|                | <i>Table C.5 — Spandrel beams</i>                                                                                                                                 | 68        |
|                | <i>Figure C.7 — Calculation methods for determining the temperature profiles through masonry elements</i>                                                         | 71        |
|                | <i>Figure C.8 — Temperature gradient through autoclaved concrete masonry with a density of 400 kg/m<sup>3</sup> to 800 kg/m<sup>3</sup></i>                       | 72        |
| <b>Annex D</b> | <b>(informative) Temperature-dependent properties of non-loadbearing construction systems — Thermal properties of materials used in composite sandwich panels</b> | <b>77</b> |
|                | <i>Table D.1 — Comparison of expansion of materials used in composite sandwich panels</i>                                                                         | 77        |
|                | <i>Table D.2 — Comparison of specific heat capacity of materials used in composite sandwich panels</i>                                                            | 78        |
|                | <i>Table D.3 — Thermal conductivity for various densities of mineral (rock) wool at elevated temperatures</i>                                                     | 78        |
|                | <i>Figure D.1 — Thermal conductivity for various densities of mineral (rock) wool at elevated temperatures</i>                                                    | 79        |
|                | <i>Table D.4 — Constants for calculating the thermal conductivity of mineral wool at elevated temperatures</i>                                                    | 79        |
|                | <i>Table D.5 — Thermal conductivity of cellular glass</i>                                                                                                         | 79        |
|                | <i>Table D.6 — Thermal conductivity of expanded polystyrene</i>                                                                                                   | 80        |
|                | <i>Table D.7 — Thermal conductivity of extruded polystyrene</i>                                                                                                   | 80        |
|                | <i>Table D.8 — Thermal conductivity of phenolic foam</i>                                                                                                          | 80        |
|                | <i>Table D.9 — Thermal conductivity of polyisocyanate foam</i>                                                                                                    | 80        |
|                | <i>Table D.10 — Thermal conductivity of rigid polyurethane foam</i>                                                                                               | 80        |
|                | <i>Table D.11 — Thermal conductivity through the cell gas for various blowing gases</i>                                                                           | 81        |
|                | <i>Table D.12 — Typical densities of core materials used in sandwich panels</i>                                                                                   | 81        |
| <b>Annex E</b> | <b>(informative) Structural response of specific materials</b>                                                                                                    | <b>82</b> |
|                | <i>Figure E.1 — Design methods for fire limit state (FLS) design adopted in BS EN 1992-1-2</i>                                                                    | 83        |
|                | <i>Figure E.2 — Principle design methodologies adopted in BS EN 1993-1-2</i>                                                                                      | 85        |
|                | <i>Figure E.3 — Schematic representation of the compressive and tensile forces of a floor zone during fire</i>                                                    | 90        |
|                | <i>Figure E.4 — Illustration of the deflection of a multi-zone composite floor system with protected and unprotected members</i>                                  | 91        |

|                |                                                                                                                                                                                 |            |
|----------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
|                | <i>Figure E.5 — Illustration of catenary action developed in a multi-zone composite floor system</i>                                                                            | 92         |
|                | <i>Table E.1 — Notional char depths for various species after 30 min and 60 min in the standard furnace test (BS 476-20)</i>                                                    | 95         |
|                | <i>Table E.2 — Values of <math>k_{fi}</math> for different components/elements</i>                                                                                              | 96         |
|                | <i>Figure E.6A — Definition of residual cross-section and effective cross-section</i>                                                                                           | 97         |
|                | <i>Figure E.6B — Relationship between <math>k_0</math> and time of fire exposure for unprotected surfaces, and for protected surfaces where <math>t_{ch} \leq 20</math> min</i> | 98         |
|                | <i>Figure E.6C — Relationship between <math>k_0</math> and time of fire exposure for protected surfaces where <math>t_{ch} &gt; 20</math> min</i>                               | 98         |
|                | <i>Table E.3 — Determination of <math>k_0</math></i>                                                                                                                            | 98         |
|                | <i>Figure E.7 — Equations (E.17) to (E.19) illustrated</i>                                                                                                                      | 99         |
| <b>Annex F</b> | (informative) <b>Fire resistant load bearing structural solutions</b>                                                                                                           | <b>105</b> |
| <b>Annex G</b> | (informative) <b>Methodology for establishing the extended application of fire resistance test results</b>                                                                      | <b>107</b> |
|                | <b>Bibliography</b>                                                                                                                                                             | <b>114</b> |

### Summary of pages

This document comprises a front cover, and inside front cover, pages i to vi, pages 1 to 118, an inside back cover and a back cover.

---

# Foreword

## Publishing information

This Published Document is published by BSI Standards Limited, under licence from The British Standards Institution, and came into effect on 31 March 2019. It was prepared by Technical Committee FSH/24, *Fire Safety Engineering*. A list of organizations represented on this committee can be obtained on request to its secretary.

## Supersession

This Published Document supersedes PD 7474-3:2011, which is withdrawn.

## Relationship with other publications

This Published Document is one of a series of documents published under the Fire Standards Policy Committee, and is a supporting document to [BS 7974](#), *Application of fire safety engineering principles to the design of buildings — Code of practice*.

Other documents in the series are:

PD 7974-1: *Initiation and development of fire within the enclosure of origin*;

PD 7974-2: *Spread of smoke and toxic gases within and beyond the enclosure of origin*;

PD 7974-4: *Detection of fire and activation of fire suppression systems*;

PD 7974-5: *Fire service intervention*;

PD 7974-6: *Evacuation*;

PD 7974-7: *Probabilistic risk assessment*.

Where appropriate, references to relevant standards are provided in order to assist the reader in understanding the design methodologies presented and to compare different approaches or sources of data. It is therefore important that PD 7974-3 is not used in isolation and reference is made to the relevant standards, particularly in relation to additional notes and subclauses describing its application.

## Information about this document

This is a full revision of the standard, and introduces the following principal changes:

- the content has been updated to include the recommendations in the latest standards and guidance documents;
- design fires for structural fire engineering have now been integrated with PD 7974-1 and a new section on design fire selection process has been introduced. Additionally, the inherent assumptions and limitations of adopting these design fires have been explicitly stated;
- the information on potential mechanisms for fire spread has been expanded;
- the potential use of risk-based concepts described in PD 7974-7 has been added for the purposes of PD 7974-3;
- information such as material properties that was available in other British Standards has been removed to avoid repetition and reduce the length of the document;
- the layout of the document has been re-arranged so that self-contained technical information is provided as an annex.

This and the other Published Documents (PDs) in this series contain guidance and information on how to undertake quantitative and detailed analysis of specific aspects of design. It is intended that they be updated as new theories, calculation methods and/or data become available.

However, it is important to recognize that the information contained within PD 7974-3 does not preclude data, information or methods of analyses from other sources, such as published peer reviewed research, manufacturers' data or codes of practice prepared on behalf of the construction materials industry, professional engineering and technical institutions and other professional bodies.

[BS 7974](#) was first published in 2001. Since then there have been substantial changes in understanding in the behaviour of fire in the built environment and how materials and construction systems respond at elevated temperatures. Not least, the structural Eurocodes on Fire Actions have been published as full European Standards. These have resulted in revised formulations on the behaviour of structural components in fire, as well as new data on the thermal and mechanical properties of the various materials used in building construction. One of the most significant and recent advances in the understanding of buildings in fire has come about as a result of studies of experimental major fires in full size structures and the ensuing guidance this has generated on analysing the structural behaviour of the framework and compartmentation.

However, where understanding the behaviour of construction systems and building products cannot be quantified, or there are no specific analyses of some aspects of fire spread beyond the enclosure of origin other than the performance of products based upon a fire resistance furnace test, a commentary is given on the particular issues that need to be considered and how these could be treated.

A fire safety engineering approach that takes into account the total fire safety package can provide a more economical solution than prescriptive approaches to fire safety. In some cases, it is the only viable means of achieving a satisfactory standard of fire safety in some large and complex buildings.

A major issue in the determination of the structural response is the application of time equivalent methods in specifying an equivalent period of heating in the standard fire resistance test furnace. Any outputs need to consider the consequences of failure in relation to the particular occupancy and building dimensions (height and compartment size) and its location in the building, for example, [BS 9999](#) specifies a risk-based approach for occupant life safety in building structures.

Fire safety engineering has many benefits. The use of [BS 7974](#) facilitates the practice of fire safety engineering and, in particular:

- a) provides the designer with an organized approach to fire safety design;
- b) allows the safety levels for alternative fire safety designs to be compared;
- c) provides a basis for selection of appropriate fire protection systems;
- d) provides opportunities for innovative design; and
- e) provides information on the management of fire safety for a building.

Fire is an extremely complex phenomenon and there are still gaps in the available knowledge. When used by suitably qualified and competent persons experienced in fire safety engineering, [BS 7974](#) and its associated PDs provide a means of establishing acceptable levels of fire safety economically, without impeding building design.

For the purpose of this Published Document, spread of fire beyond the enclosure of origin is deemed to have taken place when any material outside of the fire enclosure ignites or suffers thermal degradation. Structural response is the interaction of loadbearing and non-loadbearing elements or frames as a result of thermal and/or mechanical actions due directly or indirectly to a fire. The level of sophistication employed to evaluate fire spread can vary. For example, a simple decision can be

taken that the creation of any openings or gaps in the enclosure boundaries precipitates fire spread. Alternatively, more complex analyses can be employed to consider whether flames project from openings in the enclosure's boundaries and whether such flames ignite or degrade materials outside the enclosure.

### **Use of this document**

As a guide, this part of PD 7974 takes the form of guidance and recommendations. It should not be quoted as if it were a specification or a code of practice and claims of compliance cannot be made to it.

This publication is not to be regarded as a British Standard.

### **Presentational conventions**

The provisions of this Published Document are presented in roman (i.e. upright) type. Its recommendations are expressed in sentences in which the principal auxiliary verb is "should".

*Commentary, explanation and general informative material is presented in smaller, italic type, and does not constitute a normative element.*

Where words have alternative spellings, the preferred spelling of the Shorter Oxford English Dictionary is used (e.g. "organization" rather than "organisation").

### **Contractual and legal considerations**

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

**Compliance with a Published Document cannot confer immunity from legal obligations.**

## 1 Scope

This Published Document provides a framework for developing a rational methodology for design using a fire safety engineering approach through the application of scientific and engineering principles to the protection of people, property and the environment from fire. This Published Document considers the following issues:

- a) the conditions that lead to fire spread beyond the enclosure of fire origin (see also [Annex A](#));
- b) the selection of design fires depending on the objectives of the assessment (see also [Annex B](#));
- c) the thermal and mechanical response of the enclosure boundaries and its structure to the fire conditions (see also [Annex C](#) and [Annex D](#));
- d) the impact of the anticipated thermal and mechanical responses on adjacent enclosures and spaces; and
- e) the structural responses of loadbearing elements and their effect on structural stability, load transfer and acceptable damage according to the design and purpose of the building (see also [Annex E](#) and [Annex F](#)).

[Annex G](#) provides a methodology for establishing the extended application of fire resistance test results.

## 2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes provisions of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

BS EN ISO 13943, *Fire safety — Vocabulary*

## 3 Terms and definitions

For the purposes of this Published Document the terms and definitions given in BS EN ISO 13943 and the following apply.

### 3.1 calculations (in support of extended application)

calculation methods that can be applied to one or more parameters of a tested construction and which are based on existing physical laws, or have been empirically validated and form part of the process of defining the extended application

### 3.2 consequence

damage that would occur if the structural failure has occurred or the time-equivalent period has been exceeded

*NOTE With respect to Approved Document B of the Building Regulations for England & Wales [1], consequence is directly proportional to height.*

### 3.3 construction parameter

aspect of the design and construction of an element that can be varied and which can result in a change in the fire resistance performance

*NOTE For example, a change in one or more of the dimensions of a stud in a stud framed separating element.*

### 3.4 direct application

variation(s) in the construction and the limits of use for the element which, without further analysis, are covered by the test result in respect to the defined performance characteristics given in Interpretative Document 2 [2] and BS EN 13501-1, achieved from a fire resistance test in accordance with the appropriate European standard

*NOTE 1 Direct application is arrived at by the application of simple rules that are known, or considered by the fire community, to give equal or improved fire resistance performance by the users. The rules can be used by non-fire experts.*

*NOTE 2 Only results from one test report can be used when considering a change of an element. Any combination and use of two or more tests reports or other technical sources is regarded as extended application and dealt with accordingly.*

### 3.5 duration of steady burning

interval between onset of flashover and commencement of decay

### 3.6 enclosure

space defined by boundary elements (on all sides) around the point of origin of a fire

### 3.7 expert assessment

engineering analysis carried out by a suitably qualified and competent person so that the results of a fire resistance test can be applied to a building element in which the dimensions and construction detail are different to that tested

### 3.8 expert judgement

qualitative process carried out by a suitably qualified person when the complexity of the influence is beyond the scope of rules, to establish the resultant effect of a variation in one or more parameters on the classification awarded

### 3.9 extended application

variations in the construction to establish the limits of use for an element that has been tested in accordance with the appropriate European standard, based upon an analysis by a suitably qualified person

*NOTE The extended application can use the results from one or more test reports and can be based upon rules, calculations and expert judgement. As a result of the extended application, the fire resistance classification of an element with respect to defined performance characteristics given in Interpretative Document 2 [2] and BS EN 13501-1 can be maintained, increased or decreased when used in practice.*

### 3.10 factor

one of the possible variations that can be applied to a parameter

*NOTE For example, a change in the stiffness as a result of a dimensional change in the stud.*

### 3.11 factor influence

potential cause of a change in the fire resistance recorded by test, with respect to one or more criteria when a factor is changed

*NOTE For example, an increase in the loadbearing capacity (R) as a result of an increase in stiffness.*

### 3.12 fire safety

safety of a building and its surroundings in relation to life, property, business continuity and the environment

**3.13 fire safety engineering**

use of engineering principles for the achievement of fire safety

**3.14 frequency**

measure of the number of fires that are likely to occur in a particular structure in a given period

**3.15 localized fire**

fire that is fuel-bed controlled and is sufficiently small that it does not directly impact upon the enclosure

**3.16 place of relative safety**

predetermined place in which persons are in no immediate danger from the effects of fire

*NOTE This may be inside or outside the building depending upon the evacuation strategy.*

**3.17 probability**

likelihood of failure typically directly related to cumulative distribution curves of the time-equivalent period

*NOTE Probability is often derived using a Monte Carlo analysis to evaluate many thousands of fires with all relevant variables that influence fire severity.*

**3.18 risk**

frequency × probability × consequence

**3.19 rules**

quantitative factors that can be applied to the result of tests when defining the limits of application as a product of research and testing

*NOTE Rules are primarily used in determining the direct application of the result, as their application does not require specialist knowledge.*

**3.20 sensitivity analysis**

calculation of rate of change of output as a function of rate of change of an input parameter of input

**3.21 structural frames**

arrangement of structural materials and/or elements coming together to form a building or part thereof designed to fulfil a loadbearing function

**3.22 structural response**

interaction of loadbearing and non-loadbearing elements or frames as a result of thermal and/or mechanical actions due directly or indirectly to a fire

**3.23 thermal and mechanical parameters**

aspect of the conditions of a test that can vary in practice and influence the classification system given

*NOTE For example, the greater pressure differential that exists at the top of a larger element than the pressure differential at the top of the test specimen.*

**3.24 time equivalent**

duration of exposure in standardized fire that would result in an equivalent structural response to that of the design fire in question

## 4 Symbols

|                 |                                                                                                                                                     |
|-----------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
| $\alpha$        | coefficient of thermal expansion (mm/mmK <sup>-1</sup> )                                                                                            |
| $\alpha_c$      | coefficient of heat transfer by convection (W/m <sup>2</sup> K)                                                                                     |
| $\alpha_h$      | area of horizontal openings in the roof related to the floor area of the compartment (m <sup>2</sup> )                                              |
| $\alpha_v$      | area of vertical openings in the façade related to the floor area of the compartment (m <sup>2</sup> )                                              |
| $\beta_0$       | design charring rate for one dimensional charring (mm/min)                                                                                          |
| $\beta_n$       | notional design charring rate (mm/min)                                                                                                              |
| $\beta_{par}$   | design charring rate under parametric heating conditions (mm/min)                                                                                   |
| $\gamma_{M,fi}$ | partial safety factor in fire                                                                                                                       |
| $\gamma_G$      | partial safety factor for permanent loads to be assigned a value of 1.0                                                                             |
| $\Gamma$        | compartment time factor                                                                                                                             |
| $\Delta_{bow}$  | lateral deflection of a wall (mm)                                                                                                                   |
| $\Delta_{head}$ | deflection of head of wall away from the heat source (mm)                                                                                           |
| $\varepsilon$   | strain, emissivity                                                                                                                                  |
| $\zeta$         | reinforcing efficiency parameter of the composite material indicating the extent to which the applied force is transmitted to the reinforcing phase |
| $\theta$        | temperature (°C or K)                                                                                                                               |
| $\lambda$       | thermal conductivity (W/mK)                                                                                                                         |
| $\rho$          | density (kg/m <sup>3</sup> )                                                                                                                        |
| $\sigma$        | Stefan Boltzmann constant ( $5.67 \times 10^{-8}$ W/m <sup>2</sup> K <sup>4</sup> )                                                                 |
| $\sigma$        | stress (N/mm <sup>2</sup> )                                                                                                                         |
| $\chi_{fi}$     | reduction factor for flexural buckling in the fire design situation                                                                                 |
| $\psi$          | partial safety factor                                                                                                                               |
| $a$             | effective height (m)                                                                                                                                |
| $a_0, a_1, a_2$ | coefficients for thermal conductivity                                                                                                               |
| $A$             | area (m <sup>2</sup> )                                                                                                                              |
| $b$             | thermal inertia (J/m <sup>2</sup> s <sup>1/2</sup> K)                                                                                               |
| $ct$            | combined thickness                                                                                                                                  |
| $C$             | specific heat capacity (J/kgK)                                                                                                                      |
| $d_{char,n}$    | depth of charring (mm)                                                                                                                              |

|                     |                                                                                                      |
|---------------------|------------------------------------------------------------------------------------------------------|
| $d_{\text{char},0}$ | charring depth for one dimensional charring (mm)                                                     |
| $d_{\text{door}}$   | thickness of a door leaf (mm)                                                                        |
| $d_{\text{ef}}$     | effective cross section (mm)                                                                         |
| $d_i$               | thickness of insulating material, i (m)                                                              |
| $d_t$               | depth of a timber beam (mm)                                                                          |
| $d_w$               | thickness of a wall (m)                                                                              |
| $D$                 | depth of enclosure (m)                                                                               |
| $e_{\Delta\theta}$  | eccentricity due to variation of temperature across masonry                                          |
| $\text{erfc}$       | complex error function                                                                               |
| $E$                 | integrity criteria                                                                                   |
| $E_{\text{d},t}$    | design load created by the fire situation at time $t$                                                |
| $E_{\text{fi},d}$   | design effect of actions for the fire situation                                                      |
| $E_m$               | Young's modulus (kN/mm <sup>2</sup> )                                                                |
| $E_p$               | plastic modulus (kN/mm <sup>2</sup> )                                                                |
| $E_{p,\theta}$      | plastic modulus at temperature $\theta$ (kN/mm <sup>2</sup> )                                        |
| $F$                 | load (kN)                                                                                            |
| $F_t$               | load at fire temperature                                                                             |
| $F_0$               | load at ambient temperature                                                                          |
| $f$                 | strength (N/mm <sup>2</sup> )                                                                        |
| $F_{\text{e-R}}$    | configuration factor describing the spatial relationship between the emitting and receiving surfaces |
| $h$                 | height (mm or m)                                                                                     |
| $h_{\text{net}}$    | net incident heat flux per unit area (kW/m <sup>2</sup> )                                            |
| $H$                 | height of the enclosure (m)                                                                          |
| $H_p$               | heated perimeter of a section (m)                                                                    |
| $I$                 | insulation criteria                                                                                  |
| $I_{\text{mean}}$   | average temperature rise on homogeneous elements                                                     |
| $k$                 | modification factor                                                                                  |
| $k_b$               | factor describing the thermal properties of the enclosure                                            |
| $k_c$               | reduction factor                                                                                     |
| $K$                 | thermal diffusivity (m <sup>2</sup> /s)                                                              |
| $L$                 | linear dimension (mm)                                                                                |
| $M$                 | moment (Nm)                                                                                          |

|                 |                                                                                                      |
|-----------------|------------------------------------------------------------------------------------------------------|
| $n$             | ratio of temperatures                                                                                |
| $N$             | design value                                                                                         |
| $N_{b,fi,t,Rd}$ | design buckling resistance                                                                           |
| $N_{Ed}$        | design value of the vertical load                                                                    |
| $O$             | opening factor ( $m^{3/2}$ )                                                                         |
| $p_c$           | compressive strength of concrete ( $N/mm^2$ )                                                        |
| $p_y$           | characteristic design strength for steel ( $N/mm^2$ )                                                |
| $P_w$           | % of moisture (by mass)                                                                              |
| $P_f$           | effective property of the fibres                                                                     |
| $P_m$           | effective property of the matrix                                                                     |
| $q$             | heat flux ( $kW/m^2$ )                                                                               |
| $Q$             | rate of heat flow ( $kW$ )                                                                           |
| $r$             | radius                                                                                               |
| $R$             | mechanical resistance                                                                                |
| $R$             | loadbearing capacity criteria                                                                        |
| $S_{05}$        | 5% fractile of a stiffness property (modulus of elasticity or shear modulus) at ambient temperature  |
| $S_{20}$        | 20% fractile of a stiffness property (modulus of elasticity or shear modulus) at ambient temperature |
| $t$             | time (s, min or h)                                                                                   |
| $T$             | temperature ( $^{\circ}C$ or $K$ )                                                                   |
| $V$             | volume ( $m^3$ )                                                                                     |
| $V_i$           | volume per unit length of an insulated element ( $m^3$ )                                             |
| $V_x$           | matrix volume fraction of a composite                                                                |
| $w$             | width of the opening (m)                                                                             |
| $w_f$           | width of the flame front (m); ventilation factor                                                     |
| $W$             | width of enclosure (m)                                                                               |
| $x$             | horizontal projection of the flame (m)                                                               |
| $x_s$           | distance from exposed surface (m)                                                                    |
| $X$             | flame length along axis (m)                                                                          |
| $z$             | vertical projection of the flame above the window (m)                                                |
| $Z$             | flame height above opening (m)                                                                       |
| $Z_w$           | height above the top of the opening (m)                                                              |
| $Z_y$           | elastic modulus about the minor axis ( $cm^4$ )                                                      |

## 5 Design approach to PD 7974-3

### 5.1 General

A framework for the application of engineering approaches to fire safety in buildings is provided in [BS 7974](#).

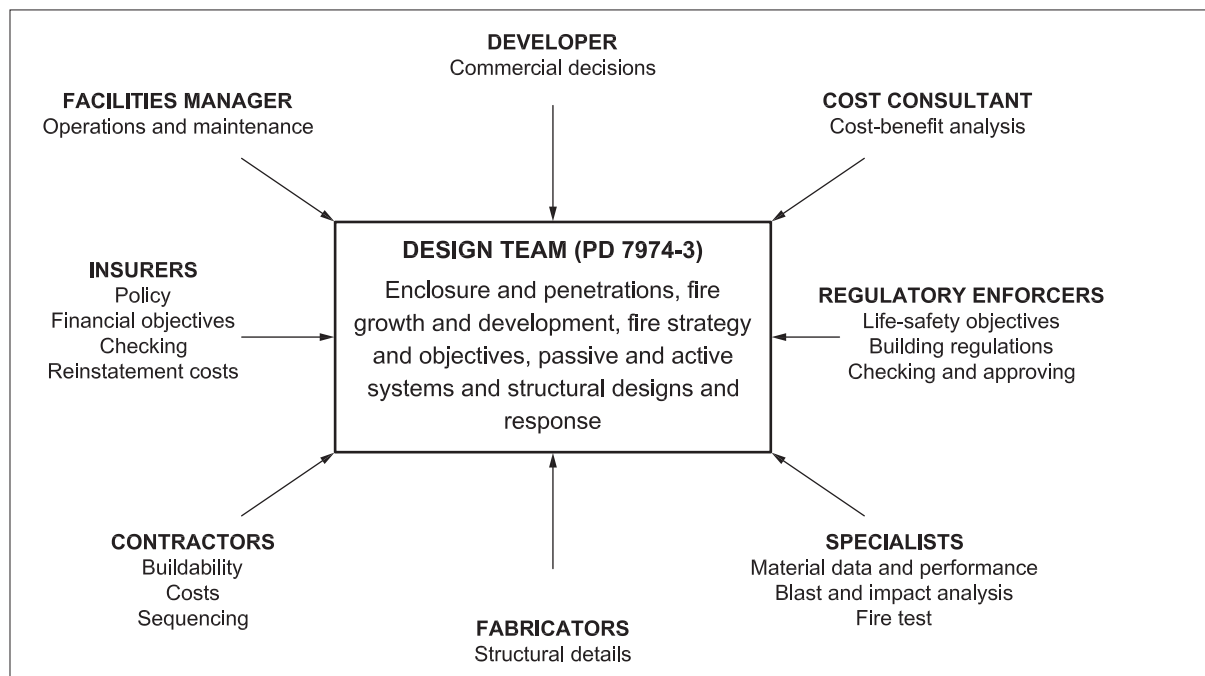
[BS 7974](#) assists with the design process. The quantitative design analysis is divided into a number of separate sub-systems. Each sub-system can be used in isolation when analysing a particular aspect of design, or can be used in combination as part of an overall fire evaluation of a building. The parameters are often inputs into one sub-system and outputs from another.

Each of the sub-systems concentrates on the quantified analysis state of the [BS 7974](#) framework, however additional guidance specific to the relevant sub-system is useful when considering the overall framework. This subclause provides guidance on the interaction between PD 7974-3 and the overall [BS 7974](#) framework and defines the process for quantitative analysis of the structural response and the likelihood of fire spread beyond the room of fire origin.

### 5.2 Interaction with BS 7974 framework

The [BS 7974](#) framework is shown in BS 7974:2019, Figure 1. The preliminary part of the framework is to conduct a qualitative design review (QDR) comprising several components, defined in [BS 7974](#), during which the relevant sub-systems should be considered. The parties that might be involved in PD 7974-3 are listed in [Figure 1](#). Not all parties need to be involved, and those who are do not have to be involved throughout the whole process. This is not an exhaustive list and the person responsible for conducting the PD 7974-3 study should ensure all relevant parties are involved at the appropriate time. The personnel involved in the QDR can vary throughout the process.

**Figure 1** — Interaction between the various professions and the design team in addressing PD 7974-3 factors



### 5.3 Functional objectives

The functional objectives for the assessment should be defined (see [BS 7974](#)).

## 5.4 Identification of fire hazards and possible consequences

In the context of PD 7974-3, the primary hazards and possible consequences derive from structural failure and/or fire spread beyond the enclosure of fire origin.

Therefore, as part of the QDR, all potential mechanisms of fire spread and potential routes for fire spread that would prevent the functional objectives being met should be identified. See [Annex A](#) for further information on fire spread mechanisms.

## 5.5 Identification of acceptance criteria and appropriate methods of analysis

### 5.5.1 General

The acceptance criteria, as defined in the QDR, should be applicable to the fire safety objective. The basis of any assessment or sub-assessment can be empirical or theoretical, the accuracy can be approximate or realistic, the analysis can be deterministic or risk-based and the measure can be qualitative or quantitative.

Regardless of what combination is adopted, the acceptance criteria should be compatible with the functional objectives, hazards and consequences, trial fire safety design and analysis method.

The acceptance criteria may use predetermined levels of acceptance, such as the criteria specified in BS EN 1363-1 and BS EN 1363-2, or they can be derived to mitigate the identified hazard.

### 5.5.2 Factors influencing acceptance criteria

Mechanisms of failure for loadbearing elements can result from material degradation, loss of material, thermally induced stresses and strains, delamination or debonding of composite materials, connection failure, etc. The acceptance criteria should be selected to adequately protect against the relevant mechanisms of failure and might include:

- a) minimum permissible strength and/or stiffness;
- b) minimum permissible loss of material;
- c) maximum allowable stress or strain or deflection;
- d) maximum allowable rate of change of stress or strain or deflection;
- e) maximum allowable material temperature;
- f) maximum allowable rate of change of material temperature; and
- g) maximum allowable increase of axial forces.

The following factors should be considered when analysing the security of relevant spaces:

- integrity and smoke tightness of the elements forming the structure in respect of the leakage of fire and gaseous combustion products into compartments other than the compartment of fire origin;  
*NOTE 1 This is usually the product of collapse of boundary elements, deflection or distortion, propagation of cracks and fissures, or the burning through or melting out of component parts.*
- insulation and radiation of the elements forming the structure in respect of ambient temperature within the exit routes and places of relative safety.

*NOTE 2 This is usually the product of tightness but, prior to any loss of smoke tightness and/or integrity, it is influenced by the conducted/convective and radiant heat emitted by the fire separating elements of structure.*

The standard criteria used in the fire resistance tests, as appropriate to the element being tested, might have little or no direct relationship to the critical tenability levels. However, for common

situations it can be assumed that there is an adequate level of redundancy in the solution derived if they are used.

## **5.6 Establishing trial fire safety designs**

### **5.6.1 General**

Having identified and evaluated the potential hazards and their consequences, the designer should mitigate the hazards, and/or demonstrate that the consequences of the hazards are acceptable. The trial design is the designer's initial attempt at developing a solution likely to meet the desired fire safety objective, which is then tested through quantitative analysis (within the context of this Published Document). Typically, the trial design should consider:

- fire resistance of the structure including any applied fire protection;
- extent, frequency and performance of fire barriers;
- influence of any suppression measures;
- effectiveness of, or need for, smoke control;
- fire service intervention and effectiveness; and
- reliance upon future management.

The trial design should also consider the level of redundancy, robustness and reliability that is acceptable, and specifications should be produced to ensure these levels.

### **5.6.2 Redundancy**

Redundancy or diversity ensures that an alternative is available if a particular feature or system becomes compromised. Examples of redundancy include:

- alternative structural load paths; or
- multiple means of protection (e.g. passive fire protection and sprinklers).

### **5.6.3 Robustness**

The robustness of the system is its ability to perform its function, even if the exposure conditions are not exactly as predicted and the condition of the element at the time of the event is worse than anticipated.

### **5.6.4 Reliability**

Reliable systems are those likely to perform as required. Reliability can be improved through the use of reliable components, and these are subjected to appropriate maintenance and testing.

## **5.7 Establish fire scenarios for analysis**

[BS 7974](#) provides considerable advice on the selection of fire scenarios. With PD 7974-3, the following should be considered.

- a) In order for fire or smoke to spread beyond the enclosure of origin it is often assumed that a post-flashover fire occurs, which is not necessarily true as a localized or travelling fire can also lead to compartmentation failure.
- b) When assessing the performance of structural elements it is often assumed that a fully developed compartment fire represents the worst case. This is usually true but a localized fire sometimes represents the worst case, for example, in structures that are susceptible to restrained thermal expansion.

- c) It is often assumed that all elements being heated simultaneously represents the worst case, which is not necessarily true. A travelling fire can induce different structural responses to a uniform fire and can be more severe.
- d) Failure can often occur in the decay phase of a fire so it might be necessary to include decay in the analysis.

The behaviour of real fires is very sensitive to the amount of ventilation available. Well-vented fires tend to be shorter and hotter than under-ventilated fires. The performance of structural and separating elements is sensitive to the combustion temperature and duration of fire exposure and the hottest or the longest fires do not necessarily represent the worst case. Therefore, the number and range of design fires should be carefully considered to ensure a reasonable range of conditions is evaluated.

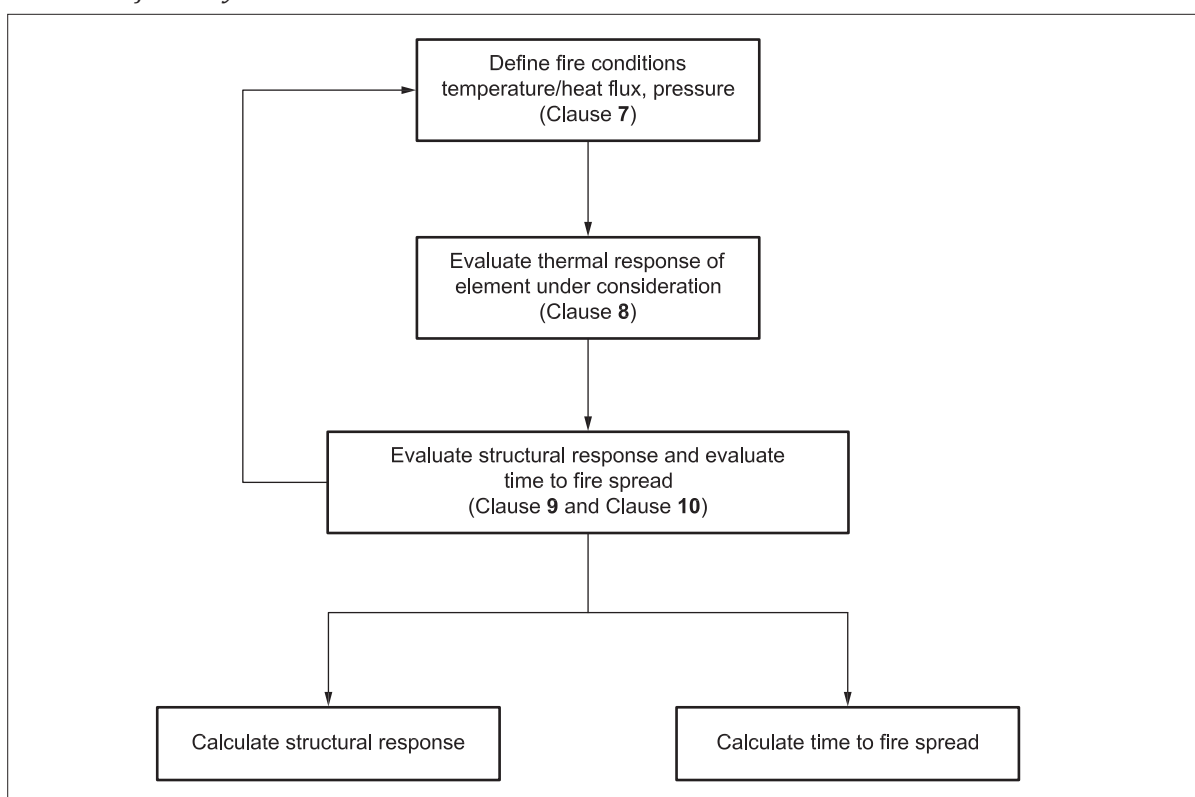
## 5.8 Analysis

### 5.8.1 General

The primary focus of each of the [BS 7974](#) sub-systems is the analysis, and the results of the analysis should be supplied by the sub-systems as output to the assessment stage of the [BS 7974](#) framework. The process should be completed for each of the fire scenarios and each of the potential routes of fire spread identified within the QDR.

The process for analysis that should be conducted as part of PD 7974-3 (within the limitations described in [Clause 7](#)) is defined in [Figure 2](#). Each step can be conducted sequentially or combinations of the steps can be conducted simultaneously.

**Figure 2** — Procedure for analysis within PD 7974-3



### 5.8.2 Defining analysis methods

The science behind each of the parts of the analysis of PD 7974-3 is complex and there are several methods. These include prescriptive guidance, testing, empirical relations, expert judgement and varying complexities of quantified analysis. Each method has its own associated accuracy and range

of applicability. It is up to the designer to select the appropriate method for the problem in hand, and this is a function of the objectives, the potential hazards and consequences, the required accuracy and the required output.

The analysis method should be compatible with the functional objectives, mechanisms of fire spread and the acceptance criteria.

### **5.8.3 Defining fire conditions**

PD 7974-1 provides information on defining fire conditions depending on the compartment characteristics.

It is not only the temperature within the enclosure that is important. Any pressure differential between the inside of the enclosure and the adjacent areas has a significant influence on the rate at which the tenability of the protected spaces is lost. Turbulence in the fire could make the results of some fire tests inappropriate if the construction materials are not robust enough to withstand this. When defining the fire conditions, the designer should consider the temperature, pressure conditions and turbulence.

### **5.8.4 Heat transfer and thermal response**

The fire conditions should be used to evaluate the heat transferred into and throughout the elements of the structure and/or enclosure boundaries.

### **5.8.5 Structural response**

#### **5.8.5.1 General**

The structural response assessment should consider material degradation (e.g. strength and stiffness), thermal expansion and structural boundary conditions (e.g. connections surrounding structure).

#### **5.8.5.2 Changes in building characteristics**

Analysis undertaken in accordance with PD 7974-3 could identify changes to the enclosure boundaries such as failure of surfaces, opening of gaps, or alteration to the structural form, e.g. deflection or collapse of loadbearing elements of structure. These changes in the characteristics of the building should be evaluated in their own right as part of the QDR process as they can compromise the fire strategy objectives. The changes might also need to be considered as variable boundary conditions when analysing adjacent enclosures within the building.

If the structural response analysis identifies changes in building characteristics, these should be assessed to determine whether the design fire characteristics need to be revisited.

---

## **6 Analysis methods**

### **6.1 General**

The potential for spread of a fire from the enclosure of origin is influenced by the thermal and mechanical response of the enclosure's boundaries (walls, roof, doors and windows). There are many forms of analysis that can be used to evaluate the thermal and/or structural response to fire. The selected method should be compatible with the functional objectives, hazards and consequences, trial fire safety design and acceptance criteria.

### **6.2 Basis of analysis**

The basis of analysis can be empirical, theoretical or semi-empirical.

Empirical methods include standard fire tests, experiments and experiential data where real fire behaviour, heat transfer and/or structural response are estimated by comparison with empirical data. Fire, heat transfer and structural response can be complex, and in certain circumstances, empirical methods have to be used because theoretical methods do not exist. Similarly, a key advantage of empirical methods is the associated physical verification. However, care should be taken to ensure that the empirical method is adequately conservative and representative of the real fire, heat transfer and structural response such that comparisons of behaviour are valid.

Theoretical methods include analytical calculations and numerical simulations. They might comprise simple approximations to a complex series of sub-models. The fire, heat transfer and structural response might be considered separately or coupled. In certain circumstances, theoretical methods have to be used because real enclosures and structures are often too large or complex to be represented adequately by empirical methods. Typically, theoretical models are sufficiently quick and cost-effective to allow multiple assessments and consideration of the impact of variables or uncertainty. As with empirical methods, care should be taken to ensure that the theoretical model is adequately conservative and representative of the real fire, heat transfer and structural response such that prediction of behaviour is valid. Furthermore, it should be ensured that the theoretical models and sub-models are adequately verified and validated for the intended use.

Appropriate fire and structural models should be selected for the scenario under consideration. For example:

- a) It is not possible to use the standard fire curve to make an accurate prediction of the performance of a whole-frame structure, but it can be used to compare the relative performance of two different whole-frame structural options. When the element is homogeneous, it might also be possible to predict the possibility of integrity failure, but this is not in absolute terms and the designer should analyse the confidence limits within which the calculated value stands.
- b) Standard furnace tests might not be suitable for exposed structural timber whereby the fire curve is influenced by the timber itself being a fuel.

The designer should select an analysis method and level of sophistication to assess the trial fire safety design against the functional objectives.

### 6.3 Accuracy

The analysis can range from a simple approximation to an accurate representation of reality.

The accuracy should be sufficient for the analysis in question and should be compatible with the functional objectives. For example, in certain circumstances, the overall structural response can be sufficiently accurately represented by the isolated response of its constituent structural elements; whereas, in other circumstances, the overall structural response can only be sufficiently accurately represented by the assembly of all or multiple constituent structural elements.

### 6.4 Means

Deterministic assessments have non-probabilistic inputs and variables and give the same answer for any given set of input. Inevitably fire, heat transfer and structural response involve probabilistic data and variables. Therefore, for deterministic assessments to be valid, it is typically necessary to ensure adequate conservative inputs and variables and/or adequate margins/factors of safety against the acceptance criteria.

Risk-based assessments include at least one probabilistic input or variable.

## 6.5 Measures

Measures of assessment are typically described as being qualitative or quantitative. In practice, it is not a binary situation and the measure can range from little quantification to fully quantified justifications. The amount of quantification should be commensurate with the reliance being placed on it.

Assessments can be qualified through interpretation of data and evidence, expert judgement and/or logic and reasoning.

---

## 7 Evaluation of fire conditions

### 7.1 Design fire characterization

The characterization of design fires and the associated thermal load to the structure is discussed in PD 7974-1. More information on design fires is given in [Annex B](#).

The characterization requires definition of temperature (or heat flux) and potentially pressure, both spatially and with respect to time, and can range from homogeneous, steady state to spatially and time-dependent heating and cooling. Fire characteristics can be derived from a range of sources including expert judgement, experimentation, standardized fires, simplified temperature–time curves, and advanced modelling (CFD, zone, etc.). For the use of time equivalence, see [Clause 10](#).

### 7.2 Selection of design fires

#### 7.2.1 General

Structural response can be sensitive to both spatial and time-based variations in a heating regime [3], [4], [5]. For example:

- a) Non-homogeneous heating can result in greater thermally induced stress and/or strain than homogeneous heating and consequently higher restrained thermal expansion.
- b) Homogeneous heating can result in a higher proportion of structure at reduced strength than non-homogeneous heating.
- c) Rapid heating can induce a higher thermal gradient in partially exposed elements than steady state or gradual heating.
- d) Cooling can result in restrained thermal contraction.

The designer should select the design fires for a structural response assessment such that the temperature/heat flux/pressure conditions as relevant with respect to space and time are sufficiently accurate or onerous to test the structural response (or reliability where a risk-based assessment is undertaken) against the acceptance criteria and functional objectives.

#### 7.2.2 Applicability and limitations

In some instances (for example, determining the limiting temperature of simple beams or columns, benchmarking trial safety designs that are not susceptible to non-homogeneous heating or rate of heating, or where heating is likely to be steady state and homogeneous), steady state, homogeneous fire conditions might be sufficient. Additionally, the value of temperature or heat flux used, particularly in comparative studies, might not be critical. In other situations, detailed spatial variations with respect to time might be necessary.

Standardized fires were typically developed as a means of benchmarking structural response to a sufficiently onerous representation of reality. They can be very useful for testing structural response and potential failure mechanisms (particularly for comparative assessments of different trial fire safety designs), but they are unlikely to be applicable where an accurate assessment of structural

response is required or for situations where structural response is likely to be significantly impacted by restrained thermal expansion or contraction or rapid or differential heating. This would also apply in comparative studies.

Homogeneous, time-based heating conditions, e.g. parametric fires, can be used as a more accurate characterization of reality and/or to test the impact of rate of heating and/or cooling. Both might require more than one design fire. As with standardized fires, they are only applicable when fire conditions are sufficiently homogeneous, homogeneous fire conditions are conservative in respect of structural response or the structural response is not sensitive to differential spatial heating.

Travelling fires allow for fire conditions to be characterized spatially with respect to time. Whilst this might be the most realistic and/or onerous characterization of a fire, there is an increased number of variables: shape and dimensions; rate; direction; path of travel; and temperature or heat flux in three dimensions. Therefore, it might be necessary to consider multiple fire scenarios.

### 7.2.3 Changing characteristics

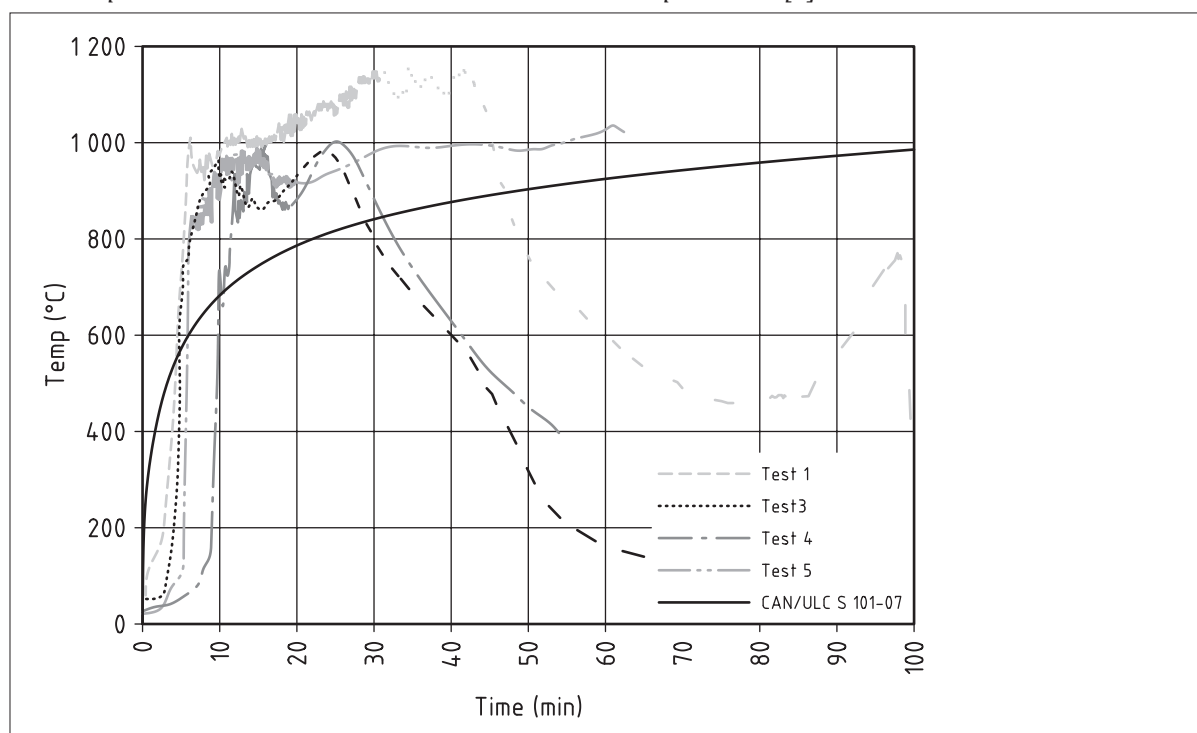
The initial characterization of fires might have to be changed iteratively through the analysis process. For example, where openings are provided between compartment floors (atriums, open stairs, etc.) and no passive/active measures apart from suppression systems are provided to restrict fire spread, and it is assumed that suppression systems fail, a multi-storey or vertically travelling fire might need to be considered. Similarly, when calculating the fire severity within a compartment, if that fire severity is higher than the fire resistance of the surrounding construction, it might have to be assumed that the surrounding construction fails and the domain of analysis (both for design fires and structural response) changes.

### 7.2.4 Combustible enclosures

Combustible materials, such as timber or bamboo, are sometimes used over more traditional construction materials, such as steel or concrete. When combustible structural members are exposed to a fire (i.e. not protected with fire-rated construction for the whole duration of the expected fire), they can alter the fire dynamics leading to increased fire durations and increased external flaming from the openings [6]. See [Figure 3](#). This is due to the increase in fuel load, the potential for secondary flashover (in the event that the structure does not experience self-extinguishment, where relevant) and the reduction in the geometry of the structural members as a result of the consumption of the combustible material by the fire [7].

Combustible elements can possess fire resistance even when they are left exposed. However, traditional methods of specifying fire resistance by separating the design fire selection process and the subsequent heat transfer and mechanical response assessment (similarly to the principles described in this Published Document) might not always be appropriate for combustible buildings.

Additionally, the structural performance of timber buildings is not based on a maximum temperature, but rather on a temperature profile and the charring (of the wood) which can continue to affect the capacity of the material even during the decay stage of a fire. Delamination needs to be prevented for laminated members such as CLT through appropriate use of fire-resting adhesives [6].

**Figure 3** — Gas temperature in non-combustible and combustible compartments [8]

## 8 Evaluation of thermal response

### 8.1 Thermal response of elements within enclosure

The thermal response of any construction element can influence:

- the heat balance within the enclosure and, accordingly, the ongoing fire conditions;
- their mechanical response and their separating function; and
- the structural response of structural elements.

The thermal response of structural members can be determined from:

- empirical data based upon data and observations from fire tests ([10.3.2](#));
- simplistic calculations of the temperature response based on first principles ([10.3.4](#)); or
- advanced calculations ([10.3.5](#)).

More information on heat transfer and thermal response of specific materials is given in [Annex C](#). The thermal properties for non-loadbearing construction systems are given in [Annex D](#).

Each of the component mechanisms of fire spread can be quantified using engineering models and analysis. However, the level of sophistication available and the reliability of the results achieved vary widely amongst the different mechanisms. This reflects up-to-date understanding and the level of analysis typically required for practical design purposes.

### 8.2 Empirical data

Several materials have been extensively evaluated under the standard fire test using either full-size or indicative specimens. The results have then been used to develop relationships between the size of member versus heating rates under various standard fire heating periods and temperature profiles/ gradients through the structural element in the form of design charts or monograms for use by non-specialist designers.

### 8.3 Simplistic calculations

Where the thermal properties of a structural element are known, its thermal response can be calculated using basic heat transfer theory.

The energy from the fire is imparted to any exposed surfaces of an element of the structure within, or outside, the enclosure through conduction and radiation. The net heat flux to which an element's surface is exposed,  $q_{\text{net}}$ , is the sum of the convective and radiative incident fluxes:

$$q_{\text{net}} = q_{\text{net,c}} + q_{\text{net,r}} \quad (1)$$

where:

$q_{\text{net}}$  is the net incident heat flux (kW/m<sup>2</sup>);

$q_{\text{net,c}}$  is the convective heat flux (kW/m<sup>2</sup>);

$q_{\text{net,r}}$  is the radiative heat flux (kW/m<sup>2</sup>).

Heat transfer by convection follows Newton's Law, where the heat flux is proportional to the difference in temperature between that of the exposed surface of the element,  $T_{\text{surface}}$ , and the impinging hot gases,  $T_{\text{g}}$ . The convective heat flux per unit surface area,  $q_{\text{c}}$ , of the element is given by:

$$q_{\text{c}} = \alpha_{\text{c}} (T_{\text{g}} - T_{\text{surface}}) \quad (2)$$

where:

$q_{\text{c}}$  is the convective heat flux (kW/m<sup>2</sup>);

$\alpha_{\text{c}}$  is the coefficient of heat transfer by convection (W/m<sup>2</sup>K);

$T_{\text{g}}$  is the temperature of the fire gases (K);

$T_{\text{surface}}$  is the temperature of the exposed surface element (K).

The convective heat transfer coefficient,  $\alpha_{\text{c}}$ , is a function of the fire gases' flow pattern and velocity, and can be difficult to quantify in practice. For fully-developed fires, the contribution of convection to the hot-face heat transfer is small and  $\alpha_{\text{c}}$  should be assigned a value of 25 kW/m<sup>2</sup>K (independent of temperature). This value could also be conservatively used for less severe or growing fires. For more severe fully-developed fires, a higher value for  $\alpha_{\text{c}}$  of 50 kW/m<sup>2</sup>K is more appropriate. At the non-exposed face of an element, where some cooling is expected to occur through convection and radiation,  $\alpha_{\text{c}}$  should be assigned a value of 4 kW/m<sup>2</sup> or 9 kW/m<sup>2</sup> where the effects of radiation are considered. Further guidance is provided in BS EN 1991-1-2.

When evaluating the radiative heat transfer between fires and non-combustible solids in the enclosure, the relationship becomes more complex as the ongoing interaction between the fire and the receiving surface causes the amount of radiative heat transfer to change continually. The interaction can be modelled by the relationship:

$$q_{\text{r}} = \phi \varepsilon_{\text{m}} \varepsilon_{\text{f}} \sigma [(T_{\text{g}})^4 - (T_{\text{surface}})^4] \quad (3)$$

where:

$q_{\text{r}}$  is the radiative heat flux of the receiver (W/m<sup>2</sup>)

$T_{\text{g}}$  is the temperature of fire gases within the compartment (K);

$T_{\text{surface}}$  is the surface temperature of the exposed element (K);

$\sigma$  is the Stefan-Boltzmann constant, i.e.  $5.67 \times 10^{-8}$  W/m<sup>2</sup>K<sup>4</sup>;

$\phi$  is the configuration factor, describing the geometrical relationship between the radiating hot gases and the receiving surface;

*NOTE In the absence of further analysis, the configuration factor can be set at unity. Practical values for the configuration factor are illustrated in [Figure C.1](#).*

$\varepsilon_m$  is the surface emissivity of the member;

$\varepsilon_f$  is the emissivity of the fire.

## 8.4 Advanced calculations

The thermal response of the exposed elements to the imposed heat flux is governed by the geometry and construction of each of the exposed structural members. The prediction of the thermal response of the element itself requires solving the governing formula of transient conduction subject to the appropriate boundary conditions, as described by Formula (4) within homogeneous and isotropic solids.

$$\frac{\delta}{\delta x} \left( K \frac{\delta T}{\delta x} \right) + \frac{\delta}{\delta y} \left( K \frac{\delta T}{\delta y} \right) + \frac{\delta}{\delta z} \left( K \frac{\delta T}{\delta z} \right) + \frac{Q}{\rho C} = \frac{\delta T}{\delta t} \quad (4)$$

where:

$T$  is temperature (K);

$x, y, z$  are planes of reference;

$t$  is time (s);

$Q$  is internally generated heat (kW);

$\rho$  is density (kg/m<sup>3</sup>);

$C$  is specific heat capacity (J/kgK);

$K$  is thermal diffusivity (m<sup>2</sup>/s).

Given the transient conditions in Formula (4) it is not possible to offer an exact solution, even for relatively simple boundary conditions; numerical analysis is typically used to find practical solutions using the finite element or finite difference methods. Computer software packages have been used to solve Formula (4). However, the designer should be satisfied that any model used is valid. Typically, the use of numerical models requires the choice of a time step for analysis. The smaller the time step, the more likely it is that a convergent solution and accurate results will be achieved. However, small time steps also increase the number of calculations required and increase the simulation run times. Within finite, element-based systems a similar effect is encountered with the allocation of mesh size. The designer should be satisfied that key model parameters such as time step and mesh size have been set at a level at which reductions cannot meaningfully increase the accuracy of the solution. This is typically achieved by conducting appropriate sensitivity studies.

## 8.5 Quantitative analysis of heat flow by conduction

The imposition of heat flux to the exposed side of a boundary causes a temperature gradient through the body of the boundary from the exposed surface to the unexposed surface where the boundary material is homogeneous. Fourier's Law states:

$$q_{\text{cond}} = -KA_a \frac{dT}{dN} \quad (5)$$

where:

$\frac{dT}{dN}$  is the temperature gradient in the direction orthogonal to the area (K/m); and

– indicates that heat always flows from hotter to cooler surfaces.

Heat ceases to flow between areas of equal temperatures. Under steady state conditions where no internal heat is generated, the Laplace equation can be used:

$$\frac{d^2T}{dx^2} \times \frac{d^2T}{dy^2} \times \frac{d^2T}{dz^2} = 0 \quad (6)$$

where  $x, y, z$  are the orthogonal directions.

The general formulae of conduction can be applied numerically for any particular application using, for example, finite difference or finite element techniques. In some cases, exact solutions are available, such as calculating the temperature rise in semi-infinite plane wall exposed to steady heat flux. However, solving the governing formulae for applications in fire safety design is often problematic due to the transient heat flux imposed and the temperature dependency of the thermal diffusivity. The designer should recognize the additional resources required to model transient conduction into enclosure boundaries and, in particular, should avoid the use of ambient heat flow techniques and ambient material properties such as U-value methods. A range of proprietary computer software is available to allow the analysis of transient conduction into solid members [9].

For solid homogeneous materials, it is possible to calculate the unexposed face temperature rise if the conductivity of the material is known, together with the gas temperature of the enclosure and the heat transfer coefficients of the material. The calculation is simpler if the temperature of the exposed face is known as a result of experimental testing against the appropriate exposure conditions.

If the construction is non-homogeneous, it is unlikely a model exists that would enable the unexposed face temperature to be calculated with accuracy. In these situations, the unexposed face temperature can only be established by measurements undertaken during a test in order to provide effective values under well-defined heating conditions. This approach is important where changes in physical properties result in endothermic or exothermic reactions. In cases where good contact between components forming a composite can be maintained at elevated temperatures, the thermal behaviour can be established using reduced scale specimens. Where delamination at elevated temperatures is likely, unexposed face temperatures can only be established by exposing large specimens to fire. Standard tests available for establishing these measurements are based upon [BS 476-20](#) or BS EN 1363-1.

The fire resistance test represents only one possible fire scenario and one set of exposure conditions and, in reality, unexposed face temperatures can vary from the conditions measured in the test. The thermal properties could also be influenced by the rate of heating.

Based upon the quantity of heat being conducted through an enclosure boundary, it is possible to quantify the temperature at any location through its thickness, including the temperature on the unexposed surface. The unexposed surface is outside the enclosure of fire origin and its ignition constitutes fire spread.

Predicting the occurrence of ignition is dependent on small-scale experiments that might not be readily scalable to real building assemblies. Fire spread will not occur if the temperature rise on the unexposed face remains below 180 °C at all locations and below 140 °C as a mean. These temperatures represent the failure criteria in [BS 476-20](#) for heat flow to the unexposed face of the test specimen. These failure criteria have long been used to define insulation failure in standard fire resistance tests, and their adoption gives the designer some assurance that a conservative solution has been reached. Persistent ignition of the unexposed face requires a sufficient quantity of heat being conducted through the system at a rate in excess of its surface cooling, such that the temperature rise of a minimum thickness is raised to a level in excess of the material's characteristic pyrolysis temperature. Most organic solids undergo pyrolysis in the range of 275 °C to 375 °C.

Polymeric materials are susceptible to decomposition and undergo pyrolysis in the range of 200 °C to 400 °C.

## 8.6 Quantitative analysis of heat flow by convection

The flow of heat from the enclosure of fire origin through fixed openings is described in PD 7974-2. However, many of the methods described are inappropriate for describing heat flow from post-flashover fires or from small and irregularly shaped openings, such as those created during a fire.

In general terms, the rate of heat flow from the enclosure of fire origin can be calculated using Formula (7):

$$q_{\text{conv}} = MC_g(T_g - T_o) \quad (7)$$

The mass flow rate of gas from the enclosure is a function of the area of the opening through which flow is taking place. For post-flashover fires, it can be conservatively assumed that  $M$  has reached a steady value of:

$$M = 0.5 A \sqrt{h_w} \quad (8)$$

PD 7974-2 offers guidance on how to predict the temperature of hot gases given information on their convective heat content and their mass flow rate. The temperature of the gases exiting through the opening from the enclosure decreases as the distance from the opening increases. Guidance for predicting the temperature of flames issuing from openings is given in [8.8](#).

## 8.7 Quantitative analysis of heat flow by radiation

A fire radiates heat at a rate which can be calculated by:

$$q_{\text{rad}} = \varepsilon_g \sigma T_g^4 A_{\text{rad}} \quad (9)$$

Alternatively, fires can be represented as a surface or multiple surfaces with a surface emissive power:

Surface emissive power = radiative heat release rate divided by surface area.

The magnitude of the radiative heat flux on any surface outside the enclosure of fire origin is a function of several variables, including:

- the relative positions of emitting and receiving surfaces;
- the emissivity of the emitting and receiving surfaces;
- transmissivity and absorptivity of any fluids or solids through which radiation passes;
- the temperature of the receiving surface; and
- re-radiation and associated change in temperature of surrounding surfaces.

Accordingly, the surface material of the receiver and its location governs the level of radiation exposure outside the fire of origin. Guidance is given in [8.3](#) on how the effects of radiation can be quantified for different materials.

In many cases, it is possible to meet the design objective of analysing radiative fire spread potential using a simplified approach. If the emitting and receiving surfaces are assumed to have emissivity

values of unity and the receiving surface does not increase in temperature continuously over time, the radiative flux can be characterized as:

$$q_{\text{rec}} = F_{\text{e-R}} q_{\text{rad}} \quad (10)$$

where:

$F_{\text{e-R}}$  is the sum of all configuration factors.

Complex surfaces can be approximated by summing the configuration factors of multiple, more simple surfaces and time-based assessments can be conducted by changing size and shape and temperature of emitting surfaces with respect to time.

Commonly used configuration factors can be found in [10] or alternative references in heat transfer theory.

The designer should note the relative locations of the emitting and receiving surfaces and recognize the need to combine configuration factors for most practicable situations.

A range of convenient methods has been developed to allow evaluation of the potential for radiative fire spread between openings from an enclosure and a parallel plane some distance away.

These methods are also applicable to evaluation of the radiation emitted from the hot unexposed face of an enclosure. This could assist in determining a limiting temperature for the unexposed face of an enclosure. For analysis purposes  $T_g$  in Formula (9) should be replaced by  $T_{\text{surface}}$ , the temperature of the unexposed surface (in kelvins).

Whilst specific guidance on the calculation of the thermal response of materials is given in this clause, a useful surface temperature model for ignition hazard analysis is given by:

$$T(x, t) = T_0 + \frac{\varepsilon_{\text{rec}} q_r}{\alpha_c} \left[ \operatorname{erfc} \left\{ \frac{0.5x_s}{\sqrt{Kt}} - \exp(\alpha_c x_s + K \alpha_c^2 t) \right\} \operatorname{erfc} \left( \frac{0.5x_s}{\sqrt{Kt}} + \frac{\alpha_c}{K} \sqrt{Kt} \right) \right] \quad (11)$$

where:

$t$  is the time from start of exposure(s).

Formula (11) assumes that the exposed solid surface can be treated as semi-infinite and is exposed to a radiating hot gas, e.g. a flat ceiling above an opening.

In addition, the potential for a radiative heat flux to cause remote ignition and fire spread from the enclosure could affect persons outside the enclosure of fire origin to an intolerable level. For example, people might not be able to escape past an opening from the fire enclosure because of excessive radiation. This hazard has been recognized in building design, leading to protection of external openings adjacent to stairways and control of glazed openings onto corridors.

## 8.8 Characterizing the condition of fires spreading from openings in enclosures

When examining the potential for convective or radiative fire spread from an enclosure, it might be necessary to characterize the shape, size and temperature profile of flames emerging from openings in the enclosure boundaries.

In the first instance, the fire can be assumed to completely fill the area of the opening of the enclosure, burning at a temperature or heat flux not less than the maximum assumed within the enclosure. When evaluating the potential for fire spread to surfaces outside the enclosure, the emissivity of the fire at its source should be taken as unity.

The flow of hot gases from an enclosure entrains air and forms a smoke plume in the adjacent space. The recommended mass entrainment [11] into the plume above an opening,  $M_{\text{opening}}$ , is given by:

$$M_{\text{opening}} = 0.68(A_w \sqrt{h_w})^{\frac{1}{3}}(Z_w + a)^{\frac{5}{3}} + 1.59A_w \sqrt{h_w} \quad (12)$$

where:

$M_{\text{opening}}$  is the mass flow rate in plume at height,  $Z_w$ , (kg/s);

$A_w$  is the area of opening (m<sup>2</sup>);

$h_w$  is the height of opening (m);

$Z_w$  is the height above the top of the opening (m);

$a$  is the effective height (m) =  $2.4A_w^{2/5}h_w^{1/5} - 2.1h_w$

Entrainment Formula (12) assumes a convective heat release,  $q_{\text{conv}}$  (kW), from the enclosure of:

$$q_{\text{conv}} = 1260A_w \sqrt{h_w} \quad (13)$$

Details on the methods used for determining the spread of smoke and hot gases are given in PD 7974-2.

## 9 Behaviour of separating elements in fire

### 9.1 Behaviour of fire-resisting separating elements

#### 9.1.1 General

Predicting the behaviour of some materials, e.g. glass (see 9.1.6) and polymers (see Clause 8) is made more difficult by their change in state, normally into a “plastic” condition. Many of these materials have well-documented transition temperatures, but when only exposed on one face, the time at which they change state is related to the heat loss from the unexposed face, the mass and thickness. Physical testing is normally the only method by which the behaviour of such products can be characterized.

If the element is designed to resist fire spread, its ability to do so should be determined by one of the methods in Clause 8. Most of the evidence readily available to support the performance of a common form of construction is determined by the standard tests. Much of this evidence is only available from private industry, as most of the linings, and many of the structural studs and joists are of proprietary construction. This evidence should be obtained from the relevant manufacturers or suppliers.

A problem associated with the direct use of this evidence relates to the fire resistance rating having been determined using a relatively small element (walls 3 m × 3 m, floors 4 m × 3 m) which is frequently far less than the size incorporated in the building. The use of such evidence in a prescriptively driven fire safety strategy (e.g. building regulations or code compliant case) presents few problems to the designer because the prescription takes the size change into account. However, if, in a fire engineered strategy, there is a need to consider the performance in larger and/or less restrained applications, the applicability of fire resistance test evidence to the as-built condition is not clear and is often overlooked.

Crucially, the designer should consider the impact of distortion in one element on adjacent elements. Distortion due to thermal restraint and other mechanical forces can produce gaps, particularly at three-dimensional junctions. These cannot be tested and can induce loads on adjacent non-loadbearing elements to the extent of seriously impairing their function. Loadbearing elements can be deemed to have satisfied their performance requirements with regard to protection for a particular period in the horizontal condition, even if they have deflected beyond the deflection criteria limits used in standard fire testing. Deflections beyond these limits can be extremely

damaging to separating barriers when beams, for example, are located directly above or pass through these types of non-loadbearing elements. If these situations do arise it might be necessary to limit distortion to lower levels than the limits of loadbearing capacity permit [12]. This should be reviewed by the designer.

Almost all separating elements are penetrated in practice for the purpose of access, light transmission, vision or the provision of services. It is important that the manner by which these are closed off does not compromise the fire resistance that the solid structure provides.

### **9.1.2 Elements primarily composed of concrete or masonry**

#### **9.1.2.1 General**

Concrete is used either in the form of cast in situ or blocks and slabs to form floors and walls.

Cast in situ construction can be either reinforcement, for both floors and walls, or pre-stressed in the case of floors. Some walls that are sufficiently thick might be un-reinforced, although this is unusual.

#### **9.1.2.2 General consideration of response of concrete elements**

The initial response of concrete to heating is expansion. Until the temperatures are reached at which the cement bond starts to break down, the aggregate expands causing the exposed face to expand relative to the cooler main bulk of the material. This can induce the unusual effect of horizontal concrete separating elements “hogging” (negative bending moment) during the early stages of heating. The density of the concrete dictates the amount of heat that is conducted into the core of the material, hence the rate at which erosion takes place. The nature of the aggregate generally determines the density of concrete, with lightweight clay aggregate at the lower end of the range and gravel aggregates at the upper end. However, foamed concrete can be produced by the injection of air/gas to create artificially low densities. Quite weak, low-density concrete has very low thermal conductivity and generally exhibits high resistance to erosion during heating.

The influence that the thermal conductivity of concrete has on its mechanical response depends upon the nature of the construction. If the concrete element is used horizontally it normally incorporates reinforcing steel to compensate for its inherent weakness in tension. The ability of the reinforcement to carry either the self-weight or any applied loading is determined by its temperature, and this in turn is influenced by the amount of concrete cover between the strands or mesh and the fire.

Where the overall concrete thickness or cover to the reinforcement is insufficient to meet the required fire resistance, such deficiency can be compensated for by the use of non-combustible insulation such as fibrous and cementitious sprays, insulating boards, lightweight mortars and gypsum plasters. The required thickness is calculated from high temperature, non-steady state thermal conductivity data supported by evidence of “stickability” in respect of a concrete substrate.

Un-reinforced elements, such as mass concrete walls, should remain stable until the concrete strength has deteriorated to a point where the loadbearing capacity has effectively been lost.

#### **9.1.2.3 Integrity performance of concrete**

Concrete has a high natural integrity, being a relatively homogenous substance. This is enhanced by the aggregate normally being held together by steel reinforcement. Being of significant thickness, a solid slab is unlikely to fissure during fire exposure unless it experiences large deformations. The behaviour of a solid concrete element normally differs to the elements abutting it so that the primary cause of an integrity failure could be differential movement between the concrete element and any adjacent or incorporated elements.

It is normal practice to recommend the thicknesses of concrete cover to the steel reinforcement, as in BS EN 1992-1-2, although this is related to the loadbearing capacity of the element rather

than calculating the performance of “integrity only” elements. When using this as a measure of performance in predicting integrity behaviour, loadbearing capacity should be satisfied even when large distortions are achieved.

Where apertures are formed in cast in situ constructions to permit the incorporation of stairways, doorways or windows, the exposed edges are prone to spalling. Spalling is likely to be more of a problem in high-strength concrete rather than in normal or low-strength/low-density concrete. See BS EN 1992-1-2 for more information on spalling of concrete. The major indication of this is a loss of fixings for any installed element, e.g. a window or door. Consequently, all fixings should be made away from any concrete edge(s) where spalling could occur. Where proprietary fixings have been tested and issued with a classification under European Technical Approvals, a fixing type/depth/concrete grade may be provided. All lintel reinforcement should be used such that the stresses are to be redistributed around the opening. To reduce the risk of spalling BS EN 1992-1-2 can be used for the depth of concrete cover to the steelwork in relation to all the heated faces of the wall, including the reveal of any aperture. Excessive moisture content can lead to an increased risk of spalling.

#### **9.1.2.4 Insulation performance of concrete**

It should be relatively easy to predict the unexposed surface temperatures of concrete by modelling. When using test data in support of predictive calculations, the free moisture content at the time of measurement affects the temperature profile. For moisture levels other than those tested, ASTM E110 - 09c provides a method for making corrections.

#### **9.1.2.5 Masonry and brick walls**

Blockwork walls can be loadbearing or non-loadbearing. BS EN 1996-1-2 provides tabulated data for the fire resisting performance of both loadbearing and non-loadbearing walls.

Walls constructed using masonry and blockwork experience a temperature gradient between their exposed and unexposed faces. This induces significant thermal bowing (lateral displacement) which, if unrestrained, results in excessive movement. If the head is unrestrained the bowing occurs at the top, but if both the top and bottom are fixed, maximum bowing occurs at mid-height. The insulation properties of the brick or blockwork directly influence the extent of bowing, with the greatest displacements occurring with materials having lower heat transfer properties. Bowing can restrict conventional thickness brick or blockwork walls to a maximum height of 3 m to 4 m, assuming the base is adequately fixed, beyond which instability occurs. The magnitude of this movement might be as expected from a one-dimensional cantilever. A non-loadbearing wall is more likely to be unrestrained at the head than a wall supporting an imposed load.

A wall expands as it is heated. If insufficient allowance is made to accommodate this movement, a load is imposed upon the construction assembly even though it might have been designed as non-loadbearing. This occurs when it abuts against part of the structure that is relatively stiff, i.e. the underside of a beam or floor slab. Any loading of this type normally starts off as being eccentric, as only the exposed face is heated and therefore expands. However, with prolonged heating the temperature differential between the hot and cold faces reduces and the loading becomes more concentric. If an allowance is to be made to prevent distortion due to restrained expansion, the gap should be sealed with a proven linear gap sealing system, although performance can only have been established under standard heating conditions. Guidance on linear gap sealing can be found in BS EN 1996-1-2 and LPCB guidance [13]. Additional information is given in the ASFP publication on fire stopping and penetration seals [14]. An inherently fire-resisting beam or a beam that is fully fire protected could still deflect significantly and yet continue to carry its design load. Consequently, any non-loadbearing wall or partition fixed beneath such a beam could still experience applied loads at the fire limit state (FLS).

The ability of an unrestrained blockwork wall to tolerate out-of-plane distortion also depends upon the quality of the mortar bond between the blocks. The choice of mortar is therefore critical to obtaining the correct balance between strength and thermal properties.

When analysing the likely performance of a non-loadbearing blockwork wall using engineering judgement (see [Annex G](#)), the following constructional parameters should be considered:

- height of wall (R, E);
- thickness of block (R, E, I);
- thermal conductivity of block (R, I);
- end fixity (R, E);
- expansion allowance (if necessary) (R, E);
- moisture content (I).

*NOTE For each parameter the criteria likely to be influenced are identified in parenthesis, using the codes R (loadbearing capacity), E (integrity) and I (insulation).*

The list excludes exposure and mechanical parameters that should be considered if non-standard heating conditions or a modified loading exists. Such exposure parameters might identify acceptable limits to the heating conditions. Changes in the load should also be reviewed.

#### 9.1.2.6 Concrete beam and block floors

It is assumed that all floors are loadbearing and that ceiling membranes (see [BS 476-22](#)) are unlikely to be constructed from lay-in concrete components. Floors such as these are constructed from primary beams and in-filled with lay-in proprietary secondary floor slabs. BS EN 1992-1-2 can be used to evaluate the ability of the floor slabs to contain a fire and, as these are proprietary, test evidence against standardized test conditions is also available. The main beams can be evaluated (see [Clause 10](#)), but the usual methodology for establishing the conformity with BS EN 1992-1-2 might not be appropriate to non-standardized heating conditions. The lay-in slabs are simply supported and covered with a non-structural concrete screed.

If a “fire-rated” suspended ceiling is fixed beneath a lay-in concrete floor it only contributes to the fire resistance if it has been tested in accordance with [BS 476-21](#), with a floor having a similar thermal/mechanical response.

*NOTE A fire resistance test to [BS 476-23](#) is not appropriate as its scope does not cover such constructions and there are differences in furnace pressures and failure criteria between tests to [BS 476-21](#) and [BS 476-23](#).*

Excluding fire exposure conditions or mechanical parameters which cover all aspects of fire behaviour, the following parameters of a lay-in concrete floor construction influence the performance in respect of the criteria identified in parenthesis:

- span of slabs (R, E);
- bearing (R, E);
- thickness of slab (R, E, I);
- position and dimensions of any reinforcement (R);
- concrete strength (R, E);
- thermal conductivity/density (I);
- expansion allowance, if necessary (R, E);
- moisture content (I);
- gaps (E);

- presence and properties of any screed (E, I).

All fire resistance tests should be performed with the moisture content in equilibrium with the laboratory environment to represent conditions encountered by the element in practice.

### 9.1.3 Elements primarily composed of metal

#### 9.1.3.1 General

Aluminium is typically used for roofing and cladding as part of a composite system. Generally, steel is used in any application where fire resistance is a primary requirement.

Steel is rarely used on its own to construct a separating element, except as a simple form of non-insulating cavity barrier as permitted in some prescriptive design codes. However, it is frequently used as the primary component in the construction of a number of “closures”, such as:

- hinged or pivoted doors;
- sliding doors;
- roller shutters (vertical/horizontal); and
- dampers.

Steel and aluminium are used as major components in the construction of sandwich panels (see [9.1.5.1](#)):

- a) as a facing to some forms of proprietary lightweight partitioning systems; or
- b) as suspended ceiling panels, the majority of which are not designed to provide fire protection.

For external applications, steel and aluminium can both be used as part of a cladding system for insulating walls and roofs. Walls might need to be fire resistant when close to a boundary, as designated by prescriptive regulations and codes or the fire strategy. Roof systems should prevent fire penetration close to junctions with compartment walls or adjacent to escape routes by means of a protected zone, where the resistance to the penetration and spread of fire is controlled [\[12\]](#). Roofing systems are not usually designed to contain fire, only to resist inward penetration. However, some applications might require fire resistance from within, such as in the protection of high level escape routes or where collapse of the roof would lead to progressive failure due to dynamic loading on other building elements such as fire resisting walls or elements of structure, or where the roof structure provides support to floors below that are ‘hung off’ the roof. External cladding might require fire resistance from inside or outside depending upon the fire strategy approach taken.

#### 9.1.3.2 Integrity performance of metal

The initial influence of heat on any metal is that of expansion but this is followed by phase changes, resulting in a, usually detrimental, alteration in the physical properties. In the case of aluminium and its alloys, melting occurs at temperatures of around 590 °C to 650 °C. Steel does not melt until significantly higher temperatures are reached and it is extremely rare for a fire of such intensity to occur. However, after prolonged exposure at high temperatures of, typically, 1 000 °C, severe oxidation of carbon steel occurs. Although sheet steel does not normally fissure, there is a minimum thickness gauge that can be tolerated to satisfy the gap criteria of integrity.

Unless steel is heavily insulated the cotton pad method for evaluating integrity is not generally appropriate as the radiation from the surface itself could cause the pad to ignite. However, due to the resistance of steel to fissuring, it can provide high levels of integrity resistance regardless of whether one of the mechanisms is unsuitable. Measuring joints between panels are the exception and such gaps can only be measured by gap gauges.

### 9.1.3.3 Insulation performance of metal

Metals are unlikely to satisfy the criterion of insulation for any significant duration without the aid of applied insulation. In comparison with other building materials, metal has a high level of conductivity. The rise in temperature of the unexposed face of, e.g. a simple steel element, can be predicted by means of 3D transient state thermal analysis models. These models can make predictions when steel is used in conjunction with simple forms of insulation, but when the construction is more complex and the number of interfaces between materials increases, the accuracy of a thermal model is reduced. Test evidence, including that generated by the standard exposure conditions, might be the only way of determining the unexposed face temperature, or at least correlating any calculated temperature.

Connections between exposed and unexposed facings create local heat paths capable of producing “hot spots”, but this is unlikely to result in a significant fire spread risk, although they could cause a test failure. The face of an insulating metal door, both at the edges of the door leaves and the adjacent door frame, are unlikely to satisfy the insulation criteria. Historically this has not been regarded as a hazard as materials are not likely to be “stacked” in contact with the unexposed face of a door. Consequently, many doors in prescriptive regulations are exempt from the need to satisfy the insulation criterion. This should be reviewed if the door ever becomes redundant. Uninsulated doors radiate significantly with the associated life safety, ignition, and fire spread risks, and they should only be used in the construction of refuges after due consideration to the effects of radiation and smoke leakage.

### 9.1.3.4 Radiation of metal

Metals, particularly steel, reach high temperatures when exposed to fire and radiate heat readily into any place of relative safety (see [Clause 8](#)).

## 9.1.4 Elements primarily composed of timber

### 9.1.4.1 General

Timber is used extensively in the construction of floors and walls as loadbearing members.

Untreated timber-based products are rarely used to form a fire-resisting barrier due to surface spread of flame. However, when suitably treated, they can be used as linings in many separating applications.

Timber or wood-based board materials are used primarily for the following separating applications:

- web(s) of composite timber (I) beams or box beams;
- timber-based linings applied to stud or joisted elements; and
- fire-resisting door assemblies.

### 9.1.4.2 General fire behaviour of wood-based products

When timber surfaces are exposed to heat they lose moisture, leading to caramelization of the cellulose, a precursor to carbonization or charring. While thermal degradation of the fibres takes place at low temperatures, carbonization or charring often occurs following the ignition in short term, post-flashover fire behaviour.

There are two forms of ignition: spontaneous and pilot ignition. Spontaneous ignition typically results from radiating heat sources where there is no direct flame. Pilot ignition occurs in the presence of flames capable of igniting the volatile gases produced during heating. Fire spread within an enclosure is typically the result of a series of pilot ignitions, whereas spontaneous ignition is often the cause of fire spread outside of the enclosure, from barriers providing integrity but not insulation. The temperature at which ignition occurs is not fixed but is related to the level of heat flux received, moisture content, the magnitude of any convective cooling and many other related actions. A

conservative approach is to assume that pilot ignition and the onset of charring and reduction occurs when surface temperatures attain 350 °C. Spontaneous ignition can be expected at incident heat fluxes in excess of 25 kW/m<sup>2</sup> [15].

A timber component exposed to heat experiences differential movement, with the exposed face bowing away from the fire due to shrinkage on that face. Unburnt timber distorts if it does not have sufficient cross-section dimensions to resist this movement. Surface charcoal is an excellent insulator with respect to both convective and conductive heat transfer, as long as the outer layer is not crushed by any of the other components. This char layer is diathermanous and, as radiation becomes the dominant heat transfer mode, pyrolysis starts to occur at the interface with the solid timber. Beyond the charred interface, there is a boundary layer at a temperature just above ambient in which the normal cold state physical properties apply. During short durations of exposure to high temperatures the heat-affected zone is narrow and can effectively be ignored. Long durations of fire exposure result in a change in physical properties [16].

#### 9.1.4.3 Integrity performance of timber (E)

Solid timber is unlikely to have an integrity failure until it has almost completely charred, at which stage fissuring of the thermally degraded residual timber can lead to a gap through which hot gases can pass. Composite timber-based boards, e.g. particle board, plywood or medium density fibreboard, are less likely to fissure until the board has almost been consumed, due to the more random orientation of fibres. Although not documented for vertical applications, integrity is expected for 90% of the time to consumption and the same for composite boards such as chipboard, assuming that all board joints are made over studs and the fixings are adequate. For boards used in the horizontal plane, i.e. transverse to the studs and not backed up by noggins/duanges (cross-timbers), the duration before integrity failure occurs is less than with vertical components. This is dependent upon the quality and frequency of fixings and the self-weight of the board. Evidence of performance, even from standard tests should be used to quantify the protection provided.

Timber is a hygroscopic material and contains between 1% and 20% water. Heat exposure drives this water off, causing shrinkage. In the case of solid timber, the shrinkage typically occurs transverse to the grain. In board materials, shrinkage is typically equal in all directions as there is no dominant grain direction. The introduction of resins, such as those used in chipboard, modifies the rate of shrinkage.

Shrinkage can cause premature loss of integrity at junctions between timber and timber-based products, or between these materials and any adjacent construction. Solid form or gunned intumescent mastics are used to compensate for shrinkage and maintain a tight gap until the material is consumed. They function almost regardless of the exposure conditions, albeit higher temperatures can exhaust the material quicker.

The rate of consumption or charring of timber is not significantly influenced by increases in gas temperature over 400 °C to 900 °C. Above this range, where the radiative component of the heat flux is much higher, the rate of charring increases and this should be considered when calculating the consumption rate and associated fissuring time for non-standard heating conditions.

#### 9.1.4.4 Insulation performance of timber

Timber has a very low thermal conductivity and is therefore an excellent insulator. Wood-based board materials are generally denser than natural wood and contain significant percentages of resins or other chemicals so their thermal conductivity is higher. As timber does not exhibit critical changes of state when heated, there are no 3D transient state thermal analysis models available to evaluate timber constructions. Timber and wood-based materials satisfy the insulation criteria of the

standard test until nominally 5 mm of material remains. The material ignites before it reaches surface temperatures that could generate ignition of adjacent cellulose.

### 9.1.5 Elements constructed from composite panels

#### 9.1.5.1 General

Composite panels, consisting of a structural core with metal faces on each side, are an increasingly common building component due to the large spans and heights they can accommodate, coupled with fast erection methods. Sandwich panel constructions are used as separating elements in:

- internal walls (fire-rated and non-fire-rated) forming part of an internal envelope or cellular layout;
- horizontal ceilings (fire-rated and non-fire-rated) as a membrane ceiling (including walk-on ceilings);
- external walls in “boundary” situations.

There are a number of alternative core materials in regular use, e.g. foamed polymeric, mineral rock fibre and other foamed insulating materials. Data on the thermal properties are given in [Annex D](#). A high temperature tolerant core is needed if the element is to provide fire resistance. Although panels constructed with combustible cores could still restrict fire spread, this usually involves incorporating steel cover plates and additional fixings to both sides over and around joints. The use of high temperature tolerant cores does not automatically indicate fire resistance, especially at the heights and spans used in buildings. These sizes are generally in excess of the sizes tested and the use of composite panels at these sizes should be supported by an extended application analysis. Some insurers, however, do test the fire performance of composite sandwich panels for inside corner configurations at a height of 15 m as part of routine certification, although not typically for fire resistance.

Guidelines on the correct use and design of enclosures constructed from composite panels can be found in the Guide published by the International Association for Cold Storage Construction (IACSC) [[17](#)].

#### 9.1.5.2 Integrity performance of composite panels

Typically the facings are steel, providing the structural strength to support the panel's self-weight. These facings are capable of resisting fire penetration for a significant duration through the main body of the panel. If the panel facings are aluminium they melt at fairly modest temperatures, resulting in a loss of integrity unless the insulation is of such a type, and fixed in such a manner, that it can protect the unexposed lining. Plain carbon steel experiences severe oxidation at temperatures in excess of 1 000 °C and, if the steel gauge is too small, this could lead to fissuring, particularly when significant distortion causes the oxidized surface to delaminate. However, until these temperatures are reached steel can satisfy the gap criteria of the standard test. As stated in [9.1.3.2](#), the cotton pad is not a suitable method for establishing the integrity of steel linings unless they remain well insulated by the core material.

Steel readily expands and, if restrained, could cause significant distortion. If the joints are not adequately designed and/or constructed this can result in an integrity failure, most likely occurring at joints between panels rather than through the body of the panel. Analysis of such tests has shown that the “free edge”, usually incorporated in a test specimen as a requirement of the test standard, can create an artificial mode of failure. The need to use a free edge when testing metal faced sandwich panels has been questioned in ISO/TR 834-3.

Gaps in panels containing cores that do not melt or erode significantly are easier to seal and retain integrity better than those that melt or erode.

### 9.1.5.3 Insulation performance of composite panels

As steel has a high thermal conductivity it transmits heat readily, so the temperature rise on the unexposed face of a composite panel is primarily influenced by the nature of the core. If the core is metal then the heat from the exposed metal sheet is rapidly transmitted to the unexposed face, so raising its temperature. If, however, the insulation remains intact then the rate of temperature rise of the unexposed metal face is reduced depending upon the thermal conductivity of the infill material. In practice, either the insulation melts or is eroded, or its characteristics change as a result of, for example, the loss of binders/fibres. The rate of temperature rise of the unexposed face is therefore significantly higher than might be anticipated using the cold state insulation values.

The temperature rise of the unexposed face is higher when the unexposed face is adjacent to openings and through-joints due to heat paths generated through the assembly. Thickness in metal connections, for the purpose of strength or stiffness, can result in “hot-spots”, but in a fire engineering strategy these localized increases might not compromise the fire safety objectives.

### 9.1.5.4 Radiation of composite panels

The amount of radiation emitted from the unexposed face of a composite panel construction depends upon the insulation remaining in place and reducing the temperature of the unexposed face lining. Metals, when they reach high temperatures, radiate heat readily into the place of relative safety. Even without the benefit of effective insulation, if both linings can remain in place, a significant reduction in the radiation from the unexposed face can be achieved.

## 9.1.6 Elements primarily composed of glass

### 9.1.6.1 General

With the exception of glass bricks and some proprietary forms of frameless glazing, fire-resisting glass is used in combination with timber, steel or concrete framing. Glass is used in the construction of the following fire separating elements:

- vertical glazed internal fire screens;
- curtain walling; and
- horizontal glazed membrane ceilings.

Conventional soda/lime window glass used for normal glazing applications, even in its toughened state, should not be relied upon for any significant level of integrity unless it has been prepared and installed in a manner designed to provide fire resistance.

If fire resistance is required, the glass should be specifically designed to provide separation during the late pre-flashover or post-flashover conditions (see [9.3](#)).

### 9.1.6.2 General consideration of the response of glass elements

There are many different types of fire-resisting glass, which broadly fall into three major categories:

- a) monolithic glasses, wired and unwired, which do not provide any significant level of insulation;
- b) composite glasses consisting of glass in combination with intumescent/ablatives materials, which control temperature rise and provide protection from radiation; and
- c) coated monolithic glasses which restrict radiative heat flow.

As these products provide very different levels of fire protection they should be glazed by methods appropriate to their behaviour at high temperatures. Even the individual monolithic glasses need different glazing methods for consistent performance. Coated glasses are directional in their performance and fail prematurely if the uncoated side is attacked by the fire.

Since the average temperature of the glass determines whether the product is rigid or starting to flow, the ambient conditions on the unexposed face are critical to its mechanical response.

#### 9.1.6.3 Mode of failure of monolithic glasses

Cracking induced by differential temperatures on its exposed surface is the primary mode of failure for a conventional glass (monolithic clear glass of a soda-lime silica composition). Glass has a high coefficient of thermal expansion which causes significant cracking of the exposed surfaces. If glass is to act as a barrier to fire, it should be retained in position by a robust glazing system that prevents the edges from becoming hot. As a consequence, large strains are generated between the exposed and protected glazed surfaces and this can lead to thermally induced cracking. Glass that incorporates integral steel wires can retain the fragmented glass sections together as one unit. This type of glass can satisfy the integrity criterion even when cracked. If a clear, unwired monolithic glass is intended to provide fire resistance, it should be arranged such that the strain developed between the exposed and unexposed areas does not generate excessive levels of stress.

There are several ways that this can be achieved. Toughening the glass by heat-treatment methods improves its strength, thereby making it capable of resisting the development of high stress levels, although a change in composition might also be needed. In isolation this is unlikely to be adequate and, therefore, the thermally induced strain should also be reduced by, for example:

- a) using glasses with lower coefficients of thermal expansion;
- b) reducing the edge cover to the glass pane to a minimum; or
- c) using glazing systems that have improved thermal conductivity.

Typically, edge cover is restricted to a maximum of less than 10 mm when using toughened unwired soda/lime glasses to prevent unacceptable stresses being generated.

If monolithic unwired glass is to be used, glass with a lower coefficient of expansion, such as borosilicate, is the preferred option. This type of glass can accommodate significantly higher levels of edge cover (up to approximately 25 mm) before failing as a result of differential temperatures. Clear ceramics exhibit zero expansion characteristics and work almost independently of the glazing system, but these cannot be made into safety glasses without laminating, and care should be exercised in this process because of the flammability of polyvinyl butyl interlayers.

#### 9.1.6.4 Mode of failure of laminated glasses

With insulated glasses, the initial reaction to heat and the resulting mode of failure is very different. There are three types of products:

- a) multi-laminated glass with rigid interlayers of clear sodium silicate-based intumescent product between panes of soda/lime glass;
- b) gel glasses with a void between two panes of soda/lime composition glass, filled with a gel that sets rigid and becomes opaque when subject to heat; and
- c) “sandwich” glasses with a rigid clear cast core between two soda/lime glasses.

The first of these achieves its performance by the activation of the intumescent interlayers that progressively expand and erode throughout the test. The exposed pane of glass cracks early but is retained on the surface by the sticky activated intumescent layer which turns opaque and acts as a barrier to heat transfer by radiation. The action of the intumescent layer protects the next pane of glass from direct exposure to heat but, in the process, the pressure generated can crack the glass. Eventually all interlayers become activated and the exposed material is eroded along with any of the remaining intumescent product. The unexposed face surface temperature can be kept below the insulation criteria of the standard fire resistance test for periods up to 80 min, depending

upon the thickness and the number of interlayers. Integrity can invariably be maintained for a period significantly beyond the duration for which insulation is satisfied, typically 30 min or more, depending upon the pane size.

Failure of intumescent laminated glasses usually occurs as a result of a localized burn-through created by coincidental glass cracks, or by the pane becoming so weak due to cracking/fragmentation of the glass that it is unable to support its own weight.

The gel or rigid core-filled glasses tend to exhibit similar integrity and insulation ratings, with failure usually resulting from a complete loss of infill core due to erosion. The weight of these glasses puts undue pressure onto the fixings and, if the glazing framing is being eroded, then the failure of any fixings could contribute to the loss of the entire glass area.

#### **9.1.6.5 Consideration of other factors**

Currently, the only method of establishing the contribution of the fire glasses to the containment of a fully developed fire is by an engineering analysis that utilizes test evidence from fire resistance tests. Glass is a temperature-sensitive material in terms of differential surface temperatures, rate of heating and mean temperatures. Consequently, evidence of performance against the standard test conditions should not be assumed to apply to a wide range of exposure conditions, especially if fluctuations are likely. If the fire engineering analysis indicates that temperatures higher than the standard curve are likely to exist, then the onset of slumping could occur earlier. Monolithic glasses do not lend themselves to prediction using time-equivalent methods. Wired glass, borosilicate composition glass and the insulated glasses can be considered as more robust to variations in temperature than other types of glass. The influence of thermal shock from fixed water suppression systems should also be considered for non-wired glasses.

Attempts have been made to model the behaviour of glass in fires, but this has been aimed at conventional annealed soda/lime composition glass in developing fires. They do not reproduce the critical characteristics of special composition fire-resisting glasses.

#### **9.1.6.6 Integrity performance of glass**

Monolithic clear glasses can produce an integrity failure as a result of cracking (see [9.1.6.3](#)). They can also fail as a result of the glass slumping, i.e. losing its inherent stiffness and self-supporting ability, thereby pulling out from the glazing system at or near the top of the individual panes. This produces a gap through which hot gases and flames can escape. Laminated insulating glasses can experience an integrity failure as a result of cracks in the glass accompanied by erosion of the interlayer local to the cracks, or by the total collapse of the pane as a result of failure of the fixings.

The performance of all types of monolithic glass can be improved by creating an insulated, cool frame around the perimeter that resists the tendency of the glass to “slump”. The application of pressure to the glass edge can also help to resist slumping. This can be achieved by clamping the edges, generating a uniform pressure by utilizing a restrained pressure-producing intumescent product which might also help insulate the glass edge.

These measures are incompatible with the restricted edge cover permitted for clear, toughened soda/lime glasses so these glasses are unlikely to reliably go beyond their softening temperature. This is typically reached between 40 min and 45 min for 6 mm thick glass under the standard test conditions. Even with deep glazing systems and edge pressure, the tendency to slump can make it difficult for large panes of wired soda/lime glass to resist slumping for one hour or more under standard heating conditions. To reduce slumping for both clear soda/lime glasses with their restricted edge cover, and large panes of wired soda/lime glass, high temperature adhesives are often used in the glazing rebates on the upper edges. Little is known of the long-term reliability of high