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Densified Housing: Analysis of Fire Resistance Requirements

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Fire Research Group Limited, funded by the Building Research Levy

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Densified Housing: Analysis of Fire Resistance Requirements

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Preface

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The research described in this report is funded by the Building Research Levy.

Table of Contents

List of Tables

List of Figures

1. Executive Summary

1.1 Introduction

This is a report describing a risk-informed analysis of the levels of fire resistance appropriate for densified housing in New Zealand. Fire resistance ratings (FRR) are currently prescribed in C/AS2 for buildings up to 20 storeys high. This includes residential occupancies of multiple household units with shared escape routes. For the purpose of this report, we have taken the term ”densified housing” to include both medium and high density housing, and excluding standalone dwellings.

The analysis of fire resistance needed presented in this report is intended to provide the Ministry of Building Innovation and Employment (MBIE) with more robust data to make an informed decision regarding the scope and level of fire resistance necessary for compliance with the Building Code and for the compliance documents C/AS1, C/AS2 and C/VM2. It is also intended to be useful to fire engineers when undertaking performance-based structural fire design. Some aspects of this report may be also relevant to Clause B1 (Structure) of the Building Code when considering exposure to fire as a load case.

This investigation has only considered building structures that are noncombustible or adequately protected such that the building materials enclosing compartments do not contribute additional fuel to the fire. Exposed or inadequately protected mass timber compartments are therefore excluded.

1.2 Fire resistance ratings

Section 4 provides a detailed analysis of current C/AS2 requirements where fire resistance ratings depend on the risk group; whether fire sprinklers are installed, and whether fire separations are required for life safety or property protection. Notably, the fire resistance ratings required by C/AS2 do not change as the building height increases, except for instances where height determines the use of a property rating instead of a life rating. The maximum fire resistance rating applicable to multi-unit or densified housing of risk group SM is 60 minutes regardless of building height.

Comparisons are also made with prescriptive acceptable solutions used in Australia, England, Canada and the USA. It is found fire resistance requirements in New Zealand for multi-storey densified housing (especially for taller buildings) are significantly lower than for these comparable countries. This questions the risk settings for densified housing in taller buildings in New Zealand and has prompted the current study.

1.3 Method overview

The approach used for the analysis was to determine a statistical distribution for the expected fire severity in densified housing based on the characteristics of densified housing stock in New Zealand and to construct a cumulative density function from which the fraction of structurally significant fires exceeding a given fire severity can be determined. A structurally significant fire was assumed to be one that reached flashover and had the potential to lead to structural or barrier fire spread failure in the event of a fire.

The distribution of fire severities was calculated using Monte Carlo simulations for a time-equivalence calculation where the primary inputs included the fire compartment dimensions, the area of openings providing ventilation during a postflashover fire and the amount of fuel present (i.e. fire load in the form of combustible building contents). All these inputs were also described with a statistical distribution based on either relevant New Zealand data where applicable and review of international literature and common practices where local data was not available. The interior surfaces of the fire compartment were assumed to be gypsum plasterboard for the analysis.

Time-equivalence is a common methodology for comparing the fire severity of a fire with the fire resistance of a building element, where a 'failure' is assumed to occur when the fire severity exceeds the fire resistance. The time-equivalence method used was based on comparing the maximum temperature reached by a protected steel section in a real fire (represented as either a parametric fire or a traveling fire) with the time at which the same maximum temperature is reached by the same section exposed to a standard fire resistance test.

Two different parametric fires were considered 1) the EN 1991-1-2 Annex A parametric fire; and 2) the DIN EN 1991-1-2 National Annex parametric fire. A traveling fire (or localised fire) was assumed where the parametric fires were outside their limits of applicability in a given fire simulation. Each simulation case involved 100,000 runs to construct the cumulative density function for the fire severity. The recommendations subsequently made assumed fires based on the DIN EN 1991-1-2 parametric fire and the traveling fire methodology. The Monte Carlo simulations made use of an open source code called SfePrapy developed by OFR Consultants in the UK.

The next step was to estimate the probability of a failure by taking into account estimates of the reported fire frequency rate in densified housing, the proportion of reported fires that are structurally significant, the probability of manual extinguishment by fire fighters and sprinkler effectiveness (when installed) were also considered and then to compare with target allowable failure probabilities per year.

The report reviews international practice and discusses various safety targets with potential applicability to structural fire resistance and fire spread. These are shown in Table E1. These are similar to cost-optimised target indices given in ISO 2394, but alternative criteria such as those in ASCE/SEI 7-16 from the American Society of Civil Engineers could also be considered.

Table E1. Suggested target failure probabilities considering the trigger heights used in C/AS2.

	Consequence class (or building class)			
	CC2A		CC2B	CC3
	Low consequences	Low-mod consequences	Mod consequences	Large consequences
Building height, m	< 10	> 10 and ≤ 25	> 25 and ≤ 60	> 60
Reliability index, β (-)	3.7	3.9	4.2	4.4
Allowable failure prob. per year	$\approx 1 \times 10^{-4}$	$\approx 5 \times 10^{-5}$	$\approx 1 \times 10^{-5}$	$\approx 5 \times 10^{-6}$

The probability of a structurally significant fire p_{fi} was evaluated based on a combination of the probability of ignition and subsequent interventions prior to the fire becoming fully developed. This followed the Natural Fire Safety Concept approach from Europe that underpinned EN 1991-1-2.

$$p_{fi} \times P_{f,fi} \leq P_{f,a} \tag{1}$$

$$p_{fi} = n \times p_1 \times p_2 \times p_3 \times p_4 \tag{2}$$

where
n is the number of household units in the building.
p_1 is the probability of a severe fire occurring (per household unit per year).
p_2 is the probability of unsuccessful fire suppression by fire service intervention.
p_3 is the probability of unsuccessful fire suppression associated with fire alarm and detection systems (i.e. earlier warning and notification of fire).
p_4 is the probability of unsuccessful fire suppression by active fire protection systems (sprinkler).

The conditional probability of a failure given a structurally significant fire, $P_{f,fi}$ is extracted from the complimentary cumulative density function from the Monte Carlo simulation producing a collection of time equivalence values i.e. $1 - P(t_{eq,i \leq x})$. The probability of a failure is then calculated by $p_{fi} \times P_{f,fi}$ which can then be compared to the target probability.

1.4 Results

The outputs of the simulations and calculations allows failure probability curves to be constructed as shown in Figure E1 for an unsprinklered building and in Figure E2 for a sprinklered building, where the number of household units is given on the vertical axis and the probability that the calculated fire severity exceeds a nominal fire resistance rating (in minutes) is given on the horizontal axis. Logarithmic scales have been used on both axes. These plots assume that:

- the frequency of a reportable fire event per year is 2.7×10^{-3} per year per household unit.
- the proportion of total fires that will become fully developed or reach flashover (in the absence of active suppression) is 18%.
- $p_1 = 2.7 \times 10^{-3} \times 0.18 = 4.86 \times 10^{-4}$ fires per household unit per year.
- $p_2 = 0.2$ for a professional fire brigade in an urban area assuming that firefighting intervention can be initiated within 30 minutes. The impact of assuming $p_2 = 1.0$ was also considered for potential application to tall buildings.
- $p_3 = 0.0625$ assuming an automatic smoke detection and fire service notification system will always be present in densified housing.
- $p_4 = 0.1$ for the probability of a sprinkler system not being effective.

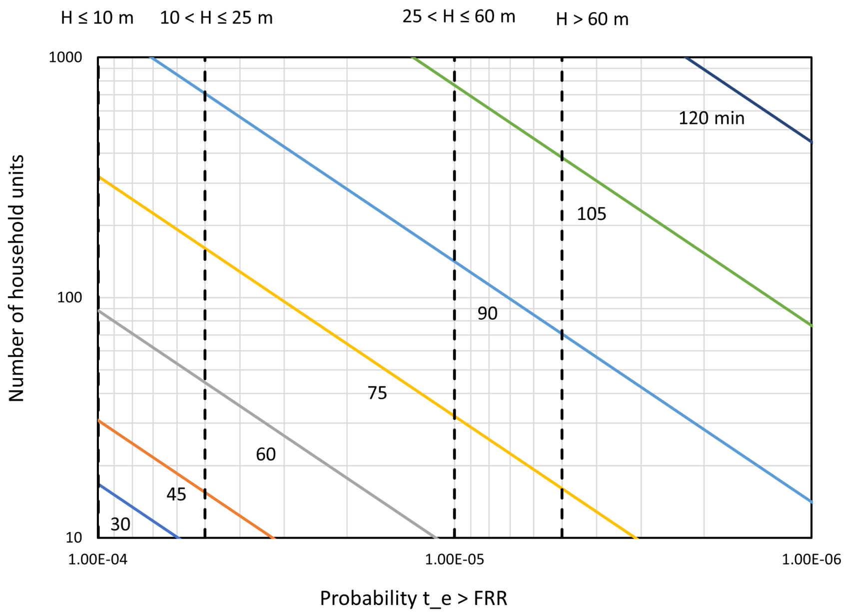

Figure E1. Failure probability curves for fire severities in the range 30 to 120 minutes, assuming the DIN EN 1991-1-2 NA + travelling fire model versus number of household units in the building without fire sprinklers. Vertical dashed lines indicate suggested target failure probabilities for buildings of various height, H.

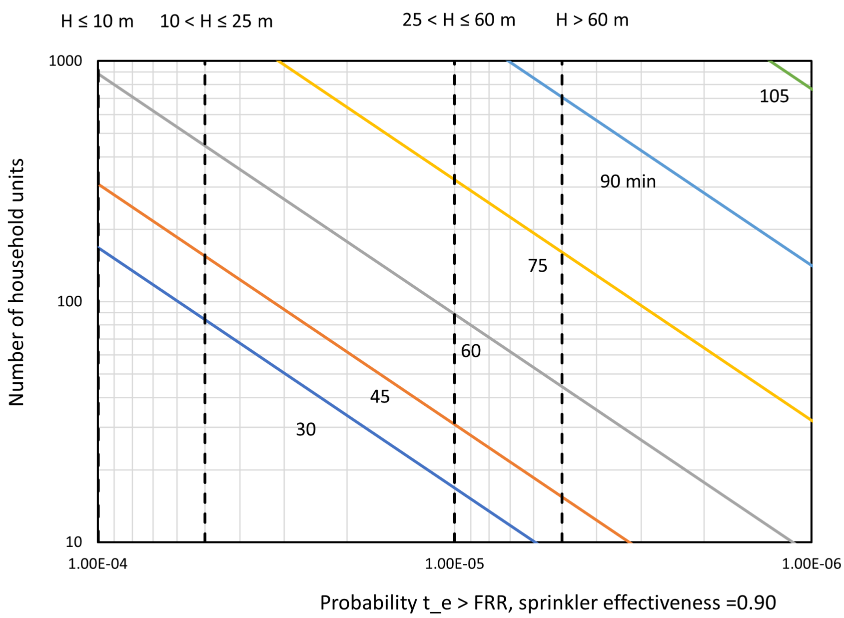

Figure E2. Failure probability curves for fire severities in the range 30 to 120 minutes, assuming the DIN EN 1991-1-2 NA + travelling fire model versus number of household units in the building with fire sprinklers of effectiveness 0.90. Vertical dashed lines indicate suggested target failure probabilities for buildings of various height, H.

Relevant data from the preceding plots, are expressed in tabular form as shown in Table E2 which proposes new fire resistance ratings for multi-storey densified housing based on target probabilities of failure according to the building height and number of household unit per storey.

Table E2. Proposed fire resistance ratings in multi-storey densified housing based upon building height H or number of storeys S (values in brackets include sprinklers of assumed effectiveness 0.90) [min] based on DIN EN 1991-1-2 NA + travelling fire model.

Method	Household units per storey	Fire resistance ratings based upon building height H or number of storeys S (values in brackets include sprinklers) [min]		
		≤ 10 m S ≤ 4 storeys	10 < H ≤ 25 m 5 < S ≤ 9 storeys	25 < H ≤ 60 m 10 < S ≤ 20 storeys
C/AS2	-	**60** (30)	**60** (30)	N/A (**30**)
SFEPRAPY	6	**45** (30)	**75** (30)	105 (**90**)
SFEPRAPY	12	**60** (30)	**75** (45)	120 (**90**)
SFEPRAPY	18	**60** (30)	**90** (60)	120 (**90**)
SFEPRAPY	24	**75** (30)	**90** (60)	120 (**90**)
SFEPRAPY	30	**75** (30)	**90** (60)	120 (**90**)
Allowable failure probability per year		$\approx 1\times10^{-4}$	$\approx 5\times10^{-5}$	$\approx 1\times10^{-5}$

1.5 Conclusions and recommendations

The demand and need for more densified housing is increasing in New Zealand and this creates potential fire safety challenges to be resolved. This study has found that, unlike in many other countries and jurisdictions, existing fire resistance ratings in C/AS2 do not change with building height or with the size of the building (or number of household units), however the consequence of fire does increase with building height and with the number of people (or number of household units) potentially exposed in the event of fire. A comparison of the height limits and fire resistance ratings of primary structural elements for residential buildings with and without fire sprinkler systems following the prescriptive guidance in various countries, including the proposed ratings for New Zealand from the current study is shown in Table E3.

The following recommendations are made:

Regarding regulation and design

1. MBIE (and designers) should consider adopting the target annual failure probabilities for medium and high density residential buildings to guide the requirements set out in C/AS1, C/AS2 and C/VM2.
2. MBIE (and designers) should consider adopting risk informed fire resistance ratings such as those given in this report for medium and high density residential buildings

for the specified building height and number of household units per storey based on the stated target annual failure probabilities.

3. MBIE (and designers) should reconsider the use of a design FLED of 400 MJ/m^2 currently specified in C/VM2 and implicitly assumed in C/AS1 and C/AS2 for residential buildings and instead adopt a design value based on a distribution as recommended in Australia (i.e. mean 500 MJ/m^2, standard deviation 150 MJ/m^2).

4. MBIE (and designers) should reconsider the current use of the EN 1991-1-2 Annex F ”time-equivalence formula” such that uncertainty in inputs and explicit safety factors accounting for consequence (e.g. building height) be included.

5. Designers should be aware that to fully address the issue of structural fire resistance in any building type, the building capacity to resist the fully developed fire also needs to be addressed. Although beyond the scope of this report, this is particularly important for timber buildings with exposed structural timber elements. The design objectives should be made clear and where necessary, additional fuel load contributed by the building structure and envelope should be accounted for in the structural fire design.

Regarding further research

1. The analysis described in this report should be repeated for other common building types such as offices and retail buildings in New Zealand.

2. Further analysis should be carried out exploring the potential impact on the results due to increased contribution of exposed structural timber elements to the design fuel load.

3. Further analysis should be conducted to explore any potential further reductions in the FRR for sprinklered buildings where agreed additional enhancements to the design, maintenance and operation of the sprinkler system are included - noting that corresponding reductions in the levels of embodied energy in the building would also be expected.

4. Further research is needed to better quantify the fire loads in modern densified housing considering the contributions from buildings contents, fittings as well as the building structure and envelope should be carried out.

5. Further research is needed to quantify the area of available ventilation in fires in modern densified housing should be carried out, taking into account the prevalent use of double-glazing.

Table E3. Height limits and fire resistance ratings of primary structure for residential buildings with and without fire sprinkler systems following the prescriptive guidance in various countries.

Storeys	New Zealand		NZ (proposal) Max 12 units per storey		NZ (proposal) Max 30 units per storey		USA		Australia		Canada		England **	
	With Sprinklers	Without sprinklers	With Sprinklers	Without sprinklers	With Sprinklers	Without sprinklers	With Sprinklers	Without sprinklers	With Sprinklers	Without sprinklers	With Sprinklers	Without sprinklers	With Sprinklers	Without sprinklers
20+							180		90		120		120	
20	30		90		90		180		90		120		120	
19	30		90		90		180		90		120		120	
18	30		90		90		180		90		120		120	
17	30		90		90		180		90		120		120	
16	30		90		90		180		90		120		120	
15	30		90		90		180		90		120		120	
14	30		90		90		180		90		120		120	
13	30		90		90		180		90		120		120	
12	30		90		90		120		90		120		120	
11	30		90		90		120		90		120		120	
10	30		90		90		120		90		120		120	
9	30	60	45	75	60	90	120		90		120		90	
8	30	60	45	75	60	90	120		90		120		90	
7	30	60	45	75	60	90	120		90		120		90	
6	30	60	45	75	60	90	60		90		60		60	
5	30	60	45	75	60	90	60		90		60		60	
4	30	60	30	60	30	75	60		90		60		60	60
3	30	60	30	60	30	75	0 *		90	90	45	45	60	60
2	30	60	30	60	30	75	0 *		90	90	45	45	30	30
1	0 *	0 *					0 *	§	0 *	0 *	0 *	0 *	0 *	0 *
	FRR	FRR	FRR	FRR	FRR	FRR	FRR	FRR	FRR	FRR	FRR	FRR	FRR	FRR

§ International Residential Code can be used for one- and two-family dwellings and townhouses up to 3 storeys without fire sprinklers.
* FRR may be required to protect tenancies and egress routes, or to limit fire spread across boundaries.
** ADB only applies to "common building situations".

Key:

- Combustible materials generally permitted.
- Fire-protected timber (typically requires two layers of fire grade plasterboard).
- Fire-protected timber (limited areas of wood can be exposed on walls and ceiling).
- Non-combustible materials required.
- Primary structure can be combustible, except external wall (unless proven by test).
- Primary structure can be combustible, except external wall.

2. Introduction

2.1 Project aim

In New Zealand, fire resistance ratings (FRR) are currently prescribed in C/AS2 [1] for buildings up to 20 storeys high. This includes residential occupancies of multiple household units with shared escape routes which are primarily the subject of this research.

However, the basis for these prescribed fire ratings is not very robust and they have not been derived considering the change in risk tolerance for buildings of different size and height. Some of the fire ratings given in C/AS2 are lower in comparison with other comparable countries with similar building control regimes. This is especially the case with tall residential buildings where the lower ratings mean there could be a higher risk of building collapse or unacceptable fire spread in these buildings given the same severe fire occurring in New Zealand relative to other countries.

In this event, the performance expected by the New Zealand Building Code (NZBC) [2] (e.g. Clause C6) would most likely not be achieved. As building height increases, the likelihood of occupants being located above the fire floor increases along with higher potential consequences should a fire occur. This translates to an increase in risk. Societal tolerance of a large fire leading to the collapse of a tall building or to multiple deaths due to fire spread (e.g. Grenfell Tower) is lower compared to low-rise residential buildings where typically only a very small number of injuries or deaths occur in any given fire event.

At the current time, for buildings above 20 storeys there is no Acceptable Solution or Verification Method or other accepted methodology referenced by the NZBC that tells a designer what fire resistance rating should be provided. Therefore, an objective risk-informed analysis of the amount of fire resistance needed in these buildings would help to ensure the specified fire ratings are sufficient and provide the Ministry of Building Innovation and Employment (MBIE) with more robust data to make an informed decision regarding the scope and level of fire resistance that should be required under the Building Code and in the compliance documents.

This first part of the project comprises a literature review to gather information, including the:

- relevant practices in other countries
- methodologies used by others in the selection of fire resistance ratings
- compiling relevant data with respect to the fire incidence and severity in residential buildings
- identifying key characteristics of densified housing that influence fire safety and structural fire performance.

We then propose a methodology for undertaking a risk analysis to develop a rational basis for setting risk-informed fire resistance requirements for buildings comprising multi-storey densified housing in New Zealand to be conducted in the next stage of the project. For practicality, the methodology will need to be applied to a population of buildings rather to any individual building or a specific type of structural system or material. For that reason we will investigate simplified approaches of where fire severity can be related to fire resistance primarily using structural adequacy in fire as a proxy.

This investigation has only considered building structures that are noncombustible or adequately protected such that the building materials enclosing compartments do not contribute additional fuel to the fire. Exposed or inadequately protected mass timber compartments are therefore excluded.

2.2 What is densified housing?

BRANZ distinguishes low, medium and high density housing as follows [3]:

- Low-density housing (LDH) includes stand-alone dwellings, generally 1–2 storeys, on a full section ($\leq$ 800 m^2), a half section ($\leq$ 400 m^2) or clustered on sites of varying sizes.
- Medium-density housing (MDH) includes multi-unit dwellings (up to 6 storeys).
- High-density housing (HDH) includes apartment buildings greater than 6 storeys and unit sizes ranging from studio apartments to 3–4-bedroom apartments.

For the purpose of the present study we have taken the term ”densified housing” to include both medium and high density housing. An example of a typical 6 storey MDH development is shown in Figure 1.

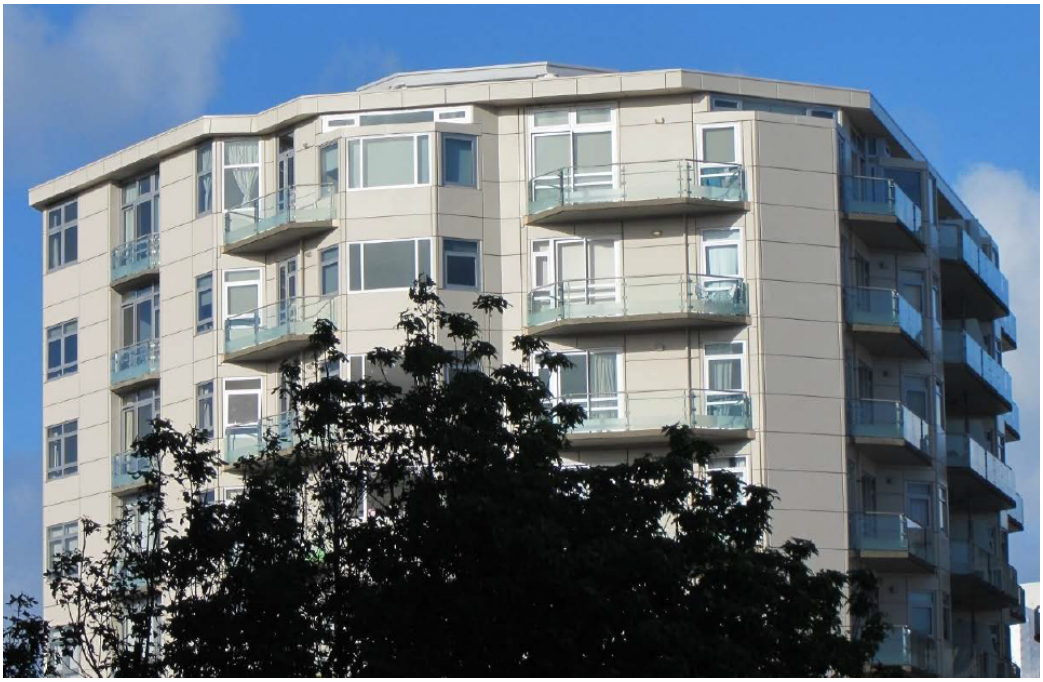

Figure 1. Example of a typical 6 storey MDH development [4]. (Photo BRANZ Ltd.)

3. Background

3.1 New Zealand building legislation

The New Zealand Building Code is contained in Schedule 1 of the Building Regulations 1992 [2]. Clause C concerns protection from fire with Clause C1 stating that the objectives of clauses C2 to C6 are to:

(a) safeguard people from an unacceptable risk of injury or illness caused by fire,

(b) protect other property from damage caused by fire, and

(c) facilitate firefighting and rescue operations.

These objectives are partially fulfilled by meeting functional and performance requirements regarding fire spread and structural performance in fire.

While there are multiple functional requirements that touch on fire spread, the most relevant for the present study are C3.1, C3.3 and C6.1.

Clause C3.1 states that buildings must be designed and constructed so that there is a low probability of injury or illness to persons not in close proximity to a fire source.

Clause C3.3 states that buildings must be designed and constructed so that there is a low probability of fire spread to other property vertically or horizontally across a relevant boundary.

With respect to structural stability, Clause C6.1 states that structural systems in buildings must be constructed to maintain structural stability during fire so that there is:

(a) a low probability of injury or illness to occupants,

(b) a low probability of injury or illness to fire service personnel during rescue and firefighting operations, and

(c) a low probability of direct or consequential damage to adjacent household units or other property

The term "low probability" is not defined in the building code.

Performance requirements relating to Clause C6.1 are given in Clauses C6.2, C6.3 and C6.4 as follows:

> C6.2 Structural systems in buildings that are necessary for structural stability in fire must be designed and constructed so that they remain stable during fire and after fire when required to protect other property taking into account: (a) the fire severity, (b) any automatic fire sprinkler systems within the buildings, (c) any other active fire safety systems that affect the fire severity and its impact on structural stability, and (d) the likelihood and consequence of failure of any fire safety systems that affect the fire severity and its impact on structural stability.
>
> C6.3 Structural systems in buildings that are necessary to provide firefighters with safe access to floors for the purpose of conducting firefighting and rescue operations must be designed and constructed so that they remain stable during and after fire.
>
> C6.4 Collapse of building elements that have lesser fire resistance must not cause the consequential collapse of elements that are required to have a higher fire resistance.

3.2 What is the purpose of fire resistance?

Fire resistance is not a defined term in the NZBC but the test standard AS 1530.4 [5] defines fire resistance as: *"the ability of an element of construction, component or structure to fulfill, for a stated period of time, the required structural adequacy, integrity, thermal insulation or other expected duty specified during exposure to a fire"* which gives rise to the concept of a 'fire resistance rating' in the NZBC at the compliance document level.

Two of the reasons that fire resistance is necessary are: 1) to ensure that the structural system in the buildings is able to maintain structural stability for an adequate period, and 2) to ensure fire separations are capable of limiting fire spread in the event of fire so that there is a low probability of direct or consequential damage to adjacent household units.

In densified housing, while life safety is paramount, protection of neighbouring property by preventing fire spread between household units is also important as fire spread that leads to building-wide conflagrations will potentially leave tenants without access to their homes for some lengthy period including loss of their personal effects. Fire resistant construction capable of containing fire to a single household unit is therefore required along with careful design of facades to avoid such conflagrations as illustrated in Figure 2 [6].

Figure 2. Fire in a condominium development in Norfolk, VA April 2021. (Source: 13newsnow.com [6]. Credit bystander (left), Anne Sparaco (right)).

Common practice is to rely on the prescriptive fire ratings i.e. FRR's given in C/AS2 or to calculate a period of fire resistance that is intended to be sufficient to withstand a full enclosure fire for an adequate period without failure following the procedures given in C/VM2. At the current time, neither of these approaches explicitly consider the likely probability of failure as expressed by the probability of the design fire severity or the design fire load being exceeded. Societal tolerance of failure is more difficult to determine but can be guided by traditional structural engineering practice, as well as considering the implicit safety or risk factors apparent in other codes and standards. FRRs represent the period of time that structural or fire separating elements or assemblies are able to perform their fire-resisting function when subjected to a standard fire resistance test.

Law and Bisby [7] provide a comprehensive history of the use of fire resistance with a focus on United Kingdom codes and standards.

3.3 Enclosure fires

Figure 3 illustrates a typical time temperature curve for a fire occurring within an enclosure with different stages shown as the fire proceeds. Initially there is an incipient period where the fire is initiated and this can be very short or non-existent or very long depending on the fuel types and ignition sources. Once a flame is established on the surface of the fuel, the fire may start to grow, increasing in size and producing gaseous combustion products that accumulate within the enclosure increasing in temperature. As long as there is sufficient fuel and ventilation, the fire may become large enough to cause flashover in the enclosure followed by a fully developed stage where the enclosure temperatures are more steady. At this stage the rate of burning may be ventilation-controlled determined by the area of openings that allow air/oxygen to enter and react with the fuel vapours. As the fuel is consumed, the fire temperature eventually decays until the available fuel is depleted and the fire extinguishes.

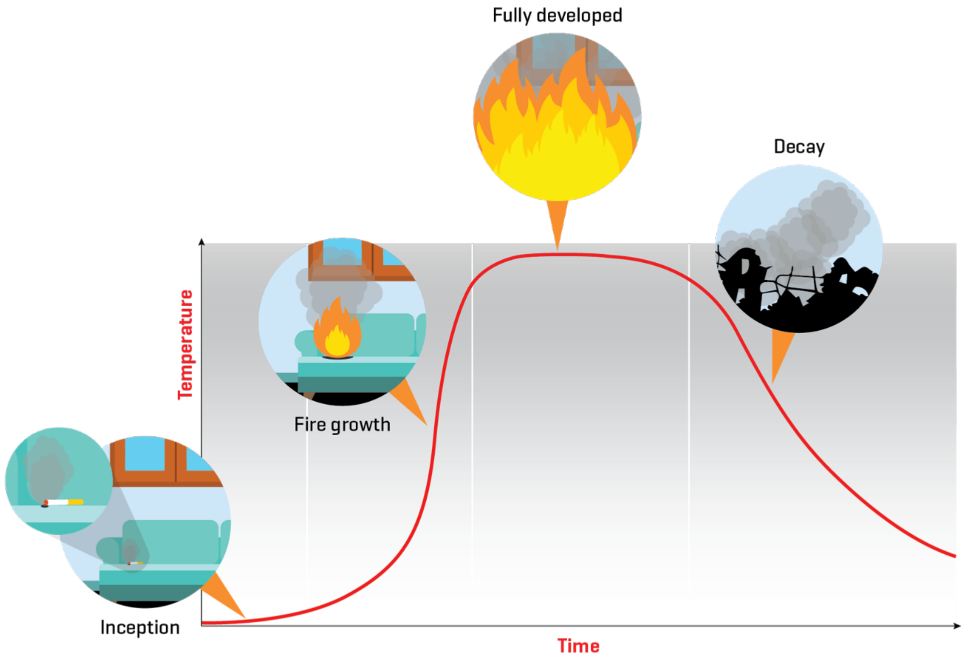

Figure 3. Time temperature and different stages describing the course of a fire. (Image BRANZ Ltd.)

3.4 Standard fire resistance tests

Fire resistance is measured in a test furnace (see Figure 4) where the building element such as a wall or a floor system is exposed to a standardised heating regime intended to mainly represent the fully developed period of the enclosure fire. A standard time temperature regime, such as that shown in Figure 5 from AS 1540 Part 4 [5] has an ever-increasing temperature i.e. there is no decay phase, with the test terminated after a designated time or when the failure criteria in the test have been reached.

Figure 4. Fire doors during a standard fire resistance test. (Photo BRANZ Ltd).

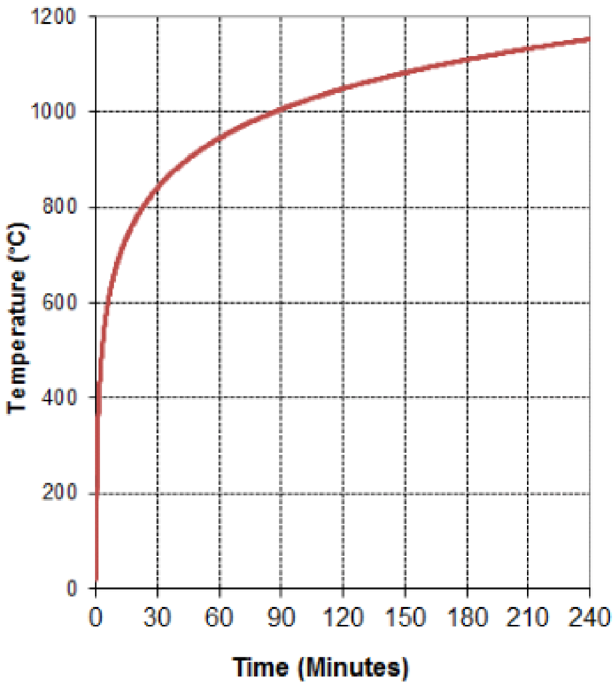

Figure 5. Standard time temperature curve [5].

As noted by Law and Bisby [7], the standard fire is essentially unchanged after more than a century since it was first set out in 1917 as the original curve in the ASTM test standard E119 [8]. Based on their review of the history of fire resistance testing, they posited that structures that were 'fully protected' were intended to resist a burnout fire, and that structures with partial and temporary protection were required only to provide a notional amount of fire resistance – that might have some utility in terms of fire-fighting or evacuation. These ideas correspond to the way fire resistance was also incorporated into building compliance documents in New Zealand as discussed later in subsection 4.1.

3.5 Time equivalency concept

In comparing Figure 3 and Figure 5, it can be seen that the shape of the standard fire resistance time temperature curve can be quite different than for a real fire in an enclosure. These differences are due to the amount, location and properties of the fuel, the area of openings and the size and properties of the bounding surface materials of the enclosure. While furnace tests could be conducted to more closely follow the expected temperature in a real enclosure, it is not very practical due to the large number of potential scenarios that could apply, even within a single building. Therefore, methods have been developed to determine the period of time a structural system is required to withstand a standard fire resistance test, that would result in the same structural response that would occur when that same structural system is exposed to the actual enclosure fire. These methods are known as time equivalency.

There are numerous time equivalency methods that have been published in the literature, with a comprehensive summary and review given by MacIntyre et al. [9, 10]. The two most common concepts used for time equivalency are the maximum temperature concept and the equal energy concept. These are graphically illustrated in Figure 6 and Figure 7 from MacIntyre et al. [9]. Minimum capacity methods are also sometimes used.

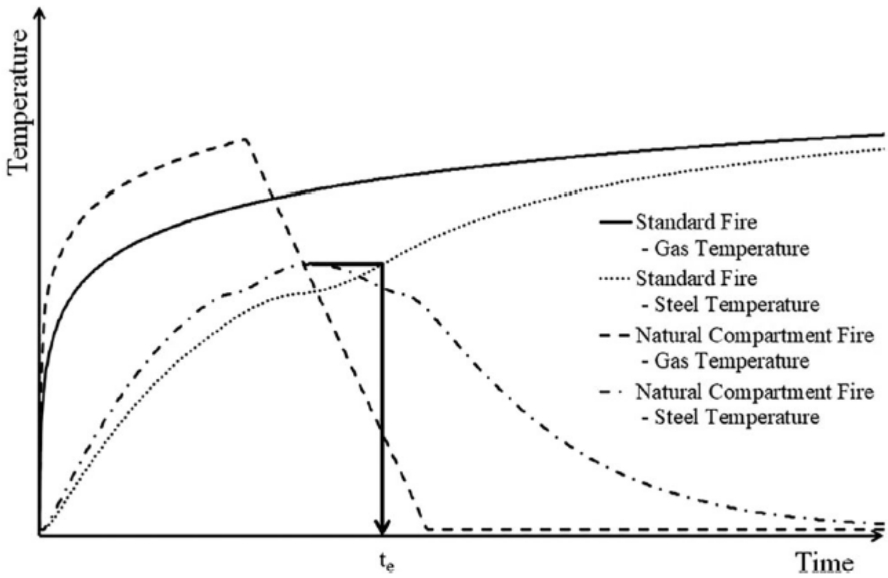

Figure 6. A graphical representation of the maximum temperature time-equivalence calculation. Reproduced from MacIntyre et al. [9].

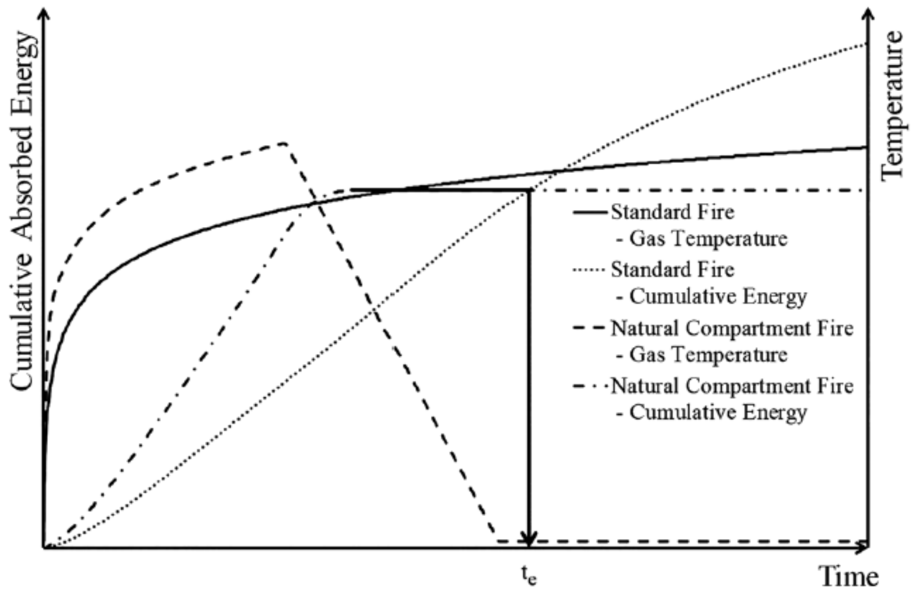

Figure 7. A graphical representation of the equal energy time equivalence calculation. Reproduced from MacIntyre et al. [9].

The method of time equivalency that was previously used in Pre-2012 C/AS1 [11] is known as the Eurocode Formula derived using the maximum temperature concept. The same formula is also implicitly the basis of the FRR given in the current C/AS2 [1] with inherent assumptions and with the values rounded. This formula is discussed later in subsection 7.2 of this report.

3.6 What is reliability?

Thomas [12] introduced the concept of fire safety system effectiveness as a combination of two factors, efficacy and reliability. Efficacy is the degree to which a system achieves an objective, given that it operates. The efficacy could be quite different depending on the objective e.g. preventing deaths versus preventing property damage. Thomas defined reliability as the probability that the system operates when required, and is therefore unaffected by the objective.

In the context of fire resistance, Hopkin et al. [13] have defined reliability as - "The percentile (fractile) of fires that a building should be capable of resisting." They explain "... *as the frequency of fires and consequence of failure increases, the reliability of the fire resistance system must increase. This typically manifests in an increase in a building's fire resistance expectation as height increases.*" [14]

ABCB provides a more general definition for fire protection systems in Datasheet C2 [15] where reliability is stated as the probability that a system performs to a level consistent with the fire protection system specification.

AS/NZS 1170.0 (Structural Design Actions - General Principles) defines reliability as *"Ability of a structure or structural element to fulfil the specified criteria, including the working life, for which it has been defined - Note: Reliability covers structural safety and serviceability, and can be expressed in terms of probability"* [16]. AS/NZS 1170.0 requires that a structure be designed and constructed in such a way that it will, during its design working life, with appropriate degrees of reliability sustain all actions and environmental influences likely to occur.

AS/NZS 1170.0 includes the concept of importance level which groups different types and uses of structure by the consequences of a structural failure. There are five importance levels as shown in Table 1 of which the standard is only applicable for the first four. A more detailed description of these with examples are also provided in AS/NZS 1170.0.

Table 1. Consequence of failure for importance levels [16].

Consequences of failure	Description	Importance level	Comment
Low	Low consequences for loss of human life, or small or moderate economic, social or environmental consequences	1	Minor structures (failure not likely to endanger human life)
Ordinary	Medium consequences for loss of human life, or considerable economic, social or environmental consequences	2	Normal structures and structures not falling into other levels
High	High consequences for loss of human life, or very great economic, social or environmental consequences	3	Major structures (affecting crowds)
		4	Post-disaster structures (post disaster functions or dangerous activities)
Exceptional	Circumstances where reliability must be set on a case by case basis	5	Exceptional structures

For a given importance level and design working life, AS/NZS 1170.0 gives an annual probability of exceedance for the ultimate and serviceability limit states. Although the standard recognises an ultimate limit state for fire, it only gives an annual probability of exceedance for wind, snow and earthquake. While fire is not mentioned, the idea that a structure could be required to withstand a design fire load with a specified annual probability of being exceeded has merit.

If fire were treated similarly to earthquake, the acceptable probability of exceeding (the structural design fire) for the ultimate limit state over a 50 year building life would be 0.1 (1/500 per year) and 0.05 (1/1000 per year), for importance level 2 and 3 buildings respectively.

Alternatively, if fire were treated similarly to snow assuming a more local effect, instead of earthquake or wind which affect multiple structures in a single event, the acceptable probability of exceeding (the structural design fire) for the ultimate limit state over a 50 year building life would be 0.33 (1/150 per year) and 0.2 (1/250 per year), for importance level 2 and 3 buildings respectively.

The importance levels in AS/NZS 1170.0 also align with those included in Clause A3 of the NZBC [2] reproduced in Appendix A which are also stated to be for the purposes of clause C (i.e. Protection from Fire). The most relevant and common importance level for densified housing would be Importance Level 2 which is described as being *"Buildings posing normal risk to human life or the environment, or a normal economic cost, should the building fail. These are typical residential, commercial, and industrial buildings."*

However Importance Level 3 could also be relevant for some tall buildings due to the higher consequence of failure and the additional risk factors for the occupants. Importance Level 3 is described as *"Buildings of a higher level of societal benefit or importance or with higher levels of risk-significant factors to building occupants. These buildings have increased performance requirements because they may house large numbers of people, vulnerable populations, or occupants with other risk factors, or fulfil a role of increased importance to the local community or to society in general."*

Clause A3 of the NZBC [2] also gives examples of specific structures for Importance Level 3. A high-rise residential building is not one of the examples given, however a building with a capacity of 5000 or more people is included. To reach a capacity of 5000 people, a 40-storey building would require about 31 apartment units per level (assuming an occupancy of 4 persons per unit) or about 62 units per level in a 20-storey building.

4. Fire Resistance Ratings in Residential Buildings

4.1 New Zealand

4.1.1 Current 2020 C/AS1 and C/AS2 requirements

Risk group SH is for single residential dwellings including simple multi-unit residential where no more than two units are located one above the other and all units have independent escape routes. The only fire resistance rating required by C/AS1 [17] is 30 minutes and this would be applicable for any fire separation walls or floors between household units. External walls may also require a fire resistance rating when located within 1 m from a relevant boundary or, in the case of household units one above the other, when within 5 m from a relevant boundary.

The Acceptable Solution for Protection from Fire for buildings other than risk group SH is C/AS2 [1] with amendment 2 effective from 5 November 2020 being current at the time of this report. For these buildings, fire resistance ratings depend on the risk group; whether fire sprinklers are installed, and whether the fire separation is required for life safety (Life Rating) or property protection (Property Rating) as shown in Table 2. Densified housing that is not within the scope of C/AS1 is considered to be risk group SM and covered by C/AS2 in which case the required fire resistance rating will either be 30 or 60 minutes depending on whether fire sprinklers are installed as can be seen in Table 2. Notably, the fire resistance ratings required by C/AS2 do not change as the building or escape height increases, except for instances where height determines the use of a property rating instead of a life rating. Therefore the maximum fire resistance rating applicable to multi-unit or densified housing of risk group SM is 60 minutes regardless of building height. This rating applies to the primary structural elements, floors, external walls and fire separations (including the intertenancy walls) where fire rating is required.

Table 2. C/AS2 life and property ratings [1].

Table 2.4	Life and property ratings in minutes			
Risk group	Unsprinklered		Sprinklered	
	Life	Property	Life	Property
SM	60	60	30	30
SI	n/a	n/a	60	60
CA	60[1]	120	30[1]	60
WB	60[1]	120 (180[2])	30[1]	60 (90[2])
WS	n/a	n/a	60[1]	180
VP	60[1]	60	30[3]	30[3]

Notes:

1. When the *escape height* is greater than 10 m the *exitways* shall have *fire separations* with an *FRR* meeting the *property rating* (refer to Paragraph 4.9.2).
2. Where the *building* is less than 15 m to the *relevant boundary* and the storage height is greater than 3.0 m the *FRR* shall be 90 minutes where sprinklered and 180 minutes where unsprinklered.
3. The sprinkler system can be substituted for cross ventilation in accordance with Paragraph 4.1.3.

4.1.2 Pre-2012 C/AS1 requirements

The NZBC Acceptable Solution approach prior to 2012 was more detailed and C/AS1 at the time covered all the occupancy risk groups. Fire resistance ratings were specified as either F-ratings (to protect occupants, adjacent household units and sleeping areas in the same building and firefighters – equivalent to the life rating in the current Acceptable Solutions) or S-ratings (intended to prevent fire spread for the complete burnout of the firecell – equivalent to the property rating in the current Acceptable Solutions).

Table 3. Pre-2012 C/AS1 S ratings for fire hazard categories 1, 2 and 3 [11].

Table 5.1: **Values of t_e for Calculating the S Ratings for Fire Hazard Categories 1, 2 and 3**
Paragraphs 2.2.1, 5.5.2, 5.5.3, 6.10.5, 6.20.15

	Fire Hazard Category 1 (FLED = 400 MJ/m²)					Fire Hazard Category 2 (FLED = 800 MJ/m²)					Fire Hazard Category 3 (FLED = 1200 MJ/m²)				
	A_h/A_f					A_h/A_f					A_h/A_f				
A_v/A_f	0.00	0.05	0.10	0.15	0.20	0.00	0.05	0.10	0.15	0.20	0.00	0.05	0.10	0.15	0.20
0.05 or less	90	60	50	40	40	180	120	100	80	80	240	180	140	140	120
0.06	80	50	50	40	40	160	110	90	80	80	240	160	140	120	110
0.07	70	50	40	40	40	150	100	80	80	70	220	160	140	120	110
0.08	70	50	40	40	30	140	90	80	70	70	220	140	120	110	100
0.09	60	40	40	30	30	140	90	80	70	70	200	140	110	110	100
0.10	60	40	40	30	30	120	80	70	70	70	180	140	110	100	100
0.11	50	40	30	30	30	110	80	70	70	60	160	120	110	100	100
0.12	50	40	30	30	30	100	70	70	60	60	160	110	100	100	90
0.13	50	40	30	30	30	100	70	70	60	60	160	110	100	90	90
0.14	50	30	30	30	30	90	70	60	60	60	140	100	100	90	90
0.15	40	30	30	30	30	80	70	60	60	60	120	100	90	90	90
0.16	40	30	30	30	30	80	60	60	60	60	110	100	90	90	90
0.17	40	30	30	30	30	80	60	60	60	60	110	90	90	90	90
0.18	40	30	30	30	30	70	60	60	60	60	110	90	90	90	80
0.19	30	30	30	30	30	70	60	60	60	60	110	90	90	80	80
0.20	30	30	30	30	30	70	60	60	60	60	100	90	80	80	80
0.25 or greater	30	30	30	30	30	60	60	50	50	50	90	80	80	80	80

Notes:

1. **Determining S rating**
   $S = kt_e$ where $k = 1.0$ for unsprinklered *firecells* and 0.5 for sprinklered *firecells*. Therefore in this table the t_e values are the same as the *S ratings* for unsprinklered *firecells*.
2. **Interpretation**
   A_f = floor area of *firecell* (m²)
   A_v = area of vertical openings in *external walls* of the *firecell* (m²)
   A_h = area of horizontal openings in roof of *firecell* (m²)
   Linear interpolation is permitted where values of A_v/A_f or A_h/A_f lie between those given in the table.
3. **Location of openings**
   Openings to allow *fire* venting should be located in the most practicable manner to provide effective cross-ventilation. This reduces structural *fire* severity and facilitates *fire* fighting operations.
4. **Effective openings**
   a) Only those areas of *external walls* and roofs which can dependably provide airflow to and from the *fire* shall be used in calculating A_v and A_h. Such areas include windows containing non-*fire* resistant glass and likely to break shortly after exposure to significant heat.
   b) An allowance can be made for air leakage through the *external wall* of the *building* envelope. The allowance for inclusion in A_v shall be no greater than 0.1% of the *external wall* area where the wall is lined internally, and 0.5% if unlined.
   c) Only roof venting which is specifically designed to open or melt rapidly in the event of *fire* shall be included in the area A_h.
   d) For single floor *buildings* or the top floor of multi-floor *buildings*, where the structural system supporting the roof is non-rated and directly exposed to the *fire* (i.e. no ceiling installed), A_h/A_f may be taken as 0.2.
5. **Areas not regarded as openings**
   For the purpose of calculating A_v it shall be assumed that doors in *external walls* are closed. Wall areas clad in sheet metal shall not be included in the area A_v.
6. **Intermediate floors**
   Where a *firecell* contains *intermediate floors*, separate calculations shall be made to determine t_e, first by taking A_f as the total floor area in the *firecell* (as defined in Paragraph 2.3.3), then by taking A_f separately as the floor area of each level. The highest value of t_e shall be used to determine the *S rating*.
7. **Background to table**
   Table 5.1 is derived using Equation E3 from Annex E, Eurocode DD ENV 1991-2-2: 1996, Eurocode 1: Basis of Design and Actions on Structures, Part 2.2 Actions on Structures Exposed to Fire (together with United Kingdom National Application Document); British Standards Institution, London, England. A *firecell* height of 3.0 m has been assumed and a thermal inertia factor corresponding to the most severe conditions (i.e. those which generate the highest t_e values and which correspond to use of $k_b = 0.09$ in Equation E3) for typical materials of *firecell construction*. For *firecells* which differ from these assumptions, especially with regard to the materials of *construction*, more accurate answers may be obtained with specific *fire* engineering design, which is mandatory for *fire hazard category* 4.

The S-ratings given in C/AS1 Table 5.1 and reproduced here in Table 3 were derived from the Eurocode time-equivalent formula. This formula is a simplified method for determining the required fire resistance (S Rating in Table 3) that takes into account the fuel load density, the amount of ventilation and thermal properties of the enclosure. Residential buildings were considered to be Fire Hazard Category 1 and following Table 3 the minimum fire resistance needed was 30 minutes for a well ventilated enclosure and the maximum fire resistance was 90 minutes for a poorly ventilated enclosure. Again, these values were determined regardless of building height.

4.2 Comparison with other countries

In a detailed analysis of prescriptive requirements from a selected number of countries, Table 4 shows a comparison between the typical fire resistance rating for primary structural elements in a multi-storey residential building. The prescriptive codes or solutions examined were: 1) New Zealand - C/AS2 (2020) [1], 2) USA - International Building Code (2015 with 2021 amendments) [18]; 3) Australia - National Construction Code (2019) [19]; 4) Canada - National Building Code of Canada (2015 with 2020 Amendments) [20] and 5) England - Approved Document B [21]. The table also shows the maximum heights permitted without installing fire sprinklers and heights at which combustible construction is permitted. Combustible construction can represent an additional hazard and if not adequately protected can provide an additional source of fuel that would increase the fire severity and make fire-fighting more difficult. The information in Table 4 is only indicative and greatly simplified as there may be other factors affecting these requirements such as the number of escape routes.

While C/AS2 generally requires the same FRR for both primary structural elements and other fire separations, this is not necessarily the case for the prescriptive solutions in the other countries. For example, in Australia (NCC) and in the USA (IBC), nonloadbearing intertenancy walls separating the household or occupancy unit need only be 60 minutes, even though the primary structure would require a higher FRR. This would seem to be appropriate given the differing consequences of a structural failure in the building potentially endangering a much larger number of occupants or firefighters compared to the failure an intertenancy separation which would potentially endanger a smaller number of occupants on a single floor.

It can be seen that for Acceptable Solution C/AS2, the FRR does not change with height per se but a reduction is made as a result of a tradeoff for sprinkler installation. All other countries have the FRR increase with height with the exception of the National Construction Code in Australia which requires a 90 minute FRR for all heights regardless of sprinklers.

It is also seen that the building height at which sprinkler systems are required varies from country to country, where in New Zealand it applies when the escape height is greater than 25 m (i.e. about 8 or 9 storeys). This is higher than for the other countries included in Table 4.

At the maximum height of 20 storeys permitted under C/AS2 where all the juridictions shown require fire sprinklers to be installed, C/AS2 requires only 30 min FRR for a residential building, the International Building Code, USA [18] requires 180 min FRR; Australia [19] requires 90 min FRR; Canada [20] requires 120 min and England [21] requires 120 min. The requirements in New Zealand are significantly lower than for all these comparable countries. This questions the risk settings for densified housing in taller buildings in New Zealand and has prompted the current study.

In another study, Östman conducted a survey of timber load-bearing elements in residential buildings using prescriptive or preaccepted requirements that she sent to colleagues and contacts from international networks in 40 countries [22]. Preliminary findings are shown in Table 5. It should be noted that in this table the maximum number of storeys and maximum height are for buildings with timber load bearing elements. It should also be noted that the FRR values shown for New Zealand refer to the unsprinklered case (60 min) and not the sprinklered case (30 min).

4.3 New Zealand verification method

An alternative compliance pathway to the Acceptable Solution C/AS2 in New Zealand is C/VM2 [23], a verification method for protection from fire.

Section 2.4 of C/VM2 describes options for determining a 'full burnout design fire' to be used for structural design and for assessing fire resistance of separating elements. It is stated that this shall be based on complete burnout of the firecell with no intervention by manual fire-fighting or by automatic fire extinguishing systems.

The three options given for modelling the full burnout design fire are:

- Use a time-equivalent formula to calculate the equivalent fire severity and specify building elements with a fire resistance rating not less than the calculated fire severity. In this case, an equivalent fire severity of 20 minutes shall be used, if the calculated value is less.
- Use a parametric time versus gas temperature formula to calculate the thermal boundary conditions (time-temperature) for input to a structural response model, or
- Construct an HRR versus time structural design fire. Then, taking into account the ventilation conditions, use a fire model or energy conservation equations to determine suitable thermal boundary conditions (time/temperature/flux) for input to a structural response model.

The particular form of the time-equivalent formula included in C/VM2 is discussed later in subsection 7.2 of this report.

Table 4. Height limits and fire resistance ratings of primary structure for residential buildings with and without fire sprinklers systems following the prescriptive guidance in various countries.

Storeys	New Zealand		USA		Australia		Canada		England **	
	With Sprinklers	Without sprinklers	With Sprinklers	Without sprinklers	With Sprinklers	Without sprinklers	With Sprinklers	Without sprinklers	With Sprinklers	Without sprinklers
20+			180		90		120		120	
20	30		180		90		120		120	
19	30		180		90		120		120	
18	30		180		90		120		120	
17	30		180		90		120		120	
16	30		180		90		120		120	
15	30		180		90		120		120	
14	30		180		90		120		120	
13	30		180		90		120		120	
12	30		120		90		120		120	
11	30		120		90		120		120	
10	30		120		90		120		120	
9	30	60	120		90		120		90	
8	30	60	120		90		120		90	
7	30	60	120		90		120		90	
6	30	60	60		90		60		60	
5	30	60	60		90		60		60	
4	30	60	60		90		60		60	60
3	30	60	0 *		90	90	45	45	60	60
2	30	60	0 *		90	90	45	45	30	30
1	0 *	0 *	0 *	§	0 *	0 *	0 *	0 *	0 *	0 *
	FRR	FRR	FRR	FRR	FRR	FRR	FRR	FRR	FRR	FRR

§ International Residential Code can be used for one- and two-family dwellings and townhouses up to 3 storeys without fire sprinklers.

* FRR may be required to protect tenancies and egress routes, or to limit fire spread across boundaries.

** ADB only applies to "common building situations".

Key:

- Combustible materials generally permitted.
- Fire-protected timber (typically requires two layers of fire grade plasterboard).
- Fire-protected timber (limited areas of wood can be exposed on walls and ceiling).
- Non-combustible materials required.
- Primary structure can be combustible, except external wall (unless proven by test).
- Primary structure can be combustible, except external wall.

Table 5. Maximum number of storeys/maximum height and fire resistance requirements on load-bearing elements in residential buildings – prescriptive / preaccepted requirements. Preliminary data [22].

Country	Max number of storeys[a]		Max height, m		Same for wood	Addi-tional req. for wood	PFB design allowed	Valid since	Fire resistance requirements, minutes Residential buildings – Max number of storeys			
	Unspr.	Spr.	Unspr.	Spr.					1–2	3–4	5–8	> 8
Australia	2–3	–	–	25	Yes	Yes	Yes	2019	60/30	60–90	90	–
Austria	(7)	–	22		Yes	Yes	Yes	2019	–	–	–	–
Belarus	2	–	–	–	No	No	No	2018	–	–	–	–
Belgium	NL	NL	NL	NL	Yes	No	Yes	2020	–	–	–	–
Bulgaria	–	5	–	12	Yes	No	No	2010	–	30	60	120
Canada	3	6	–	18	No	No	Yes	2015	45	45–60	60[b]	–
China/new	3	5	10		Yes/no	Yes	Yes	2020	–	–	–	–
Croatia	(7)	(7)	22	22	Yes	Yes	Yes	2015	30	60	90	–
Czech Rep.	5	5	12	12	No	Yes	Yes	1980+	30	–	–	–
Denmark	3	3	–	–	No	Yes	Yes	2020	60	60	–	–
Estonia	4	8	–	–	No	Yes	Yes	2017	30	60–180	120–240	–
Finland	2	8	9	28	Yes/no	Yes	Yes	2018	30	60[c]	60[f]	–
France	7	7	–	–	Yes	Yes	Yes	1992	(15)	30	60	90
Germany	(4)	(4)	13	13	No	Yes	Yes	2019	30	60	–	–
Greece	NL	NL	NL	NL	Yes	No	No	2018	30	60	60	120
Hungary	3	3	14	14	Yes	Yes	Yes	2021	15	30		
Iceland	8	NL	23	NL	Yes	No	Yes	2012	30/ 90[d]	90/60[e]	90/60[e]	120/90[e]
Ireland	3	4	10	10	No	Yes	(No)	2006	30	60		
Italy	NL	NL	NL	NL	Yes	No	Yes	2006			60	90/120
Japan	3	3	16	16	Yes	Yes	Yes	2019	60/45	60		
Latvia	(2)	6	–		Yes	Yes	(Yes)	2018	30	60[c]	60[f]	
Lithuania	(3)	(3)	10	10	Yes	No	Yes	2020		45		
Netherlands	NL	NL	NL	NL	Yes/no	No	Yes/no	2012		60	90	120
New Zealand	20	20	25	–	Yes	No	Yes	2019	60	60	60	60
Norway	4	4	–	–	Yes	No	Yes	2007	30	60		
N Macedonia	NL	NL	NL	NL	Yes	Yes	No	1984				
Poland	8	>8	25	>25	Yes	No	No	2017	30	30	30	120
Portugal	NL	NL	NL	NL	Yes/no	No	No	2009	30	30	60	90
Romania	3	4	–	–	No	Yes	Yes	1999				
Russian Fed.	1–2	1–2	–	–	Yes	No	Yes	2020	0–15			
Serbia	1–2	1–2	6–9	6–9	Yes	Yes	Yes	2019				
Slovakia	3	3	–	–	No	No	No	2019	15–30	30–45		
Slovenia	6	(7)	–	22	No	Yes	Yes	2019				
Spain	NL	NL	–	–	Yes	No	Yes	2019		60	90	120
Sweden	NL	NL	NL	NL	Yes	No	Yes	2012	60	60	60/90	90
Switzerland	(30)	(30)	100	100	Yes	Yes	Yes	2015	30	30	60/30	90/60
Turkey	NL	NL	NL	NL	No	No	No	2007				
Ukraine	NL	NL	NL	NL	Yes	Yes	Yes	2016	30	30	60	120–180
UK	(4)	NL	30	NL	Yes	No	Yes	2020	30	60	90/-[e]	120/-[e]
US	4	18	19.8	83	No	Yes	No	2021	0	30	60	120

Note: NL: No Limit.
[a]Storey height estimated to 3 m, if not specified in national answers.
[b]for 5–6 storeys.
[c]additional details apply.
[d]if different storeys.
[e]with sprinklers.

5. Typology of Densified Housing

5.1 Building height classification

BRANZ have reported the storey-height distribution for building consents for MDH during 2015 and 2016 as shown in Figure 8. About 78% of MDH was 3 storeys or fewer, and most had timber framing [4].

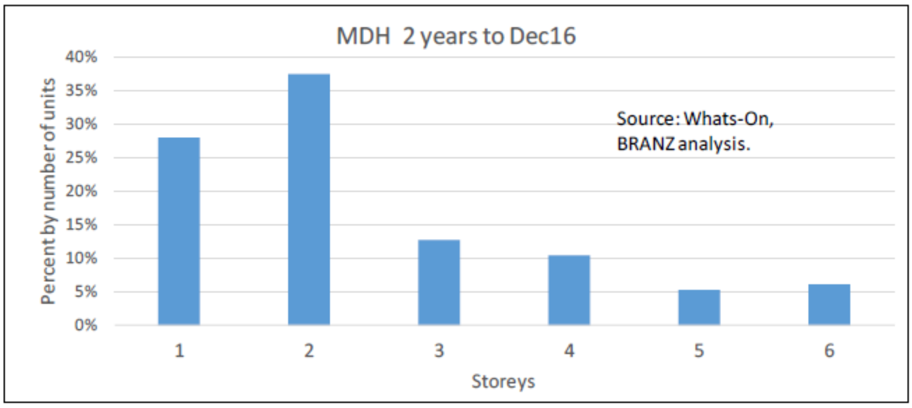

Figure 8. Storey distribution of MDH from building consents in the two years to Dec 2016 [4]. (Image BRANZ Ltd.)

The Australia Bureau of Statistics when reporting numbers of apartments have categorised them into four categories based on height [24]: low rise (1 to 3 storeys), medium rise (4 to 8 storeys), high rise (9 to 19 storeys), and super high rise (20 or more storeys).

5.2 Number, area and geometry of residential units

BRANZ [25] has reported data from Stats NZ that indicates, as at the 2013 Census, low-density standalone housing made up 81.1% (1,193,358 dwellings) of the total occupied New Zealand housing stock where three out of four were single storey. Medium-density housing such as units and apartments made up 18.1% (266,748 dwellings) of occupied private dwellings.

The total number of multi-unit dwellings that are physically attached to at least one other dwelling unit was estimated by Page to be approximately 312,000 in 2016 in New Zealand [4]. MDH were estimated to account for 127,000 of these with the total number of 1,826,000 for all dwellings. Page also reported that MDH units were being built at a rate of about 6,800 per year, and this number was expected to grow at about 5% per year through to 2025. By then, MDH will represent about 35% of all new dwellings [4]. Figure 9 illustrates the trend in the supply in number of new multi-units for the different types of unit.

The trends in building consent floor areas in New Zealand by region over the period 2007 to 2016 as reported by Page [4] are shown in Figure 10. The typologies included apartments, retirement villages, townhouses, flats and terraces with apartments showing the most variation over time and between regions.

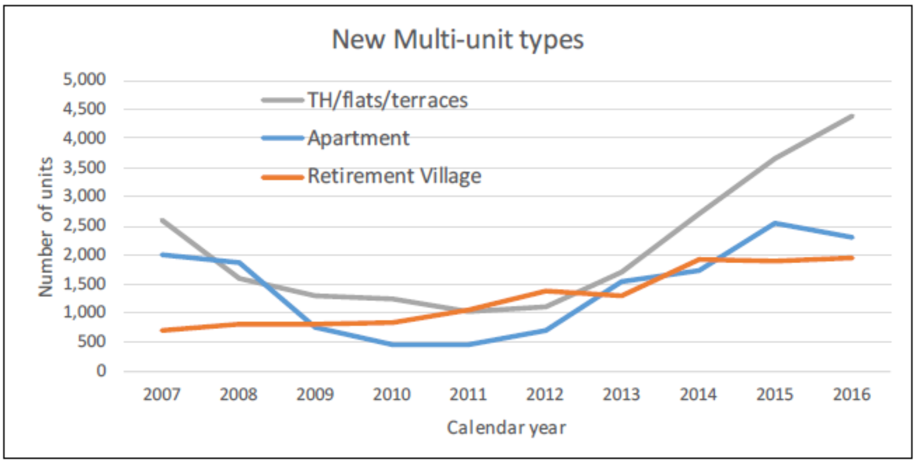

Figure 9. Types of multi-units [4]. (Image BRANZ Ltd.)

Figure 10. MDH building consent average floor areas [4]. (Image BRANZ Ltd.)

Based on building consent data from Stats NZ, over the five year period from 2016 to 2020, there were 63,258 new household units throughout New Zealand consented for apartments, townhouses, units and other dwellings (excluding houses). This data is summarised by floor area in Appendix B Table B1 and Figure B1. The average floor area for these building typologies was determined to be 111 m^2 [26].

Taking the number and floor area of new consented apartments, townhouses, units and other dwellings (excluding houses) over the period 2016 to 2020 as being representative of the floor area of densified housing in New Zealand, Figure 11 shows the number of total housing units falling within various floor area bands. The same data is described with a cumulative frequency distribution as shown in Appendix B Table B2 and as shown in Figure 12.

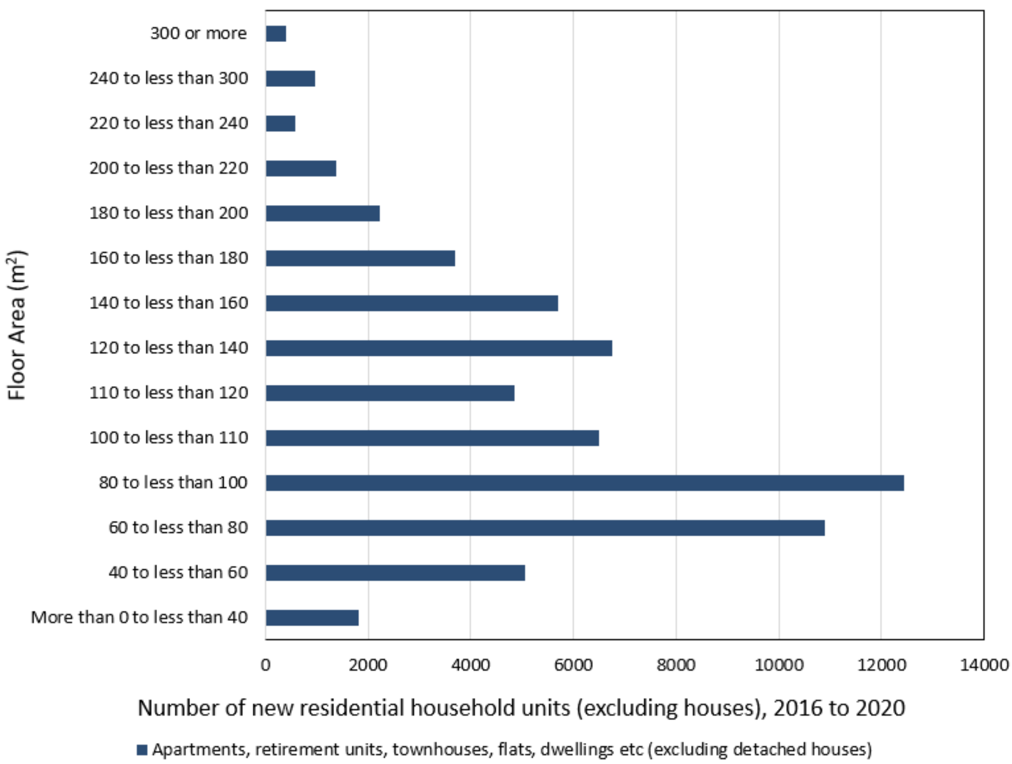

Figure 11. Number of residential units excluding detached houses consented over the period 2016 to 2020 by floor area (Source: Stats NZ).

For comparison, Brandon [27] reported on a review of 513 compartments in residential buildings constructed within the past decade in the UK to provide a statistical overview of modern apartment design. He also included 185 compartments in large residential mass timber buildings. The distributions established for the compartment area is shown in Figure 13. The data was from The Cube, Dalston Lane and Stadthaus buildings, all of which are in London. Not unexpectedly, the average apartment size for this sample in London is significantly less than for apartments in New Zealand.

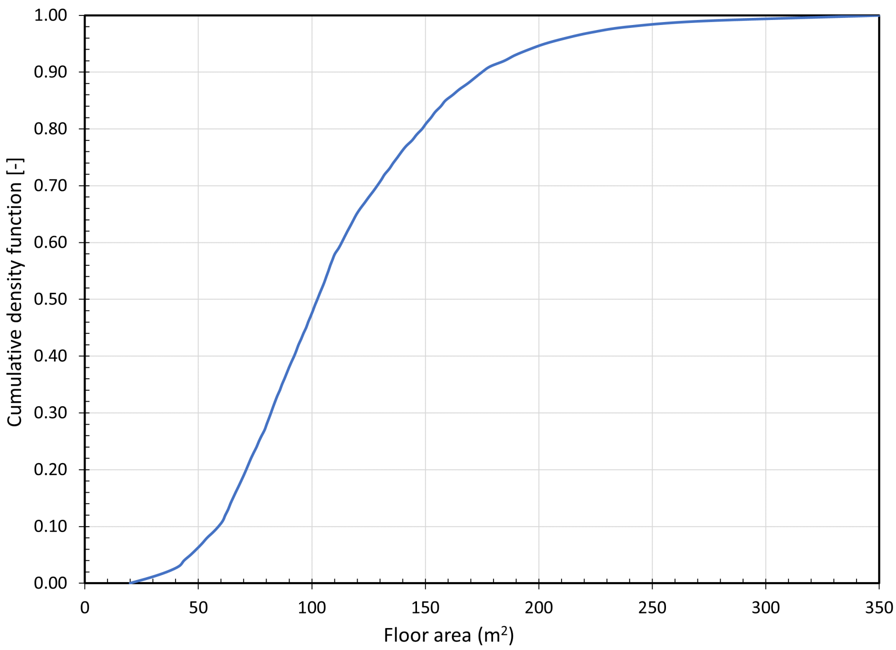

Figure 12. CDF of the floor area for residential units excluding detached houses consented over the period 2016 to 2020. (Source: Stats NZ).

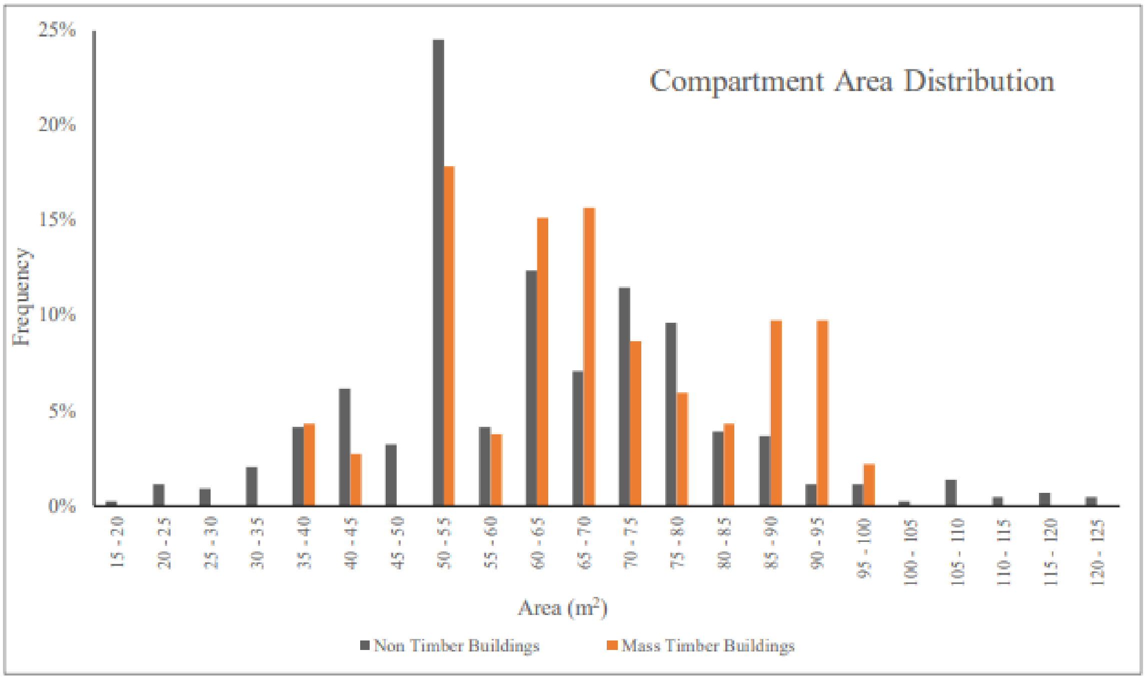

Figure 13. Compartment area frequencies from residential buildings (n=513 for non-timber buildings and n=185 for mass timber buildings) [27]. (Image: RISE, Sweden.)

In the analysis by Kirby et al. [28] for BSI, assumptions regarding the floor area and compartment height are given in Table 6. These were based on engineering judgement. It appears from the floor area for residential occupancies that they may have referred to room sizes rather the entire dwelling unit or apartment (firecell).

Table 6. Variations in compartment geometry adopted for each occupancy by BSI Task Group [28].

	Occupancy type			
Geometric parameter	Hospital	Residential	Manufact.	Manufact. & storage
Floor area m^2	9 to 750 SD	9 to 30 SD	400	400
Compartment height m	2.45 to 4.0 SD	2.4	3.5 to 6.0 SD	3.5 to 6.0 SD

SD = Square distribution

5.3 Openings

The area of openings in a compartment is an input to fire severity calculations, with the opening being a source of air/oxygen for the fire. Areas of glazing, assumed to fallout during fully developed fire are typically used in calculations, with the remained non-glazed area assumed to remain in place. Brandon [27] established distributions for the opening factor based on the glazed area in compartments in residential buildings constructed within the past decade in the UK as shown in Figure 14. The opening factor was defined as $O = A_o\sqrt{h_o}/A_t$ where A_o is the area of the openings, h_o is the weighted height of the openings and A_t is the internal surface area of the compartment and includes the openings.

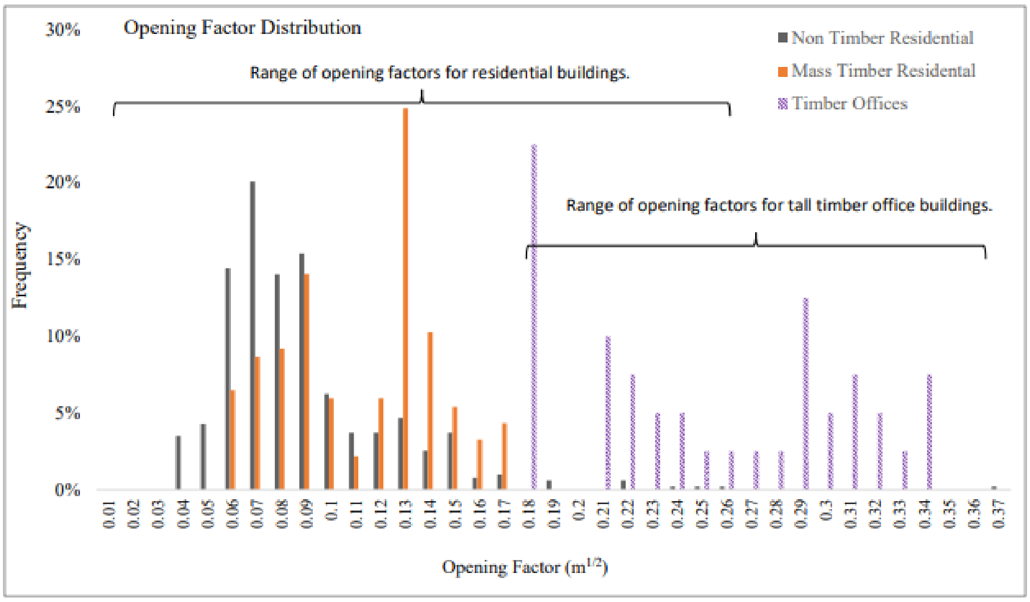

Figure 14. Opening area frequencies from residential buildings (n=513 for non-timber buildings and n=185 for mass timber buildings) [27]. (Image: RISE, Sweden.)

The behaviour of glazing in the event of fire is an important determinant for the severity of the fire. Cracking at elevated temperatures leading to fallout of glass provides an opening for the air/oxygen to enter the enclosure to support the combustion process. The total area of the glazed window units in the apartments provides an upper limit to the area allowing fire ventilation, but it is possible and even likely that the actual area may be less than this maximum value. The size of the openings that allow air/oxygen to enter the compartment may lead to a fire that is either fuel-controlled where there is excess air to support the combustion process, or it may be ventilation controlled where there are more fuel pyrolysates generated that can completely burn inside the compartment given the amount of air/oxygen available. The highest compartment temperatures are reached when there is just enough oxygen available to burn the fuel pyrolysates. This is illustrated in Figure 15 showing a data correlation developed by Thomas and Heselden [29] for the maximum fire temperature reached in a compartment for a given opening factor. In this case, the opening factor is defined differently as given by Equation 3 where A_T is the area of the compartment boundaries excluding the floor, A_w and h are the area and height of the opening respectively.

$$O_F = \frac{A_T}{A_w h^{1/2}} \tag{3}$$

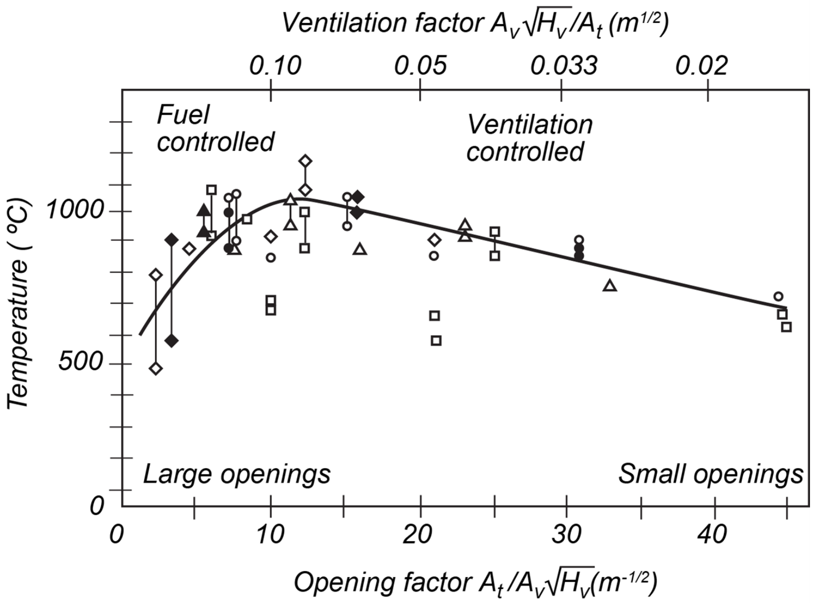

Figure 15. Maximum temperature measured inside the compartment vs the opening factor [29]. (Redrawn: Building Research Establishment.)

Even if the window area is known for a given enclosure, there is uncertainty as to the area that will be available to provide ventilation in a fire. This could depend on factors such as: the status (open/closed) of the window at the time of the fire; the type (single- or double-glazing) and thickness of glazing; the frame materials, and the location of the glazing with respect to the fire location. While deterministic models have been developed to predict glass breakage (e.g. [30, 31]) these tend to relate to glass fracture and not necessarily glass fallout. Jørgensen et al. [32] carried out an experimental study on the influence of the frame shading width on the cracking and fallout of glass monolithic window panes exposed to radiant heat flux. In their experiments the amount of glass fallout was highly random ranging from no fallout to 81.6%. They did not consider any pressure build-up that could influence the fallout and concluded that further research was needed to extend the results to insulating glass units to predict the amount of glass fallout during a fire.

Therefore, the available ventilation in a fire is essentially a stochastic variable, although the maximum area based on window sizes are commonly used by practitioners to calculate fire severity in conjunction time-equivalent formula. It should be noted that the maximum area of glazing is not necessarily a conservative assumption, as illustrated by Figure 15.

The probabilistic model code of the Joint Committee on Structural Safety (JCSS) provides an expression for a truncated log-normally distributed variable, which is used as a modifier for the maximum opening factor, O_{max} as follows [33]:

$$O = O_{\text{max}}(1 - \zeta) \tag{4}$$

where:
O is the opening factor
O_{max} is the maximum available opening factor (based on compartment geometry)
ζ is a random parameter following a truncated lognormal distribution.

Kirby et al. [28], as part of a task group to BSI, developed a new set of fire resistance tables based on a time equivalence approach and adopted uniform distributions (also known as a square distribution) for opening area (10 to 20% of the floor area) and opening height (30 to 90% of the compartment height) for residential occupancies as shown in Table 7. These distributions appear to be based on expert judgement by the BSI task group.

Table 7. Variations in ventilation conditions adopted by BSI Task Group [28].

Ventilation parameter	Occupancy type			
	Hospital	Residential	Manufact.	Manufact. & storage
Area (% of floor area)	10 to 30 SD	10 to 20 SD	2.5 to 20 SD	2.5 to 20 SD
Height (proportion of compartment height)	0.3 to 0.8 SD	0.3 to 0.9 SD	0.3 to 0.8 SD	0.3 to 0.8 SD

SD = Square distribution

In a review of fire resistance expectations for high-rise apartment buildings in the UK, Hopkin [14] assumed the ventilation area was in the range 10% and 25% of the floor area with the lower bound being informed by Table 27 of BS 9999 [34], whilst the upper bound represented the limit of application for the time equivalence formula as presented in BS EN 1991-1-2 [35]). In his analysis, the ventilation area normalised relative to apartment floor area was randomly sampled from a uniform distribution resulting in a unique ventilation condition per iteration.

5.4 Occupant density distributions

Hopkin et al. [36] used the English Housing Survey (EHS) to provide a means of determining occupant density by including data on the number of residents and the total floor area of dwellings. They found apartments were in general more densely occupied (compared to all dwellings) with a mean of 38.7 m^2 /person and a standard deviation of 20.9 m^2 /person. They also found that in the context of exemplar single-stair residential buildings in the UK, that the design capacity of the stair was unlikely to be exceeded.

6. Fires in Densified Housing

6.1 Fire frequency

Robbins et al. [37] reviewed the residential fire incident statistics in New Zealand over the period 1995 - 2005 and determined a mean of 3140 fire incidents per year. They also determined the mean number of fire incidents per 1000 residential structures per year as 0.27% on a per annum basis (or 2.7×10^{-3} fires per year per residential structure) with the number of residential buildings based on New Zealand census data. The summary of New Zealand residential fire statistics (assuming a normally distributed sample) from Robbins et al. [37] is shown in Table 8.

Table 8. Summary of New Zealand residential fire statistics (assuming a normal distribution) [37].

	Range of years	Min	Mean	95th Percentile	Max	StdDev
Fire incidents /yr	1995-2005	2,770	3,140	3,450	3,450	224
Fire incidents /yr	1986-2005	1,862	2,850	3,450	3,450	470
Fire incidents /1000 residential structures /yr[a]	1995-2005	1.9	2.7	3.3	3.4	0.5
Residential structures (1000s)[a]	1995-2005	910	1,178	1,447	1,483	190
Fatalities /yr	1995-2005	15	21	28	28	4.2
Fatalities/1000 fires/yr	1995-2005	4.7	6.8	8.9	9.5	1.3
Injuries /yr	1995-2005	180	240	300	300	38
Injuries/1000 fires/yr	1995-2005	57	77	88	88	9.9

Note
[a] These residential building stock values are based on New Zealand census data from 1991, 1996, 2001 and 2006.

Manes and Rush compared the USA and UK fire frequencies data provided in Table A.2 of PD 7974-7:2003 [38] which presents the overall probability of fire starting in various types of occupancy. For residential buildings, the probability of a fire starting on a per annum basis is given as 0.133% and 0.151% for the UK and USA, respectively based on 2014-15 data. This compared with 0.3% stated in PD 7974-7:2003 [38]. The revised value of 0.13% for dwellings was included in PD 7974-7:2019 [39].

The fire frequency rate of 0.3% from PD 7974-7:2003 was also referenced by Yung [40] for apartment buildings. This value lies between a mean rate of 0.27% and upper 95th percentile of 0.33% fire incidents per year per residential structure in New Zealand over the period 1995-2005 as reported by Robbins et al. [37].

NFPA 557 [41] gives the fire frequency rate for places where people sleep other than homes, as 43 fires per million square meters per year (4.3×10^{-5} fires/m^2/yr). The reported fire frequency rate in residential buildings has declined in the UK and USA - possibly it may have also declined in New Zealand since 2005. This could be due to better fire detection systems, and the higher usage of smoke alarms and sprinkler systems in these buildings.

6.2 Probability of a flashover (or structurally significant) fire

NFPA 557 [41] provides estimates of the fraction of fires that are structurally significant in places with detection and alarm systems where people sleep other than homes for various types of construction as shown in Table 9. The data is based on fires reported to U.S. municipal fire departments in the period 1989 to 1998. The type of construction is related to those referenced in NFPA 220 [42]. Protected, ordinary construction includes that where columns and the underside of wood floor and roof decks have fire-resistive coatings. Protected, wood frame construction includes that where interior wall and ceiling surfaces of habitable spaces are protected by a fire resistive covering. The data applies to hotels and motels, dormitories and barracks, boarding homes, home hotels and nursing homes etc. It is not strictly applicable to apartment-type buildings. The fraction is given as 0.18 for unprotected wood frame construction reducing to 0.13 for protected wood frame construction. For the case of unprotected, wood frame construction, the impact of sprinklers is to reduce the fraction of fires that are structurally significant from 0.18 to 0.03 i.e. a reduction of 77%.

Table 9. Fraction of fires that are structurally significant in places with detection and alarm systems where people sleep other than homes [41].

Type of construction	No sprinklers present	Sprinklers present
Fire resistive	0.04	0.02
Protected, noncombustible	0.04	0.02
Unprotected, noncombustible	0.05	0.03
Protected, ordinary	0.09	0.02
Unprotected, ordinary	0.12	0.03
Protected, wood frame	0.13	0.03
Unprotected, wood frame	0.18	0.03

Probability of a reported fire developing into a structurally significant (post-flashover) fire in unsprinklered buildings was reported by Yung [40] as 15.5% for Australian apartment buildings compared to 18.3% for similar buildings in Canada and USA.

Narayanan and Whiting [43] analysed New Zealand fire incident data for the period 1986 to 1993. Apte et al. [44] used their analysis and presented the probability of different fire types in New Zealand apartment buildings as shown in Table 10. Flashover fires were considered to be those that spread beyond the room of fire origin and represented 22.3% with 3.7% unknown.

Data Sheet B2 of the NCC Fire Safety Verification Method [15] also summarised this data as shown in Table 11 where the unknown fire type data for New Zealand was redistributed over the the other three fire types. ABCB have proposed a characteristic value

Table 10. Probabilities of fire types for apartment buildings in New Zealand [44].

	No. of fires	% of fires	No. of deaths
Smouldering fire	417	26.0%	2
Non-flashover fire	770	48.0%	4
Flashover fire	358	22.3%	13
Unknown	59	3.7%	2
Total	1604	100%	21

Table 11. Proportions of flashover fires in dwellings [15].

Fire type	Australia	USA	Canada	NZ
Smouldering fire	24.5%	18.7%	19.1%	27.0%
Non-flashover fire	60.0%	63.0%	62.6%	49.8%
Flashover fire	15.5%	18.3%	18.3%	23.2%

of 18% be adopted for the proportion of potential fully developed fires for NCC Class 2 buildings (i.e. dwellings).

The natural fire safety concept valorisation project (NFSC) [45] underpinning EN 1991-1-2 calculates the probability of a structurally significant fire p_{fi} based on a combination of the probability of ignition and subsequent interventions prior to the fire becoming fully developed.

$$p_{fi} = p_1 \times A \times p_2 \times p_3 \times p_4 \tag{5}$$

where

p_1 is the probability of a severe fire occurring including the influence of occupants and standard fire service (per m^2 per year). It is intended to include the actions of occupants and a public fire brigade in preventing a fire from developing into a severe fire, and so is not the same as the frequency of fire occurrence. The NFSC recommends p_1 in the range $4 - 9 \times 10^{-7}$ per m^2 per year.

A is the area of compartment/occupancy (m^2).

p_2 is the probability of unsuccessful fire suppression by fire brigade intervention (considering improved professionalism/performance) and depending on the brigade type and the time between alarm and intervention by firefighters. See Table 12.

p_3 is the probability of unsuccessful fire suppression associated with fire alarm and detection systems, alternatively considered as a reduction factor if automatic detection and/or automatic transmission of the alarm to the fire brigade is present. See Table 13.

p_4 is the probability of unsuccessful fire suppression by active fire protection systems (sprinkler). See Table 14.

Table 12. Reduction factor depending on fire brigade type and the time between alarm and fire-fighting intervention [45].

	Time between alarm and firefighting intervention		
P_2, type of fire brigade	< 10 min	$10 < t \leq 20$ min	$20 < t \leq 30$ min
Professional	0.05	0.1	0.2
Non-professional	0.1	0.2	1

Table 13. Reduction factor for automatic fire detection and automatic transmission of alarm [45].

Active measures	P_3
Detection by smoke	0.0625
Detection by heat	0.25
Automatic alarm transmission to fire brigade	0.25

Table 14. Reduction factor for sprinkler system [45].

Type of sprinkler	P_4
Normal (e.g. according to regulations)	0.02
High standard (e.g. 2 independent water supplies)	0.01 - 0.005
Low standard (e.g. not according to regulations)	≥ 0.05

6.3 Fire loads

In New Zealand, it has been customary to use a characteristic design value for the fire load energy density (FLED) of 400 MJ/m^2 of floor area for residential household units. This can be found in the current C/VM2 Table 2.2 [23]. However, this value was also used much earlier following the introduction of the performance-based New Zealand Building Code in 1992. The Annex to Fire Safety Documents [46] included Table A1 where multi-unit residential dwellings were assigned to be Fire Hazard Category 1. The basis for the specified FLED values is shown in Table 15 where it is stated that they are intended to represent the upper 80 percentile value [46]. The reason for selecting a characteristic value of 400 MJ/m^2 for residential buildings is not entirely clear other than a decision made that the FHC 1 category was deemed more applicable than the FHC2 category.

Table 1 of C3/AS1 [47] shown here as Table 16 provided values for the equivalent time of fire exposure (te) used to calculate the S Rating where fire hazard category 1 was equated to a FLED of 400 MJ/m^2. This table was similar to that shown in Table 3 from 2005 but with slightly different values of te ranging from 21 min to 65 min for FHC 1.

EN1991-1-2 Annex E [35] gives a mean fire load density of 780 MJ/m^2 with an 80 percentile characteristic value of 948 MJ/m^2 (Gumbel distribution assumed) which is subsequently modified by a number of factors for active measures and a 0.8 factor for combustion efficiency.

Table 15. Extract from Appendix A 2.1 of Approved Document C4 [46]

Fire hazard category (Note 1)	Range of FLED (MJ/m²) (Note 2)	Design value of FLED (MJ/m²) (Notes 2, 3)
1	0 - 500	400
2	501 - 1000	800
3	1001 - 1500	1200
4	> 1500	
Column 1	2	3

NOTES:

1. The fire hazard category for a given purpose group is as given in Table A1.

2. FLED is expressed as MJ fire load/m² floor area.

3. Each fire hazard category covers a number of purpose groups with design (80 percentile) fire load energy densities of these groups lying in the range stated in column 2 of the above table. The design value of FLED for fire determination of S rating associated with each fire hazard category is also taken as the 80 percentile value of this range, in accordance with accepted practice. This design value adopted also directly covers the specific FLED associated with almost all purpose group uses which come within each fire hazard category.

PD7974-7 [48] recommends a Gumbel type I distribution for dwellings with a mean of 780 MJ/m^2 and 0.3 for the coefficient of variation. The source of this mean value of 780 MJ/m^2 for dwellings appears to originate from european data in the CIB W14 Design Guide for Structural Safety [49] but there is wide variability in the data reported for dwelling/residences even within the CIB W14 publication. It is not clear whether this design fire load density is applicable to New Zealand although it appears to be widely used in the United Kingdom and in Europe based on its inclusion in EN1991-1-2 and PD7974-7.

Table 16. Values of t_e for calculating the S Ratings for fire hazard categories 1, 2 and 3 [46]

Table 1: **Values of t_e for calculating the S ratings for fire hazard categories 1, 2 and 3**
Paragraphs 2.12.5 and 3.2.4

	Fire Hazard Category 1 (FLED = 400 MJ/m²)					Fire Hazard Category 2 (FLED = 800 MJ/m²)					Fire Hazard Category 3 (FLED = 1200 MJ/m²)				
	A_h/A_f					A_h/A_f					A_h/A_f				
A_v/A_f	0.00	0.05	0.10	0.15	0.20	00	0.05	0.10	0.15	0.20	0.00	0.05	0.10	0.15	0.20
0.05 or less	65	43	36	32	30	130	87	72	64	60	195	130	108	96	90
0.06	60	40	34	30	28	120	81	67	61	57	180	121	101	91	85
0.07	56	38	32	29	27	111	75	63	58	54	167	113	95	87	82
0.08	52	35	30	28	26	103	70	60	55	52	155	105	90	83	78
0.09	48	33	29	26	25	96	66	57	53	50	144	99	86	79	76
0.10	45	31	27	26	24	89	62	55	51	49	134	94	82	77	73
0.11	41	30	26	25	24	83	59	53	49	48	124	89	79	74	72
0.12	39	28	25	24	23	77	56	51	48	47	116	85	76	72	70
0.13	36	27	25	23	23	72	54	49	47	46	109	81	74	70	68
0.14	34	26	24	23	22	68	52	48	46	45	102	78	72	69	67
0.15	32	25	23	23	22	64	50	47	45	44	91	75	70	68	66
0.16	30	24	23	22	22	61	48	46	44	44	86	73	68	66	65
0.17	29	24	22	22	22	58	47	45	44	43	86	71	67	66	65
0.18	27	23	22	22	21	55	46	44	43	43	82	69	66	65	64
0.19	26	23	22	21	21	52	45	43	43	42	79	68	65	64	63
0.20	25	22	21	21	21	50	44	43	42	42	76	66	64	64	63
0.25 or greater	22	21	21	21	21	44	42	41	41	41.	66	63	62	62	62

Notes:

1. **Interpretation:**
A_f = floor area of firecell (m²)
A_v = area of vertical openings in external walls of the firecell (m²)
A_h = area of horizontal openings in roof of firecell (m²)

Linear interpolation is permitted where values of A_v/A_f or A_h/A_f lie between those given in the table.

2. **Location of openings**
Openings to allow fire venting should be located in the most practicable manner to provide effective cross-ventilation. This reduces structural fire severity and facilitates fire fighting operations.

3. **Effective openings**
a) Only those areas of external walls and roofs which can dependably provide airflow to and from the fire shall be used in calculating A_v and A_h. Such areas include windows containing non-fire resistant glass and likely to break shortly after exposure to significant heat.

b) An allowance can be made for air leakage through the external wall of the building envelope. The allowance for inclusion in A_v shall be no greater than 0.1 % of the external wall area where the wall is lined internally, and 0.5 % if unlined.

c) Only roof venting which is specifically designed to open or melt rapidly in the event of fire shall be included in the area A_h.

d) For single floor buildings or the top floor of multi-floor buildings, where the structural system supporting the roof is non-rated and directly exposed to the fire, A_h/A_f may be taken 0.2.

4. **Areas not regarded as openings**
For purpose of calculating A_v it shall be assumed that doors in external walls are closed. Wall areas clad in sheet metal shall not be included in the area A_v.

5. **Intermediate floors**
Where a firecell contains intermediate floors, separate calculations shall be made to determine t_e, first by taking A_f as the total floor area in the firecell (as defined in Paragraph 3.2.1(c)), then by taking A_f separately as the floor area of each level. The highest value of t_e shall be used to determine the S rating.

Amd 1
Dec '93

6. **Background to table**
Table 1 is based conservatively on unpublished information currently being used to develop a suitable series of Eurocodes. The table contents will be reviewed at the time of Eurocode publication. Less conservative results may be obtained with specific fire engineering design, something which is mandatory for fire hazard category 4.

Bwalya [50] conducted a survey of Canadian living rooms using a web-based questionaire with 598 respondents with results summarised in Table 17. His survey was primarily focused on combustible items found in living rooms, family rooms or recreation rooms located on either the main floor or basement level. The limitations of this type of approach needs to be recognised and includes: a) much of the information obtained is qualitative, b) the accuracy of any quantitative information cannot be easily verified, and c) many assumptions have to be made in order to quantify the combustibles.

Table 17. Mean values of fire load and fire load density for various living rooms [50].

Housing category	Mean fire load (MJ)	Mean fire load density (MJ/m^2)	Standard deviation (MJ/m^2)	No. of samples
2 storey detached	7800	390	160	231
Bungalow	7790	410	270	118
Apartment	7920	440	272	64
2 storey town home	8300	490	240	58
2 storey semi-detached	7920	440	300	29
3 storey detached	8190	390	240	28
3 storey town home	6290	370	240	14
Duplex	8360	440	190	12

Xie et al. [51] have published a review of fire load density in residential buildings summarising investigations from a number of countries including New Zealand as shown in Table 18. They also presented data specifically related to residential bedrooms in Table 19. They noted that the fire load generally increases with a reduction in area as shown in Figure 16. The New Zealand data refers to a survey by Yii [52] included data collected for four residential bedrooms.

Table 18. Fire load density in residential buildings – literature review from Xie et al. [51]. Reprinted by permission from Springer.

Year of publication	Country/region	Mean (MJ/m^2)	St. Dev. (MJ/m^2)	Method	No. of rooms	Investigator [Refs.]
1942	USA	795[a]	73[a]	Combination	75	NBS [27]
1970	Sweden	720	104	–	–	Thomas [7]
1975	Europe	670	133	–	–	Thomas [7]
1980	USA	1174[a]	–	Inventory	261	Issen [38]
1981	USA	320	88	–	–	Campbell [39]
1989	Japan	629[a]	216[a]	Questionnaire	2723	Kose et al. [40]
1991	USA	512[a]	–	–	–	Bush et al. [41]
1995	India	487	255	Inventory	413	Kumar and Rao [23]
2000	New Zealand	724	107	Combination	4	Yii [34]
2004	Canada	600	200	Questionnaire	74	Bwalya et al. [25]
2004	Canada	410	230	Questionnaire	598	Bwalya et al. [26]
2009	China	520	135	Weighing	70	Li et al. [42]
2010	China	616	164	–	55	Wang et al. [43]
2011	Canada	594	146	Real estate websites	515	Bwalya et al. [24]
2012	China	565	276.1	–	418	Liu et al. [44]

[a] Fire load density value is converted from kg/m^2 to MJ/m^2 by net calorific value of wood, 18.5 MJ/kg
– information is not available

Table 19. Data on fire load density of bedrooms in residential buildings [51]. Reprinted by permission from Springer.

	Floor area (m^2)		Fire load density (MJ/m^2)			
No. of rooms	Max	Min	Max	Min	Mean	St. dev.
42	15	6	1166	422	765	168
40	25	15	908	357	550	132
4	32	25	445	357	409	42

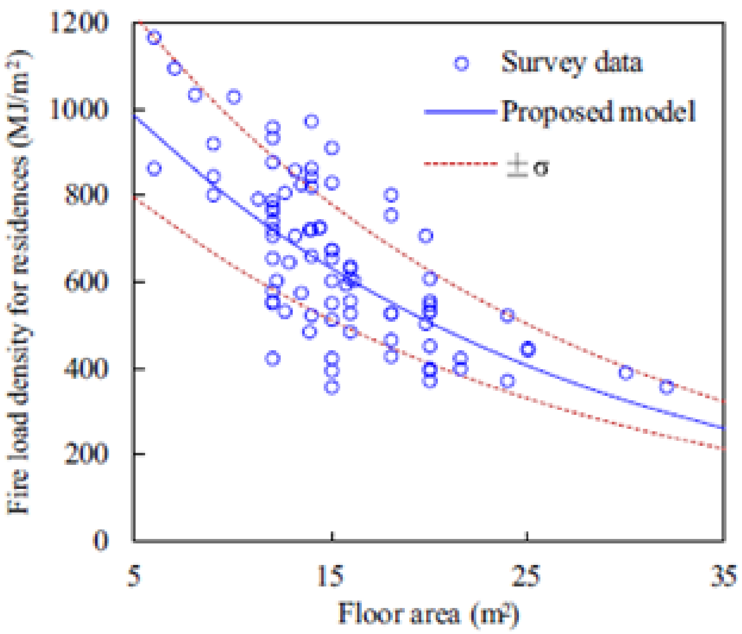

Figure 16. Comparison between fire load density model and survey data for residential buildings [51]. Reprinted by permission from Springer.

Recent full-scale fire testing conducted by Su et al. [53] included typical residential contents with a design fire load of 550 MJ/m^2 as being representative for North America. A photo of this fire load is shown in Figure 17. An inventory of contents from this report showing each item of furniture and the associated energy in MJ is shown in Table 21.

Figure 17. Photo of the moveable fire load used in full scale fire testing where the fire load energy density was 550 MJ/m^2 [53]. Reprinted by permission from National Research Council.

Data Sheet B2 of the NCC Fire Safety Verification Method [15] provides a set of characteristic fire load distributions for NCC buildings as shown in Table 20. There are four different groupings or fire load categories given ranging from low to very high. The proposed distribution for Class 2 i.e. dwellings is a normal distribution with a mean of 500 MJ/m^2 and standard deviation of 150 MJ/m^2 and a minimum value of 200 MJ/m^2. This is the medium fire load category in Table 20. This approach is similar to the Fire Hazard Categories used in New Zealand albeit with slightly different values and a distribution defined. The upper 80th percentile of this distribution for residential occupancies is about 630 MJ/m^2 and is still notably higher than the stated 80th percentile of 400 MJ/m^2 as typically used in New Zealand for design today.

Table 20. Characteristic Fire Load Distributions for NCC Buildings [15].

Building class	Fire load category	Mean fire load (MJ/m^2)	Standard deviation (MJ/m^2)	Min (MJ/m^2)	Max (MJ/m^2)
Class 6, 7b, 8, 9b	Very high	1000	750	300	2500
Class 5, 9b	High	780	115	200	unlimited
Class 2, 3, 4, 9b, 9c	Medium	500	150	200	unlimited
Class 7a (excl. stackers)	Low	300	90	100	unlimited
Class 9a (ward areas)	Low	300	90	100	unlimited

Table 21. Inventory of furniture from Su et al. with MJ given in last column [53]. Reprinted by permission from National Research Council.

Item	Manufacturer / Supplier	Product name	Article / Model / Description	Dimensions, mm X	Y	Z	Material	Mass, kg 1	2	3	4	5	6	Mean	SD	Total mass, kg	Heat value,	Energy, MJ
Gypsum paper	US Gypsum	FireCore Type X	-	9100	2700	0.25	Paper	-	-	-	-	-	-	-	-	9.4	17	159
				4600	2700	0.25	Paper	-	-	-	-	-	-	-	-	4.7	17	80
				9100	4600	0.25	Paper	-	-	-	-	-	-	-	-	8.0	17	136
																22	-	**375**
Flooring	trafficMASTER	-	38701	1290	194	7	Hardboard	1.478	1.484	1.492	1.500	1.500	1.484	1.5	0.0	241.1	19.9	4797
Console table	IKEA	HEMNES	502.821.39	390	1570	740	White pine	25.934	-	-	-	-	-	25.9	-	25.9	19.2	498
12" cabinets	Home Depot	Base	B120HD	610	305	876	White pine	17.988	18.378	18.384	18.432	18.498	-	18.3	0.2	91.7	19.2	1760
36" cabinets	Home Depot	Sink Base	B360HD	610	914	876	White pine	26.426	25.982	26.264	26.240	26.856	-	26.4	0.3	131.8	19.2	2530
Table	IKEA	GAMLEBY	602.470.27	2010	780	740	White pine	29.540	-	-	-	-	-	29.5	-	29.5	19.2	567
Chairs	IKEA	HARRY	201.058.31	450	490	960	White pine	5.064	4.926	5.230	5.276	5.368	5.640	5.3	0.2	31.5	19.2	605
Bookcases	IKEA	HEMNES	402.821.30	890	370	1970	White pine	27.770	27.676	-	-	-	-	27.7	0.1	55.4	19.2	1065
TV unit	IKEA	HEMNES	202.421.02	1480	465	570	White pine	30.656	-	-	-	-	-	30.7	-	30.7	19.2	589
8-Dresser dresser	IKEA	HEMNES	003.185.98	1600	500	950	White pine	54.258	-	-	-	-	-	54.3	-	54.3	19.2	1042
Armchair frame	IKEA	JENNYLUND	300.475.48	730	760	850	White pine	18.326	18.406	-	-	-	-	18.4	0.1	36.7	19.2	705
Armchair cushions	IKEA	JENNYLUND	-	510	460	120	PU Foam	1.524	1.550	-	-	-	-	1.5	0.0	3.1	29	89
Sofa frame	IKEA	EKTROP	401.850.30	2180	860	900	White pine	43.700	-	-	-	-	-	43.7	-	43.7	19.2	839
Sofa cushions	IKEA	EKTROP	-	1670	700	120	PU Foam	13.996	-	-	-	-	-	14.0	-	14.0	29	406
Side table	IKEA	HEMNES	802.821.52	550	550	500	White pine	8.028	8.370	-	-	-	-	8.2	0.2	16.4	19.2	315
Coffee table	IKEA	ARKELSTROP	302.608.07	1380	650	520	White pine	16.342	-	-	-	-	-	16.3	-	16.3	19.2	314
Night stands	IKEA	TARVA	502.196.09	480	390	620	White pine	9.254	9.168	-	-	-	-	9.2	0.1	18.4	19.2	354
Bed frame	IKEA	HEMNES	202.421.02	1470	2000	400	White pine	32.058	-	-	-	-	-	32.1	-	32.1	19.2	616
Bed drawers	IKEA	HEMNES	103.262.96	1470	2000	200	White pine	7.812	8.084	4.286	4.246	-	-	6.1	2.1	24.4	19.2	469
Bed frame slats	Home Depot	Whitewood	569062	1331	102	51	White pine	9.254	-	-	-	-	-	9.3	-	9.3	19.2	178
Mattress	IKEA	MOREDAL	802.773.82	1340	1870	170	PU Foam	17.938	-	-	-	-	-	17.9	-	17.9	29	520
Desk	IKEA	HEMNES	502.821.44	1550	650	740	White pine	36.474	-	-	-	-	-	36.5	-	36.5	19.2	700
Desk hutch	IKEA	HEMNES	202.821.26	1520	250	630	White pine	20.868	-	-	-	-	-	20.9	-	20.9	19.2	401
Desk Chair	IKEA	HARRY	201.058.31	450	490	960	White pine	4.886	-	-	-	-	-	4.9	-	4.9	19.2	94
Wood cribs	Lowes*	HT 591	28 pcs 2 in. x 2 in x 12 in.	305	305	305	White pine	4.454	4.482	4.444	4.570	-	-	4.5	0.1	18.0	19.2	345
Counter top	Home Depot	-	2 in. x 12 in. & 2 in. x 4 in.	660	2210	38	Douglas fir	32.436	30.572	-	-	-	-	31.5	1.3	63.0	21	1323
Counter top	Home Depot	-	2 in. x 12 in. & 2 in. x 4 in.	660	1210	38	Douglas fir	17.292	-	-	-	-	-	-	-	17.3	21	363
Wood cribs	Lowes*	-	6 pcs 2 in. x 4 in x 12 in. 6 pcs 2 in. x 4 in x 30 in.	762	305	152	White pine	10.316	9.868	10.222	9.732	9.394	9.822	9.9	0.3	59.4	19.2	1140
* Unspecified														**Without drywall paper**		**1144**	-	**22622**
														With drywall paper		**1166**		**22997**

Area	**41.86**	**m2**
Load density (w/o paper)	**540**	**MJ/m2**
Load density (w/ paper)	**549**	**MJ/m2**

6.4 Fire growth characteristics

Hopkin et al. [54] analysed the Home Office dwelling fires dataset considering the fire damage area and the time from ignition to fire and rescue service arrival. They determined approximated lognormal distributions for the maximum heat release rate (HRR) and fire growth rate of residential fires. Based on their analysis they concluded that a fast t^2 fire with a growth rate coefficient of 0.0469 (as assumed in C/VM2) represented the 99.5 percentile for both apartments and dwellings assuming a log-normal distribution.

6.5 Fire sprinkler system effectiveness

In 2001, Feeney examined the effectiveness of automatic sprinkler systems in New Zealand with the aim of quantifying the likelihood of a fully developed fire occurring in sprinklered buildings [55]. He analysed data collated for the entire history of sprinkler installations in New Zealand and Australia at that time to obtain conditional probabilities confirming the effectiveness of sprinklers to control fires. For the specific range of building types and occupancies included in the study which included apartments, he determined the annual probability that a fire will grow to reach full development in a sprinklered building in New Zealand was extremely unlikely (less than 1.2×10^{-5}). Feeney was interested in the performance of steel structures in fully developed fire and concluded that certain types of structural steel frames in sprinklered buildings did not require passive fire protection to meet performance requirements of the Building Code of the time.

Gravestock examined system effectiveness for sprinkler systems in a 2008 study [56]. His focus was on systems for multi-storey commercial and residential buildings using a combination of published reliability data, calculated availability ranges, industry information, and system survey information. This included using fault trees to describe the relationship between different aspects of system effectiveness and to quantify for generic design types the expected value, and upper and lower bounds of system effectiveness. His definition of effectiveness was a combination of the on-demand reliability, availability and efficacy. As a first order estimate, Gravestock recommended an effectiveness value of 90% for sprinkler systems in apartment buildings.

In 2012, Marsh Limited extended the Gravestock research and reported on a study examining the effectiveness of a range of fire protection systems in major buildings [57], where high-rise apartments were considered to be a major building.

Frank et al [58] published a review of sprinkler system effectiveness studies in 2013. They recommended that due to the majority of sprinkler failures being related to human error, component based study data should not be used exclusively without comparison to system-based study data. They also concluded if using a probabilistic model, a uniform, triangular or PERT distribution shape may be the most appropriate to use with a peak between 90% and 95% and upper and lower bounds estimated from the applicable studies for the situation being considered.

BS 7974 Part 7 [39] reports sprinkler effectiveness values for an apartment occupancy stated to be based on New Zealand experience. The sprinkler effectiveness ranges from a lower bound of 61%, an expected value of 90% and an upper bound of 97% for a dual supply with the expected value surprisingly offering no advantage over the single town's main supply. In the source document for the data in BS 7974 Part 7, it is recommended that for design purposes, a system effectiveness value of 0.90 be used for an NZS 4541 sprinkler system in an apartment occupancy, i.e., the expected value in Table 22 with reference to the study by Gravestock [56]. It is also noted that effectiveness is defined as the product of availability, reliability and efficacy as defined in Table 22.

The ABCB [15] suggests typical design values for Australian sprinkler systems as shown in Table 23. They also suggest that where detailed probabilistic analysis is undertaken that assume either:

1. a uniform distribution between the low and high estimates be used (i.e. 87 to 97% for residential occupancies)
2. a triangular distribution with the highest frequency at the typical value; or
3. a normal distribution with a mean of the typical value and a standard deviation of 4.6% (based on the recommendation of Frank et al. [59]). They also note that the normal distribution may require truncating (i.e. an upper/lower bound) to ensure the assumed distribution does not exceed a value of 100%.

It is expected that this guidance could also be used for New Zealand sprinkler systems.

Table 22. Sprinkler effectiveness (%) for apartments given by BS 7974 Part 7 based on New Zealand experience.

Water supply	Expected	Lower	Upper
Single town's main supply	90	59	97
Diesel pump and tank	90	46	97
Dual supply: Diesel pump, tank and town's main	90	61	97

Table 23. Typical design value for Australian sprinkler systems [15].

NCC Building Class	Reliability (typical)	Efficacy (typical)	Effectiveness (typical)	Effectiveness (low)	Effectiveness (high)
Residential 2, 3 & 4	95%	97%	92%	87%	97%
General 5, 6, 7a, 8 & 9	90%	96%	86%	81%	91%
Storage 7b	84%	97%	83%	78%	89%

7. Fire Models

7.1 General

This section describes several options for the fire severity model to be used in this project. As a minimum, the model needs to be able to be run as part of a Monte Carlo method and include (or easily be used in conjunction with) a time-equivalency calculation. Potential choices include:

1. the use of the time equivalence formula given in Annex F of EN 1991-1-2 [60];
2. use of the parametric time-temperature equations from Annex A of EN 1991-1-2:2002 [60];
3. alternative parametric time-temperature equations from the German National Annex of DIN EN 1991-1-2/NA [61] (also known as the iBMB parametric fire curves [62]);
4. the BFD curve using a single equation to model the temperature of both the growth and decay phases of an enclosure fire [63, 64];
5. travelling fires [65]; or
6. a zone model for fully developed fire, such as B-RISK [66].

Options 2, 3 and 4 are all types of parametric fire intended for representing uniform fires in enclosures, option 2 being the best known and most commonly used. Options 3 and 4 are variations that potentially provide improved characterisation of the decay phase of the fire. Option 5 is intended for larger compartments where a uniform fire assumption may not be appropriate. In the case of options 2 to 5, a separate time-equivalency method must be used. The most common are either based on equal maximum temperature or equal energy. The various time-equivalency options are reviewed by MacIntyre et al. in some depth [9, 10]. Potentially all options, either singularly or in combination, could be used in the subsequent analysis to be conducted in this project with the results compared.

7.2 Time equivalence formula

A time equivalence formula is given in Annex F of EN 1991-1-2 [67].

It is stated in Annex F that the method is material dependent and is not applicable to composite steel and concrete or timber constructions. However this formula (or an earlier version of it) with modifications has been used in New Zealand Building Code compliance documents dating back to 1992 as a means of determining fire resistance ratings [1, 11, 47]. C/VM2 [23] also includes a version of this formula.

A revised version of Annex F was published in a background paper to the UK National Annex to BS EN 1991-1-2 in the document PD 6688-1 [68]. This revised Annex was a replacement for Annex F from EN 1991-1-2 for use in the United Kingdom. The main differences were:

- Unprotected steel was dealt with differently. In EN 1991-1-2 a correction factor was calculated for unprotected steel and incorporated in the time equivalence formula. However, this does not appear in PD 6688-1 where instead the time equivalence formula is limited to a maximum of 30 minutes for unprotected steel.

- PD 6688-1 used a more conservative set of conversion factors k_b than EN 1991-1-2 depending on the thermal properties of the enclosure.

- PD 6688-1 recognised the need for an additional safety or risk factor to be applied to the time equivalence calculation that related to the use and height of the building. It was a calibration considered necessary to reflect current practice and recognising that numerical outputs from the time equivalent formula should not be used in isolation but rather be part of an overall fire strategy for the building or structure. The risk factors proposed (in the absence of any more detailed risk analysis) ranged from 0.65 for non-residential buildings below 5 m in height to 3.3 for institutional residential buildings above 30 m in height. The risk factor for a building higher than 30 m containing residential dwelling units was 2.65. The table of risk factors for residential buildings is shown in Table 24. Some of the background to the UK National Annex to EN 1991-1-2 was published by Kirby [69].

Table 24. PD 6688-1 Height associated with multiplication risk factors in residential buildings [68].

	Height associated with multiplication risk factors (m)					
Occupancy	0.65	1.0	1.35	2.0	2.65	3.3
Residential (dwelling)	-	$0-5$	$5-18$	$18-30$	>30	-
Residential (institutional)	-	-	$0-5$	$5-18$	$18-30$	>30
Residential (other)	-	$0-5$	$5-18$	$18-30$	>30	-

The C/VM2 [23] form of the time equivalence formula includes a different set of k_b factors depending on thermal properties and shown in Table 25. It also includes an F_m factor shown in Table 26 to account for the expected behaviour of the structural system as well as sprinklers. This factor is applied to the design FLED specified as shown in Table 27.

The scope of C/AS2 [1] is limited to buildings up to 20 storeys high. The scope of C/VM2 [23] is less precise, but it does include a comment that states, as an example, that tall buildings (greater than 60 metres or 20 storeys in height) are outside its scope. Therefore at the current time, buildings higher than 20 storeys would most likely be designed as an 'Alternative Solution'. One approach could be drawing upon design parameters and assumptions included in C/VM2 but as agreed by the fire engineer, peer reviewer and the building consent authority during the FEB process.

Table 25. Factors for various lining materials in C/VM2 [23].

Table 2.4 Conversion factor k_b for various lining materials

Typical values for $\sqrt{k\rho c}$ J/m²s$^{0.5}$K	*Construction* materials	k_b
400	Very light highly insulating materials	0.10
700	Plasterboard ceilings and walls	0.09
1100	Light weight concrete ceilings	0.08
1700	Normal weight concrete ceilings	0.065
>2500	Thin sheet steel roof and any wall systems	0.04

NOTE:

(i) k=thermal conductivity (W/m K)
ρ=density (kg/m^3)
c=specific heat (J/kg K)

(ii) To account for different thermal properties of the walls, ceiling and floor it is permissible to calculate an effective thermal property and determine the k_b factor by interpolation from Table 2.4.

An effective thermal property $\sqrt{k\rho c} = (\Sigma(b_j A_j))/(A_t - A_v)$ where:

A_j = area of the enclosed surface *j*, openings not included

b_j = thermal property ($\sqrt{k\rho c}$) of enclosure surface *j*

Where a surface comprises multi-layers with different materials, it is only the first few centimetres on the fire exposed side that are relevant for the purposes of this calculation.

Errata 2 Amend 4

Amend 4 Jul 2014

Amend 4 Jul 2014

Table 26. Factors to be applied to the FLED in C/VM2 [23].

Table 2.3 F_m factors to be applied to FLED

	Sprinklered *firecell*	Unsprinklered *firecell*
For calcuations of *fire* duration[1] and for *fire* resistance of all non-structural elements[2] Fire resistance of structural elements not covered by the description in the row below	0.50	1.00
Fire resistance of structural elements in a structural system which is unable to develop dependable deformation capacity under post-*flashover fire* conditions [3]	1.00	1.25

Notes

1. Life safety calculations of the duration of the *fire* (total duration of burning) may use the *FLED* as modified by the F_m factor in the table.
2. This table does not prescribe that all non-structural elements require fire resistance based on fire duration. However, where calculation of *fire* resistance of non-structural elements is based on *fire* duration, this table gives the F_m value to be applied to the *FLED*.
3. This factor accounts for impact of non-uniform *fire load* and/or ventilation and hence local increase in actual structural *fire* severity on a structural system which has less resilience to accommodate variations from the calculated *fire* severity. For this purpose the structural system comprises the individual members and the connections between these members.

Errata 1 Apr 2012

Amend 3 Dec 2013

Table 27. Design FLED for use in modeling fires in C/VM2 [23].

Table 2.2	Design FLEDs for use in modelling fires in C/VM2		
Design *FLED* (MJ/m²)	Activities in the space or room	Examples	
400	1. Display or other large open spaces; or other spaces of low *fire hazard* where the occupants are awake but may be unfamiliar with the *building*.	1. Art galleries, auditoriums, bowling alleys, churches, clubs, community halls, court rooms, day care centres, gymnasiums, indoor swimming pools	
	2. Seating areas without upholstered furniture	2. School classrooms, lecture halls, museums, eating places without cooking facilities	
	3. All spaces where occupants sleep	3. *Household units*, motels, hotels, hospitals, residential care institutions	
	4. Working spaces and where low *fire hazard* materials are stored	4. Wineries, meat processing plants, manufacturing plants	
	5. Support activities of low *fire hazard*	5. Car parks, locker rooms, toilets and amenities, service rooms, plant rooms with plant not using flammable or *combustible* fuels	Amends 3 and 4
800	1. Spaces for business	1. Banks, personal or professional services, police stations (without detention), offices	Amend 3 Dec 2013
	2. Seating areas with upholstered furniture, or spaces of moderate *fire hazard* where the occupants are awake but may be unfamiliar with the *building*	2. Nightclubs, restaurants and eating places, *early childhood centres*, cinemas, *theatres*, libraries	
	3. Spaces for display of goods for sale (retail, non-bulk)	3. Exhibition halls, shops and other retail (non bulk)	
1200	1. Spaces for working or storage with moderate *fire hazard*	1. Manufacturing and processing moderate *fire load* 2. Storage up to 3.0 m high other than *foamed plastics*	
	2. Workshops and support activities of moderate *fire hazard*	3. Maintenance workshops, plant and boiler rooms other than those described elsewhere	Amend 3 Dec 2013
400/tier of car storage	Spaces for multi-level car storage	Car stacking systems. The design floor area over which the design *FLED* applies is the total actual car parking area	
800/m height, with a minimum of 2400	1. Spaces for working or storage with high *fire hazard*	1. Chemical manufacturing and processing, feed mills, flour mills 2. Storage over 3.0 m high of *combustible* materials, including temperature controlled storage	Amend 4 Jul 2014
	2. Spaces for display and sale of goods (bulk retail)	3. Bulk retail (over 3.0 m high)	

MBIE [70] consulted in 2017 on a proposed change to C/VM2 Table 2.3, which would have provided Fm factors to use in fire severity calculations in buildings taller than 60 m. The proposed table is shown in Table 28. Assuming a baseline fire severity calculation based only on ventilation and fuel load for an apartment of say 60 minutes; the proposed revised Fm factor would have meant for sprinklered buildings 60 to 100 m high, at least 60 min FRR would have been specified for the columns and 45 min for the floors, beams and fire separations. For buildings more than 100 m high, this would have meant at least 90 min FRR would have been specified for the columns and 75 min for the floors, beams and fire separations. In all cases, fire doors would have needed FRR no more than 30 min. The proposed changes to C/VM2 Table 2.3 did not proceed.

Table 28. Factors proposed to be applied to the FLED in C/VM2 in 2017 MBIE consultation [70].

Revise Paragraph 2.4.1 Modifications to the design FLED:

Table 2.3: F_m factors to be applied to FLED

Table 2.3	**F_m factors to be applied to FLED**	
Building height	**Sprinklered firecells**	**Unsprinklered firecells**
≤ 60m	0.5	1.0
> 60m and ≤ 100m	1.0 for columns 0.75 for floors, beams and fire separations	2.0
> 100 m	1.5 for columns 1.25 for floors, beams and fire separations	3.0

Note:
For fire doors within fire separations the F_m factor shall be 0.5 for sprinklered firecells and 1.0 for unsprinklered *firecells*. Maximum fire resistance rating shall be 120 minutes FRR for *FLED* of < 1200 MJ/m^2.

Explanation:

- The Verification Method C/VM2 currently does not address building height risk. The amendment addresses clauses NZBC C3.9, C4.5, C5.8 and C6.2 where the likelihood and consequence of failure of structure during fire in tall buildings need to be considered.
- Failure of fire safety systems such as sprinklers and passive protection in tall buildings could have significant impact on occupants, firefighters and wider society.
- The factors to be applied to the FLED allow for uncertainty in sprinkler activation, structural protection and non-uniform fire loads.
- This table 2.3 removes the term 'dependable deformation' as it is no longer applicable, as modern material has dependable deformation.
- The F_m factor is higher for columns because a single column can be affected by a severe local fire generated by high local FLED in the vicinity of that column to a greater extent than a floor system. Failure of beams or floor systems is less susceptible to global structure collapse due to load sharing capabilities.

With regard to multi-storey steel and composite steel/concrete structures, Clifton and Abu [71] also proposed modifications to the F_m factors from C/VM2, stated to be taking into account the level of fire load and the nature of the structural response to severe fires. Clifton and Abu state the latter recognises that some elements of the structural system, such as columns and beam to column connections, have less robustness in fully developed fire than floor systems comprising composite slabs on supporting beams and therefore require design to a higher level of structural fire severity in order to develop the required hierarchy of structural system behaviour in fully developed fires. Their proposed F_m factors are shown in Table 29.

Table 29. Proposed F_m factors for fire load modification for height and sprinklers [71].

Height of the top occupied storey across access level	F_m for sprinklered buildings	F_m for unsprinklered buildings
Two storey	0.5 for columns and beam to column connections and slab panel supporting beams 0.25 for floors and other beams	1.0
≤ 10 m	0.5 for all members	1.0
> 10 m and ≤ 25 m	0.75 for columns and beam to column connections 0.6 for beams and floors	1.0
> 25 m and ≤ 60 m	1.0 for columns and beam to column connections 0.75 for beams and floors	1.25 (this will be rare and not used in new buildings)
> 60 m and ≤ 100 m	1.25 for columns and beam to column connections 1.00 for beams and floors	not used
> 100 m	1.50 for columns and beam to column connections 1.25 for beams and floors	not used

The equivalent time of standard fire exposure is defined by:

$$t_{e,d} = q_{f,d} k_b k_m w_f \tag{6}$$

$$w_f = \left(\frac{6}{H}\right)^{0.3} \left[0.62 + \frac{90(0.4 - \alpha_v)^4}{1 + b_v \alpha_h}\right] \tag{7}$$

where:
$q_{f,d}$ is the design fire load density (MJ/m^2) including F_m factor
k_b is a conversion factor for various materials
k_m is modification factor for the structural material
w_f is a ventilation factor
$\alpha_v = A_v/A_f$ and $0.025 \leq \alpha_v \leq 0.25$
$b_v = 12.5(1 + 10\alpha_v - \alpha_v^2)$
$\alpha_h = A_h/A_f$
A_f is the floor area (m^2)
A_v is the area of vertical window and door openings (m^2)
A_h is the area of horizontal openings in the roof (m^2)
H is the average height of the space (m).

7.3 EN 1991-1-2 Annex A parametric curves

The parametric time-temperature equations from Annex A of EN 1991-1-2:2002 [60] were selected here as they have widespread use internationally in structural fire engineering. Application of the equations enable a temperature time curve to be developed with examples shown in Figure 18 [72].

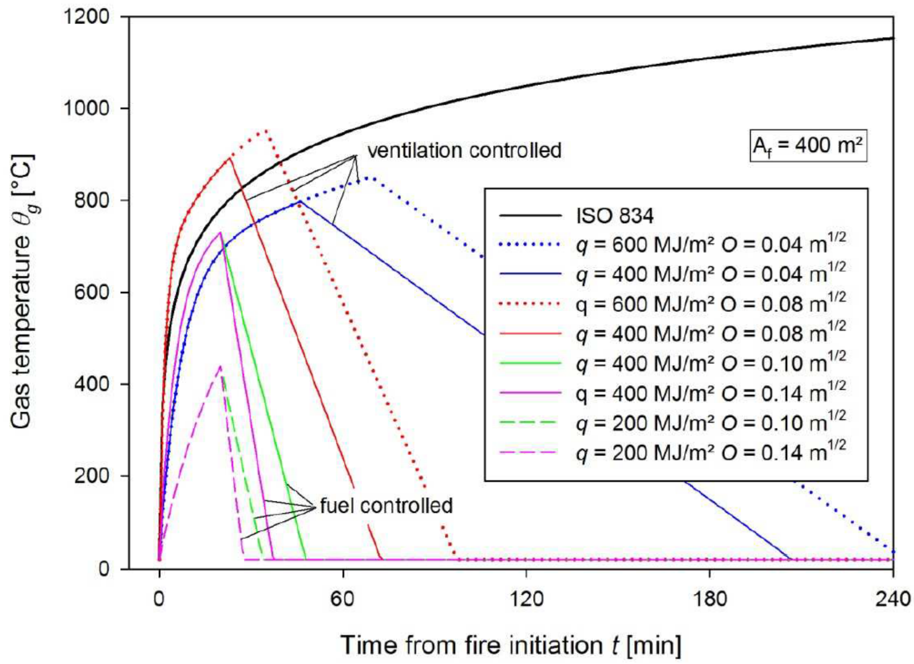

Figure 18. ISO 834 standard fire and EN 1991-1-2 parametric fires for different fire load and ventilation [72].

EN 1991-1-2:2002 [60] states that the following time temperature equations are valid for compartments up to 500 m^2 with a maximum compartment height of 4 m and assumes that the compartment fire load will be completely burned out.

The parametric expressions have been validated against a large body of fire data from tests conducted in the United Kingdom by Corus Fire Engineering and the Fire Research Station (now BRE). In the majority of cases, an excellent correlation was achieved between the test data and the analytical calculations. In cases of poor correlations, predictions of the fire conditions were more onerous and thus the results were conservative. Figure 19 presents the agreement between the parametric equations in EN1991-1-2:2002 Annex A [60] against real fire tests. The correlation coefficient is noted as being 0.75 [73].

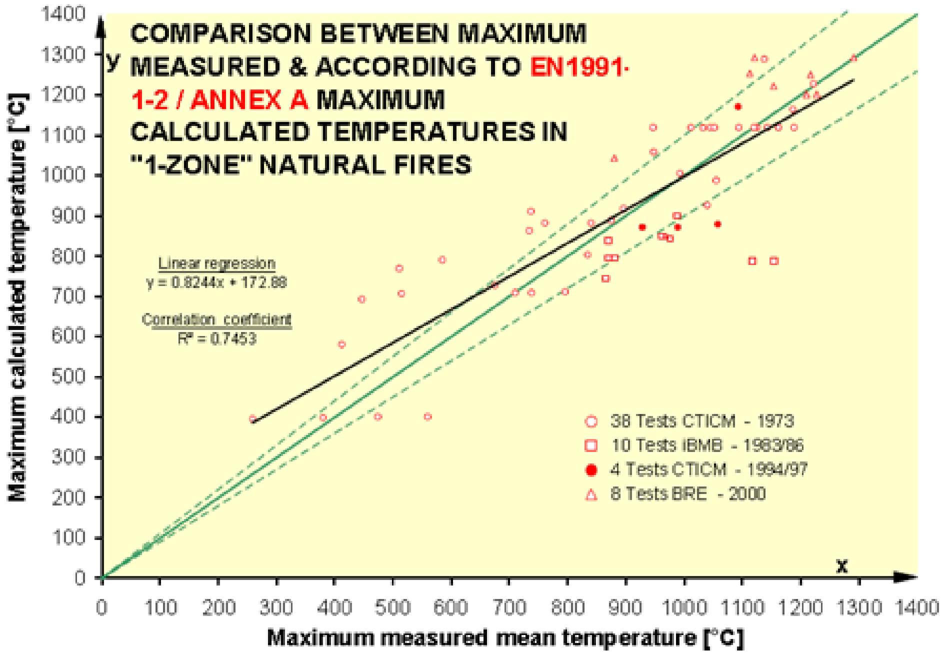

Figure 19. Parametric equations in EN1991-1-2:2002 compared to real fire tests [73].

7.4 DIN EN 1991-1-2/NA parametric curves

The DIN EN 1991-1-2/NA:2010-12 [61] parametric curves are based on the iBMB parametric fire curves as developed by Zehfuss and Hosser [62]. They are derived from heat balance models for realistic natural design fires, taking into account the boundary conditions of typical compartments in residential and office buildings. Figure 20 from Fu et al. [74] compares the EN 1991-1-2 Annex A curves with the DIN EN 1991-1-2/NA curves for the same fire load (600 MJ/m^2) and opening factors (0.02 to 0.20 m$^{0.5}$).

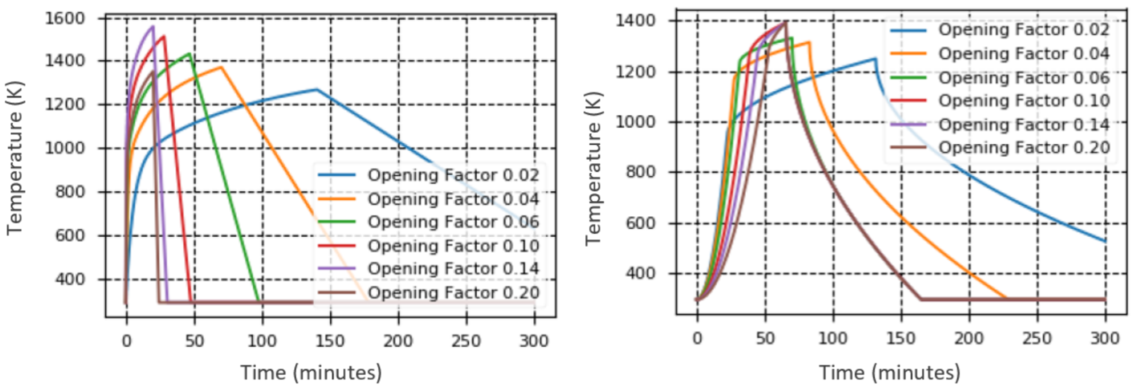

Figure 20. Parametric time temperature curves EN 1991-1-2 Annex A (left) and DIN EN 1991-1-2/NA (right). Adapted from [74].

These parametric curves were developed to address some limitations of the EN 1991-1-2 Annex A parametric curves of the time that only described the fully developed phase of the fire without considering the growth phase. However, Zehfuss and Hosser state the most critical point is that the parametric temperature–time curves of Eurocode 1-1-2 Annex

A have no temporal connection with the rate of heat release of Eurocode 1-1-2 Annex E. The design fire for the DIN EN 1991-1-2/NA:2010-12 parametric curves is defined in terms of a rate of heat release. Figure 21 shows the graphical illustration of the functions that describe these curves. Full details of the equations are given elsewhere [61, 62].

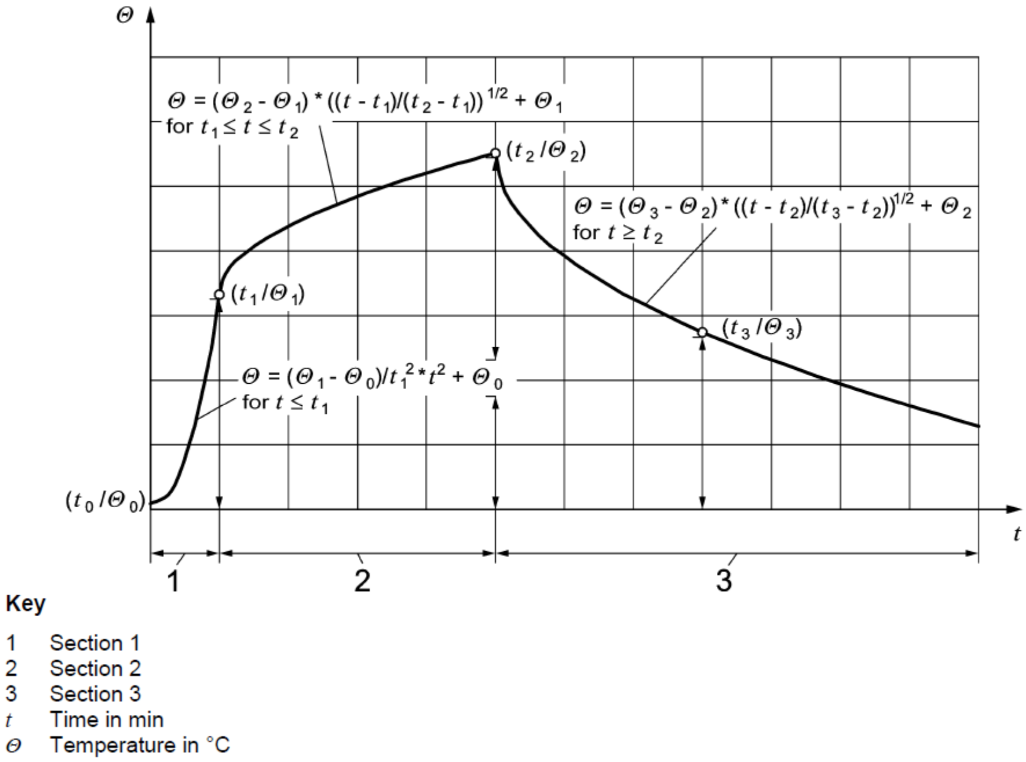

Figure 21. Mathematical description of the DIN EN 1991-1-2/NA:2010-12 parametric time temperature curves parametric fire curves in 3 sections. Extracted from [61].

7.5 Travelling fires

In some compartments, a fire has been observed to travel or migrate around the compartment such that the burning is not uniform throughout the compartment. It can also be thought of as a localised fire that moves. Recognising that accidental fires in large, open-plan compartments often do not burn simultaneously throughout the whole enclosure, Stern-Gottfried and Rein developed a travelling fires design methodology [65] also recently included in ISO/TS 16733-2:2021 [75].

The methodology considers a range of possible fire sizes and is aimed at producing results consistent with the requirements of structural fire analysis. In a case study of a generic concrete frame they found that fires that are around 10% of the floor area are the most onerous for the structure, producing rebar temperatures equivalent to those reached from exposure to 106 min of the standard fire and approximately 200 °C hotter than that calculated using the Eurocode 1 parametric temperature–time curve. Following a detailed sensitivity analysis they concluded that the most sensitive input parameters are related to the building design and its use and not the physical assumptions or numerical implementation of the method [65].

Hopkin [76] subsequently proposed a simplified design fire approach for a one dimensional spreading fire within a large compartment that built upon the work undertaken by Stern-Gottfried by including a thorough description of growth, decay and transient temperature development. Further improvements were then made by Rackauskaite et al. [77] who introduced the concept of flame flapping to account for variation of temperatures in the near-field region due to natural fire oscillations.

Example travelling fire time-temperature curves at a given structural element are illustrated in Figure 22 [74]. Where used in the current study the travelling fire method (TFM) as proposed by Stern-Gottfried and Rein, and as adapted by Hopkin and Rackauskaite has been used by application of procedures developed by Fu et al. [74] as described later in report.

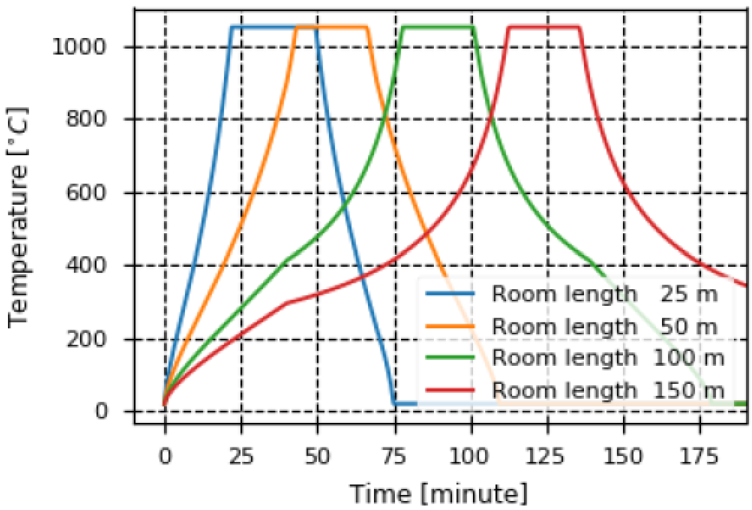

Figure 22. Example travelling time-temperature at structural element. Extracted from from [74].

7.6 Fraction of window fallout

For a given enclosure, the maximum opening area is based on the physical dimensions of the openings. However, to account for less than 100% glazing fallout, the JCCS Probabilistic Model Code [78] recommends the actual value of the opening factor f be modelled as a random quantity according to Equation 8 where ξ is a random parameter following a truncated normal distribution with a mean of 0.2, a standard deviation of 0.2, minimum value of 0 and a maximum value of 1.

$$f = f_{\max}(1 - \xi) \tag{8}$$

8. Derivation of Risk Based Design Fires

8.1 General

This section describes a methodology for deriving the design value for the fire load energy density and is the same as used in a 2005 publication titled "Implementation of Eurocodes. Handbook 5 Design of buildings for the fire situation. Guide to basis of structural reliability and risk engineering related to Eurocodes supplemented by practical examples." by Jean-Baptiste Schleich [73]. This procedure is also described in the European commission report "Eurocodes: Background & Applications Structural Fire Design" [79].

The handbook sets out a performance-based credible approach to the analysis of structural safety in case of fire which takes into account real fire characteristics and active firefighting measures using a general procedure known as the 'Global Fire Safety Concept' as illustrated in Figure 23.

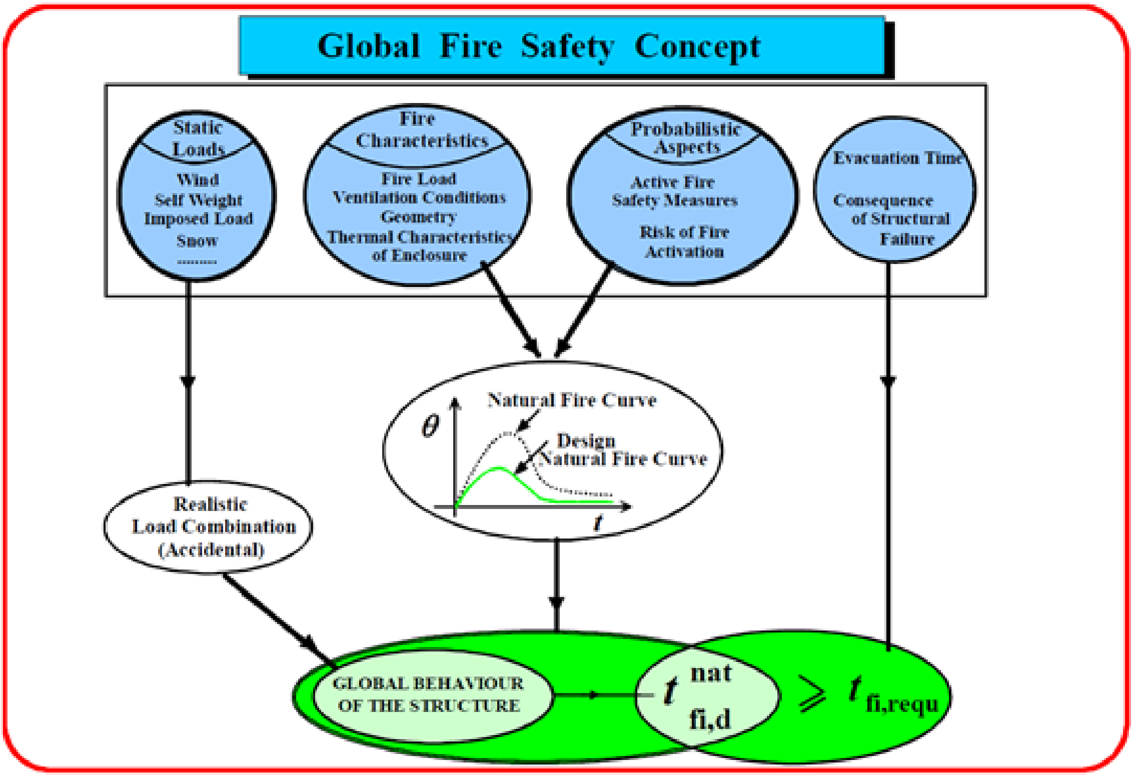

Figure 23. Successive steps of the global fire safety concept. Extracted from Schleich [73].

The methodology described in this section was that used to determine a sprinkler differentiation factor of 0.61 as used in Annex A of PD 6688-1-2:2007 [68] and EN 1991-1-2 [80]. This is equivalent to the F_m factor given in Table 2.3 of C/VM2 in respect of sprinklers. The F_m factor was not derived but was established by expert consensus based on historical practice in New Zealand and is also sometimes referred to as a 'sprinkler trade-off'. It has been used as a multiplier to a specified fire load energy density value to find the design value for use in a time-equivalent formula (also given in C/VM2) as one of the methods able to be used for determining the fire severity and fire resistance.

8.2 Selection of the target probability of failure

There are no commonly-accepted target reliability values for structural performance under fire exposure in any part of the world. However, the assumption of a target failure of probability of 7.23×10^{-5} per building life is defined in EN 1990 for structural design. The global fire safety concept study used 7.23×10^{-5} in deriving the sprinkler differentiation factor in EN 1991-1-2 [80], while clause 6.2.2 of NFPA 557 [41] states 1.0×10^{-6} per year. However, these do not take into account the different consequences of failure for building of different height e.g. treating a low-rise structure as having the same risk as a high-rise structure. The target values could therefore reasonably be increased or decreased as deemed appropriate for the specific building. Ideally, this is the role of the building regulator not the engineer. This topic is discussed more fully in section 9.

Additional conservatism for a high-rise structure can therefore be allowed for by selecting a lower target probability for failure, or alternatively by applying a safety factor to the fire severity and fire resistance specified for structural elements.

An example of the latter approach is used in PD 6688-1-2:2007 (Background paper to the UK National Annex to BS EN 1991-1-2) where a multiplicative risk factor of 2.65 is applied to the calculated outputs of time equivalence calculations for a residential building above 30 m in height as previously shown in Table 24. This would mean that, in current UK practice, where a calculated time equivalence is 30 minutes, the required fire resistance of the structural elements provided would be 80 minutes for a residential building above 30 m. No such safety factor is used in C/AS2 or C/VM2.

With respect to sprinkler trade-offs, Buchanan [81] outlines a probabilistic argument based on safety factors. He gives the following example:

> *"If, for example, the fire resistance normally specified for a burnout of a fire compartment in an unsprinklered building has an inherent safety factor of 2.0, then in the unlikely event of a fire and a sprinkler failure, that safety factor could be reduced to as low as 1.0, hence a 50% reduction. Such an argument can only be used if the method of specifying fire resistance is sufficiently conservative in the first instance."*

Practice Advisory 18: Fire safety design for tall buildings issued by MBIE [82] as guidance information in accordance with section 175 of the Building Act 2004 states the following:

> *"The protracted time usually required for occupant evacuation and firefighter operations requires the structure of tall buildings to remain stable for the full duration of a fire. Overall global structure instability is not an acceptable performance outcome while occupants or firefighters are in the building, or where structural collapse due to the effects of fire causes damage to other property. A cautious assessment of the fire severity associated with complete fire burnout and design strategies for maintaining structure stability is needed. This structural fire performance requirement applies to tall buildings in order to comply with Building Code Clauses B1 and C6."*

Practice Advisory 18 applies to buildings taller than 70 metres in height or 20 levels.

8.3 Calculation of the fire load differentiation factor

A fire load differentiation factor (also known as a 'partial safety factor') to account for sprinklers can be calculated following the approach used in EN 1991-1-2. A building life of 50 years is assumed as per the New Zealand Building Code (see Section 113, Building Act 2004). The following gives an example of the calculation.

Given an ignition frequency (P_i) of 3.0×10^{-3} fires per year per apartment unit, and the building life (y) of 50 years, the probability of ignition over the life of the apartment ($P_{i,50}$) is:

$$P_{i,50} = P_i \times y = 3.0 \times 10^{-3} \times 50 = 1.5 \times 10^{-1} \tag{9}$$

Given the probability of the ignition developing into a structurally significant (post-flashover) fire (P_{fo}) is 15.5%, the probability of a structurally significant fire over the life of the apartment ($P_{fi,50}$) is:

$$P_{fi,50} = P_{i,50} \times P_{fo} = 1.5 \times 10^{-1} \times 0.155 = 2.33 \times 10^{-2} \tag{10}$$

assuming there is no automatic suppression and no fire service intervention [1].

If the target failure probability ($P_{t,50}$) is 7.23×10^{-5} for the ultimate limit state, the permitted probability of structural failure in case of a structurally significant fire (P_{ffi}) is:

$$P_{ffi} \leq P_{t,50}/P_{fi,50} = P_{fi,t} = 7.23 \times 10^{-5}/2.33 \times 10^{-2} = 3.11 \times 10^{-3} \tag{11}$$

The target failure probability may be achieved by improved reliability considerations.

The 'fire load differentiation factor' is defined as a global factor related to fire load, γ such that the design fire load $q_{f,d} = \gamma q_{f,k}$ where $q_{f,k}$ is the characteristic fire load.

The global factor related to fire load for a target failure probability $P_{t,50}$ is calibrated for the building life, such that for the base case (no sprinklers etc), $\gamma = 1$.

Put another way, a probability of 3.11×10^{-3} is considered acceptable for a structurally significant fire where the design fire load is exceeded (i.e. failure). This can be accomplished using a higher fire load in the absence of any intervention, or a lower fire load in conjunction with an intervention (say sprinklers) with a known failure rate.

Schleich [73] calculates γ as:

$$\gamma = \frac{q_{f,d}}{q_{f,k}} = 0.863605\left[1 - 0.233909(0.577216 + \ln - \ln[\Phi(0.9\beta_{fi})]\right] \tag{12}$$

Where Φ is the normal cumulative distribution function.

β_{fi} = reliability index (related to P_{ffi}) = inverse of the standard normal cumulative distribution with P_{ffi} as the argument. The target reliability index is related to the probability of failure as shown in Figure 24.

EN 1991-1-2 gives a differentiation factor with sprinklers of 0.61. This assumes an automatic water extinguishing system with no independent water supply with a probability of the sprinklers failing to extinguish the fire of 0.02; a probability of there being a fully engulfed compartment fire over the life of the building (55 years) of 2.2×10^{-2} for floor

[1] Fire service intervention is separately considered with another factor in the EN methodology.

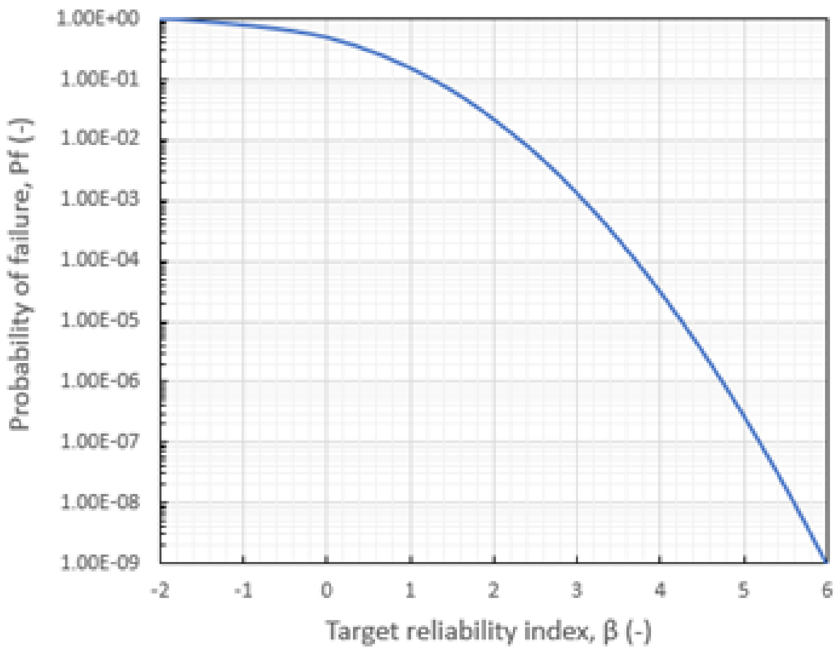

Figure 24. Relationship between probability of failure and the target reliability index.

area of 1000 m^2. The target failure probability for the structure was taken as 7.23×10^{-5} over the life of the building corresponding to a structural reliability index of 3.8.

Using these assumptions, the probability of there being a fully engulfed compartment fire over the life of the building if the building were sprinklered is:

$$P_{fi,55} = 2.2 \times 10^{-2} \times 0.02 = 4.4 \times 10^{-4} \tag{13}$$

The reliability index β_{fi} can be calculated assuming a Gaussian normal distribution where Φ^{-1} is the inverse of the standard normal cumulative distribution.

$$\beta_{fi} = \Phi^{-1}\left(7.23 \times 10^{-5}/2.2 \times 10^{-2}\right) = \Phi^{-1}(0.00329) = 2.717 \text{ without sprinklers} \tag{14}$$

$$\beta_{fi} = \Phi^{-1}\left(7.23 \times 10^{-5}/4.4 \times 10^{-4}\right) = \Phi^{-1}(0.1643) = 0.977 \text{ with sprinklers} \tag{15}$$

The global factor γ applying to the characteristic fire load is 1.742 without sprinklers and 1.0612 with sprinklers using Equation 16. This assumes that the fire load is represented by a Gumbel Type I distribution with a variation coefficient of 0.3 with an 0.8 fractile for the characteristic fire load.

$$\gamma = 0.863605\,[1 - 0.233909(0.577216 + \ln - \ln[\Phi(0.9\beta_{fi})]] \tag{16}$$

The differentiation factor δ for the sprinklered case (with no independent supply) is:

$$\delta = \frac{\gamma \text{ with sprinklers}}{\gamma \text{ without sprinklers}} = \frac{1.0612}{1.74} = 0.61 \tag{17}$$

Table 30. FLED sprinkler differentiation factors.

Sprinkler failure rate	Target failure probability over the building life 7.23×10^{-5}	1.00×10^{-5}	1.00×10^{-6}
1%	0.53	0.63	0.69
2%	0.61	0.68	0.74
3%	0.66	0.72	0.76
5%	0.71	0.76	0.80
10%	0.78	0.82	0.84

Table 30 shows the calculated differentiation factors for sprinklers with different target failure probabilities and sprinkler failure rates, with the EN 1991-1-2 reduction value of 0.61 highlighted for sprinklers.

9. Safety Targets

Ensuring an adequate level of safety in fire safety designs is not a simple process and involves meeting various design goals and objectives with competing constraints that include physical, social and financial components. Performance based fire safety design has traditionally been treated in a deterministic manner, through application of specific models or equations such as time equivalent formula in a scenario-based analysis. The likelihood of the scenario occurring is often not considered [83].

Various literature has discussed safety targets with respect to fire safety engineering design in recent years, and a brief summary of some of this is given in this section.

9.1 National Fire Safety Concept

In the European Commission valorisation project report for the Natural Fire Safety Concept, Schleich and Hosser [45] comment that the target failure probability of 1.00×10^{-6} per year for the Eurocodes is for the ultimate limit state for structural fire resistance under normal conditions. However they say that the required safety in case of fire as expressed by the target failure probability P_t could be differentiated depending on the occupant evacuation capabilities as follows:

$P_t = 1.0 \times 10^{-4}$ per year for normal evacuation

$P_t = 1.0 \times 10^{-5}$ per year for difficult evacuation

$P_t = 1.0 \times 10^{-6}$ per year for no evacuation (e.g high-rise buildings).

9.2 Van Coile, 2015 - time equivalency formula of EN 1991-1-2

Van Coile describes a method for determining a reliability-based equivalent standard fire duration such that the safety level obtained is consistent with the traditional design calculations considering the ISO 834 standard fire [72]. He compared the obtained equivalent fire duration with the equivalent fire duration given by the equivalency formula of EN 1991-1-2 but found it to be non-conservative in many situations. To remedy this, he derived a safety factor which could be applied together with the formula given in EN 1991-1-2, in order to ensure safety when applying a performance based design methodology.

Van Coile proposes the following equation for the time equivalency formula with the safety factor included and variables presented as defined in subsection 7.2.

$$t_{\text{ISO,eq}} = 1.45 q_{f,d} k_b k_m w_f \tag{18}$$

9.3 ISO 2394, 2015 - reliability for structures

ISO 2394 [84] is an International Standard providing general principles on reliability for structures and describes the concept of the Life Quality Index (LQI). The LQI can be expressed in the following principal form:

$$Q = g^q e \tag{19}$$

where g is the GDP per capita, e is the life expectancy at birth and q is a measure of the trade-off between the resources available for consumption and the value of the time of healthy life.

ISO 2394 states that the specified maximum acceptable failure probabilities should be chosen depending on the consequence and the nature of failure, the economic losses, the social inconvenience, and the amount of expense and effort required to reduce the probability of failure. If structural failures are associated with risk of loss of human lives the marginal life saving costs principle applies and this may be used through the LQI. It also says in all cases the acceptable failure probabilities should be calibrated against well-established cases that are known from past experience to have adequate reliability.

According to ISO 2394, the consequences of structural failure may be categorised in accordance with Table 31.

Table 31. ISO 2394 consequence classes for structures [84].

Consequence class	Example structures
Class 1	low rise buildings where only a few people are present, minor wind turbines, stables, etc
Class 2, lower group	most buildings up to 4 storeys, normal industrial facilities, minor bridges, major wind turbines, smaller or unmanned offshore facilities
Class 2, upper group	most buildings up to 15 storeys, normal bridges and tunnels, normal offshore facilities, larger and or hazardous industrial facilities
Class 3	high rise buildings, grandstands, major bridges and tunnels, major offshore facilities, nuclear facilities, etc

ISO 2394 includes specified maximum annual failure probabilities as a function of relative costs of reducing the failure probability and the consequences of failure shown here in Table 32.

Table 32. ISO 2394 Specified maximum annual failure probabilities as a function of relative costs of reducing the failure probability and the consequences of failure [84].

Relative cost of reducing the failure probability	Minor consequences of failure	Moderate consequences of failure	Large consequences of failure
Large	10^{-3}	5×10^{-4}	10^{-4}
Normal	10^{-4}	10^{-5}	5×10^{-6}
Small	10^{-5}	5×10^{-6}	10^{-6}

9.4 Hopkin, 2017 - need for safety targets

Hopkin et al. [83] give a brief overview of the two safety foundations typically applied in deterministic fire safety design. These are the collective experience of the profession where there are no observations of unacceptable performance in multiple fire events based on past practice - a process of refinement of codes and standards that is reliant on trial and error over many years. This approach does not necessarily work very well in the case of very low probability events or in the case of permitting new and innovative technologies. Their second example of a safety foundation is by applying a large level of conservativeness in a scenario-based analysis. This also relies on the collective experience of the profession. Both these cases are represented by the illustration on the left side of Figure 25. An alternative safety foundation requires an explicit evaluation of the safety level illustrated on the right side of Figure 25. This requires the probabilities of different scenarios to be considered and the uncertainty associated with the the calculation inputs. Essentially this means conducting a probabilistic risk analysis (PRA).

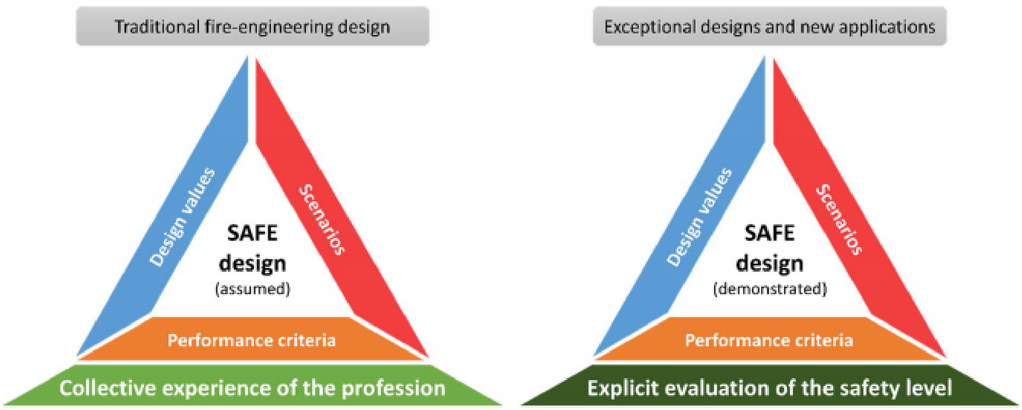

Figure 25. (Left) assumed basis of safe design, (Right) demonstrated basis of safe design where experience is not an adequate basis. Extracted from [83].

Hopkin et al. [83] provide a simple example of a probability concept tree in Figure 26 where the reliability of the sprinkler system must be taken into account to correctly identify the probabilities of the different scenarios and input uncertainty.

Hopkin et al. recognise that defining ALARP is difficult as it requires a balancing of whole-life investments with uncertain safety benefits. While this can be done explicitly by applying cost-benefit analysis (CBA, or Lifetime Cost Optimisation), the valuation of uncertain future costs and benefits quickly becomes particularly challenging.

Hopkin et al. express the view that, in structural engineering, directly valuing the costs and benefits is regularly avoided by introducing safety targets that specify the maximum probability of failure considered acceptable, and calibrated through CBA. Thus, the target safety levels applied in structural engineering (i.e. those found in the Joint Council on Structural Safety (JCSS) probabilistic model code [78]) ensure that an adequate safety level is obtained, while implicitly taking into account the costs and benefits of safety investments [83].

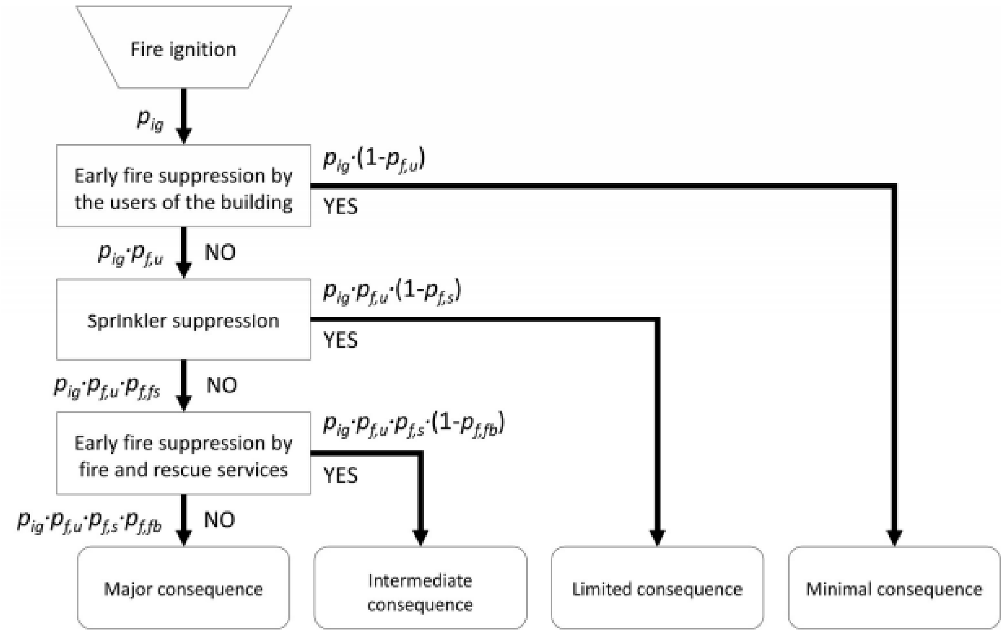

Figure 26. Concept probability tree – The consequence of fire occurrence are dependent on sprinkler operation. Extracted from [83].

Hopkin provides a call to action -

> *"The fire safety profession has often relied in the past on so-called magic numbers and golden rules entrenched in standards and against which the adequacy of alternative solutions are often gauged. The field has progressed now to the point that the tools and techniques available can be applied to explicitly determine the safety levels achieved. The next step is to address the foundation of safe design and to explicitly probe the safety level which is appropriate for a given case. A concerted effort by the fire safety community to address uncertainties and to determine target safety levels as is done in, for example, structural engineering, therefore, has the potential to significantly improve the process of demonstrating adequate safety for exceptional designs and new applications. In the absence of this, the foundation on which a performance based solution is accepted is just another crude golden rule, based on precedent. " [83].*

9.5 Van Coile et al., 2017 - the meaning of Beta

In order to inform the development of reliability targets for structural fire design, Van Coile et al. [85] discuss the background of the ambient reliability targets. They derive a simplified cost-optimisation technique and say that ambient safety targets cannot readily be scaled as a function of the fire occurrence rate for application to structural fire engineering problems, but conclude that different common ambient reliability targets are broadly comparable when taking into account differences in assumptions and applications. Their derivations were concerned with ultimate limit state design (i.e. loss of structural stability).

In ambient structural engineering design, determining future costs and benefits of safety investments is often avoided by the application of a target reliability index, β_t [86]. The index corresponds with the accepted maximum (target) failure probability, $P_{f,t}$ [86] through Equation 20, with Φ the standard cumulative normal distribution function.

$$P_f = \Phi(-\beta) \tag{20}$$

Van Coile et al. [85] presented target values for a 1-year reference period taken from the Probabilistic Model Code [86] that was developed by the Joint Committee on Structural Safety (JCSS). These are shown in Table 33 and are applicable to structural systems. These recommended values were derived from a calibration process with respect to existing practice [12]. The target values are given as a function of the ratio ξ of the failure plus reconstruction cost to the construction cost, and consider an obsolescence rate of 3%.

Table 33. Target β-values for structural systems (1 year), JCSS [86] and adopted in ISO 2394:2015 [84]

Relative cost of safety measures	Consequences of failure Minor ($\xi < 2$)	Moderate ($2 < \xi < 5$)	Large ($5 < \xi < 10$)
High	3.1	3.3	3.7
Moderate	3.7	4.2	4.4
Low	4.2	4.4	4.7

9.6 Hopkin et al., 2017 - applicability of ambient temperature reliability targets

Hopkin et al., 2017 [87] discuss how ambient temperature target probabilities of failure, such as those based on cost optimisation or documented in EN 1990, can be used to inform fire resistance design solutions. They appraise the spectrum of fire severities expected within a simple steel structure office building using Latin Hypercube Sampling (LHS). They conclude that ambient reliability targets have relevance but it may be preferable to define two reliability targets for structural performance for: (1) during evacuation, and (2) longer term probability of failure (burn-out).

Hopkin et al. also note that reliability based methods are at the core of Eurocode structural design, and that for a design following EN 1990 [88] and the partial factors in Annex A, the safety target is 1.3×10^{-6} for a one year reference period corresponding to a reliability index (β) of 3.8 over the conceptual design life (50 years) of a building.

9.7 American Society of Civil Engineers ASCE/SEI 7-16

ASCE/SEI 7-16 (Minimum design loads and associated criteria for buildings and other structures) is a loading standard for general structural design in the USA [89]. ASCE/SEI 7-16 gives target reliability values for load conditions that do not include earthquake, tsunami or extraordinary events and are dependent on the risk category of the building. The target reliability indices (β) are provided for a 50-year reference period.

The ASCE/SEI 7-16 risk categories I to IV are very similar to the NZBC Importance levels 1 to 4 respectively (see Appendix A).

Table 34. Target probability (annual probability of failure, P_F) and associated reliability indices[1] β for load conditions that do not include earthquake, tsunami or extraordinary events [89].

	Risk Category			
Basis	I	II	III	IV
Failure that is not sudden and does not lead to widespread damage	$P_F = 1.25 \times 10^{-4}$ per year ($\beta = 2.5$)	$P_F = 3.0 \times 10^{-5}$ per year ($\beta = 3.0$)	$P_F = 1.25 \times 10^{-5}$ per year ($\beta = 3.25$)	$P_F = 5.0 \times 10^{-6}$ per year ($\beta = 3.5$)
Failure that is either sudden or leads to widespread progression of damage	$P_F = 3.0 \times 10^{-5}$ per year ($\beta = 3.0$)	$P_F = 5.0 \times 10^{-6}$ per year ($\beta = 3.5$)	$P_F = 2.0 \times 10^{-6}$ per year ($\beta = 3.75$)	$P_F = 7.0 \times 10^{-7}$ per year ($\beta = 4.0$)
Failure that is sudden and results in widespread progression of damage	$P_F = 5.0 \times 10^{-6}$ per year ($\beta = 3.5$)	$P_F = 7.0 \times 10^{-7}$ per year ($\beta = 4.0$)	$P_F = 2.5 \times 10^{-7}$ per year ($\beta = 4.25$)	$P_F = 1.0 \times 10^{-7}$ per year ($\beta = 4.5$)

[1] The target reliability indices (β) are provided for a 50-year reference period.

9.8 Van Coile et al., 2018 - hierarchies of acceptance criteria

While probabilistic risk assessment (PRA) is commonly accepted as a tool for performance based design in fire safety engineering, Van Coile et al. [90] posit that the position of PRA in the design process, the relationship between different acceptance concepts (absolute, comparative, ALARP), and the responsibilities of the designer all remain unclear. In this paper they aimed to clarify these aspects by investigating the safety foundation of fire safety solutions and showing that PRA is necessary for demonstrating adequate safety when no appeal can be made to the collective experience of the profession.

Van Coile et al. [90] state that:

> *"PRA is not a methodology for 'future fire safety engineering', but rather a necessary methodology to provide an objective safety foundation for uncommon fire safety designs. Acknowledging that what constitutes 'acceptable safety' is subjective and may change over time, an objective proxy of 'adequate safety' is defined and proposed as a benchmark against which to assess the adequacy of fire safety designs. In order to clarify the PRA process, a hierarchy of different acceptance concepts is presented. Finally, it is shown how, depending on the applied acceptance concepts, the designer takes responsibility for different implicit assumptions regarding the safety performance of the final design."*

9.9 LaMalva et al., 2018 - SFPE proposed framework

LaMalva et al. [91] describe recent efforts within SFPE to develop a reliability-based framework for structural design fires. The proposed framework is based on parametric equations in Annex A of the Eurocode 1 with provisions for reliability-based treatment of certain input parameters. It is noted that the simplified framework does not explicitly address issues of risk perception.

9.10 Hopkin et al., 2018 - the J-value

Hopkin et al. [92] discuss how a decision support indicator ('The J-value') can be used to help inform decisions on fire safety. The J-value has been introduced in other engineering fields for assessing the efficacy of safety features. The J-value has been derived from societal welfare considerations (the Life Quality Index - LQI) and Hopkin et al. [92] adopted it for applications in fire safety engineering.

Arnott et al. [93] used the J-value to assess the cost-effectiveness of a proposal for mandating the retrofitting of existing high rise residential buildings (HRRBs) in England with sprinkler systems and for the Ministry of Housing, Communities and Local Government proposal to reduce the trigger point from greater than 30 m to greater than 18 m in height for all new-build HRRBs. Arnott et al. [93] also found the J-value to be easy to interpret, with an outcome less than unity indicating that a safety scheme offers a net-benefit to society. Contrary, a value exceeding unity highlights that the safety scheme is likely beyond society's capacity to commit resources (ie, a net-disbenefit).

9.11 PD 7974-7, 2019 - probabilistic risk assessment

British Standard Publication PD 7974-7:2019 [48] Application of fire safety engineering principles to the design of buildings - Part 7: probabilistic risk assessment was recently revised in 2019. This document provides guidance on probabilistic risk analysis in support of BS 7974 and sets out the situations in which a probabilistic risk assessment can add value to traditional deterministic analyses and outlines acceptance criteria for the assessment.

PD 7974-7 provides an generalised frequency - consequence diagram using log scales as shown in Figure 27. This diagram shows three region: an intolerable region where the design is unacceptable irrespective of the benefit; a de minimus or negligible region where the design is acceptable without further justification; and an intermediary ALARP region where the design is only acceptable if the risk is "As Low As Reasonably Practicable". In this region, a design is acceptable when all reasonably practicable risk reduction measures have been implemented. A risk reduction measure is not reasonably practicable if implementing the measure (in terms of the sacrifices) would be grossly disproportionate to the reduction in risk or the safety benefit achieved. Essentially this implies there should be some cost benefit evaluation or lifetime cost optimisation of the risk reduction measures.

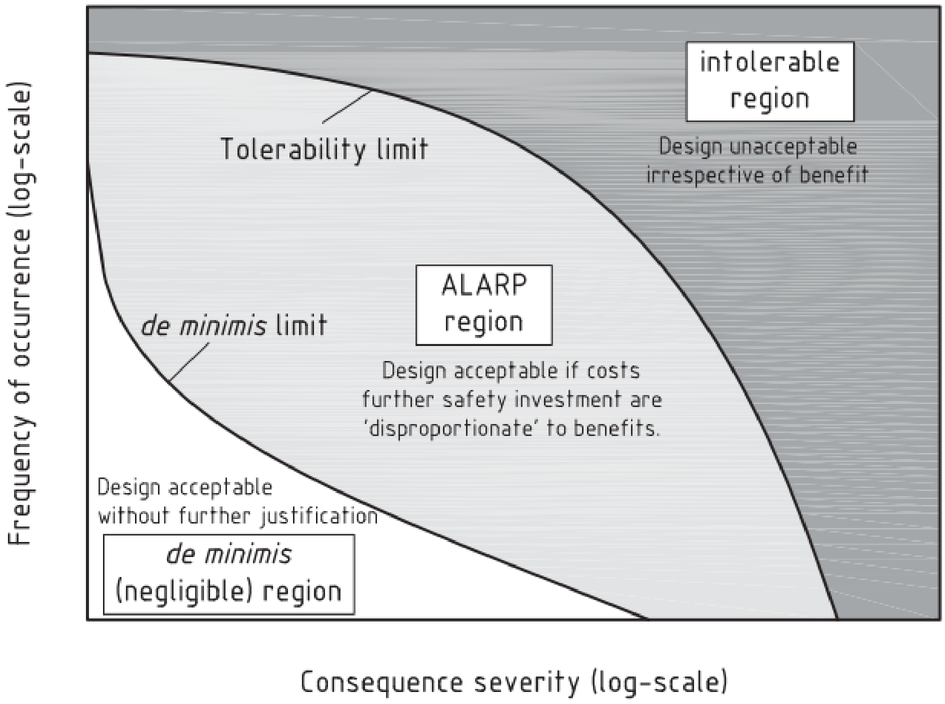

Figure 27. Illustrative fN curve – Societal acceptance criterion for a disaster: Relationship between consequence severity (event severity) and the frequency of event (event likelihood). Extracted from [83]. Reprinted by permission from Springer.

9.12 Mohan et al, 2021 - risk tolerability limits

Mohan et al. [94] proposed a simple framework for setting risk tolerability limits. Their framework provides practical guidance for the application of international fire safety guidance, such as the recently published guidance PD 7974-7:2019. They point out that PD 7974-7 is hindered by two main constraints: (1) it requires risk tolerability limits to be set, but lacks guidance on defining them for a specific building project, and (2) no reference case studies are given that demonstrate the application of PRA methods to fire engineering design. In order to help fill this gap, Mohan et al. propose a risk tolerability framework. Their procedure is outlined in Figure 28.

The societal tolerability limit is defined by the following parameters: (1) an anchor point; (2) slope; (3) cut-offs for cumulative frequency and/or consequence with the process shown in Figure 29. The anchor point is selected through stakeholder consultation or alternative methods . They recommend to establish the maximum tolerable frequency F10 of death (as commonly approximated by exposure to untenable conditions) for 10 persons to aid communication with non-risk experts. The individual tolerability limit suggested in Table A.1 of PD 7974–7:2019 is 10^{-4}/year. The slope of the tolerability limit is assumed to reflect the degree of risk aversion. They note that UK tolerability limits have a slope of -1 whereas the Netherlands has adopted a slope of -2.

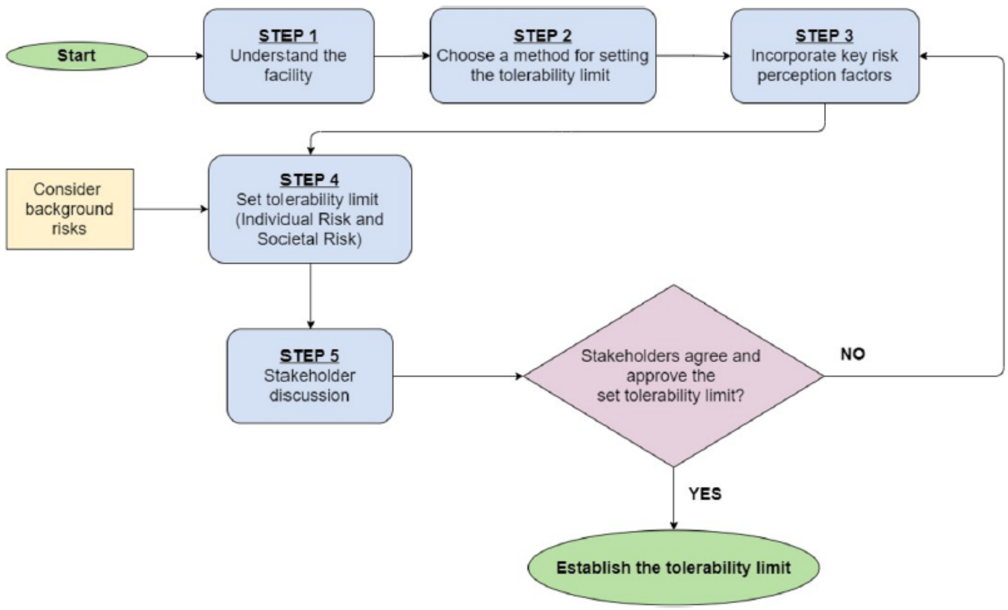

Figure 28. Proposed procedure for setting the tolerability limit for fire engineering PRA. [94]. Reprinted by permission from Springer.

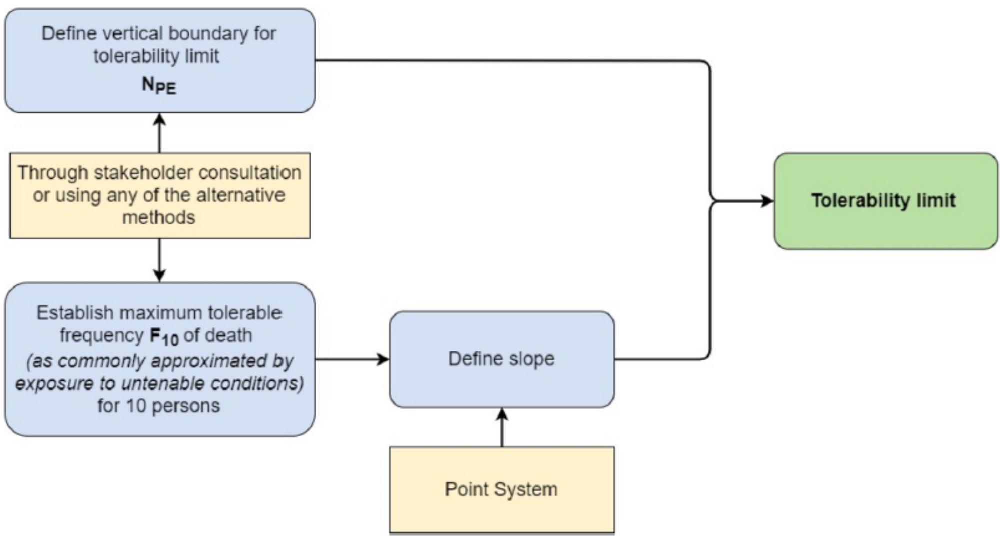

Figure 29. Flowchart illustrating the steps for setting up a societal tolerability limit. [94]. Reprinted by permission from Springer.

They also give an example application for an office building with an FC diagram shown in Figure 30. For this example an anchor point aligning with UK HSE criteria is set at (10, 10^{-3}) i.e. the maximum tolerable frequency (F_{10}) of exposure to untenable conditions for 10 persons or more is 10^{-3} per year. The corresponding de minimis value for 10 persons or more is shown as 10^{-5} per year. The maximum possible number of fatalities on this floor of the office building representing the maximum number of exposed persons is 1790. Readers are referred to the paper by Mohan et al. [94] for a full description and discussion of the method and example.

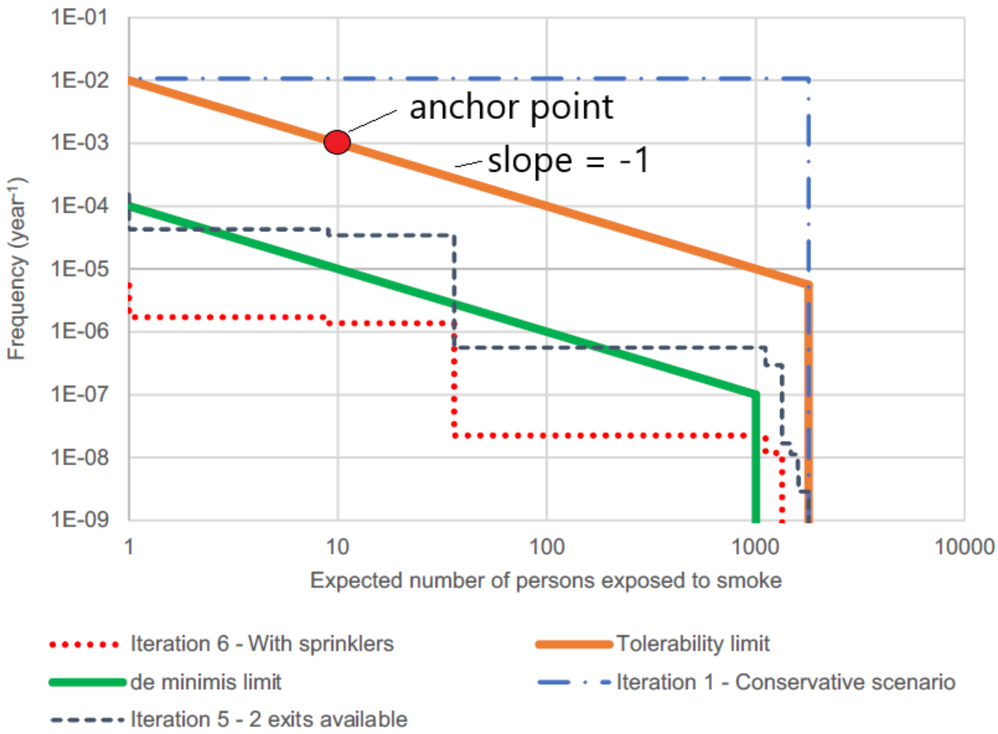

Figure 30. Example FC diagram for an office building [94].

9.13 ABCB, 2021 - draft acceptance criteria

The Australian Building Codes Board (ABCB) has published draft acceptance criteria for exposure to untenable conditions as part of a fire safety quantification project for potential use in conjunction with the National Construction Code (NCC) [95]. The proposed draft criteria for individual risk and for societal risk are shown in Table 35 and Table 36 respectively. In the NCC multi-storey densified housing would be categorised as a Class 2 building.

Table 35. Allowable individual risk of exposure to untenable conditions [95].

Number of people exposed to untenable conditions	Individual risk pa (lower tolerable limit)	Individual risk pa (upper tolerable limit)
$\geq$ 1 building class 2, 3, 4, 9a or 9c	5×10^{-6}	5×10^{-4}
$\geq$ 1 building class 5, 6, 7a, 7b or 9b	1×10^{-6}	1×10^{-4}

Table 36. Allowable societal risk of exposure to untenable conditions [95].

Number of people exposed to untenable conditions	Societal risk pa (lower tolerable limit)	Individual risk pa (upper tolerable limit)
≥ 5	8.9×10^{-7}	8.9×10^{-5}
≥ 10	3.2×10^{-7}	3.2×10^{-5}
≥ 20	1.1×10^{-7}	1.1×10^{-5}
≥ 50	2.8×10^{-8}	2.8×10^{-6}
≥ 100	1.0×10^{-8}	1.0×10^{-6}
≥ 200	3.5×10^{-9}	3.5×10^{-7}
≥ 500	8.9×10^{-10}	8.9×10^{-8}
≥ 500	3.2×10^{-10}	3.2×10^{-8}

The ABCB also offers the following guidance for the application of these draft criteria [95]:

> *"If the lower tolerable limits (individual and societal) are not exceeded by the proposed Performance Solution the individual and societal risk criteria can be considered to be satisfied."*
>
> *If the upper tolerable limits (individual or societal) are exceeded by the proposed Performance Solution the individual or societal risk criteria have not been satisfied and modifications to the proposed solution will be required.*
>
> *If the individual and / or societal risks presented by the proposed Performance Solution lie between the lower and upper allowable risks the proposed Performance Solution can be considered to have been satisfied if the following additional criteria is satisfied if it can be demonstrated that:- the individual and / or societal risk presented by the Performance Solution is less than or equal to that presented by a similar Deemed-to-Satisfy compliant reference building that is considered to represent a tolerable risk."*

Moinuddin and Tan [96] plot comparative F-N curves from ABCB with those UK, Netherlands and Denmark as shown in Figure 31. The ABCB curve was stated to have come from the ABCB Tolerable Risk Handbook [97] noting that the curve varies from the data in Table 35 and Table 36. It is also notable that the UK risk acceptance criteria from the HSE is significantly less stringent than for the other countries shown.

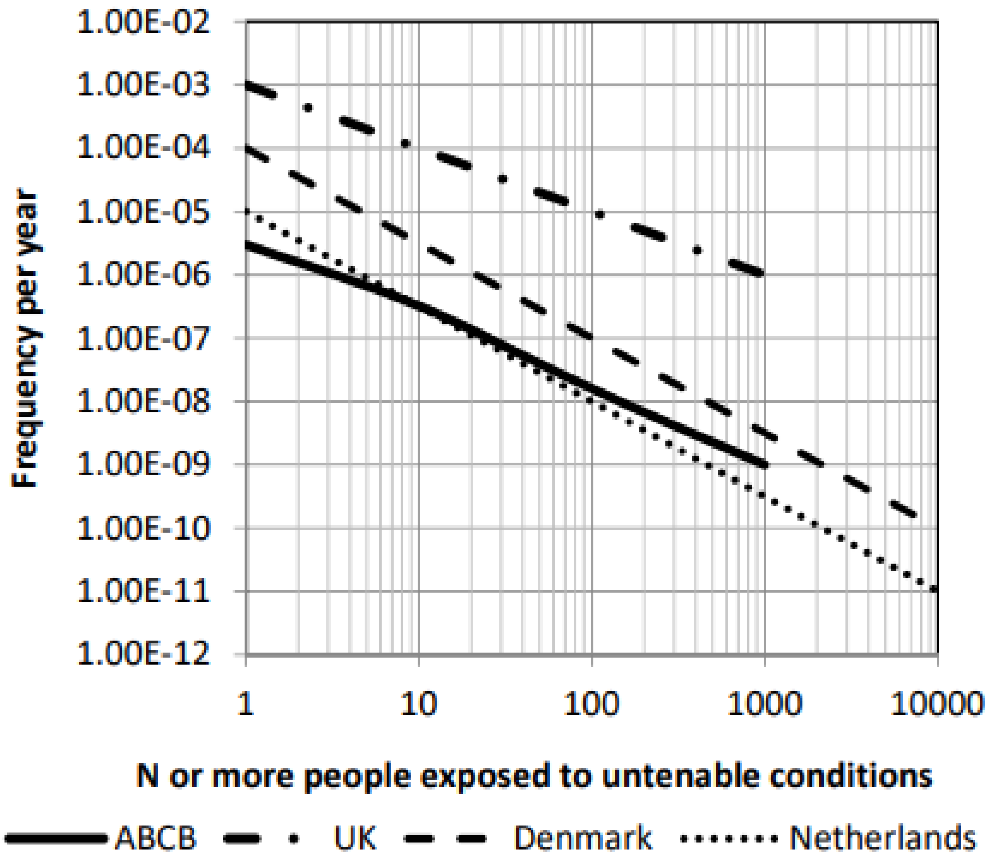

Figure 31. International F-N curve criterion lines superimposed on the ABCB Tolerable Risk Handbook [96].

10. Structural Fire Reliability

10.1 Wong., 1999 - reliability of structural fire design

In a Master of Engineering project at the University of Canterbury, being an early New Zealand study of this type, Wong [98] assessed a typical structural steel design exposed to fire for its reliability. He estimated the probability of failure of structural steel elements exposed to a wide range of fully developed fires using Monte Carlo simulation. He concluded that deterministic or "single value" analysis in design can give very misleading results if the variability in properties and the full range of possible scenarios are not taken into account, and that applying reliability assessment to structural fire design is of great value in highlighting any deficiency or shortcoming in a design.

10.2 Kirby et al., 2004 - BSI task group

Kirby et al. [99] described work done by a BSI task group who developed a new approach for specifying fire resistance requirements for inclusion in a new code of practice for fire safety design, construction and use of buildings (now BS 9999 [34]). The methodology involved graphical time equivalent fire engineering calculations used in a probabilistic (monte carlo) manner.

The reason given by Kirby et al. [28] for selecting the graphical time equivalent method based on maximum temperature reached by protected steel rather than a simpler time equivalent formula as the basis for the approach was: a) factors for the insulation characteristics of the compartment boundaries in the latter change in broad steps rather than in gradual increments; and b) the latter does not consider the influence of fire growth rates, which may be slow, medium or fast.

Input distributions for the fire load were taken from BS 7974 of the time and engineering judgement was used for other variables such as room size and minimum and maximum opening areas. These are summarised in Table 37 and Table 38. Analysis also included the sprinklered case where a sprinkler reduction factor of 0.61 was applied to the fire load distribution as given in EN 1991-1-2.

Table 37. Fire load density adopted in the parametric temperature time fire analysis for residential buildings [99].

	Fire load density (at each fractile) MJ/m^2				
	100%	95%	90%	80%	Avg
Residential	1200	970	920	870	780

The output from their analysis for residential buildings is shown in Figure 32. Since the cumulative distribution curves only accounted for fire severity in engineering terms, further considerations were needed to account for fire fighting requirements, consequences of failure and evacuation characteristics of occupants leading to recommended fire resistance levels shown in Table 39. See also the discussion in subsection 7.2 and Table 24. It is important to appreciate that correlation of building height with risk and fire resistance as manifested in Table 39 was anchored or calibrated to the existing prescriptive guidance

Table 38. Variables adopted in the parametric temperature time fire analysis for residential buildings [99].

	Compartment height (m)	Ventilation height (prop. of compartment height)	Floor area (m^2)	Ventilation area (percentage of floor area) (%)
Residential	2.4	0.3 to 0.9	9 to 30	5 to 20

within Approved Document B such that the 80% fractile corresponded with a building 18 m in height.

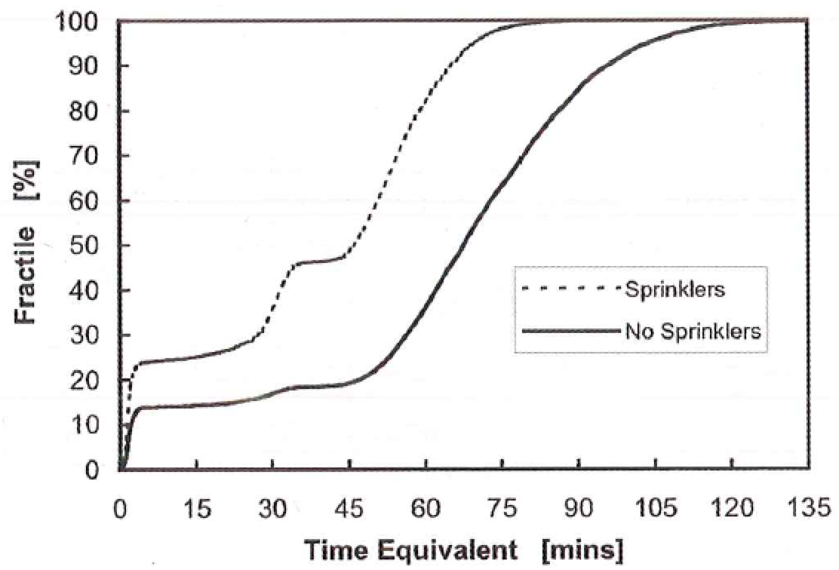

Figure 32. Cumulative distribution for residential buildings [99].

10.3 PEER performance based earthquake engineering framework

The Pacific Earthquake Engineering Research (PEER) Center's Performance Based Earthquake Engineering (PBEE) framework is a linear methodology which is based upon obtaining in turn output from each of the following analyses: hazard analysis; structural analysis; loss analysis, and finally decision making based on variables of interest, such as downtime or cost to repair [100]. Lange et al. [100] demonstrated an application of the PEER framework to structures in fire. The output of the analysis is a set of annual cost and downtime curves associated with one possible engineering demand parameter. They used peak compartment temperature as the intensity measure but other measures could also be more suitable e.g. cumulative incident radiation as proposed by Shrivastava et al. [101]. Selamet and Akcan [102] also followed the approach of Lange et al. in a preliminary probabilistic risk assessment of high-rise buildings in case of a fire event also taking the maximum fire temperature as the intensity measure.

Table 39. Proposed fire resistance periods for sprinklered and non-sprinklered buildings [99].

	Building height, m					
	0 - 5	5-11	11-18	18-30	30-60	>60
non-sprinklered	60*	90	105	120	135	150
sprinklered	45*	60	75	75	90	105

* Reduced to 30 min for single owner occupancy.

10.4 Law et al., 2015 - risk based framework

Law et al. [103] discuss the challenge of meeting fire safety goals and the constraints of the building while attempting to achieve an appropriate balance of safety. These challenges are the fire safety goals and the constraints of the building and the physical world. The appropriate balance of these challenges is a solution as illustrated in Figure 33.

Law et al. [103] give examples of an application in the context of time equivalence analysis. They found that the existing time equivalence methods do not adequately consider the challenges, and proposed an alternative risk based approach for structural fire resistance. They say that this approach is sufficiently flexible that its component pieces can be improved and updated as new engineering techniques become available.

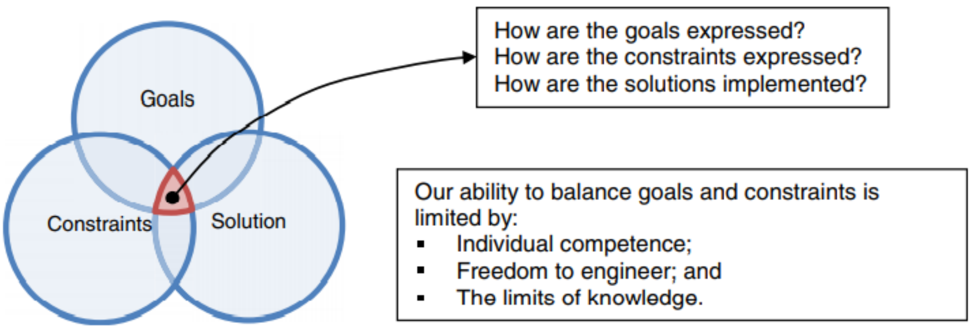

Figure 33. Design challenges, questions, and limitations [103]. Reprinted by permission from Springer.

Their method for defining structural fire engineering goals (described below) uses a benchmarking technique similar to that already adopted in BS 9999:2008 [34]. Their approach to defining the required performance was based on maintaining a constant level of risk across all building stock, irrespective of occupancy or height.

The contribution of the sprinklers to the structural reliability can be expressed as shown in Equation 21, where r_T is the aggregate reliability of the structure, r_{sp} is the sprinkler reliability and r_{st} is the reliability of the structure in the event of sprinkler failure. Law et al. [103] present Figure 34 and Table 40 to illustrate the approach.

$$r_T = r_{sp} + (1 - r_{sp}) \times r_{st} \tag{21}$$

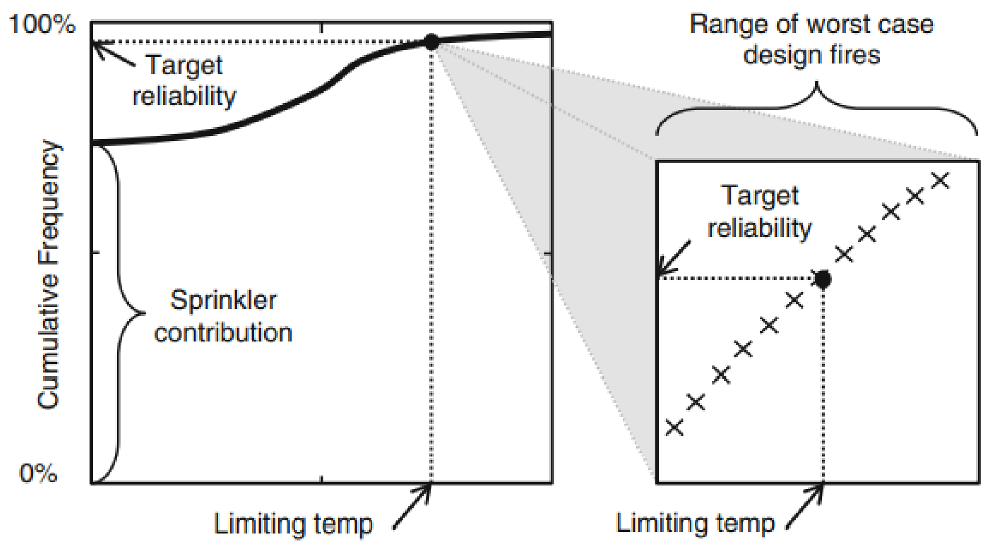

Figure 34. Determining the optimum fire resistance period [103]. Reprinted by permission from Springer.

Table 40. Design Structural Reliability. Based on Law et al. [103].

Building height (m)	Design reliability	Structural reliability with: 75% Reliable sprinklers	90 % Reliable sprinklers	95% Reliable sprinklers
10	35%	N/A	N/A	N/A
20	84%	35%	N/A	N/A
30	93%	71%	28%	N/A
40	96%	84%	60%	19%
50	97%	90%	74%	48%
60	98%	93%	82%	64%
80	99%	96%	90%	80%

10.5 Hopkin et al., 2016 - fire resistance demands for tall residential buildings

Hopkin et al. [13] state that reliability methods have gained traction as a tool for quantifying the acceptability of design solutions, and it has become common in the UK for designers to express their performance objective in terms of reliability, ie the percentile (fractile) of fires that a building should be capable of resisting.

Acknowledging that previous efforts by other researchers have focussed upon expressing the required reliability (the goal) as a function of only building height and use, Hopkin et al. describes a calibration to the ADB for England and Wales for single means of escape residential buildings. They proposed a generalised form of risk as given by Equation 22 with the terms defined in Table 41.

$$\text{Risk} = F_n P_f \left(C_i + C_e\right) \tag{22}$$

Table 41. Components of risk - elaboration of key terms. Extracted from Hopkin et al. [13].

Component	Elaboration	Comments
F_n	$F_{i,n}t_{des}$	Frequency of the fire occurrence (F_n - number of expected fires) is described in terms of the likely number of fires occurring within a particular usage zone ($F_{i,n}$ - fires per year) of a building throughout the course of the structure's design life (t_{des} - years)
P_f	$(1 - R_{frs})$	The probability that a fire brings about failure is the complement of the design reliability of the fire resistance system (R_{frs} - the percentage of possible fires the system is capable of resisting). The manifestation operates on the premise that (a) the fire is severe enough to bring about the failure of an isolated element, and (b) enough structural elements are affected to lead to structural instability.
C_i	$\Sigma(e_n O_n)/O_b$	The internal occupancy is described in terms of 'effective occupant storeys'. The building in its entirety is interrogated to establish the fraction (e_n) of the occupants O_n which may be in the building at the time of failure. This is done by interrogating the occupancy and evacuation mode associated with each usage zone (n) and summing. The outcome is normalised relative to a baseline number of occupants per storey O_b.
C_e	H/h_b	The overall relevant height of the building (H-m) is normalised relative to a baseline storey-to-storey height (h_b - m) to describe the 'external' aspect of consequence in terms of 'effective height storeys', for dimensional consistency with C_i.

10.6 Hopkin, 2017 - high-rise UK apartment buildings

Hopkin [14] carried out a review of fire resistance expectations for high-rise UK apartment buildings, examining the impact of increasing height on the fire risk and the role of sprinkler systems. They observed that, in the context of prescriptive structural fire resistance, buildings are afforded a fire resistance period based upon their height and use and expressed the view that the broad aim of such prescriptive guidance is the delivery of a consistent level of risk across all building types. They conclude that for this to be achieved, as the frequency of fires and consequence of failure increases, the reliability of the fire resistance system must increase and that this typically manifests in an increase in a building's fire resistance expectation as height increases.

This study reviews the concept of fire resistance as a height dependant metric for residential buildings, identifying the limitations of such an approach, utilising single stair apartment buildings as a basis for demonstration and further investigations.

Hopkin proposes a risk correlation that seeks to explicitly define the structural fire resistance design goal (reliability of the fire resistance system) as a function of both height and occupancy. He calibrated the correlation against UK statistical data to determine what might constitute a common building and found that in single stair buildings, an appropriate benchmark case would constitute 7 apartments per level, ranging in size from 1 to 3 bedrooms (28 m^2 to 101 m^2).

He then uses this benchmark case to determine a risk score which, for the purpose of achieving a consistent level of risk, becomes a constant in his risk correlation. The correlation indicates that for the different cases analysed, despite being of the same height, have significantly different fire resistance system reliability demands (96.3% to 98.5%) and, thus, fire resistance demands (154 min to 173 min). Hopkin concluded that, if conventional structural fire resistance thresholds are not to be exceeded (in the UK typically limited to 120 min), then, in tall residential buildings, the reliability/efficacy of the sprinkler system becomes increasingly important.

10.7 Hopkin et al., 2018 - LQI applied to two Mumbai residential towers

Hopkin et al. [104] presented a case study concerning a probabilistic performance based structural fire engineering analysis which served to inform the fire resistance requirements for two adjacent high-rise residential concrete structures in Mumbai, India. An appropriately low probability of structural element failure in the event of fire was based on the relevant Society's Capacity to Commit Resources (SCCR). Following a series of Latin Hypercube Sampling studies including various design fire and heat transfer considerations, it was determined that a fire resistance period of 120 minutes was appropriate for the two towers.

10.8 Wade & Frank, 2019 - industrial and warehouse buildings

Wade and Frank [105] investigated fire resistance requirements applied to external boundary walls in single-storey industrial and warehouse buildings in New Zealand. They did a probabilistic analysis using latin hypercube sampling methods in conjunction with the graphical time-equivalence method and constructed probability distributions for the required fire resistance ratings. Cumulative frequency distribution curves showing the fire resistance percentiles were presented. As part of the analysis, both the graphical time equivalence method and the cumulative radiant energy (CRE) method were used and the cumulative frequency curves compared as shown in Figure 35. For case A with the lower FLED, the CRE method provided slightly less conservative results when compared to the graphical time-equivalence method, however for Case C with the higher FLED the CRE provided a more conservative result.

10.9 Fu et al., 2019 - monte carlo simulation using SfePrapy

Fu et al. [74] developed a library of a probabilistic functions written in the programming language Python that can be used to estimate the distribution of fire severities expected within an enclosure for a given scenario. They illustrate the application of the Python library with an exemplar 18 m tall office building design case, where the required structural fire resistance is computed based upon the (conditional) reliability targets underpinning BS 9999.

The Structural Fire Engineering PRobabilistic reliability Assessment PYthon (SfePrapy)

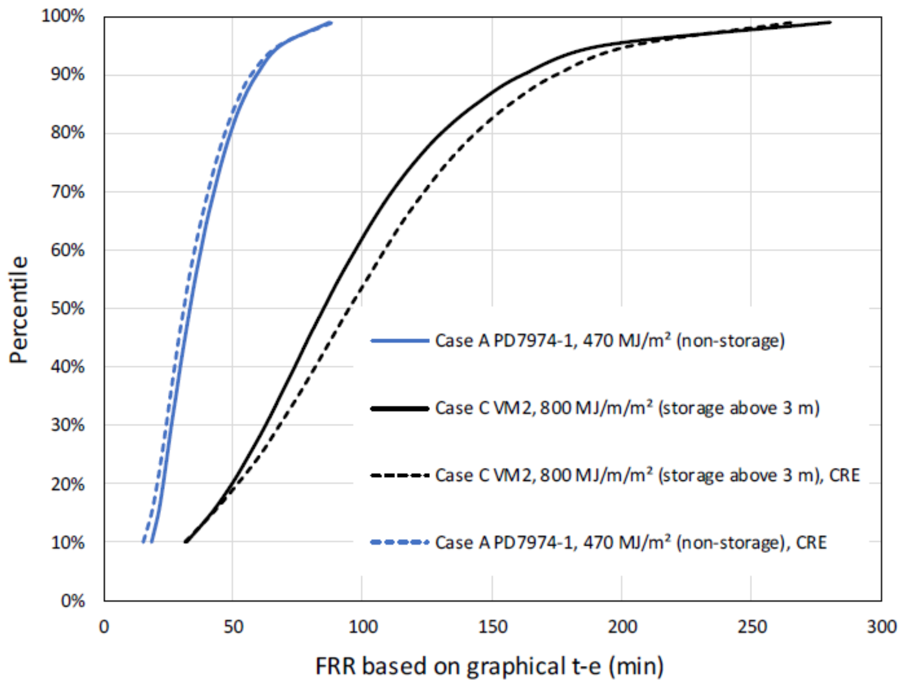

Figure 35. Comparing cumulative frequency distribution for FRR based on t-e and FRR based on CRE method. Extracted from Wade and Frank [105].

library allows the PRA procedure to be automated to provide readily verified modules that can be assembled by users for a given application. SfePrapy is a probabilistic analysis package that estimates the distribution of fire severities expected within an enclosure for any given scenario, e.g. varying enclosure geometry, building type, window areas etc. SfePrapy is available on PYPI and GitHub. SfePrapy currently adopts an approach for determining the structural fire resistance requirements for a building and employs the equivalent time of exposure concept (based on maximum temperature method for protected steel sections as previously described in subsection 3.5 and as used by Kirby et al. [99]) to develop the cumulative density function (CDF) of the time equivalence values [74].

A novel feature of SfePrapy is the switching between a uniform parametric fire and a travelling fire depending on the sampled inputs for a given simulation. Fu et al. state that the travelling fire model is used unless all the following conditions are satisfied in which case the parametric design fire is used [74].

- Fire load density per unit enclosure surface area is between 50 and 1000 MJ/m^2 inclusive (as per EN 1991-1-2 Annex A).
- There must be sufficient ventilation for the fire to develop the heat release rate necessary to near-simultaneously ignite all combustibles to represent a flashover condition. Thus, the opening factor must be 0.02 or greater (as per EN 1991-1-2 Annex A).
- The compartment must not be over-ventilated to the extent that too much energy is able to leave the fire compartment, thus resulting in low temperatures and a low likelihood of involvement of all combustible materials. The opening factor must be 0.2 or less (as per EN 1991-1-2 Annex A).

- The fuel at the point of origin must not have been fully consumed in the time taken for the fire to spread to involve the rest of the compartment.

The Monte Carlo Simulation (MCS) procedure adopted by Fu et al. [74] is illustrated in Figure 36.

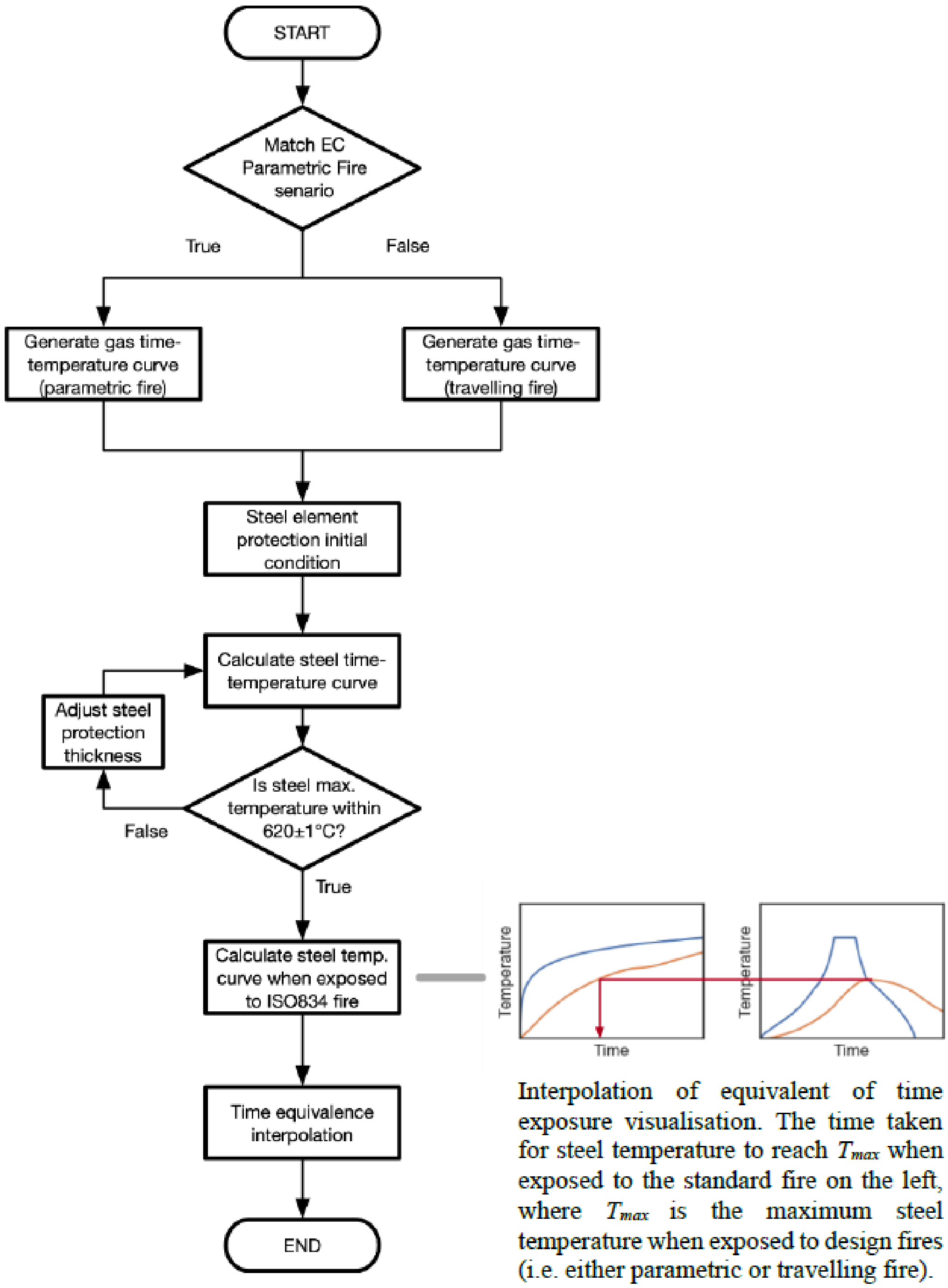

Figure 36. The process of a single MCS in determining structural fire resistance. Extracted from [74].

10.10 Fu et al., 2021 - an improved reliability approach

Fu et al. [106] then revisited the work of Kirby et al. [99] resolving some of the key limitations and incorporating advancements in the field using the SfePrapy tool [74]. One of the advancements is the fire model selection able to switch between a parametric model for uniform fires and the travelling fire model for cases that are outside the stated limits of the parametric fire (see section 7). This was previously illustrated in Figure 36. Fu et al. then use the SfePrapy tool to assess the recommended fire resistance for structural elements for office, retail and residential type buildings but linked to both the building consequence class and its total floor area. They adopted the cost-optimised failure probabilities from the JCCS probabilistic model code and ISO 2394:2014 with the added tentative connection between Consequence Class and reliability index as shown in Table 42 and assuming a "normal" relative cost of reducing the failure probability (see Table 31).

Table 42. Consequence class, building height (no. of storeys) and allowable failure probability considering residential, retail and office type buildings [106].

	Consequence class (or building class)		
	CC2A	CC2B	CC3
No. of storeys	< 4	> 4 and ≤ 15	> 15
Reliability index, $\beta(-)$	3.7	4.2	4.4
Allowable failure probability per yr	$\approx 1 \times 10^{-4}$	$\approx 1 \times 10^{-5}$	$\approx 5 \times 10^{-5}$

The probability of a structurally significant fire p_{fi} was evaluated based on a combination of the probability of ignition and subsequent interventions prior to the fire becoming fully developed. This followed the NFSC approach [45] described earlier in subsection 6.2 and underpinning EN 1991-1-2.

$$p_{fi} \times P_{f,fi} \leq P_{f,a} \tag{23}$$

$$p_{fi} = p_1 \times A \times p_2 \times p_3 \times p_4 \tag{24}$$

where
p_1 is the probability of a severe fire occurring including the influence of occupants and standard fire service (per m^2 per year). [6.5×10^{-7} per m^2 per year for residential based on the NFSC report .]
A is the area of compartment/occupancy (m^2).
p_2 is the probability of unsuccessful fire suppression by FRS intervention (considering improved professionalism/performance). [0.2 based on the NFSC report assuming a professional fire service is provided to intervene, should a fire occur, in 20 to 30 minutes after the alarm activation.]
p_3 is the probability of unsuccessful fire suppression associated with fire alarm and detection systems. [0.0625 based upon the NFSC report assuming that smoke detectors are provided in the residential areas.]
p_4 is the probability of unsuccessful fire suppression by active fire protection systems (sprinkler). [0.09 based on PD 7974-7:2019 [39] and sprinkler statistics as garnered by the NFPA in 2017 [107].]

The conditional probability of a failure given a structurally significant fire, $P_{f,fi}$ is the complimentary CDF of the MCS producing a collection of time equivalence values i.e. $1 - P(t_{eq,i \leq x})$. Fu et al. [106] conducted 100,000 iterations from the input data shown in Table 43 and generated the CDF shown in Figure 37.

Table 43. Key parameters adopted for the time equivalence MCS for residential occupancies [106].

Parameter	Distribution	Value
Fire load density (MJ/m^2)	Gumbel	Mean: 780 SD: 234
HRR per unit area (MW/m^2)	Uniform	0.32 to 0.57
Room height (m)	Uniform	2.4 [1]
Floor area (m^2)	Uniform	9 to 30
Window height to floor area ratio (-)	Uniform	0.3 to 0.9
Window area to floor area ratio (-)	Uniform	0.05 to 0.2
Fuel combustion efficiency (-)	Uniform	0.8 to 1.0
Glazing breakage percentage (-)	Complementary lognormal [2]	Mean: 0.2 SD: 0.2
Model uncertainty factor [3] (-)	Lognormal	Mean: 1 SD: 0.25

[1] Constant is used in lieu of random values based on a distribution.
[2] Truncated between 0 and 1.
[3] Truncated between 0 and 3.

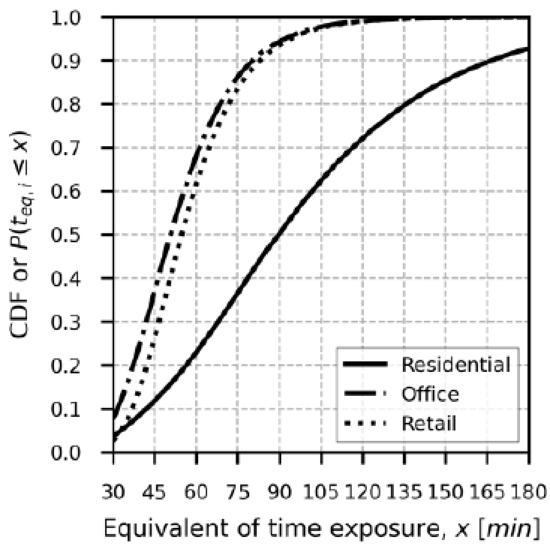

Figure 37. CDF of time equivalence. Extracted from [106].

Finally, Fu et al. [106] produced Figure 38 showing the relationship between floor area, no. of storeys, consequence class and the fire resistance required.

A limitation of the method is that all the uncertainty associated with the structural fire safety analysis is assumed in the thermal domain, i.e., through applying thermal equivalence and without consideration of uncertainty in the mechanical resistance or actions. Hopkin, et al., apply an adapted form of the SfePrapy tool to directly compute the failure probability of a protected steel element in bending given uncertainty in the thermal

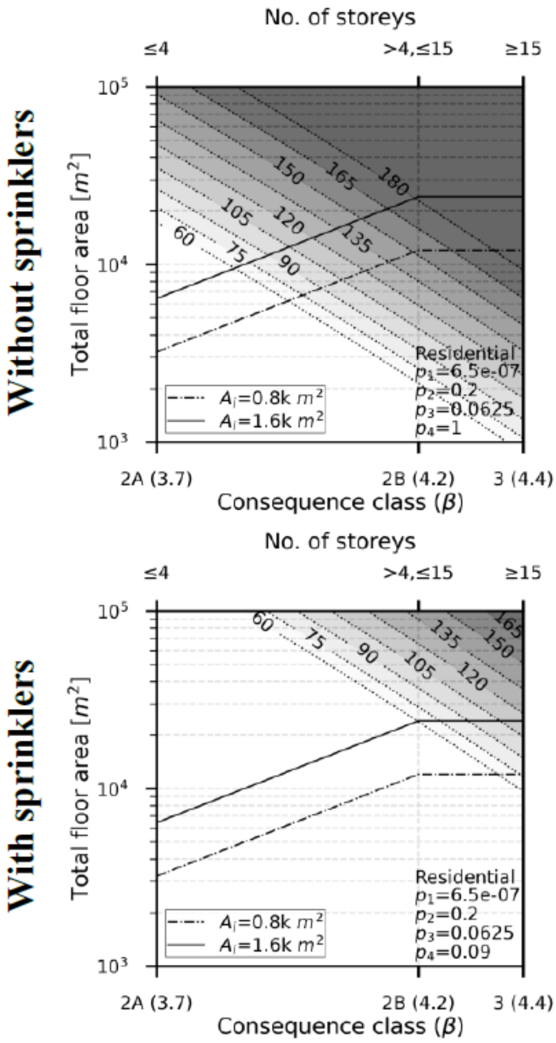

Figure 38. Contour plots of the solved structural fire-resistance rating at various building heights and total floor area (without and with sprinklers); A_i denotes floor area per storey. Extracted from [106].

and mechanical load, and uncertainty in the action. The corresponding fragility curves are subsequently adopted to compute optimized safety targets for protected steel elements.

11. Analysis Method

This section sets out the methodology and assumptions to be used in subsequent analysis to calculate the relationship between the failure probability of fire rated elements of a given FRR and the expected fire severity in multi-storey buildings comprising household units. The methodology comprises two parts. Firstly a CDF curve is determined representing the cumulative probability of the fire severity exceeding a given FRR given a structurally significant fire has occurred. Secondly, the probability of a structurally significant fire occurring is calculated.

The probability of a structurally significant fire p_{fi} is evaluated using Equation 24 based on a combination of the probability of ignition and subsequent interventions prior to the fire becoming fully developed. This follows the NFSC approach [45] underpinning EN 1991-1-2 and described earlier in subsection 6.2 and as described by Fu et al. [106].

The MCS analysis uses the SfePrapy tool [74] developed by Fu et al. [74, 106] and described earlier in subsection 10.10. This methodology resolved some of the key limitations of the Kirby et al. [99] study by incorporating advancements in the field such as applying the travelling fire methodology when the application limits of a uniform fire are reached due to window area or compartment size. The SfePrapy tool allows the EN 1991-1-2 Annex A or DIN EN 1991-1-2 NA fire models to be considered either alone or in combination with the traveling fire model (see subsection 7.5).

The time equivalence method in SfePrapy is based on the maximum temperature of a protected steel element also used by Kirby et al. SfePrapy uses the correlations detailed in BS EN 1993-1-2:2005 for the steel heat transfer calculations. The protection thickness is determined by iteration to ensure a maximum steel temperature of 550 °C with the general procedure for the MCS as previously shown in Figure 36.

11.1 Probability of a structurally significant fire and failure

The conditional probability of a failure given a structurally significant fire, $P_{f,fi}$ is extracted from the complimentary CDF from the MCS producing a collection of time equivalence values i.e. $1 - P(t_{eq,i \leq x})$. The probability of a failure is then calculated by $p_{fi} \times P_{f,fi}$ which can then be compared to the target probability.

Assumptions include:

- the frequency of a reportable fire event per year (or over the life of the building). We can assume a 50 year life. Fire incident data for New Zealand apartments gives a fire frequency of 2.7×10^{-3} per year per household unit corresponding to the mean value reported by Robbins et al. [37].

- the proportion of total fires that will become fully developed or reach flashover (in the absence of active suppression) - a value of 18% could be adopted as proposed in the relevant NCC Verification Method data sheet and consistent with fire incident data previously reported from Canada and USA.

- $p_1 = 2.7 \times 10^{-3} \times 0.18 = 4.86 \times 10^{-4}$ fires per household unit per year.

- Assume $p_2 = 0.2$ for a professional fire brigade in an urban area assuming that firefighting intervention can be initiated within 30 minutes. This has been used for all cases. The impact of assuming $p_2 = 1.0$ will also be investigated for some cases for potential application to tall buildings.

- Assume $p_3 = 0.0625$ assuming an automatic smoke detection and fire service notification system will always be present in residential buildings (as per NFSC).
- Assume $p_4 = 0.1$ for sprinkler effectiveness (as per PD 7974) assuming that the fire severity will not exceed the FRR in a building (i.e. the fire separations will not fail) where sprinklers are installed and they are 'effective'. Also consider the effect of increasing the effectiveness to 0.95 for a more reliable sprinkler system design.

11.2 Input parameters for MCS

Input parameters are summarised in Table 44 and include the following:

Enclosure inputs

- Firecell floor area - use a distribution appropriate for densified housing in New Zealand. Over the five year period from 2016 to 2020, the average floor area of new apartments, townhouses, units and other dwellings (excluding houses) in building consent data was 111 m^2 [26]. The floor area will be described by the cumulative density function shown in Figure 12.
- Compartment height in the range 2.3 to 2.7 m. This range is described as a uniform distribution.
- Compartment aspect ratio in the range 0.4 to 0.6. This range is described as a uniform distribution.
- Compartment thermal properties - Plasterboard properties are assumed with the thermal parameter k_b = 0.09 and thermal intertia $\sqrt{k\rho c} = 700$ J/m^{2}s$^{0.5}$K.

Ventilation inputs

- Ventilation through openings in walls - given the uncertainty in ventilation, and the extent to which glazing may fallout or not, then assume a uniform distribution for the opening area using the same assumptions as used in the Kirby et al. [28] study i.e. opening area in the range 10% to 20% of the floor area and opening height in the range 30 to 90% of the compartment height. These ranges are described as uniform distributions.
- In addition, the opening factor can be varied to account for less than the maximum area of glass falling out as included in the JCCS Probabilistic Model Code as previously described in subsection 7.6.

Fire inputs

- Fire load energy density (FLED) - use a distribution appropriate for apartment buildings based on the ABCB Data sheet value for Class 2 buildings of a normal distribution with mean 500 MJ/m^2 standard deviation 150 MJ/m^2 with a minimum of 200

MJ/m^2. An upper limit of 1200 MJ/m^2 will also be assumed. This does not include any contribution from combustible construction materials.

- Combustion efficiency as a uniform distribution in the range 0.8 to 1. *Noting that EN 1991-1-2 allows the combustion efficiency to be taken as 0.8. This factor is applied to the fire load density.*
- Time for maximum gas temperature in case of fuel-controlled fire, 20 minutes.

Additional DIN EN 1991-1-2/NA fire inputs

- Time of fire growth to reach 1 MW, 300 sec.

Additional traveling fire inputs

- Heat release rate density, uniform distribution in the range 320 to 570 kW/m^2
- Fire spread speed, uniform distribution in the range 0.0035 to 0.019 m/s
- Near field temperature, normal distribution with mean 1323.15 K and standard deviation 93 K and constrained in the range 623.15 to 1473.15 K
- Beam position horizontal ratio (location relative to compartment length), uniform distribution in the range 0.6 to 0.9
- Beam height within the compartment 2.3 m.

Protected steel heat transfer inputs

When using the graphical time equivalence approach based on the maximum protected steel temperature, the following inputs were used.

- Density of steel 7850 kg/m^3
- Cross section area of steel beam 0.017 m^2
- Density of the steel protection 800 kg/m^3
- Thermal conductivity of the steel protection 0.2 W/m/K
- Specific heat of the steel protection 1700 J/K/kg
- Protected section perimeter 2.14 m
- The smallest value that the protection thickness can be in the range 0.1 to 40 mm. This is used to solve for the maximum steel temperature at 550 °C for each simulation.

Parameter	Value
Fire mode 0 – EN 1991-1-2 Annex A parametric fire only 1 – Travelling fire only 2 – DIN EN 1991-1-2/NA parametric fire only 3 – Option 0 and 1 as above 4 – Option 2 and 1 as above	0
Model uncertainty factor	1
Compartment floor area - NZ Stats data	Distribution type: Sampled m^2
Compartment breadth/depth ratio	Distribution type: Uniform Upper limit: 0.6 Lower limit: 0.4
Compartment height	Distribution type: Uniform Upper limit: 2.3 m Lower limit: 2.7 m
The partial factor for DIN EN 1991-1-2/NA	1
Minimum time to peak temperature for fuel-controlled fire EN 1991-1-2 Annex A Slow: 25/60 Medium: 20/60 Fast: 15/60	0.333 hours
Compartment lining thermal inertia	700 $J{\cdot}m^{-2}{\cdot}K^{-1}{\cdot}s^{-0.5}$
Beam cross section area	0.017 m^2
Beam density	7850 $kg{\cdot}m^{-3}$
Beam failure temperature	550±1 °C
Solver max iterations	20
Beam protected perimeter	2.14 m
Protection thermal conductivity	0.2 $W{\cdot}m^{-1}{\cdot}K^{-1}$
Protection density	800 $kg{\cdot}m^{-3}$
Protection heat capacity	1700 $J{\cdot}K^{-1}{\cdot}kg^{-1}$
Fire load density Sourced from ABCB.	Distribution type: Normal Mean: 500 $MJ{\cdot}m^{-2}$ Standard deviation: 150 $MJ{\cdot}m^{-2}$ Upper limit: 1200 $MJ{\cdot}m^{-2}$ Lower Limit: 200 $MJ{\cdot}m^{-2}$
Fire growth factor	300 s
Fire combustion efficiency Data sourced from Annex F in BS EN 1991-1-2.	Distribution type: Linear Upper limit: 1 Lower limit: 0.8
Window breakage percentage The JCSS probabilistic model code noted the glazing failure percentage associated with truncated lognormal distribution ξ. The glazing failure in design fires is obtained as the maximum glazing area multiplied by $(1 - \xi)$.	N/A
Window area (as fraction of floor area)	Distribution type: Uniform Upper limit: 0.1 Lower limit: 0.2
Window height (as fraction of compartment height)	Distribution type: Uniform Upper limit: 0.3 Lower limit: 0.9
Fire travel speed for TFM Lower limit corresponds with that required to achieve a 1.0 MW fire after a time of 300 s, premised on semi-circular fire spread, after Hopkin. Upper limit is taken from experiments which were intended to replicate fires comparable to those reviewed in Rackauskaite, et al.	Distribution type: Uniform Upper limit: 0.0190 $m{\cdot}s^{-1}$ Lower limit: 0.0035 $m{\cdot}s^{-1}$
Beam position vertical for TFM	2.3 m
Beam minimum beam location relative to compartment length for TFM	Distribution type: Uniform Upper limit: 0.9 m Lower limit: 0.6 m
Heat release rate per unit area for TFM	Distribution type: Uniform Upper limit: 0.57 $MJ{\cdot}m^{-2}$ Lower limit: 0.32 $MJ{\cdot}m^{-2}$
Fire near field temperature for TFM Distribution informed by Stern-Gottfried.	Distribution type: Normal Mean: 1323 K Standard deviation: 93 K Upper limit: 1473 K Lower limit: 693 K

Table 44. Input data summary for basecase model

11.3 Fire model switchover criteria

As previously described in subsection 10.9 and by Fu et al. [74], the SfePrapy tool allows several different fire model choices to be considered in the analysis including the EN 1991-1-2 Annex A and DIN EN 1991-1-2/NA parametric fires, either singly or in combination with a travelling fire model. In the cases where both a parametric fire and travelling fire combination are used then the following switchover criteria are used dependent on the sampled input values for each simulation. In these cases, the travelling fire methodology is used when the stated limits of the parametric fire equations do not apply. Since in the analysis partitions subdividing a compartment may be present but are not considered it is possible that in some cases a uniform fire might still be more likely than a travelling fire scenario. This may be a limitation to the analysis.

EN 1991-1-2 Annex A and travelling fire

If all the following criteria are met then the EN 1991-1-2 Annex A parametric fire is used, otherwise the travelling fire model is used.

- Fire load density per unit enclosure surface area is between 50 and 1000 MJ/m^2 inclusive.
- There must be sufficient ventilation for the fire to develop the heat release rate necessary to near-simultaneously ignite all combustibles to represent a flashover condition. Thus, the opening factor must be 0.01 or greater.
- The compartment must not be over-ventilated to the extent that too much energy is able to leave the fire compartment, thus resulting in low temperatures and a low likelihood of involvement of all combustible materials. The opening factor must be 0.2 or less.
- The fuel at the point of origin must not have been fully consumed in the time taken for the fire to spread to involve the rest of the compartment i.e time taken for the fire to spread (room depth / fire spread speed) must be less than the burnout time (FLED / heat release rate density).

DIN EN 1991-1-2/NA and travelling fire

If all the following criteria are met then the DIN EN 1991-1-2/NA parametric fire is used, otherwise the travelling fire model is used.

- The ratio of the window area to floor area must be in the range 12.5% to 50%.
- The fuel at the point of origin must not have been fully consumed in the time taken for the fire to spread to involve the rest of the compartment i.e time taken for the fire to spread (room depth / fire spread speed) must be less than the burnout time (FLED / heat release rate density).

11.4 Suggested target failure probabilities for the NZBC

Considering the trigger heights of 10 m, 25 m and 20 storeys (≈60 m) used in C/AS2, the target failure probabilities given in Table 45 are proposed in order to recommend appropriate fire resistance ratings based on building height and number of household units. The values are similar to the cost-optimised target indices given in the JCSS [86] and adopted in ISO 2394:2015 [84] for a normal or moderate relative cost of safety measures (see also Table 32). While these values are proposed for the analysis presented in this report, it is the responsibility of the building regulator (i.e. MBIE) on behalf of the New Zealand government to decide on the target failure probabilities appropriate for structural fire design of buildings in New Zealand. It is intended that the present analysis will help to inform MBIE should they decide in future to make changes to C/AS2 and C/VM2.

Table 45. Suggested target failure probabilities considering the trigger heights used in C/AS2.

	Consequence class (or building class)			
	CC2A		CC2B	CC3
	Low consequences	Low-mod consequences	Mod consequences	Large consequences
Building height, m	< 10	> 10 and ≤ 25	> 25 and ≤ 60	> 60
Reliability index, β (-)	3.7	3.9	4.2	4.4
Allowable failure prob. per year	$\approx 1 \times 10^{-4}$	$\approx 5 \times 10^{-5}$	$\approx 1 \times 10^{-5}$	$\approx 5 \times 10^{-6}$

11.5 Other considerations

The present study is focussed on the fire severity or the 'demand' side of the fire severity versus fire resistance equation, with emphasis placed on developing a set of generalised results that are material independent. However, structural fire resistance is also dependent on the response of the building structural system and materials. For example, fire loads discussed in subsection 6.3 are in respect of the building contents only and therefore may not be accurate where the building structure contributes additional fuel to the fire, as could be the case in both mass timber structures as well as light timber frame construction commonly used in medium density housing in New Zealand.

Clifton [108] explored the potential for fire to breach the floors in light framed apartments in New Zealand and concluded that it was likely to occur in typical New Zealand apartments in rooms of lower ventilation and higher fire load (e.g. kitchens and bedrooms). Clifton also expressed concern at the wall linings being breached and the wall framing becoming exposed to the fire. He recommended that the walls should be designed so that breaching of the linings doesn't occur. In the event of the floors or walls being breached there is potential for additional fuel to become involved in the fire where combustible materials form part of the building envelope and structure. This increases the fire severity and reduces the structural capacity and fire resistance of the building.

There has also been extensive research over recent years concerning the fire performance of mass timber structures including the extent of charring in exposed and partially protected structures and its influence on the fire development, e.g. [27, 53, 109–111]. These topics are beyond the scope of the current report.

12. Results

The assumptions and inputs previously set out in section 11 and Table 44 form the basecase model, with the results and sensitivity analysis presented in this section.

12.1 Influence of fire model

Four different fire models (see section 7) are used in the analysis considering both uniform parametric fires and travelling fires as follows:

1. EN 1991-1-2 Annex A parametric fire
2. EN 1991-1-2 Annex A parametric fire combined with the travelling fire model
3. DIN EN 1991-1-2/NA parametric fire
4. DIN EN 1991-1-2/NA parametric fire combined with the travelling fire model

For each MCS, 100,000 simulations were run and the resulting CDF for the equivalent time of fire exposure for each fire model is shown in Figure 39. The EN 1991-1-2 Annex A parametric curves gives the most severe CDF result and the DIN EN 1991-1-2 NA parametric fire combined with the travelling fire model gives the least severe CDF. The most and least severe fire models with respect to the CDF generated are further investigated in the sensitivity analysis presented in the following subsections.

It is observed that with the DIN EN 1991-1-2 NA parametric fire combined with the travelling fire option, 72.8% of the simulations were travelling fires and 27.2% were uniform parametric fires. For the EN 1991-1-2 Annex A combined with the travelling fire option, 63.8% of the simulations were travelling fires and 36.2% were uniform parametric fires.

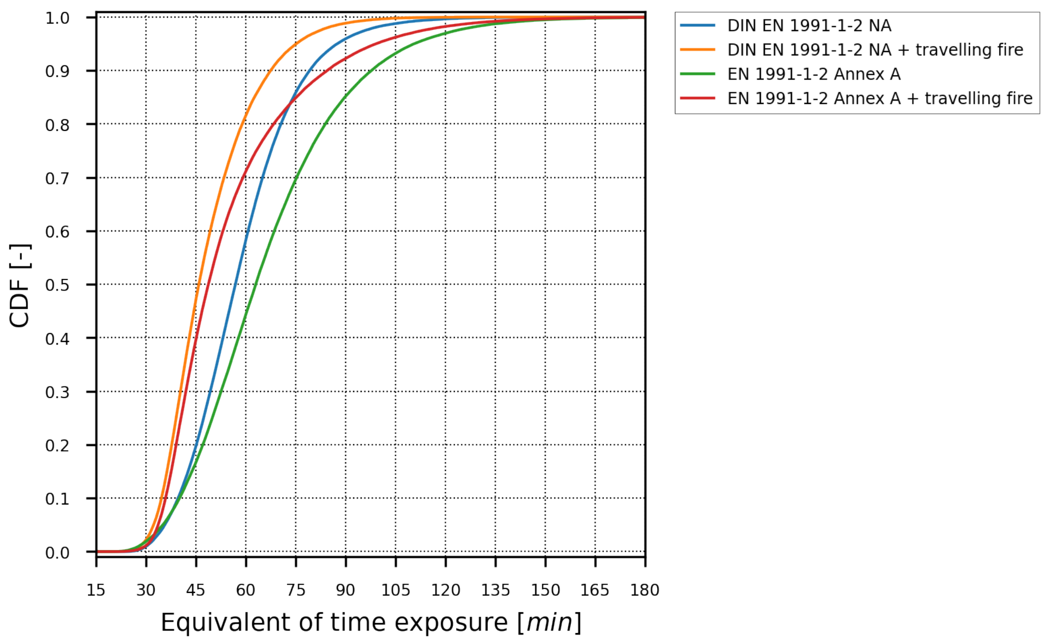

Figure 39. CDF for various fire model options with 100,000 simulations.

12.2 EN 1991-1-2 Annex A model sensitivity

Additional analysis to investigate the effect of several input parameters and assumptions when using the EN 1991-1-2 Annex A fire model is presented here.

12.2.1 Influence of room vs full compartment involvement

For each MCS, 100,000 simulations were run and Figure 40 compares the resultant CDF using the floor area distribution in Table B2 from Stats NZ for the entire household unit with a smaller room area in the range 9 to 30 m^2 as used in other studies e.g. Kirby et al. [99] and Fu et al. [106]. It is seen that full compartment involvement with the larger floor area generates a more severe CDF for the equivalent time of exposure when compared to the smaller room area.

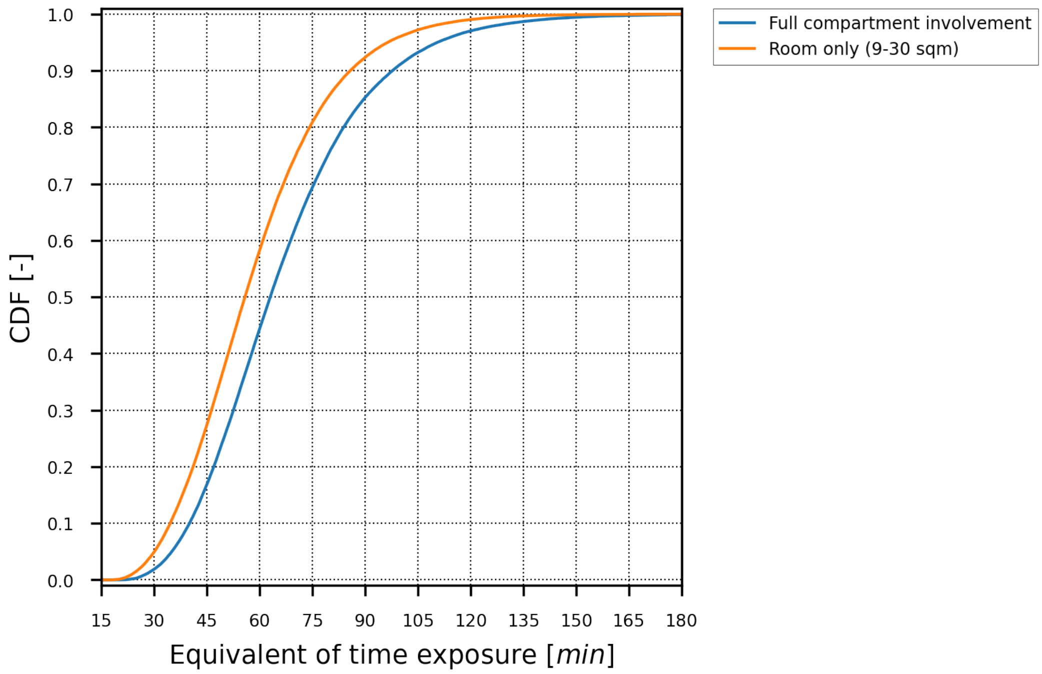

Figure 40. CDF comparing full compartment involvement based on Stats NZ data for size of household units versus room only involvement in the range 9 to 30 m^2 with 100,000 simulations.

12.2.2 Influence of partial window breakage

For each MCS, 100,000 simulations were run and Figure 41 compares the influence of assuming the maximum window area for fire ventilation with using the truncated log-normal function as recommended by JCCS Probabilistic Model Code to allow for less than complete glass fallout during the fire. The JCCS function generates a more severe CDF for the equivalent time of exposure when compared to using the maximum window area.

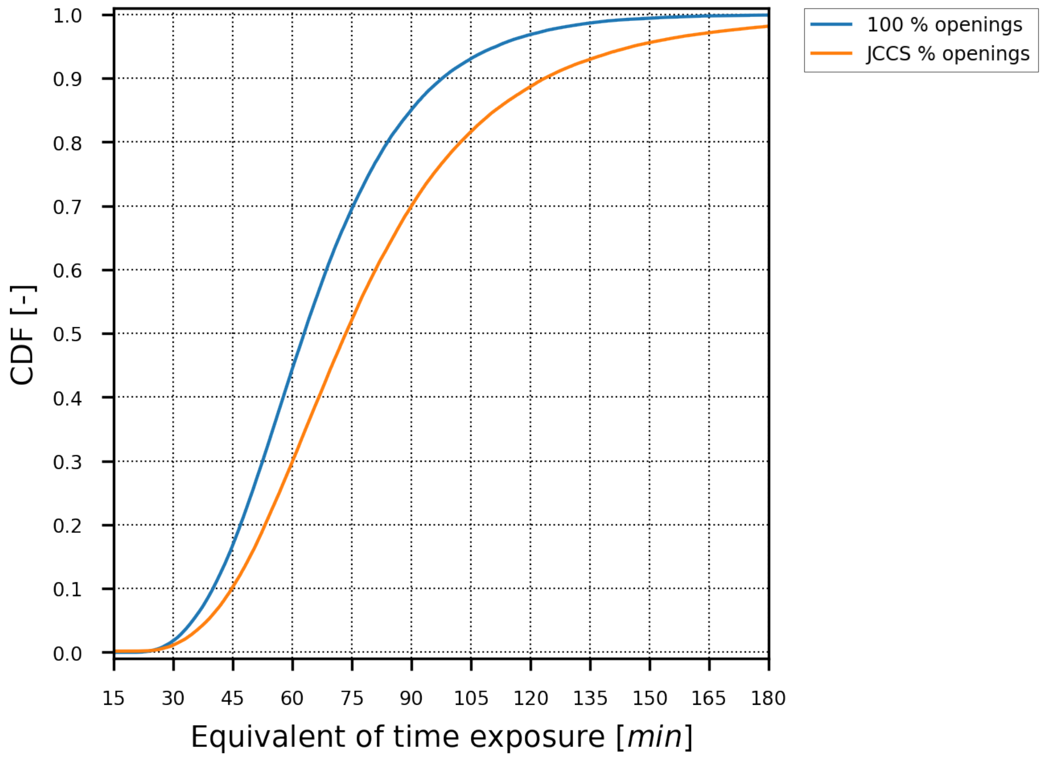

Figure 41. CDF comparing 100 % of window ventilation versus partial window breakage following JCCS truncated log-normal distribution with 100,000 simulations.

12.2.3 Influence of fire load

For each MCS, 100,000 simulations were run and Figure 42 compares the fire load distribution given in the ABCB datasheets, the distribution given in EN 1991-1-2 and PD 7974 Part 7, with a constant value of 400 MJ/m^2 from C/VM2. The EN 1991-1-2 gumbel distribution generates a significantly more severe CDF for the equivalent time of exposure and compared to the C/VM2 assumed value giving the least severe CDF for the equivalent time of exposure.

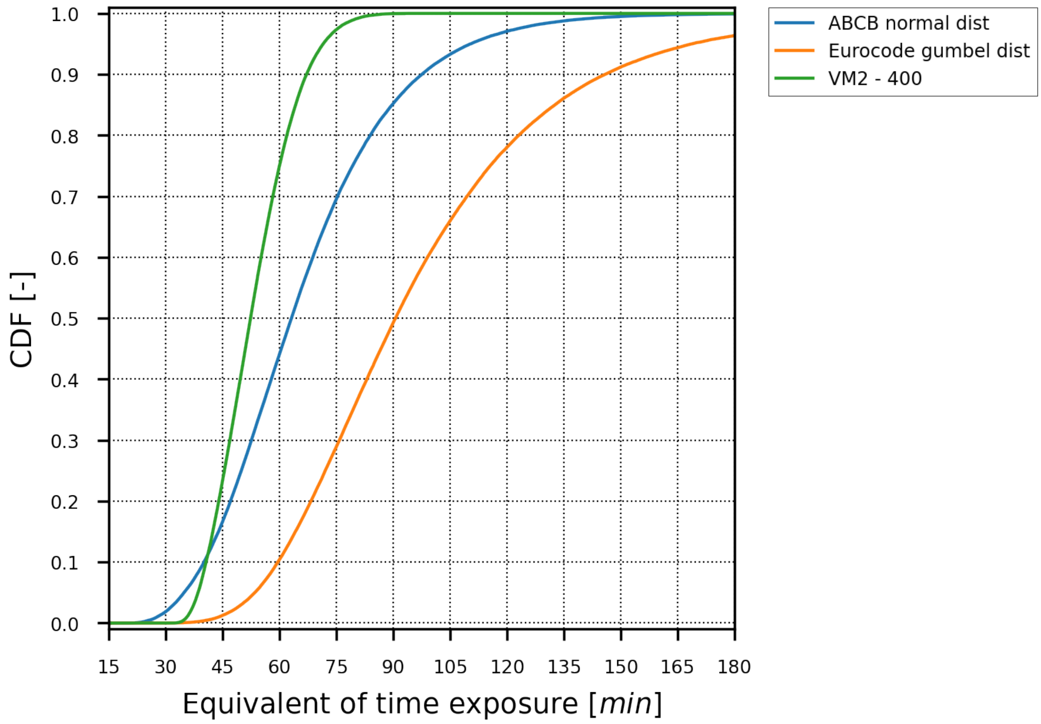

Figure 42. CDF comparing fire load assumptions for residential occupancies based on ABCB normal distribution, EN 1991-1-2 gumbel distribution and C/VM2 constant 400 MJ/m^2 with 100,000 simulations.

12.3 DIN EN 1991-1-2 NA combined with the travelling fire model sensitivity

Additional analysis to investigate the effect of several input parameters and assumptions when using the DIN EN 1991-1-2 NA combined with the travelling fire model is included here.

12.3.1 Influence of room vs full compartment involvement

For each MCS, 100,000 simulations were run and Figure 43 compares the resultant CDF using the floor area distribution in Table B2 from Stats NZ for the entire household unit with a smaller room area in the range 9 to 30 m^2 as used in other studies e.g. Kirby et al. [99] and Fu et al. [106]. It is seen that there is a switchover from the full compartment involvement generating the more severe CDF at lower fire severities but slightly less severe at higher fire severities. As previously mentioned, the analysis did not consider the partitions between rooms that subdivide a household unit. Given individual room sizes in the range 9 to 30 m^2 Figure 43 shows that ignoring these partitions is likely conservative, at least for fire severities up to about 45 minutes, and slightly non-conservative for fire severities of longer durations.

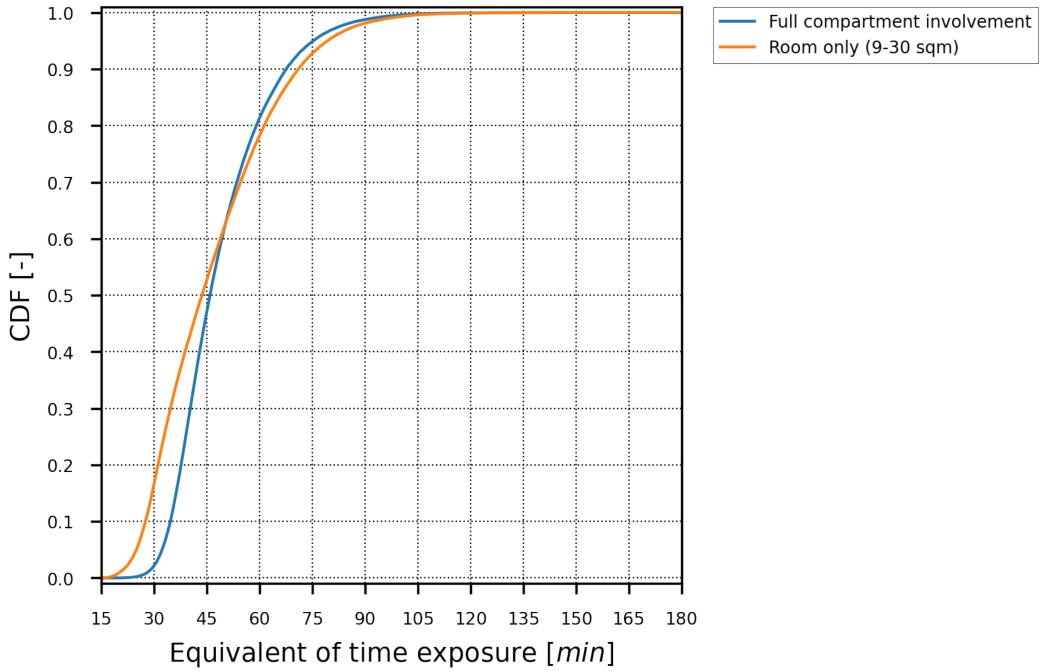

Figure 43. CDF comparing full compartment involvement based on Stats NZ data for size of household units versus room only involvement in the range 9 to 30 m^2 with 100,000 simulations.

12.3.2 Influence of partial window breakage

For each MCS, 100,000 simulations were run and Figure 44 compares the influence of assuming the maximum window area for fire ventilation with using the truncated log-normal function as recommended by JCCS Probabilistic Model Code to allow for less than complete glass fallout during the fire. It is interesting that in this case, the JCCS function generates only a very slightly less severe CDF compared to assuming the maximum area of glass fallout presumably since the travelling fire model is less sensitive to the window area.

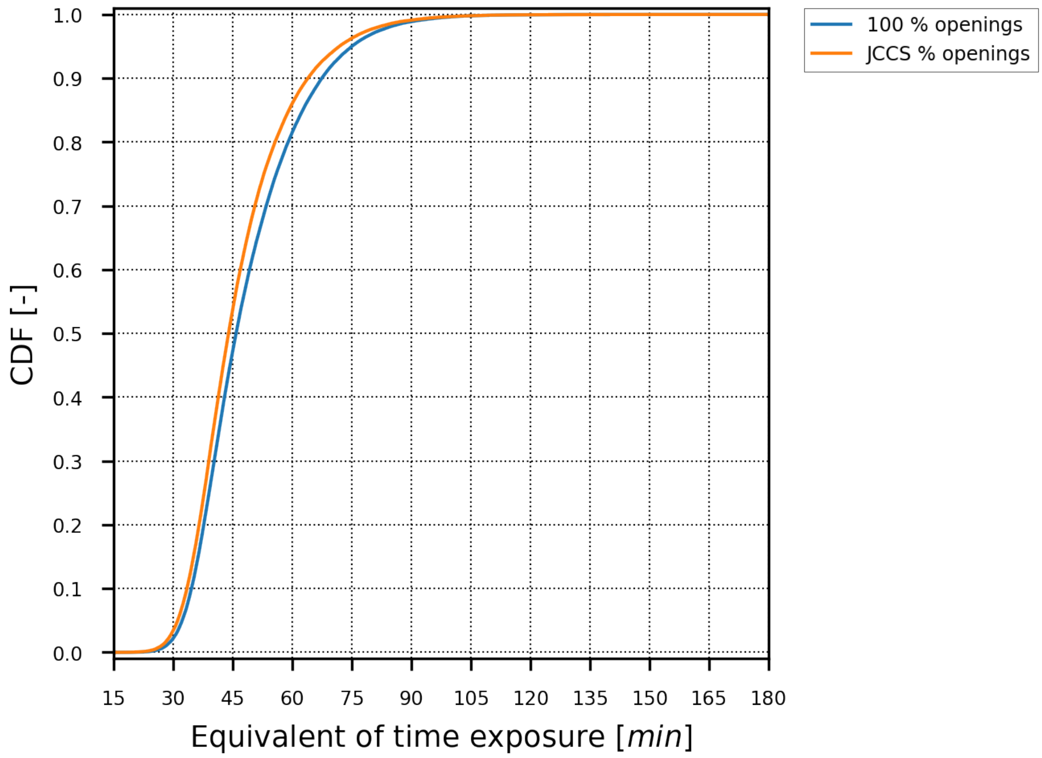

Figure 44. CDF comparing 100 % of window ventilation versus partial window breakage following JCCS truncated log-normal distribution with 100,000 simulations.

12.3.3 Influence of fire load

Comparing the fire load distribution given in the ABCB datasheets, the distribution given in EN 1991-1-2 and PD 7974 Part 7, with a constant value of 400 MJ/m^2 from C/VM2. Again, the EN 1991-1-2 gumbel distribution generates a significantly more severe CDF, and the C/VM2 value the least severe.

For each MCS, 100,000 simulations were run and Figure 45 compares the fire load distribution given in the ABCB datasheets, the distribution given in EN 1991-1-2 and PD 7974 Part 7, with a constant value of 400 MJ/m^2 from C/VM2. The EN 1991-1-2 gumbel distribution generates a significantly more severe CDF for the equivalent time of exposure and compared to the C/VM2 assumed value giving the least severe CDF for the equivalent time of exposure, although in this case the spread is not as great when compared to Figure 42.

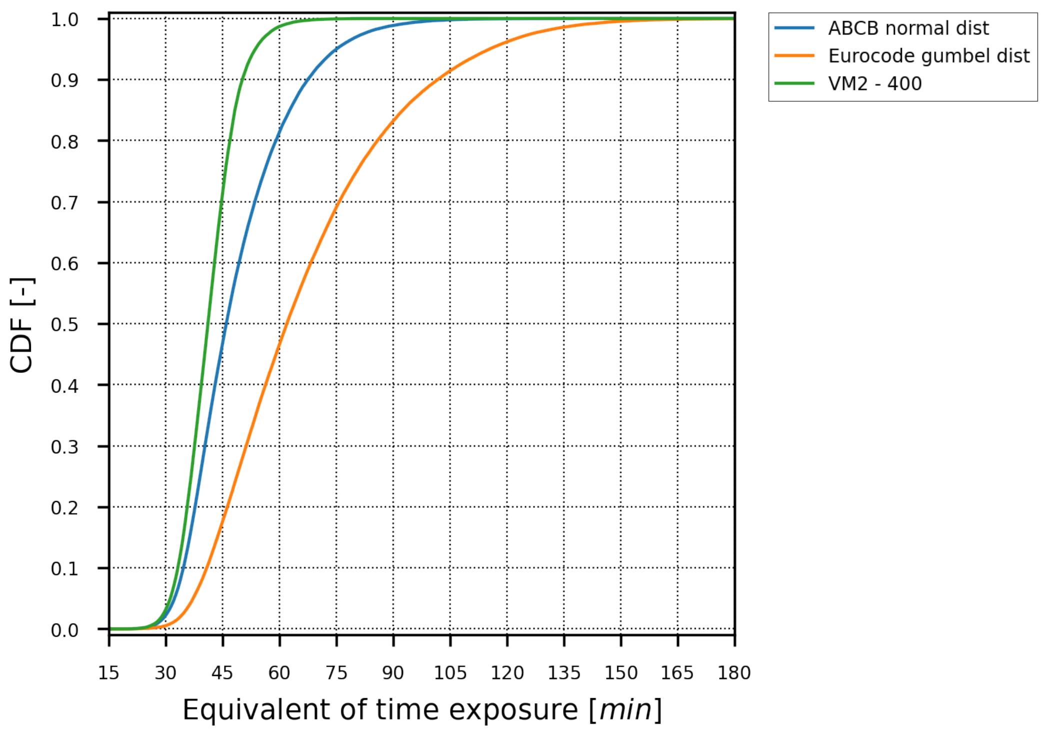

Figure 45. CDF comparing fire load assumptions for residential occupancies based on ABCB normal distribution, EN 1991-1-2 gumbel distribution and C/VM2 constant 400 MJ/m^2 with 100,000 simulations.

12.4 Failure probability for EN 1991-1-2 Annex A fire model

Given the probability of a structurally significant fire is determined as explained in subsection 11.1, and using the previously presented CDF curves for the conditional probability of a failure given a structurally significant fire, then the probability of failure can be estimated.

Failure probability curves for fire severities based on the EN 1991-1-2 Annex A fire model versus the number of household units in the building are shown in Figure 46 for the unsprinklered case and Figure 47 and Figure 48 for the sprinklered cases with effectiveness 0.90 and 0.95 respectively. The fire severities are shown in the range 30 to 120 minutes and the vertical dashed lines indicate the suggested target failure probabilities according to Table 45 for buildings in various height bands.

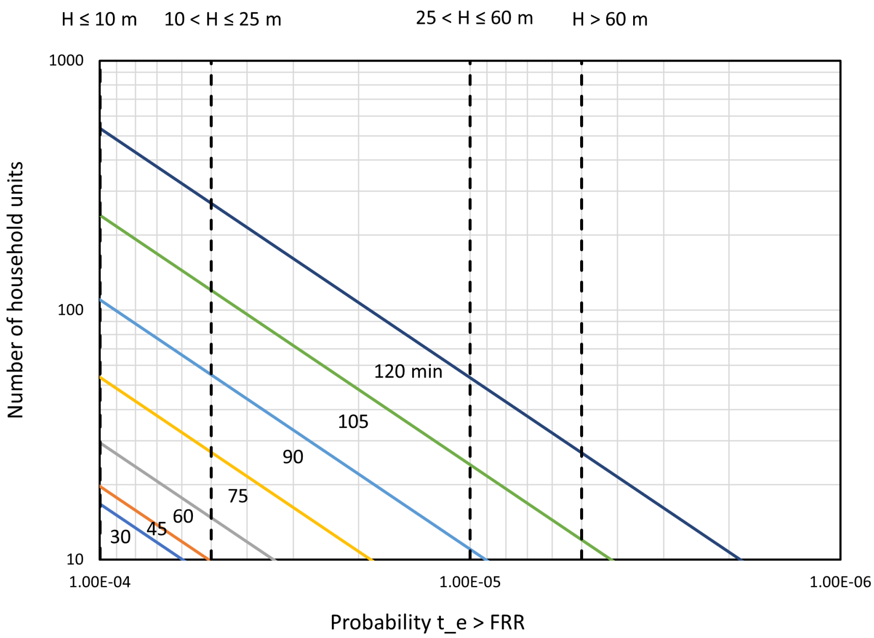

Figure 46. Failure probability curves for fire severities in the range 30 to 120 minutes, assuming the EN 1991-1-2 Annex A fire model versus number of household units in the building without fire sprinklers. Vertical dashed lines indicate suggested target failure probabilities for buildings of various height, H.

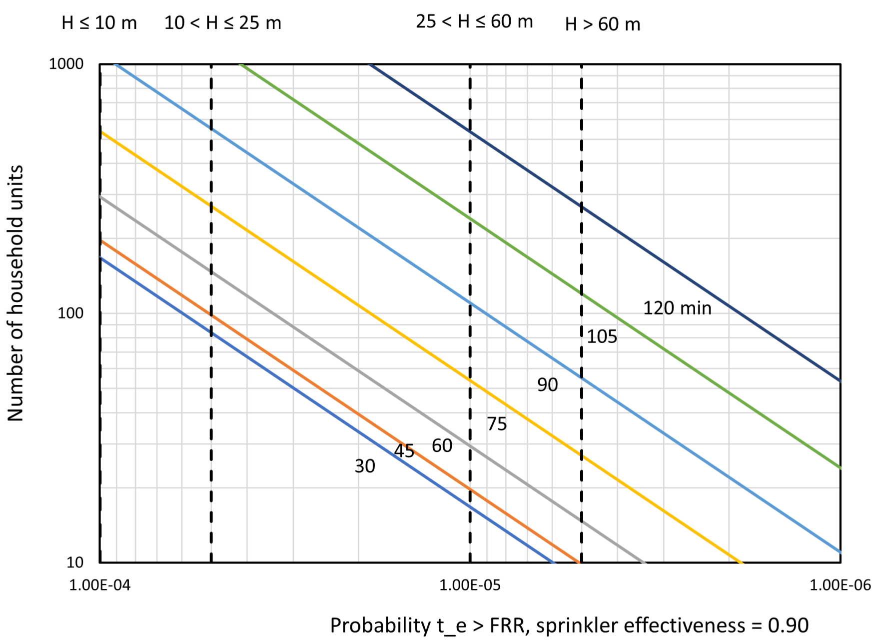

Figure 47. Failure probability curves for fire severities in the range 30 to 120 minutes, assuming the EN 1991-1-2 Annex A fire model versus number of household units in the building with fire sprinklers of assumed effectiveness 0.90. Vertical dashed lines indicate suggested target failure probabilities for buildings of various height, H.

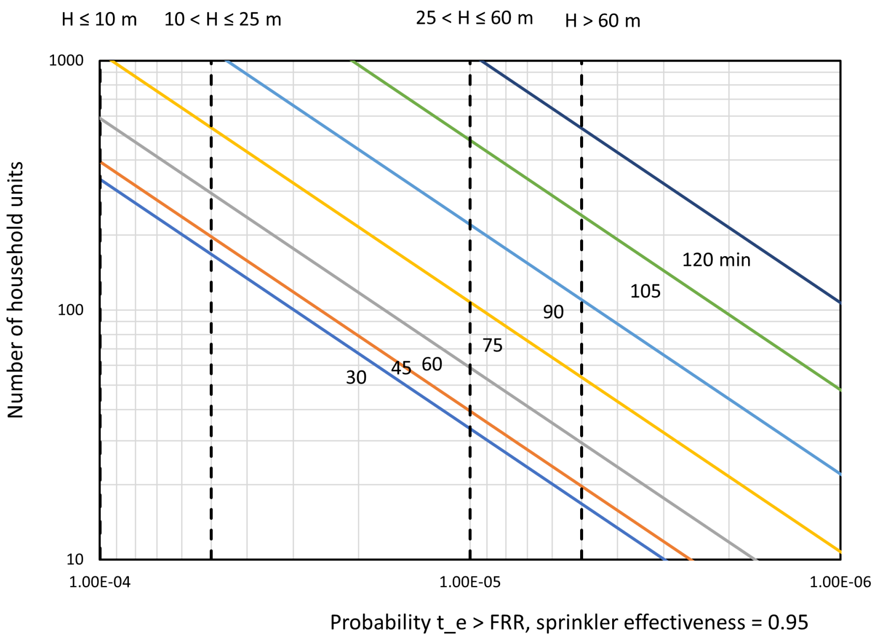

Figure 48. Failure probability curves for fire severities in the range 30 to 120 minutes, assuming the EN 1991-1-2 Annex A fire model versus number of household units in the building with fire sprinklers of assumed effectiveness 0.95. Vertical dashed lines indicate suggested target failure probabilities for buildings of various height, H.

12.5 Failure probability for DIN EN 1991-1-2 NA + travelling fire model

Failure probability curves for fire severities based on the DIN EN 1991-1-2 NA + travelling fire model versus the number of household units in the building are shown in Figure 49 for the unsprinklered case and Figure 50 and Figure 51 for the sprinklered cases with effectiveness 0.90 and 0.95 respectively. The probability of a professional fire service not extinguishing the fire has been taken as 20% (p_2=0.2). The fire severities are shown in the range 30 to 120 minutes and the vertical dashed lines indicate the suggested target failure probabilities according to Table 45 for buildings in various height bands.

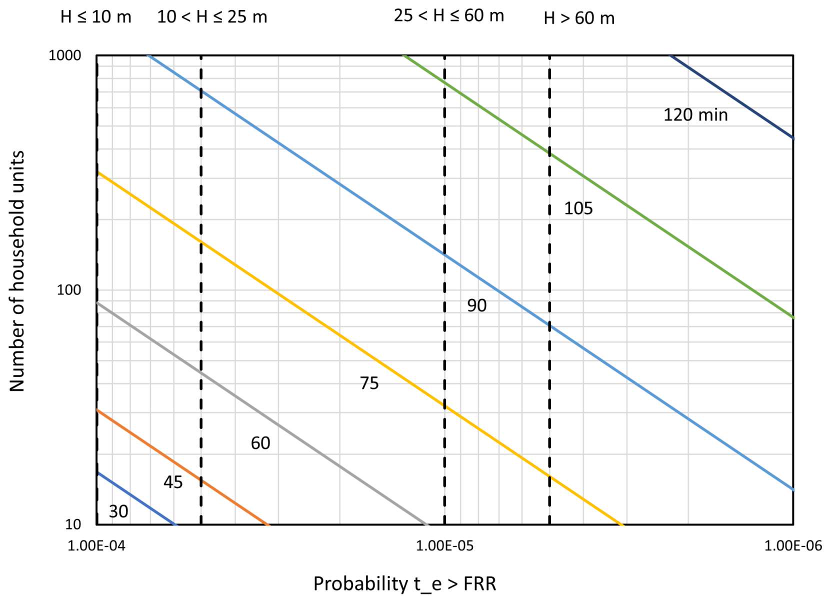

Figure 49. Failure probability curves for fire severities in the range 30 to 120 minutes, assuming the DIN EN 1991-1-2 NA + travelling fire model versus number of household units in the building without fire sprinklers. Vertical dashed lines indicate suggested target failure probabilities for buildings of various height, H.

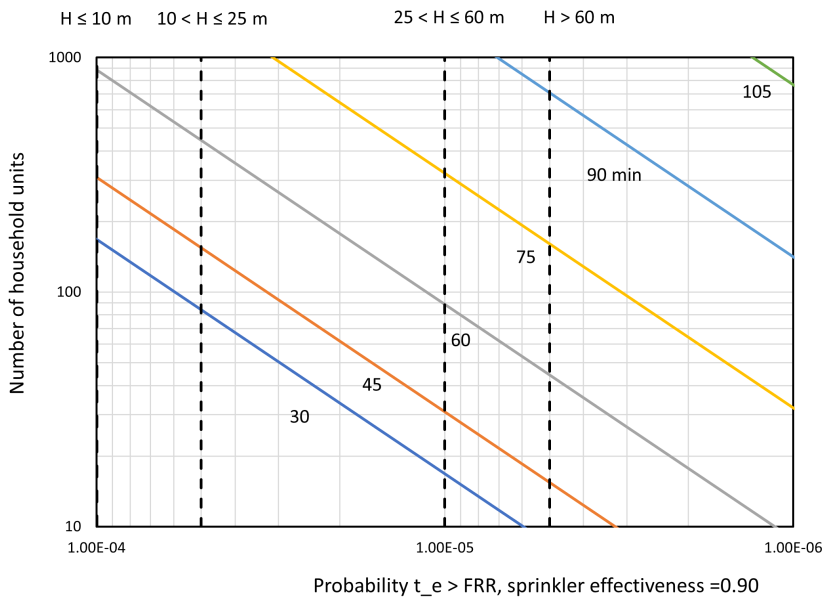

Figure 50. Failure probability curves for fire severities in the range 30 to 120 minutes, assuming the DIN EN 1991-1-2 NA + travelling fire model versus number of household units in the building with fire sprinklers of effectiveness 0.90. Vertical dashed lines indicate suggested target failure probabilities for buildings of various height, H.

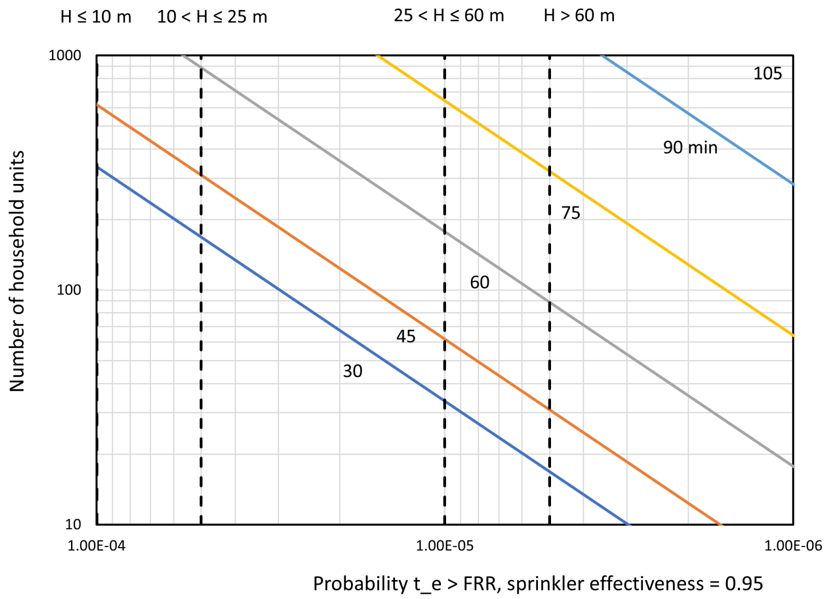

Figure 51. Failure probability curves for fire severities in the range 30 to 120 minutes, assuming the DIN EN 1991-1-2 NA + travelling fire model versus number of household units in the building with fire sprinklers of effectiveness 0.95. Vertical dashed lines indicate suggested target failure probabilities for buildings of various height, H.

The analysis was repeated assuming a professional fire service do not extinguish the fire (p_2=1) as it may more relevant to tall buildings. Failure probability curves for fire severities based on the DIN EN 1991-1-2 NA + travelling fire model versus the number of household units in the building are shown in Figure 52 for the unsprinklered case and Figure 53 and Figure 54 for the sprinklered cases with effectiveness 0.90 and 0.95 respectively.

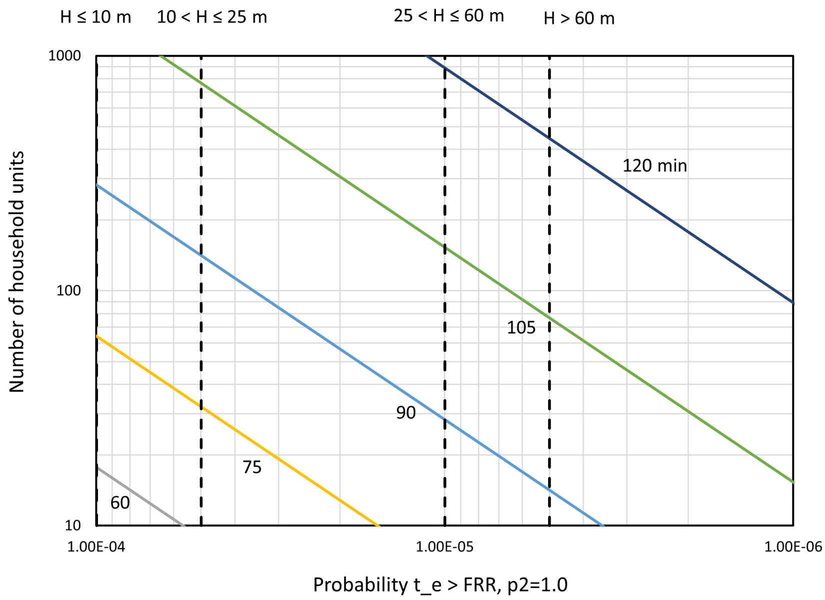

Figure 52. Failure probability curves for fire severities in the range 30 to 120 minutes, assuming the DIN EN 1991-1-2 NA + travelling fire model versus number of household units in the building without fire sprinklers and ignoring fire service intervention p_2=1. Vertical dashed lines indicate suggested target failure probabilities for buildings of various height, H.

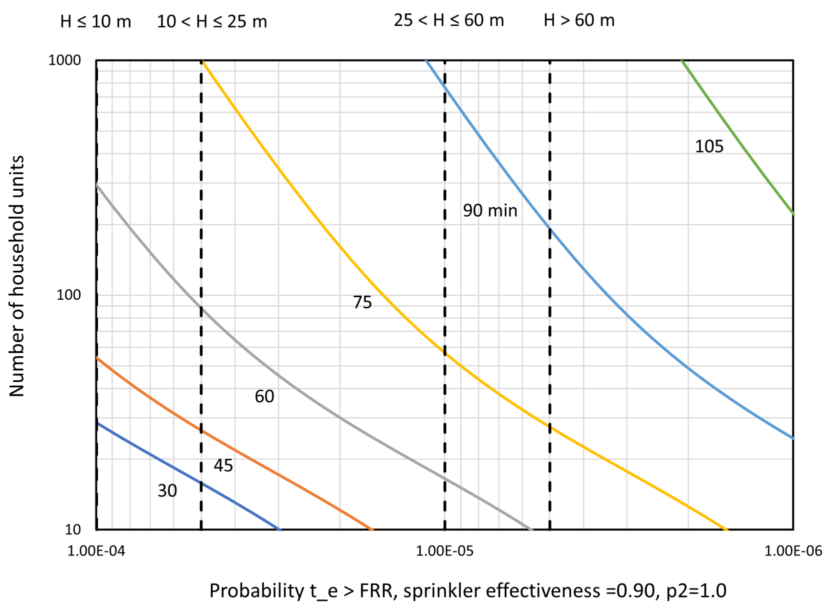

Figure 53. Failure probability curves for fire severities in the range 30 to 120 minutes, assuming the DIN EN 1991-1-2 NA + travelling fire model versus number of household units in the building with fire sprinklers of effectiveness 0.90 and ignoring fire service intervention p_2=1. Vertical dashed lines indicate suggested target failure probabilities for buildings of various height, H.

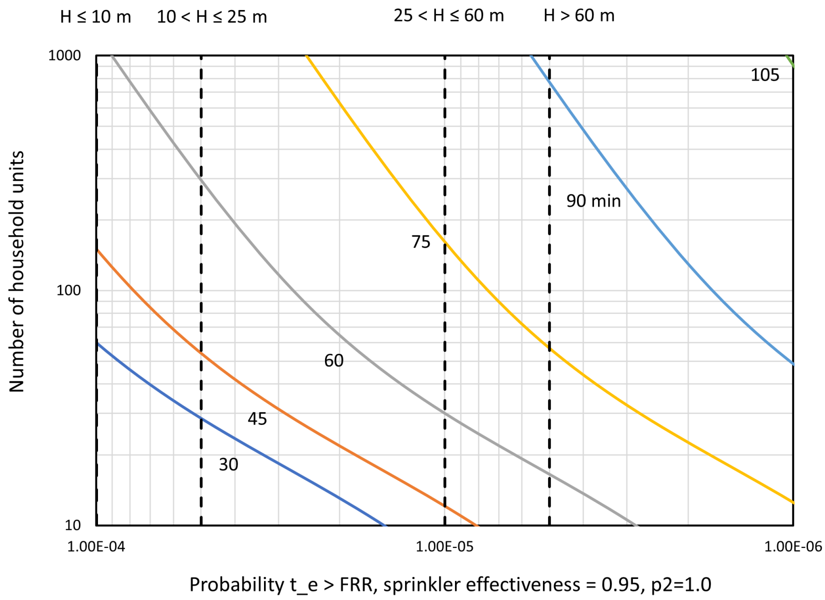

Figure 54. Failure probability curves for fire severities in the range 30 to 120 minutes, assuming the DIN EN 1991-1-2 NA + travelling fire model versus number of household units in the building with fire sprinklers of effectiveness 0.95 and ignoring fire service intervention p_2=1. Vertical dashed lines indicate suggested target failure probabilities for buildings of various height, H.

12.6 Proposed fire resistance ratings in multi-storey densified housing

The preceding failure probability plots can be interrogated to determine a rational value for the fire resistance rating, for a given target acceptable probability of failure (corresponding to a designated building height band) and total number of household units in the building. The result of this interrogation is summarised in Table 46 based on the DIN EN 1991-1-2 NA parametric fire combined with the travelling fire model results as given in Figure 49 and Figure 50 for unsprinklered and sprinklered buildings of effectiveness 0.90 respectively. For building height above 25 m, fire service intervention is ignored and instead Figure 52 and Figure 53 are used for unsprinklered and sprinklered buildings of effectiveness 0.90 respectively.

Table 46 applies only to buildings up to 20 storeys and current fire resistance requirements from C/AS2 are also shown in the table. The values shown in brackets are for the sprinklered case. Values shown in bold are the minimum requirements in the event that all buildings above 25 m are provided with a fire sprinkler system, while those below 25 m are not. No extinguishment by the fire service is assumed for heights above 25 m, whereas an 80% probability of the fire service preventing a structurally significant fire applies at lesser heights. The fire resistance ratings shown are based on the upper height in the stated range (i.e. 10 m, 25 m and 60 m).

In viewing the preceding failure probability plots, it should be kept in mind that the assumption that failure of one fire compartment leads to all occupants of the building being at heightened risk may be very conservative. For instance, when there are a very large number of apartments per storey in a relatively low-rise building, the apartments may be horizontally spread over a large area where the fire spread horizontally would be much slower in practice. It may be reasonable and more economic to cap the number of units per storey in these curves. There may also be merit in making use of additional fire walls to create separate 'buildings' with a limit on floor plate area (or number of units per storey). On the other hand, where the failure of one compartment leads to a single stair being unusable, all occupants who require that stair for evacuation are potentially at risk.

Table 46. Proposed fire resistance ratings in multi-storey densified housing based upon building height H or number of storeys S (values in brackets include sprinklers of assumed effectiveness 0.90) [min] based on DIN EN 1991-1-2 NA + travelling fire model.

Method	Household units per storey	Fire resistance ratings based upon building height H or number of storeys S (values in brackets include sprinklers) [min]		
		$\leq$ 10 m S $\leq$ 4 storeys	10 < H $\leq$ 25 m 5 < S $\leq$ 9 storeys	25 < H $\leq$ 60 m 10 < S $\leq$ 20 storeys
C/AS2	-	**60** (30)	**60** (30)	N/A (**30**)
SFEPRAPY	6	**45** (30)	**75** (30)	105 (**90**)
SFEPRAPY	12	**60** (30)	**75** (45)	120 (**90**)
SFEPRAPY	18	**60** (30)	**90** (60)	120 (**90**)
SFEPRAPY	24	**75** (30)	**90** (60)	120 (**90**)
SFEPRAPY	30	**75** (30)	**90** (60)	120 (**90**)
Allowable failure probability per year		$\approx 1\times10^{-4}$	$\approx 5\times10^{-5}$	$\approx 1\times10^{-5}$

Using the DIN EN 1991-1-2 NA parametric fire combined with the travelling fire model is the least demanding in terms of the anticipated fire severities, compared to the other options explored including the EN 1991-1-2 parametric curves alone. However, DIN EN 1991-1-2 NA parametric fire combined with the travelling fire model does attempt to address some of the limitations of the traditional EN 1991-1-2 parametric curves.

Another important parameter included in this analysis is to include a more "reasonable" assumption for the assumed fire load density in residential buildings or densified housing. The current value applied in C/VM2 of 400 MJ/m^2 is not well supported in the literature being lower than typically used elsewhere. On the other hand, the origin of the rather high fire load densities that are applied to residential buildings in the Europe are also not well known. In the present study, we have compromised by using the fire load density distribution included in the ABCB datasheet with a mean value of 500 MJ/m^2, standard deviation of 150 MJ/m^2 and minimum value of 200 MJ/m^2. Only fire load provided from the contents of the building has been considered, and not any contribution due to any exposed combustible elements of the building.

In terms of estimating the probability of a structurally significant fire in densified housing, we have included allowances for the beneficial impact that a professionally trained fire service can provide following those assumptions adopted in Europe in the development of the NFSC. Namely we have assumed that a professional fire brigade will be effective in preventing a structurally significant fire 80% of the time in buildings up to 25 m in height. Above that height we have ignored fire brigade intervention. We have also assumed that automatic smoke detection and fire service alarm notification systems are present in the buildings and this results in an additional benefit in reducing the number structurally significant fires. We have not adjusted these assumptions based on the building height beyond that noted, but this could be done if necessary. If the beneficial impacts of the fire service and early detection and warning systems are not included, the proposed fire resistance ratings shown in Table 46 would increase accordingly.

The analysis recognises that the probability of a structurally significant fire in a building increases with the number of household units in the building and that the consequences of failure increase with the number of household units and the height of the building.

The analysis also assumes that the compartment bounding construction and primary elements fail when the fire severity exceeds the fire resistance, and that failure could result in a more widespread failure or collapse of the building. Most likely this is a very conservative assumption and will depend on the particular structural systems used. In terms of the failure consequences, it should be recognised that the failure of critical structural elements, the floor separations and the construction separating each floor level from a vertical safe path potentially pose greater risk to a larger number of people in the building compared to failure of say, an intertenancy wall on one level of the building. This could be reflected if desired by requiring different levels of fire resistance for different types of element in the building. There could also be merit in subdividing large horizontally spread buildings with a firewall to reduce the number of units at risk.

13. Conclusions

The demand and need for more densified housing is increasing in New Zealand and this creates potential fire safety challenges to be resolved. This study has found that, unlike in many other countries and jurisdictions, existing fire resistance ratings in C/AS2 do not change with building height or with the size of the building (or number of household units), however the consequence of fire does increase with building height and with the number of people (or number of household units) potentially exposed in the event of fire.

An analysis of the severity of structurally significant fires in densified housing has been conducted in order to evaluate the failure probabilities of structural elements and compartmentation in this type of building typology. However, to assess the adequacy of current fire resistance levels requires target failure probabilities to be identified. While there are such target criteria found in the literature and methodologies given for their selection, it is primarily a task belonging to the regulatory authorities.

The main conclusion of this study is that the fire resistance ratings in tall residential buildings especially those above 25 m, typically fall well short of the ratings typically applied in many other countries. Analysis shows that a higher probability of failure is implicitly being accepted in New Zealand compared to many other jurisdictions, perhaps without conscious understanding and acceptance of the risks involved. Fire is a rare event and unfortunately regulatory settings are often only changed following tragic events where the outcomes have been deemed to be intolerable. It is hoped that this present study provides objective and helpful analysis to help inform future changes to C/AS2 and to provide useful information to structural fire engineers involved in the design of multi-storey densified housing.

14. Recommendations

The following recommendations are made:

14.1 Regarding regulation and design

1. MBIE (and designers) should consider adopting target annual failure probabilities for medium and high density residential buildings to guide the requirements set out in C/AS1, C/AS2 and C/VM2 such as those given in Table 45. Alternatively, by reviewing the NZBC Importance Levels descriptors to better accommodate building height and occupant load metrics, the target annual failure probabilities in Table 34 from ASCE/SEI 7-16 could be considered in conjunction with the NZBC Importance Levels instead of the ASCE/SEI 7-16 risk categories.

2. MBIE (and designers) should consider adopting risk informed fire resistance ratings such as those given in Table 46 for medium and high density residential buildings for the specified building height and number of household units per storey based on the stated target annual failure probabilities.

3. MBIE (and designers) should reconsider the use of a design FLED of 400 MJ/m^2 currently specified in C/VM2 and implicitly assumed in C/AS1 and C/AS2 for residential buildings and instead adopt a design value based on a distribution as recommended in Australia (i.e. mean 500 MJ/m^2, standard deviation 150 MJ/m^2).

4. MBIE (and designers) should reconsider the current use of the EN 1991-1-2 Annex F "time-equivalence formula" such that uncertainty in inputs and explicit safety factors accounting for consequence (e.g. building height) be included.

5. Designers should be aware that to fully address the issue of structural fire resistance in any building type, the building capacity to resist the fully developed fire also needs to be addressed. Although beyond the scope of this report, this is particularly important for timber buildings with exposed structural timber elements. The design objectives should be made clear and where necessary, additional fuel load contributed by the building structure and envelope should be accounted for in the structural fire design.

14.2 Regarding further research

1. The analysis should be repeated for other common building types such as offices and retail buildings in New Zealand.

2. Further analysis should be carried out exploring the potential impact on the results due to increased contribution of exposed structural timber elements to the design fuel load.

3. Further analysis should be conducted to explore any potential further reductions in the FRR recommended in Table 46 for sprinklered buildings where agreed additional enhancements to the design, maintenance and operation of the sprinkler system are included - noting that corresponding reductions in the levels of embodied energy in the building would also be expected.

4. Further research is needed to better quantify the fire loads in modern densified housing considering the contributions from buildings contents, fittings as well as the building structure and envelope should be carried out.

5. Further research is needed to quantify the area of available ventilation in fires in modern densified housing should be carried out, taking into account the prevalent use of double-glazing.

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Appendices

A. NZBC Clause A3 Building Importance Levels

Table A1. NZBC Clause A3 Building Importance Levels.

For the purposes of clause C, a *building* has one of the importance levels set out below:

Importance level	Description of building type	Specific structure
Importance level 1	*Buildings* posing low risk to human life or the environment, or a low economic cost, should the *building* fail. These are typically small non-habitable *buildings*, such as sheds, barns, and the like, that are not normally occupied, though they may have occupants from time to time.	• Ancillary *buildings* not for human habitation • Minor storage facilities • Backcountry huts
Importance level 2	*Buildings* posing normal risk to human life or the environment, or a normal economic cost, should the *building* fail. These are typical residential, commercial, and industrial *buildings*.	• All *buildings* and facilities except those listed in importance levels 1, 3, 4, and 5
Importance level 3	*Buildings* of a higher level of societal benefit or importance, or with higher levels of risk-significant factors to *building* occupants. These *buildings* have increased performance requirements because they may house large numbers of people, vulnerable populations, or occupants with other risk factors, or fulfil a role of increased importance to the local community or to society in general.	• *Buildings* where more than 300 people congregate in 1 area • *Buildings* with primary school, secondary school, or daycare facilities with a capacity greater than 250 • *Buildings* with tertiary or adult education facilities with a capacity greater than 500 • Health care facilities with a capacity of 50 or more residents but not having surgery or emergency treatment facilities • Jails and detention facilities • Any other *building* with a capacity of 5 000 or more people • *Buildings* for power generating facilities, water treatment for potable water, wastewater treatment facilities, and other public utilities facilities not included in importance level 4

Importance level	Description of building type	Specific structure
Importance level 3 (continued)		• *Buildings* not included in importance level 4 or 5 containing sufficient quantities of highly toxic gas or explosive materials capable of causing acutely hazardous conditions that do not extend beyond property boundaries
Importance level 4	*Buildings* that are essential to post-disaster recovery or associated with hazardous facilities.	• Hospitals and other health care facilities having surgery or emergency treatment facilities • *Fire*, rescue, and police stations and emergency vehicle garages • *Buildings* intended to be used as emergency shelters • *Buildings* intended by the owner to contribute to emergency preparedness, or to be used for communication, and operation centres in an emergency, and other facilities required for emergency response • Power generating stations and other utilities required as emergency backup facilities for importance level 3 structures • *Buildings* housing highly toxic gas or explosive materials capable of causing acutely hazardous conditions that extend beyond property boundaries • Aviation control towers, air traffic control centres, and emergency aircraft hangars • *Buildings* having critical national defence functions • Water treatment facilities required to maintain water pressure for fire suppression

Importance level	Description of building type	Specific structure
Importance level 4 (continued)		• Ancillary *buildings* (including, but not limited to, communication towers, fuel storage tanks or other structures housing or supporting water or other *fire* suppression material or equipment) required for operation of importance level 4 structures during an emergency
Importance level 5	*Buildings* whose failure poses catastrophic risk to a large area (eg, 100 km^2) or a large number of people (eg, 100 000).	• Major dams • Extremely hazardous facilities

B. Floor Area Distributions of NZ Residential Units

Table B1. Number of residential units excluding detached houses consented over the period 2016 to 2020 by floor area (Source: NZ Stats).

Floor area in sqm	Apartments	Retirement units	Townhouses, flats etc	Total units
Area not given	23	4	10	37
> 0 and < 40	337	89	1386	1812
40 to < 60	1893	539	2625	5057
60 to < 80	4291	903	5702	10896
80 to < 100	4541	1158	6740	12439
100 to < 120	2733	3056	5543	11332
120 to < 140	1021	1552	4186	6759
140 to < 160	1183	1076	3443	5702
160 to < 180	356	916	2417	3689
180 to < 200	476	320	1437	2233
200 to < 220	425	101	853	1379
220 to < 240	68	83	420	571
240 to < 300	205	178	581	964
≥ 300	142	11	235	388
Total units	17694	9986	35578	63258

Table B2. Floor area of residential units as a cumulative frequency distribution (Source: Stats NZ).

Floor area in sqm	No. of household units	Cumulative frequency
≤ 40	1812	0.029
≤ 60	6869	0.109
≤ 80	17765	0.281
≤ 100	30204	0.478
≤ 110	36689	0.580
≤ 120	41536	0.657
≤ 140	48295	0.764
≤ 160	53997	0.854
≤ 180	57686	0.912
≤ 200	59919	0.948
≤ 220	61298	0.970
≤ 240	61869	0.979
≤ 300	62833	0.994

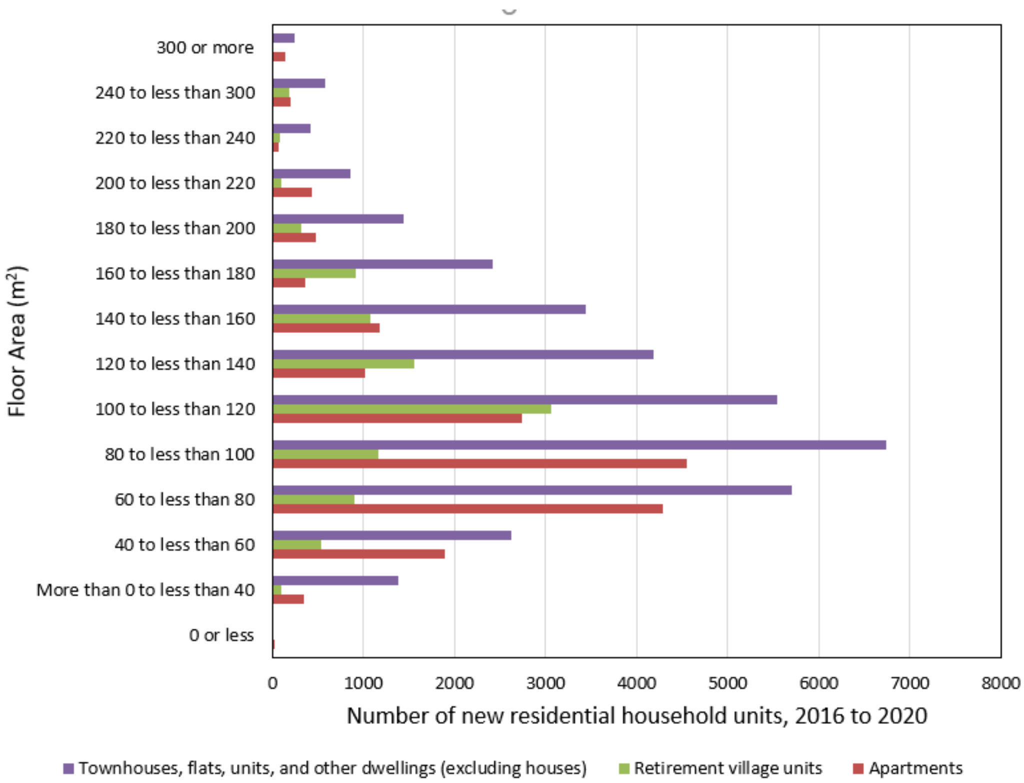

Figure B1. Number of residential units excluding detached houses consented over the period 2016 to 2020 by floor area and typology (Source: Stats NZ).