Risk-Informed Fire Safety Design of Structures

Fredrik Nystedt
Keywords
Fire safety, risk, structures, load-bearing, separating, verification, performance-based design, active systems, passive systems, sprinkler, quantitative risk assessment, reliability, design alternatives, uncertainty.

This report constitutes a final working manuscript for the headlined project.

The official project report, to which reference should be made, can be found on the LTH’s website.

"Risk-Informed Fire Safety Design of Structures"

www.lth.se

ISSN: 1402-3504
ISRN: LUTVDG/TVBB-7045-SE

BRANDFORSK 2018:4
Risk-Informed Fire Safety Design of Structures
Riskbaserad dimensionering av konstruktioner vid brand

Fredrik Nystedt

Report 7045        ISSN: 1402-3504        ISRN: LUTVDG/TVBB-7045-SE

Number of pages: 82. Illustrations: Fredrik Nystedt

Keywords: Fire safety, risk, structures, load-bearing, separating, verification, performance-based design, active systems, passive systems, sprinkler, quantitative risk assessment, reliability, design alternatives, uncertainty.

Abstract: During the last twenty years the concept of risk has been thoroughly exploited in several fire safety engineering applications. However, fire safety design of structures has remained consequence-based and only implicitly considers the impact of the scenario frequency. Thus, the possibilities to apply an active approach to ensure that the temperature does not reach a level that will cause mechanical distress to the structure are limited. Current design practice results in an unknown level of risk and a switch towards a probabilistic approach would be beneficial to designers as well as regulators. This report reviews the current design practice on fire safety of structures with a focus on risk and uncertainty, it investigates the importance of enclosure size on the fire development, and it discusses concepts, design approaches of risk in fire safety engineering.

© Copyright: Division of Fire Safety Engineering, Lund University, Lund, 2018.
Preface

This report documents the findings of a research project on risk-based fire safety design of load-bearing structures. The objective of the project is to develop methods on the design of structures in fire to make them more cost-effective. Cost-effectiveness is enabled by introducing a risk-informed design methodology that addresses explicitly performance requirements, safety levels, reliability and uncertainties allowing for a balanced approach to trade-offs between passive and active fire safety systems.

The research project contains three parts:

1. Risk concepts in fire safety design of load-bearing structures.
2. Fire safety design of load-bearing structures in large enclosures.
3. Methods to incorporate active fire protection systems in fire safety design of load-bearing structures.

The scope was broadened to include fire separating structures as well. Load-bearing structures and fire separating structures are strongly linked and sometimes fire separation is one method that could be used to ensure that the load-bearing capacity will remain.

Results from the project have been communicated at the 13th International Conference and Exhibition on Fire Science and Engineering (Interflam) in 2013 and on the 3rd European symposium on fire safety sciences (ESFSS) in 2018. A paper has been submitted to the 2019 Interflam conference.

The project has been financed by Brandforsk, the Swedish Fire Research Board, Wuz AB and Briab Brand & Riskingenjörerna AB.

Representatives from Briab Brand & Riskingenjörerna AB, DeBrand Sverige AB and NCC Building have provided comments on draft versions of this report, which is gratefully acknowledged.
Summary

Design for fire safety may be carried out by two generic approaches – a set of prescriptive rules or by a performance-based approach where analytical tools are used to verify fire safety towards a set of functional requirements and performance criteria given by the building code. Typically, these two methods are mixed when design fire safety within a building. The option to apply fire safety engineering to the design of buildings has been available during the last 20 to 40 years, depending on which aspect of fire safety being considered. Still, the fire protection of a building too often relies on general recommendations rather than scientifically-based solutions, due to a lack of standardised verification methods, acceptance criteria and procedures to ensure high-quality fire safety design. The concept of risk, i.e. the combination of the probability of a fire and a quantified measure of its consequence, has been thoroughly investigated in several fire safety engineering applications over the last decades. Although there are techniques available that allow designers to evaluate fire risks, risk acceptance criteria are missing in general. Structural fire safety design is the exemption having defined target reliabilities. Although these criteria only address the likelihood of collapse of the structural element and not explicitly the characteristics of the failure.

Structural elements can be provided with fire resistance to control the spread of fire or to prevent structural collapse, or both and it is not uncommon to perform trade-offs between passive and active fire protection systems. However, minimal effort has previously been made to understand the fundamental differences between these systems regarding their reliability and failure modes. Performance-based design of structural elements uses a heat exposure model to quantify the thermal load of the fire. The thermal load is characterised by the fire load (duration) and the intensity (air supply). Characteristic values of the fire load are found in various sources and commonly given in the building code, which ought to be used when designing for fire safety. A probabilistic approach was introduced in the mid-1970s where the probability of fire is expressed as a function of the likelihood of fire occurrence, the probability of a flashover and the probability of failure given a fully developed fire. Thus, the target probability of failure could be achieved by applying safety measures that alter the probability of any of these events. Currently, fire sprinklers do allow for a reduction in design fire load, but not any other active safety system can be considered explicitly.

Current practice on structural fire safety design is focused on expressing the thermal load that fire has on a structural member, and how this thermal load reduces its load-bearing capacity. The thermal load is a flashover fire where the temperature-time relationship in case of a natural fire is governed by the fire load, compartment geometry, material properties and available air supply. Several issues have been revoked on the application of such fires, e.g. the assumption of flashover, uniform temperature distribution and discrepancies between the fire curves and full-scale tests. There are also limitations in compartment geometry that needs to be addressed. Many buildings have compartments with far larger floor area and ceiling height than what is applicable within the current design framework.
It has been shown that upper layer temperature is the most important variable when evaluating the importance of enclosure geometry on the fire development. The higher upper layer temperature, the more heating of fuel packages and the quicker the fire will spread. There is a strong link between the upper layer temperature and both the ceiling height and the floor area. Low ceiling height will result less air entrainment in the plume and higher upper layer temperatures. Compared to floor area the ceiling height has the most substantial influence on the upper layer temperature. When the ceiling height is 6 m or higher, the size of the enclosure has relatively small importance for the fire development. The dependence between the fire development and the floor area is weak. The fire development in such enclosures would most likely be better represented by a localised fire or a travelling fire.

A passive, as well as an active system for fire safety, could both be considered as appropriate provisions to achieve adequate safety. Even though there is support of trade-offs between passive and active provisions, current regulations, guidance, as well as design practice do not treat the different aspect of risk related to these systems. By only considering the probability of collapse, the design could deviate from overall societal requirements on avoiding catastrophes or principles of robustness stating that consequences should not be disproportionate to their cause.

Traditionally, passive systems are assumed more robust. These findings are probably related to the concepts where target reliabilities are evaluated as the system is designed. Sprinklers are, on the other hand, assigned a probability of successful operation based on decades of statistics. This is an unfair comparison between the systems as a properly design sprinkler system always would prevent a fully developed fire, thus requiring no specific fire resistance on separating and structural elements. Naturally, this is not the path forward as the failure modes of both types of systems must be treated and understood. Active systems could be argued to be more forgiven as they do not care what mistakes are made to cause a fire, neither do they care if occupants act as planned or not. Passive systems are more sensitive to building use when, e.g. doors are kept open.

Future performance criteria and risk acceptance criteria should not focus solely on probabilities. Emphasis must be put on establish criteria that measure the risk of the unwanted event considering the initiating event, the number of barriers, the expected consequence and the possibility of damage control. Not until such criteria are available the full potential of performance-based fire safety design cannot be utilised.
# Table of contents

1 INTRODUCTION ..........................................................................................................................1  
  1.1 Background .............................................................................................................................1  
  1.2 Aim and objectives ....................................................................................................................5  
  1.3 Method ..................................................................................................................................5  
  1.4 General limitations ...................................................................................................................5  
  1.5 Overview ................................................................................................................................5  
2 PERFORMANCE-BASED FIRE SAFETY DESIGN .................................................................7  
  2.1 Regulatory framework .............................................................................................................7  
  2.2 Fundamentals ..........................................................................................................................10  
3 REVIEW OF CURRENT DESIGN PRACTICE ...........................................................................17  
  3.1 General fire risk concepts .........................................................................................................17  
  3.2 Structural design .....................................................................................................................25  
  3.3 Characterising fire development .............................................................................................32  
  3.4 Implications and disadvantages .............................................................................................35  
4 LARGE ENCLOSURE FIRE DEVELOPMENT MODEL .........................................................41  
  4.1 Model description ...................................................................................................................42  
  4.2 Model assumptions ..................................................................................................................43  
  4.3 Scenario characteristics .........................................................................................................43  
  4.4 Results ..................................................................................................................................43  
5 BALANCING FIRE RISK .............................................................................................................49  
  5.1 Reliability and performance of safety provisions .................................................................49  
  5.2 Design approaches .................................................................................................................55  
6 DISCUSSION ...............................................................................................................................60  
  6.1 Future design concepts .............................................................................................................60  
  6.2 Nuances of risk .........................................................................................................................61  
7 CONCLUSIONS .........................................................................................................................65  
8 REFERENCES ...............................................................................................................................67
1 Introduction

1.1 Background

Traditional fire safety regulations could be considered being built up by a number of barriers, being either preventive or protective. Barriers that are intended to work before a specific initiating event takes place (e.g. a fire), serve as a means of prevention. Such barriers are supposed to ensure that the accident does not happen, or at least to slow down the developments that may result in a severe accident. Barriers that are intended to work after a specific initiating event has taken place serve as a means of protection. These barriers are supposed to shield the environment and the people in it, from the consequences of the accident. Svenson (1991) showed how the barrier concept had been applied by practitioners of risk analysis. A barrier was defined as “equipment, constructions, or rules that can stop the development of an accident”. Svenson (1991) provided a distinction between three types of barriers; passive, active, and procedural. Passive barriers, such as fire-rated structures, would always be ready to use. Active barriers, such as fire extinguishing equipment, would require some activation before they could be used. Finally, procedural barriers, such as instructions for the use of equipment, would require a mediating agent to be effective. A distinction must be made between barrier functions and barrier systems. A barrier function represents a function that could stop the development of an accident, and barrier systems are those systems that are maintaining the barrier functions. Such systems, in case of fire, could be a well-trained fire warden, a fire compartment, an automatic sprinkler system, and the firemen’s elevator. The use of the barrier concept should be based on a systematic description of various types of barrier systems and barrier functions. The NFPA “Fire Safety Concepts Tree” (NFPA, 2007) is an excellent example of the use of the barrier concept to deal with fire risks.

In 1994 the Fire Safety Committee of the Nordic Committee on Building Regulations published a proposed model for a performance-based code for fire safety in buildings (NKB, 1994). The main idea with a performance-based code is to formulate performance requirements which secured the stipulated safety level without dictating detailed design and selection of materials. The general objective in a performance-based code could be (NKB, 1994):

“Every building and structure shall be constructed in such a way and with such materials, and their fittings and furnishings shall be such that, with regard to their use and situation, they afford satisfactory safety with respect to fire for persons who are present in the building, including secure facilities for the rescue of persons and firefighting, and with respect to the spread of fire to buildings and activities both on the same and adjoining plots. Every building and every structure shall be constructed in such a way that they provide acceptable safety against damage to property and the environment.”
In a performance-based code, compliance with the fire safety regulations can be demonstrated in two ways. Either by constructing the building by pre-accepted solutions or using analyses and calculations which document that safety against fire is satisfactory. The pre-accepted solutions sometimes also referred to as “deemed to satisfy” solutions, are used to simplify the design process and the construction of buildings by eliminating the need for analyses and calculations. The uses of analytical tools are hardly desirable or necessary for traditional buildings. The pre-accepted solutions are sometimes also published in a separate handbook, and the building is considered safe if these solutions are adopted. On the other hand, those who can perform analyses and calculations are given a real choice of freedom in establishing the fire safety design solution, without having to resort to exemptions or other deviations from the regulations. A building is considered safe irrespective of its design and construction if it complies with the performance requirements in the performance-based building code. The selection of the design method, i.e. using pre-accepted solutions or analytical tools do both results in building with adequate safety in case of fire if the performance requirements are met.

Verification is a central term in a performance-based code. When pre-accepted solutions are adopted, the designer verifies that the building has been built according to the specifications of the pre-accepted solutions. The designer does not need to show that the design is safe, as this comes automatically with the use of pre-accepted solutions. When analytical tools are used, verification becomes of utter importance. The designer must use his tools to show that the proposed design solution results in a safety level that is in line with what is accepted by the society, i.e. formulated in the performance requirements of the building code. This process of showing sufficient safety is commonly referred to as verification and could be conducted with several different methods, ranging from qualitative screening techniques to extensive quantitative analyses.

Most buildings are designed with pre-accepted solutions. However, sometimes a deviation from some of these solutions is in the interest of the builder. This process, when one pre-accepted solution is replaced by another solution, is generally considered as a design alternative or a design alternative. All design alternatives need to be verified to show that the achieved safety level complies with the regulatory requirements. This verification is done by employing analytical tools, and the result should be documented and thoroughly reviewed.

In most situations, a fire sprinkler system is not mandatory in Nordic building regulations, and the list of possible design alternatives is short when designing with pre-accepted solutions. A properly installed and operating fire sprinkler system controls the fire development at an early stage enabling occupants to escape safely as well as preventing fire spread and ensuring the structural stability of the building. However, fire sprinkler system reliability is not 100 %. Statistics show that the system is unavailable in approximately 5 to 10 of 100 fires, which enlightens the demand of additional fire safety measures.
Naturally, all fire safety features have reliabilities less than 100 %, and one of the most critical questions to be answered is on how much additional fire safety is needed in buildings with fire sprinkler?

The fire safety design process with analytical tools has also been more formalised with publications from BSI (2001) and SFPE (2007). However, neither of these publications provides enough practical guidance to the engineer, and there is a need for a straightforward guide to be used when verifying a trial design solution. Such a guide would need to address suitable methods and their use, as well as provide sufficient data on various design situations.

The current performance-based fire safety design process has been under scrutiny over the last few years. Still, both designers and authorities having jurisdiction (AHJs), put too much emphasis on the prescriptive design concepts rather than fundamentally managing and understanding fire risk. Alvarez et al. (2013a) identify several challenges with the design process, fundamentally that general guidance is applied to specific projects and that levels of performance are compared between an engineering solution and one based on prescriptive requirements. The comparative approach is also identified, by a recent Nordic initiative (Mindykowski and Strömgren, 2017), as one of the significant implications why performance-based fire safety design have not been overly successful. The fire protection of a building too often relies on general recommendations rather than scientifically-based solutions due to a lack of standardised verification methods, acceptance criteria and procedures to ensure high-quality fire safety design. Frameworks for a future risk-informed fire protection design process has been proposed (Alvarez et al., 2013b, Bjelland et al., 2014). Both concepts emphasise introducing clear performance criteria.

During the last 25 years, the concept of risk, i.e. the combination of the probability of a fire and a quantified measure of its consequence, has been thoroughly investigated in several fire safety engineering applications (Yung, 2009). Although there are techniques available that allow designers to evaluate fire risks, risk acceptance criteria are still lacking. The designer is forced to compare risk levels with prescriptive design solutions even if such is not applicable to the specific case. Absolute fire risk criteria would allow for a more transparent design process that strives towards an acceptable safety level, and that does not give any favours to either a prescriptive nor a performance-based solution. Currently, such criteria are non-existent, except for structural safety where a set of target probabilities are established in the Eurocode EN 1990 (European Standard, 2002a). However, these criteria mainly address the likelihood of collapse of the structural element and not explicitly the characteristics of the failure regarding pre-warning, consequence and partial failure.
Structural elements and compartmentation can be provided with fire resistance to control the spread of fire or to prevent structural collapse, or both. This paper will address the concepts of risk in fire safety engineering with a focus on requirements on fire resistance. One of the top-level fire safety objectives in a building code is that the building should be provided with fire resistance for a particular time. This time is not precisely defined and could be the time required for occupants to escape and the fire service to intervene, or the full duration of a fire (Buchanan and Abu, 2017).

Current practice on structural fire safety design is focused on expressing the thermal load that the fire has on a structural member and how this thermal load reduces its load-bearing capacity. The thermal load is a flashover fire where the temperature-time relationship in case of a natural fire is governed by the fire load, compartment geometry, material properties and available air supply. A natural fire is considered to have the best adaption to the specific conditions in the fire compartment, and the temperature-time curve is assessed by using empirical correlations derived from a one zone model of a fully developed compartment fire where the temperature is distributed uniformly within the room, and there is one single vertical opening.

Several issues have been revoked on the application of such fires, e.g. the assumption of flashover (Stern-Gottfried and Rein, 2012), a uniform temperature distribution (Stern-Gottfried et al., 2010) and discrepancies between the fire curves and full-scale tests (Welch et al., 2007, Barnett, 2007). There are also limitations in compartment geometry that needs to be considered. Eurocode EN 1991-1-2 (European Standard, 2002b) specifies a temperature-time relationship of parametric fire (natural fire) to be applied in compartments not larger than 500 m² with a ceiling height of no more than 4 m. Many buildings have compartments with far larger floor area and ceiling height. Thus, the guidance on the design of structures in the event of a fire in these buildings is vague and practically non-existent. Engineers are therefore forced to use methods beyond their area of applicability, and a better understanding of the fire development, particularly in large compartments is of great interest to have an efficient design process.

The requirements on fire resistance for most public buildings are related to withstanding a complete burnout. However, it is not uncommon to perform trade-offs between passive and active fire protection systems. Active systems such as fire sprinklers will control the fire development and reduce the likelihood of a fully developed fire. This reduction will typically allow for lower requirements on fire resistance. The idea is to balance the two systems achieving the same safety level as if the active system would not be present. Although, there are fundamental differences between passive and active provisions and their characteristic failure modes that need to be addressed. Without an understanding of these inherent features, it is hard to accomplish a properly balanced fire safety design solution.
1.2 Aim and objectives

This report documents the findings of a research project on risk-based fire safety design of structures. The objective of the project is to develop methods on the design of structures in fire to make them more cost-effective. Cost-effectiveness is enabled by introducing a risk-informed design methodology that addresses explicitly performance requirements, safety levels, reliability and uncertainties allowing for a balanced approach to trade-offs between passive and active fire safety systems. The overall aim is to allow for a more balanced use of active and passive provisions to prevent fire spread and structural collapse.

1.3 Method

An initial literature survey was conducted to give a comprehensive background to describe the fundamentals of performance-based fire safety engineering within the current regulatory framework. A literature study was also used to examine the current design practice regarding structures in fire and identify the disadvantages and criticism raised against it. Theories on fire dynamics and heat transfer were used to develop a model that could be applied to investigate the relationship between the enclosure ceiling height and floor area and the fire development in the enclosure. Concepts of risk in fire safety engineering were described and further developed to illustrate risk evaluation ideas, design approaches, data need, reliability as well as nuances needed to be addressed when performing trade-offs between active and passive provisions for fire safety.

1.4 General limitations

This report provides details on concepts of risk in fire safety engineering applications. These concepts are not by any means exclusive, and other approaches could be used to verify sufficient safety when an analytical design approach is adopted.

1.5 Overview

This report contains seven chapters providing essential information related to a risk-informed fire safety design process with a focus on structures. The 2nd chapter about “Performance-based fire safety design” contains an introduction to the regulatory framework that has been evolved in the Nordic countries over the past 25 years. It also provides an overview of the essentials of the performance-based fire safety design process. The 3rd chapter is a thorough “Review of current design practice” of the how structures in fire are design today. Several implications of the current process that need to be addressed in future code development are identified.

The 4th chapter on “Large enclosure fire development model” describes a model of the fire development in large enclosures with a room configuration exceeding the scope of current design methodology presented in the Eurocode. The influence of the ceiling height and floor area to the fire development is investigated.
The 5th chapter on “Balancing fire risk” present aspects of reliability and concepts how risk can be balanced by using active and passive provision for fire safety. The risk reducing capabilities of fire sprinklers are illustrated, and some design approaches outlined.

Finally, there is a discussion on future design concepts and nuances of risk needed to be addressed. Risk is a multi-facet concept with several different dimensions. Even though risk could be purely mathematical, it is necessary to broaden the perspective to deal with, e.g. peoples’ perception of risk.
2 Performance-based fire safety design

2.1 Regulatory framework

2.1.1 Hierarchal structure
NKB (1978) presents the so-called Nordic Five-Level System which is currently used by most performance-based regulatory frameworks and structures. The system is built up by the following hierarchal levels:

1. Goal: The goal addresses the interests if the society
2. Functional requirement: A functional requirement addresses a specific aspect of the building that will contribute to achieving the overall goal.
3. Performance requirement: Performance requirements are the actual requirement that should be met to fulfil the functional requirements. If possible, these requirements should be expressed in quantifiable terms.
4. Verification: This level contains instruction or guidelines for verifying compliance with the performance requirements.
5. Pre-accepted solutions: When designing fire safety in traditional buildings a set of pre-accepted solutions are available to simplify the design process and the construction of buildings.

2.1.2 Functional requirements
NKB (1994) is considered as a framework for a performance-based code, and it gives functional and performance requirements for buildings in the event of the outbreak of fire. On the top level (see hierarchal structure in section 2.1.1), the building law requires that buildings should be safe in the event of a fire. This fundamental requirement is made a bit more nuanced with the introduction of functional requirements on construction work stating that:

- The load-bearing capacity can be assumed for a specific period.
- The generation and spread of fire and smoke within the construction is limited
- The spread of fire to neighbouring construction works is limited.
- People in the construction on fire can leave it or be rescued by other means
- The safety of fire and rescue service personnel is taken into consideration.

These requirements are practically the same throughout the Nordic countries, and it is generally considered that a building must comply with the objectives of each technical requirement. These requirements could also be found among the “safety in case of fire” requirements of the construction products directive (CPD, 1988) by the European Commission. To give more details on which level of safety the society requires, a set of performance requirements are introduced. These are presented in section 2.1.3.
2.1.3 Performance requirements

The NKB (1994) outlines performance requirements on the five functional requirements presented at the overall level. The performance requirements should always be met when designing for fire safety.

Stability and load-bearing structures

NKB (1994) states that a building shall be designed in such a way that it has sufficient stability and load-bearing capacity in the event of a fire. The term “sufficient” is dependent on building type and use. For some buildings, the stability and load-bearing capacity shall be retained during the entire fire sequence. In other buildings, collapse is allowed but not before, e.g. the time required for escape, rescue and prevention of fire spread to neighbouring buildings.

Development and spread of fire and smoke in the building

Performance requirements on the growth and spread of fire and smoke in the building are divided into four groups (NKB, 1994); the outbreak of fire, the development of fire, the spread of fire inside the building and firefighting.

Fittings, furnishings and engineering services shall be such or constructed in such a way the risk of an outbreak of fire is minimised. Surface materials shall not contribute to the development of a fire in an unacceptable extent. NKB (1994) states that a building shall be divided into fire compartments and compartment groups (fire sections) in such a way that the spread of fire and smoke is reduced or impeded unless other measures prevent fire spread.

NKB suggests that fire should not be able to spread beyond a fire section, given consideration to likely firefighting input. NKB also indicates that a fire should be maintained within a fire compartment during the time which is necessary for escape and rescue of persons in the fire section. Finally, NKB (1994) recognises that buildings shall have essential firefighting equipment and be designed in such a way that the rescue personnel can operate in an effective, safe and rapid manner.

The spread of fire between buildings

NKB (1994) states that the danger if fire spread shall be prevented so that the safety of persons is satisfactory and that a fire will not cause unreasonable massive economic or social losses.

The escape of persons

Buildings shall provide facilities for a safe escape, and during the time required for escape, there shall be no occurrence of heat, fire effluents or other circumstances that will impede escape. NKB (1994) give details on the number of escape routes, the construction of doors leading to escape routes and the escape routes themselves. Some requirements are at least two independent escape routes from each fire compartment, the selection of materials in escape routes and doors in escape routes being possible to open without the use of keys.
The safety of rescue personnel

According to NKB (1994), the building must have safe access routes to be used for rescue and firefighting. The rescue personnel shall have a reasonable chance of locating and extinguishing a fire.

2.1.4 Technical guide for verification

The performance requirements are too imprecise to be used when performing verification with analytical tools. To be able to conduct a verification, the NKB (1994) has produced a technical guide that gives details on load combination to be investigated, failure criteria for the safety of persons, the stability of structures and spread of fire as well as guidance in assessing if the failure criteria are met. Figure 2.1 illustrates a schematic procedure for verification by calculation (the use of analytical tools).

![Figure 2.1 Schematic calculation procedure according to NKB (1994).](image)

The verification concept introduced by NKB (1994) is a bit of all or nothing approach where the designer either entirely uses pre-accepted solutions or fully employs an analytical approach. However, as the design procedure has developed over the past 15 years, it is more common that the designer uses pre-accepted solutions for the majority of the fire safety features in the building and only uses analytical tools to verify a few trade-offs, i.e. deviations from the pre-accepted solutions.
2.2 Fundamentals

2.2.1 Barrier groups and fire safety features

Yung (2009) introduces barrier groups when describing and categorising the fire safety features of a building. The structure presented by Yung is related to the development of the fire in the building and uses principles of “defence in depth” to show the relationship between various safety measures. Defence in depth is originally a military term where the defender seeks to delay rather than prevent the advance of an attacker. The term defence in depth is now used in many non-military contexts. Regulations on fire safety apply this principle as fire prevention does not focus all the resources only on the prevention of fire; instead, it also requires the deployment of escape routes, compartmentation, detection, extinguishers etc.

In practice, defence in depth is strongly related to redundancy, i.e. a system that keeps working when a component fails. If one escape route is blocked, the occupants can use the other, or if the outbreak of fire isn’t prevented, the fire will remain within the fire compartment. Fire safety in buildings is built up by multiple, redundant, and independent layers of safety systems, which help to reduce the risk that a single failure of a safety feature could cause consequences considered to be too severe.

CAENZ (2008) discusses fire safety measures regarding barriers related to the fire development in a building, i.e., prevent ignition, control fire growth, control smoke spread, limit fire spread within the building, prevent fire spread to other structures, means of escape, facilitate rescue operations and prevent structural collapse. Table 2.1 shows the link between performance requirements in NKB (1994) and the proposed barrier groups.

Table 2.1 Link between performance requirements and major barrier groups on fire safety.

<table>
<thead>
<tr>
<th>Performance requirement</th>
<th>Major barrier group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability and load-bearing structures</td>
<td>Prevent structural collapse</td>
</tr>
<tr>
<td>Development and spread of fire and smoke in the building</td>
<td>Prevent ignition</td>
</tr>
<tr>
<td></td>
<td>Control fire growth</td>
</tr>
<tr>
<td></td>
<td>Control smoke spread</td>
</tr>
<tr>
<td></td>
<td>Limit fire spread within the building</td>
</tr>
<tr>
<td>The spread of fire between buildings</td>
<td>Prevent spread to other buildings</td>
</tr>
<tr>
<td>The escape of persons</td>
<td>Means of escape</td>
</tr>
<tr>
<td>The safety of rescue personnel</td>
<td>Facilitate rescue service operations</td>
</tr>
</tbody>
</table>

The fire safety measures in a building are related to one or more of the phases of fire development, and CAENZ (2008) provides the following list of significant barrier groups and possible fire safety measures.
Below are lists of such safety measures related to fire development, fire spread and structural collapse.

- **To control fire growth**
  - Control fuel sources (good housekeeping).
  - Specify suitable covering materials for walls and ceilings.
  - Provide hose reels, extinguishers.
  - Install sprinklers or other suppression systems.
  - Check water supplies in the street for fire service use.

- **To limit fire spread within the building**
  - Provide compartmentation – fire resistance to walls and floors
  - Ensure that doors are closed
  - Control vertical shafts
  - Seal penetrations
  - Provide fire dampers in shafts
  - Limit the size and geometry of external windows
  - Control the fire by installing sprinklers

- **Prevent structural collapse**
  - Provide the main structural members with adequate fire resistance
  - Control the extent of the fire through compartmentation
  - Control the fire with sprinklers.
  - Remove fire gases by smoke vents.

### 2.2.2 The fire safety design process

Verifying fire safety in buildings may be performed using a variety of different methods. The INSTA 951 (Nordic Standard, 2018) outlines a fire safety design process that is illustrated in Figure 2.2 and Figure 2.3 below. Figure 2.2 refers to INSTA 950 (Nordic Standard, 2014) if pre-accepted solutions are available and propose the use of comparative methods in such cases. Although, the designer has the freedom of choice. However, the decision is required
The first steps of the design process are focused on defining the design task, the scope and the objectives. Pre-accepted solutions play an important role here as they are possible to benchmark any deviations from these solutions towards the performance of them. Which safety provisions are added, and which are removed? How do these alterations influence the functional requirements? Later, design concepts are derived, and trial design solutions are proposed and verified in close relationship with the objectives.
2.2.3 The principle of design alternatives

The fire safety features of a building are commonly designed by a mixture of prescribed solutions and those derived using analytical methods. Most often, the design solution resulting from the prescriptive approach is used as a starting point. If any of these solutions are too expensive or in conflict with other design objectives, then modifications are made to varying degrees. Such changes are referred to as technical design alternatives, i.e. deviations from the prescriptive solutions. The concept of design alternatives is quite simple. One fire safety feature is added to the building, and another is subtracted (or minimised), but the overall safety level remains within what is acceptable, see Figure 2.4.

![Figure 2.4 Principle of optimisation of fire safety in buildings.](image)

There are several reasons for applying design alternatives in the trial fire safety design. Although, for some parts of the building, the prescriptive solutions have advantages as their use is simple, well-known and not very time-consuming. A design solution can therefore often be seen as a combination of the two design methods. In the performance-based environment, adaption is a crucial element. The fire safety design should be adapted to the specific needs of the building considering various aspects such as architectural design, use, and objectives on occupant safety, property protection as well as cost-effectiveness.

In most cases, the focus of the adaption is on presenting a solution, which reduces the building cost and the adaption aims to find the most suitable level of safety for the specific building. Design alternatives is a natural part of the adaption process to find a fire safety design solution that fits both the objectives of the society and the needs of the builder. For example, alternative design solutions on other safety measures such as compartmentation, fire ratings on load-bearing structures, exit width etc., could be allowed by installing a sprinkler system. However, this requires verification towards the performance requirements, and it is necessary to evaluate how the attributes of the proposed fire features relate to the ones resulting of a prescriptive design solution. Such characteristics are, e.g. function, human action-performance, the complexity of the fire safety strategy, complexity of the fire protection system, flexibility, sensitivity, reliability, and vulnerability (Lundin, 2005).
2.2.4 Performance criteria

There are two different sets of performance criteria that could be used to verify that the proposed trial design has adequate safety:

- Comparative criteria
- Absolute criteria

In a perfect world, the designer could choose between either set of criteria in any design situation, but this is unfortunately not the case. There is a lack of absolute criteria in fire safety design, and comparative criteria are practically the only performance criteria available in most design situations.

Comparative criteria

A comparative analysis could be conducted if a prescriptive solution would apply to the building. Such analysis evaluates the performance of the analytical solution in comparison with a prescribed solution, and the following performance criteria could be implemented:

- The total fire safety in a building designed with analytical methods shall at least have the same performance as the fire safety in a building designed with prescriptive methods.
- The building with prescriptive fire safety measures is referred to as a “reference building”, and this building must be as similar to the designed building as possible. The buildings should be of equal size and belong to the same service category and safety class.

There is no need to make a direct comparison with the absolute criteria on, e.g. life-safety and fire spread. The design is considered safe as long as it performs at least better that pre-accepted solution when evaluating the appropriate fire scenarios. It is implicit understood as buildings that are designed in complete accordance with the building regulations must be considered to have a safety level that is tolerable by society.

Comparative criteria are to be used when verifying fire safety with a probabilistic analysis. The calculated risk measures for the proposed design are compared with the same measures for the prescriptive solution. The suggested trial design is acceptable if the level of risk is equal to or lower when comparing the two design solutions.

Absolute criteria

Under certain circumstances, the designer could choose to verify the fire safety of a building, without making comparisons with the safety level achieved with the prescriptive design. The capability of the fire safety design is assessed by direct evaluation of the absolute criteria on, e.g. untenable conditions for life-safety purposes or limit states for fire spread. The following performance criteria could be applied:

- The fire safety measures of a building, as a result of an analytical design approach, are considered to be sufficient if the limit states for relevant parameters are not exceeded.
- The performance of the proposed design solution shall be evaluated for all relevant fire scenarios.
2.2.5 Available verification methods

There are several different methods available to be used when verifying design alternatives. It is not always necessary to conduct a quantitative analysis. Sometimes ranking methods could be applied, but in other situations, there is a need to quantify risk and treat uncertainties in a more detailed way. Paté-Cornell (1996) presents a structure for addressing uncertainty in risk analysis and proposes six different levels on how to handle these uncertainties. A screening of suitable methods identifies a set of techniques that are available to be used when verifying design alternatives. On an overall level, the methods could be either qualitative or quantitative. Qualitative methods belong to “Level 0”, where screening techniques are used to identify risks and measures to protect the building and its occupants are introduced for each risk. Quantitative methods could belong to any of “Level 1” to “Level 5” depending on how uncertainties are treated. Two sets of quantitative methods are suggested. The first is based on “Level 2” using scenario analyses and the second is based on “Level 4” by using event trees or fault trees. From a general point of view the following methods could be used:

- Qualitative risk assessment (Level 0)
- Quantitative assessment with deterministic analysis (Level 2), implicit treatment of uncertainties
- Quantitative assessment with probabilistic analysis (Level 4), explicit treatment of uncertainties.
3 Review of current design practice

During the last twenty years, risk, i.e. the frequency and consequence of a specific scenario set, has been thoroughly investigated in several fire safety engineering applications (Hasofer et al., 2007, Yung, 2009). However, fire safety design of structures has remained consequence-based, and only implicitly considers the impact of the scenario frequency. The CIB W14 undertook pioneering work in the 1980s when publishing their probabilistic design guide on structural fire safety (Kersken-Bradley et al., 1983) and their definition of the probability that a fire-exposed structure or structural member fails is now prevalent throughout the industry:

$$ P_{\text{failure}} = P_{\text{failure|flashover}} \cdot P_{\text{flashover|fire}} \cdot P_{\text{fire}} $$

Equation [3.4][3.1]

Thus, for a structure to collapse due to fire, first ignition is required. Secondly a flashover must take place given ignition, and finally, given the flashover, failure must occur. A tolerable value on the probability of failure could be met by reducing the likelihood that a fire occurs, by reducing the probability that a flashover occurs once a fire has started or by decreasing the probability of a structural failure in the case of a post-flashover fire. Traditionally, structural fire safety design has been primarily concerned with the design of structures exposed to flashover fires. But, by using Equation [3.4] it is evident that either active or passive fire safety measures or a combination of the two could be used to achieve a tolerable risk of failure. Equation [3.4], does, however, give an incomplete picture of the prerequisites for structural failure as collapse could occur without flashover if the structural members are exposed to a localised or travelling fire. Such incidents are often ignored in the theories related to probabilistic structural design.

Buchanan (2008) calls for new knowledge on both the nature of severe fires as well as on the structural behaviour in such fires. Buchanan states that quantitative risk assessment for structural safety will add a new dimension to solve some hard issues in design. Even though the scientific background on the application of reliability-based structural design is somewhat limited, practitioners are keen on adopting methods that optimise designs and reduce construction costs, and it is of interest to regulators that the safety level is well known and understood. Thus, there is a need to bridge the gap between theory and practical application by developing tools that will utilise the concept of risk and treat uncertainties related to structural design for fire safety.

3.1 General fire risk concepts

Passive as well as active provisions for fire safety are both considered to be appropriate techniques to achieve sufficient safety, supported by the approach outlined in the Fire Safety Concepts Tree presented in the standard NFPA 550 (NFPA, 2007) The Fire Safety Concepts Tree is a general qualitative guide to fire safety. It assists in showing various elements that should be considered and their interrelationships. The top level of the Fire Safety Concepts Tree introduces two fire safety objectives:
- Prevent fire ignition
- Manage fire impact

Subsequently, these objectives contain sublevels. E.g., manage fire impact has two major branches: manage fire and manage exposed as shown in Figure 3.1. Managing fire could be done by controlling the combustion process, suppress fire or control fire by construction.

![Figure 3.1 Major branches of “Manage fire impact”. The (+) sign in the gate means that either one of the branches can achieve the top level. Adopted from NFPA (2007).](image)

The Fire Safety Concepts Tree provides a guide to identifying design strategies that may provide an equivalent of safety. “Or” gates indicate where more than one means of accomplishing a strategy in the tree is possible. A decrease in the quality or quantity of one input to an “or” gate can be balanced by an increase in another input to the same gate. This is the fundamental principle of using design alternatives in building design.

However, if the design alternatives are connected through an “and” gate, this would indicate that the combination of design alternatives and trade-ups is invalid. The “and” gate indicates that the removed safety feature is compensated by an increase of an incompatible safety feature. The presences of “or” gates in the tree indicate where alternative strategies exist and where redundancies can be built into the design to improve reliability. This process of analyzing objectives and decomposing them is adequately represented by the Fire Safety Concepts Tree, where each of the specific fire safety concepts is explicitly linked to the higher-level objective or goal.

The two fire safety objectives on the top level are to prevent fire ignition and to manage fire impact, as shown in Figure 3.1. The fire impact could be managed by either managing the fire (e.g. with an active system) or managing the exposed (e.g. with passive systems). The sprinkler system reduces the probability of a fully developed fire, and this increase in safety opens for optimisation of other measures, such as the reduced capacity of structural and separating elements.
3.1.1 Analysing and measuring risk

A probabilistic risk analysis is based on the following three questions (IEC, 1995):

- What can go wrong?
- How likely is this to happen?
- What are the consequences?

The first question is scenario-related and following two questions deals with the probability and the consequences for each scenario. The contribution to the total risk is expressed as a function of the individual scenarios, as shown in Equation [3.5].

\[ R_{tot} = \sum \{s_i, p_i, c_i\} \]  
Equation [3.5][3.2]

Where:

- \( R_{tot} \) = the total risk
- \( s_i \) = the sequence of events in scenario \( i \)
- \( p_i \) = the probability of scenario \( i \)
- \( c_i \) = the consequence of scenario \( i \)

Equation [3.5] originates from Kaplan and Garrick (1981) and is commonly referred to as the “risk triplet”. Naturally, the number of possible fire scenarios in a building is huge. Therefore, the engineer needs to choose several design scenarios that give a fair representation of the total risk.

These design scenarios should be carefully selected, ensuring that the necessary aspects of fire safety are covered. The total risk in the building is approximated by the sum of the risks of each design scenario as shown in Equation [3.6].

\[ R_{tot} \approx \sum_{i=1}^{n} \{s_i, p_i, c_i\} \]  
Equation [3.6][3.3]

Where:

- \( n \) = number of design scenarios

There are only a small number of models that can express the total risk of fire in a building, and these models are too complicated to be used in practice. The main reason for the complexity of the models is that risk is measured differently, depending on which barrier group that is studied. E.g., successful escape measures the escape possibility and limiting fire spread measures the risk of fire separation barrier failure.
Combining these different measures of risk into one single measure of total risk is utterly complicated and could only be done by the use of techniques as multi-attribute utility analysis (CCPS, 1995). When methods of total risk are either too complicated or too simple, the designer needs to perform an analysis of the fire risk at a sub-level related to each barrier group. Sufficient safety (acceptable levels of risk) is then estimated for each barrier function, i.e. to allow for rapid egress or prevent structural collapse. The total fire risk is considered acceptable if each sub-system meets its performance criteria.

In the risk analysis procedure, it is often necessary to examine many scenarios with different chains of events. Each final event, outcome or scenario can be assigned a probability of occurrence. The event tree approach may be used to structure possible sequences of events following the initial event. Event trees are logic diagrams, which can be used to illustrate the series of events involved in ignition, fire development and control, as well as the course of escape. Event tree analysis can consider both human behaviour and the reliability of installed fire protection systems. An example of an event tree is presented in Figure 3.2.

![Event Tree Example](image)

**Figure 3.2** An event tree for a simple fire risk analysis. Note that the values in the tree are only chosen for illustrating the principle.

Risk analyses with event trees are based on a high number of deterministic scenario outcome estimates, but the method is still considered probabilistic. When many sub-scenarios are considered, each with its probability, a probabilistic measure of the risk will be possible to derive (Frantzich, 1998). The risk for each scenario is calculated by multiplying the likelihood of the sub-scenario by its consequences. The total risk associated with a building is the sum of the risks for all scenarios in the event tree. Events that are covered in the event trees are generally related to the fire safety measures of the building, which could be either passive or active fire protection systems. It is also possible to include organisational safety measures. The selection of events to be included in the event tree must be made based on the initial risk screening and the proposed trial design.
Fault tree analysis is another risk analysis technique to be used in a quantitative risk assessment. Fault trees relate to event tree in such manner as they often could be used to derive the frequency of the initiating event, i.e. the outbreak of a fire in the building. Fault trees could also be used to estimate the likelihood of failure for individual events in the event tree, such as sprinkler system unavailable, etc. The fault tree has its basis in the top event, for which the frequency (or likelihood) should be calculated. By investigating which events that need to occur, either individually or in combination with each other, the fault tree receives its branches. Figure 3.3 shows a primary event tree on sprinkler water unavailability.

![Fault tree diagram]

**Figure 3.3  Fault tree for the top event “No water to sprinkler system”**.

The reason for no water being delivered to the sprinkler system could be either that there is no available water source or there is no pump capacity, which is illustrated by an “or-gate” in Figure 3.3. Both water mains must be unavailable at the same time if no water should be delivered, which is illustrated by an “and-gate”. Also, both pumps must be unavailable when firewater is needed if there should be no pump capacity.

Risks could be measured and quantified in several ways. When fault trees are used, the risk is expressed in a unit related to the top event, e.g. the probability of sprinkler failure in the event of a fire or the likelihood of fire spread through a separating barrier. In event trees, three measures of risk could explicitly be calculated, i.e. the “individual” risk, the average risk and the so-called, risk profile. The individual risk is defined as the likelihood (when a fire occurs) that at least one person will be exposed to untenable conditions. The average risk is the weighted sum of the probability and consequence of each scenario in the event tree, and the risk profile is a graphical illustration of the outcome. The calculation procedure of these risk measures is shown in Table 3.1 below.
Table 3.1 Triplets (scenario, probability and consequence) for the event tree in Figure 3.2.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Probability (given fire occurrence)</th>
<th>Consequence (people exposed to untenable conditions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprinkler available</td>
<td>0.90 x 0.70 = 0.63</td>
<td>0</td>
</tr>
<tr>
<td>Door closed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprinkler available</td>
<td>0.90 x 0.30 = 0.27</td>
<td>0</td>
</tr>
<tr>
<td>Door open</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprinkler unavailable</td>
<td>0.10 x 0.70 = 0.07</td>
<td>2</td>
</tr>
<tr>
<td>Door closed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprinkler unavailable</td>
<td>0.10 x 0.30 = 0.03</td>
<td>4</td>
</tr>
<tr>
<td>Door open</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The individual risk \( IR \) could be calculated by summarising the probability of each scenario that has a consequence that is at least one person being exposed to untenable conditions, as shown in Equation [3.7] below.

\[
IR = \sum_{i=1}^{n} p_i | c_i > 0
\]

Equation [3.7][3.4]

The individual risk in the example listed in Table 3.1 is thus 0.07 + 0.03 = 0.10 given that a fire occurs in the building. This could be interpreted as nine of ten fires lead to successful escape, and one out of ten fires causes unwanted exposure of some people. The average risk \( AR \) in Table 3.1 is calculated by Equation [3.8].

\[
AR = \sum_{i=1}^{n} p_i \cdot c_i
\]

Equation [3.8][3.5]

Using Equation [3.8] gives an average risk of 0.63 x 0 + 0.27 x 0 + 0.07 x 2 + 0.03 x 4 = 0.26, which could be interpreted as the expected number of people being exposed to untenable conditions if there is a fire in the building. The risk profile is the final measure of risk, based on Table 3.1 that is shown in this report. In order to draw a risk profile, the scenarios need to be sorted in order by the magnitude of the consequence, which already have been done in Table 3.1. The risk profile is a counter cumulative distribution function (CCDF) of the risk and Table 3.2 provides the necessary data.
Table 3.2  Data to be used when drawing the risk profile (based on information from Table 3.1 and Figure 3.2).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Consequence</th>
<th>Probability</th>
<th>CDF¹</th>
<th>CCDF²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprinkler available</td>
<td>0</td>
<td>0.63</td>
<td>0.63</td>
<td>0.27</td>
</tr>
<tr>
<td>Door closed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprinkler available</td>
<td>0</td>
<td>0.27</td>
<td>0.90</td>
<td>0.10</td>
</tr>
<tr>
<td>Door open</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprinkler unavailable</td>
<td>2</td>
<td>0.07</td>
<td>0.97</td>
<td>0.03</td>
</tr>
<tr>
<td>Door closed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprinkler unavailable</td>
<td>4</td>
<td>0.03</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Door open</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The risk profile is shown in Figure 3.4 where it is clear that the probability of a consequence of at least one (1) is 0.10, which is the same as the individual risk calculated with Equation [3.7]. The average risk is the mass centre of the risk profile.

Figure 3.4  Risk profile for the event tree in Figure 3.2, based on information in Table 3.2.

Quantitative assessment with a probabilistic analysis is performed in four steps; structure, estimate consequences, estimate and evaluate risk and document. The structuring of the verification is based on the initial risk screening where possible scenarios to be included in the event tree are derived and analysed. When each scenario has been established based on the sequence of relevant events, the designer must provide reliable probability data for each event. Such data should preferably be based on statistics or by engineering judgement. When the necessary probability data have been established, the probabilities of the scenarios could be calculated. One of the significant difficulties in using event trees in fire safety engineering

¹ In probability theory and statistics, the Cumulative Distribution Function (CDF) describes the probability that a real-valued random variable X with a given probability distribution will be found at a value less than or equal to x.

² Sometimes, it is useful to study the opposite question and ask how often the random variable is above a certain level. This is called the Complementary Cumulative Distribution Function (CCDF) or exceedance and is defined as; CCDF = 1 – CDF.
is the lack of data on, e.g. the availability of a specific safety system. Many data sources are based on data of systems design for more than 40 years ago (BSI, 2001). It is also tough to understand how “successful performance” has been measured.

The use of event tree analysis to estimate the risk of fire in a building is considered to treat uncertainties in a more explicit way than any other of the proposed verification methods. The event tree technique allows for an evaluation of the sensitivity of many parameters. For example, doors could be left open or closed, escape routes could be blocked, detection systems and sprinklers could fail etc. The event tree could also consider fire development and smoke spread. Although the event tree technique includes sensitivity analysis, the engineer must be very cautious when defining the tree so that all relevant events are incorporated (Olsson, 1999). Two significant uncertainties are related to event tree analyses. First, it is difficult to overlook if all relevant scenarios have been included in the event tree, and second, the estimation of individual probabilities of each event is often based on sparse data. The event tree must consist of all events relevant to the outcome of a particular fire. The estimation of the scenario outcome should represent a worst-credible case within each scenario. A critical task in the sensitivity analysis is to investigate whether cognitive changes to assigned probability data cause a switchover of the findings.

Traditional risk analyses use point estimates to present the risk as shown in the previous example. There are mainly two problems associated with this approach. First, it is highly desirable for decision-makers to be aware of the full range of possible risks to make balanced decisions. Second, point risk estimates frequently are very conservative as a result of the accumulation of the effects of various conservative assumptions made at intermediate steps in the analysis (Magnusson, 1997). The consideration and treatment of uncertainties in risk analysis add considerably to the credibility of the results. One approach to treat uncertainties is to employ Monte Carlo or Latin Hypercube sampling techniques as shown by Frantzich (1998).

3.1.2 Risk evaluation

Methods for developing acceptable risk have discussed in society in the last decades. While doing so, some fundamental risk evaluation principles have been derived. Risk can be evaluated, and risk criteria established using four different principles (Davidsson et al., 1997).

- The principle of reasonableness says that an activity should not involve risks that by reasonable means could be avoided. Risks that by technically and economically reasonable means could be eliminated or reduced is always taken care of, irrespective of the actual risk level.

- The principle of proportionality means that the total risk that an activity involves should not be disproportionate to its benefits.

- By using the principle of distribution, risks should be legitimately distributed in society, related to the benefits of the activity involved. Single persons should not be exposed to excessive risk in comparison with the advantage that the activity affords them.
The principle of avoiding catastrophes says that it is better that risks are realised in accidents with a lower number of fatalities. When discussing risk reduction, terms such as ALARP (As Low As Reasonably Practicable) and ALARA (As Low As Reasonable Achievable) are frequently used.

It is necessary to interpret these fundamental principles towards the field of fire safety design. The principle of reasonableness is taken care of by following the performance requirements in the regulations. The principle of proportionality says that higher fire risks are accepted in an individual building if there are certain financial benefits from it. The industry owner has a much higher responsibility to by himself, find a reasonable fire safety level. The principle of distribution related to requirements on fire compartmentation, the separation between buildings, etc. Those who cannot control the outbreak of a particular fire should neither be affected by it.

The discussion on acceptable levels of risk is commonly focused on two objectives. The first objective has the individual as its basis and weights the risk of an activity versus personal advantages. The second objective is based on a societal point of view and studies the risk versus its benefit for the society as a whole. Some countries have decided upon acceptance criteria for different activities and establishments. Wolski et al. (2000) discuss how risk perception could be included in building fire regulations. The perception of risk depends on a number of risk factors as seriousness, controllability, necessity, exposure pattern and degree of volition. By introducing risk conversion factors to the presented risk factors, it is possible to link how the risk is experienced between different building types and activities. Statistics provide information on the risk level in, e.g. residential buildings. The risk conversion factors could then be used to derive which level of risk that should be considered suitable, e.g. a high-rise office building. It is proposed that acceptance criteria for a fire in buildings should vary depending on the type of building. This is the only way to reflect the differences in risk perception. Some design guides and building codes classify the buildings into different classes to reflect risk perception. Such a classification should be based on both the building and the activity as shown by NKB (1994).

3.2 Structural design

Structural design should consider a variety of actions such as permanent actions, variable actions and accidental actions. Both permanent actions and variable actions relate to ambient conditions, and they are always present. Accidental actions are actions, challenging to define regarding intensity and frequency, which may occur because of accident or exceptional circumstance. Examples of accidental actions include explosions, impacts (collisions) and fires. Design procedures for ambient actions are very similar to those applied for accidental actions related to impact, explosion, earthquake, etc. A review of current design practice related to both ambient actions and fire is of interest to identify its strengths and weaknesses.
Over the last ten years, additional documents have been published on reliability-based design such as the ISO 2394 (ISO, 1998) as well as Eurocode 1991-1-7 (European Standard, 2006). These standards present basic methods, principles and data related to probabilistic design and its calculation procedures for ambient loads and details on the practical application regarding fire safety is limited. Thus, the CIB design guide needed further development to be used in practice and in the 1990s, a European research initiative entitled Natural Fire Safety Concept (European Commission, 2003) tried to establish a more realistic and more credible approach to analysis of structural safety in case of fire that takes account of active firefighting measures and real fire characteristics. The work resulted in a methodology to adjust the design value of the fire load considering the danger of fire activation due to the size of fire compartment and type of occupancy, as well as different active firefighting measures (e.g. sprinklers, detection and a fire brigade). The methodology is a part of Appendix E of Eurocode 1991-1-2 (European Standard, 2002b), but several European countries made reservations against its practical use.

3.2.1 Actions related to ambient loads

The requirements on structures are based on target reliabilities and are differentiated depending on the severity of a collapse. Current practice is defined as semi-probabilistic with the use of characteristic values on loads and specific partial factors. The partial factors depend on the probability of an unwanted deviation from the characteristic value, the inaccuracy of the calculation model and the consequences of collapse. Partial factors are thus an approach used to deal with uncertainty and variability because of unknown failure mechanisms, imperfect theory, higher loads, inaccurate material properties and human error. The ultimate limit state of the structure is evaluated for several load combinations, which all must meet the design criteria, i.e. the resistance, \( R \), must be greater than the stress, \( S \), applied to the structure:

\[
R - S > 0 \quad \text{Equation [3.9][3.6]}
\]

The partial factor method is one of two procedures recognised in the ISO 2394 document on Reliability of Structures for the verification of structural reliability. The other process, known as “the full probabilistic method”, uses defined distributions for load and resistance and evaluates the probability of collapse, \( P_{(R-S<0)} \), in relation to a specified risk criterion, or target reliability, \( P_{\text{target}} \). Equation [3.9] is then rewritten as shown below.

\[
P_{(R-S<0)} \leq P_{\text{target}} \quad \text{Equation [3.10]}
\]

The partial factor method is the most commonly used of these procedures as the method is supported by a set of action and material codes that provides the necessary information on calculation models, characteristic values, etc. However, efforts have recently been made by the Joint Committee on Structural Safety (JCSS) to develop a probabilistic model code (Vrouwenvelder, 2002), which deals with the basis of design regarding target reliabilities, interpretation of probabilities as well as the development of probabilistic models for structural loads and resistance. Target reliabilities are linked to structural risk acceptance criteria and
expressed either as the accepted minimum reliability or as the allowed maximum failure probability, \( P_f \). Commonly, a generalised reliability index, \( \beta \) is chosen as the reliability measure:

\[
\beta = -\Phi^{-1}(P_f)
\]

Equation [3.11][3.8]

In Equation [3.11], the inverse standardised normal distribution (\( \Phi^{-1} \)) is used to transfer the probability of failure into the reliability index. Target reliabilities are given in Eurocode EN 1990 (European Standard, 2002a), and ISO 2394, and they consider a maximum allowable individual risk of app. \( 10^{-6} \) per year as a reference. This reference value could be transformed to a maximum allowable probability of failure of the structure depending on the conditional probability of a person being killed, given the collapse of the structure. The JCSS states that the probability of structural failure should rely on the risk to life, economic consequences and type of failure. A target reliability index \( \beta \) of 4.2 (\( P_f = 10^{-5} \)) is considered as a central value for most design situation, but values between 3.1 (\( P_f = 10^{-3} \)) and 4.7 (\( P_f = 10^{-6} \)) could be used depending on the consequence class of the structure. Proposed safety levels, i.e. target probabilities only implicit consider the consequences of a collapse. Structural elements are assigned different target probabilities related to their importance regarding maintaining structural stability and the severity of the failure, i.e. the potential result is managed by the magnitude of the target reliability.

A proposal to differentiate the required safety in the event of fire depending on people evacuation has been made (European Commission, 2003). The EN 1990 requirement on \( 1.3 \cdot 10^{-6} \) per year should be applied to buildings where escape is practically impossible (e.g. high-rise buildings). For buildings with normal evacuation a target failure probability of \( 1.3 \cdot 10^{-4} \) and for buildings where escape is difficult (e.g. hospitals) a reference value that is 10 times lower is proposed. Note that the target reliability is related to the system as designed, i.e. not built. Gross errors, i.e. failure due to human error or ignorance and failures due to non-structural causes are not covered. These gross errors are supposed to be covered by design review and other quality assurance procedures.

The definition of probability used by the JCSS is the Bayesian interpretation where probabilities are considered as the best possible expression if the degree of belief in the occurrence of a specific event. The Bayesian interpretation does not claim that the probabilities are direct and unbiased predictors of the frequency of collapse that could be observed in practice. Nevertheless, if the analysis is carried out thoroughly, the probabilities will be correct when averaged over many design situations, and it will be possible to derive design values based on common practice. However, the lack of statistical data may lead to uncertainties in statistical parameters and type of distribution.
Actions are divided into different types depending on their time variation, e.g. permanent, variable and accidental actions. Permanent actions are often the sum of many individual loads, and they may be represented by a normal distribution. Variable actions do vary in time, but it is the magnitude of the most significant extreme load that occurs during the specified reference period for which the probability of failure is calculated. Accidental actions are considered in the same manner as variable actions where the magnitude of the load is of greatest interest. The partial factor method uses characteristic values on actions that in combination with a specified partial factor will meet the target reliability. Characteristic values are often selected as the 50-year load, i.e. a load value that will not be exceeded by a probability of 98 % during a reference period of one year. The resistance of the structural member is treated in a similar, but opposite manner. The characteristic value the resistance is decided by the 5 % percentile derived from material testing. Both the characteristic value of the action, \( F_k \) (stress) and the characteristic values of the resistance, \( R_k \), are assigned partial coefficients, \( \beta \) to treat uncertainty related to the variable.

The design values (\( F_d \) and \( R_d \)) are defined as follows:

\[
F_d = \gamma_{F_k} \cdot F_k
\]

\[
R_d = \gamma_{R_k} \cdot R_k
\]

Equation [3.12][3.9]

Equation [3.13]

3.2.2 Actions related to fire

Fire differs from the other accidental actions as a fire cannot be expressed in load-specific units (e.g. kN/m²). Instead, fire is defined as an in-direct action causing a reduction of the load-bearing capacity of the structural member and possible additional loads due to thermal expansion. Thus, fires cannot be treated as loads, even though they are categorised as such. Current practice is focused on expressing the thermal load that fire has on a structural member and how this thermal load reduces its load-bearing capacity. Historically, the thermal load of the fire has its basis in the nominal or standard fire curves developed for fire resistance furnace tests of building materials and elements for their classification and verification. These curves are the simplest way to represent a fire by pre-defining some arbitrary temperature-time relationships, which are independent on ventilation and boundary conditions and they are often referred to as the prescriptive design approach. In the 1970s a new set of methods were developed which allowed for an analytical approach to the design of structural fire safety compared to the predominant use of standardised fire resistance tests in the prescriptive approach. This development made it possible to quantify thermal exposure based on the conditions of a fully developed fire determined by the combustion characteristics of the fire load, the ventilation of the fire compartment and the thermal properties of the enclosing structures. Today, most national legislation within the EU recognises both these approaches when designing structural fire safety.
The legislative requirements on the load-bearing capacity in the event of fire vary with service category and safety class (NKB, 1994). Most buildings should have sufficient stability and load-bearing capacity during the entire fire sequence. In other buildings, the time required for escape, rescue and preventing fire spread to adjoining constructions are setting the demands on the structure. Buildings assigned to the lowest safety class only need sufficient stability and load-bearing capacity for at least the time required for escape. There are two different set of approaches to be used when evaluating stability in the event of a fire – the prescriptive and the analytical approach. The prescriptive approach is a classification based on the results from a standardised testing procedure according to, e.g. EN 13501 (European Norm, 2007). This approach, where the standard determines the temperature-time response, is often referred to as a “pseudo” fire as the temperature characteristics cannot be generated from basic principles. However, the building industry can get a rating on a specific structure which simplifies the design process.

The analytical approach is based on a “real” fire, called the parametric fire curve in the Eurocode 1991-1-2. The parametric fire curve can be derived using basic principles considering the fire load, compartment geometry, material properties and available air supply. The temperature-time response is based on empirical curves which can be used to determine the thermal load on a structural element and the resulting reduction in load-bearing capacity.

Pettersson et al. (1974) did pioneering work in the 1970s regarding fire safety design of structures and outlined a differentiated design procedure which was slightly modified by Magnusson (1974) to illustrate probabilistic influences (see Figure 3.5). The modification made by Magnusson indicates how the variabilities of different components are lumped together in the resistance term $R$, and the loading term $S$. The procedure in Figure 3.1 consists of three major models, i.e. the heat exposure model (H), the structural model (S) and the reliability model.
Figure 3.5 Flow diagram of fire safety design procedure of load-bearing structures Adapted from Magnuson (1974).

The flow diagram provides insight into the various variables that constitute the fundamentals of current design practice. The assessment of the design gas temperature-time curve in Figure 1 is carried out with a heat exposure model, and the CIB (Kersken-Bradley et al., 1983) presents a set of such models as well as models for a structural response. The heat exposure model (H) will be used to determine the rise of temperature as a function of time, and a structural response model (S) will be used to determine heat transfer to and within the structure and the resulting load-bearing capacity of the structure when exposed to heat. There are three types of heat exposure; standard temperature-time response (H1), time equivalence approach (H2) and a real, natural fire (H3). There are three structural models as well; individual members (S1), sub-assemblies of members (S2) and the complete structure (S3). The majority of the design is carried out in the H1/S1 domain, and when additional flexibility
is required, the $H_2/S_1$ or the $H_3/S_1$ domain is used. Purkiss (2007) states that the assessment method used to evaluate fire performance is related to the heating or temperature exposure rather than the structural model, and consequently the use of $S_2$ and $S_3$ for structural assessment is limited both by the resources required and the uncertainties introduced.

In the standard fire test ($H_1$) a structural element ($S_1$) is loaded with an equivalent load related to the stress that the element would be exposed to when placed in a structure. The element is exposed to heat following a prescribed temperature-time curve until failure of the element occurs. The time when a failure occurs is regarded as the fire rating of the structure (R 30, R 60, R 90, etc.) The prescribed temperature-time curve is defined in EN 13501. The second assessment method – time equivalence ($H_2$) is strongly linked to $H_1$ but allows for some considerations on the actual fire load, compartment geometry and construction material. Time equivalence can be shown either based on temperature or normalised heat load. The temperature-based time equivalence method provides a correlation between natural fire exposure and similar exposure in the standard fire test and can thus replace fire testing to some extent. Unlike the standard fire where the standard itself prescribes the temperature, the temperature of a natural fire ($H_3$) is a function of the compartment size, the type of compartment, available combustible material and air supply. EN 1991-1-2 provides empirical curves to express the temperature-time relationship of such fires, and it is commonly assumed that a structural element should maintain its capacity during the entire fire duration when exposed to natural fire. Figure 3.6 illustrates these three heat exposure models. Note that $H_2$ ‘translates’ the heat exposure from a real fire ($H_3$) to that of the standard fire test ($H_1$). Note that the concept of time equivalence is a crude method of comparing real fire exposure with standard test fires. The concept was developed for protected steel members and certain real fires. It has been shown to be unsafe for some other types of fires and other materials as well as it does not capture common design challenges (Thomas et al., 1997, Law et al., 2014).
The introduction of ideas concerning possible trade-offs between active and passive fire safety measures were described in the 1970s by Baldwin and Thomas (1973). The arguments behind such trade-offs are essential statistical where the active fire safety measure (e.g. sprinklers) reduced the likelihood of severe fire and thus can the passive requirement on the structure be reduced as well. The Natural Fire Safety Concept introduced a possibility to balance the passive requirement on the structure by modifying the design fire load to be applied when assessing the temperature-time relationship of a natural fire. Similar to ambient loads as described by Equation [3.12], the design fire load, \( q_{fd} \) is calculated by multiplying a partial factor with the characteristic fire load, \( q_{f,k} \):

\[
q_{fd} = \gamma_{q_f} \cdot q_{f,k}
\]

Equation [3.14]

According to the Natural Fire Safety Concept, the partial factor for the fire load is divided into sub coefficients to consider the compartment size, \( \beta_{q1} \), the building type, \( \beta_{q2} \), and the different active firefighting measures, \( \beta_{ni} \). Thus, the characteristic fire load must be multiplied by the individual sub coefficients to obtain the design fire load:

\[
\gamma_{q_f} = \gamma_{q_1} \cdot \gamma_{q_2} \cdot \cdots \gamma_{q_0}
\]

Equation [3.15]

\[
\gamma_{q_i} = \gamma_{q_1} \cdot \gamma_{q_2} \cdots \gamma_{q_0}
\]

Equation [3.16]

The EN 1991-1-2 has apprehended this concept of adjusting the design fire load in its Annex E, which is informative and not mandatory for the EU member countries to ratify. E.g., the Swedish building regulations have forbidden the use of the appendix due to some of its drawbacks. However, a partial factor of 0.61 could be applied to the characteristic fire load if the building is fitted with fire sprinklers. If a prescriptive design approach is followed, the requirement of 90 min fire rating could be reduced to 60 min in a sprinklered building. He and Grubits (2010) outline a methodology to be used when assessing risk equivalence between a sprinklered and a non-sprinklered building where the fire rating of the structure is calculated to fulfil the equivalence criterion.

They suggest that their probability-based analytical approach for determining the residual fire resistance required when sprinklers are installed as a supplement to code requirements can be applied to other active safety measures as well. Although, the approach involves knowledge of random variables, failure criteria, probabilities of failure and that the consequences of failure are of similar nature.

### 3.3 Characterising fire development

#### 3.3.1 Fire development stages

The development of a fire in an enclosure, no matter its size, could be described with three major stages, i.e. the growth or pre-flashover stage, the fully developed or post-flashover fire
and the decay period. The pre-flashover stage is characterised by localised burning and relatively low room temperature. Drysdale (2012) outlines three possible scenarios when localised burning has been established:

- The fire may burn out without involving other combustible items. This scenario could occur if the fire is initiated in an object that is isolated from other combustibles.
- The fire could self-extinguish as the fire become ventilation-controlled due to an inadequate oxygen supply.
- The fire may become fully developed and involve all exposed combustibles if there are sufficient fuel and ventilation.

Thus, following ignition, while still small, the fire will be burning free as it would do in the open. The pyrolysis rate and the energy release rate are affected only by the burning of the fuel itself and not by the presence of the boundaries of the compartment. It can grow, either because of flame spread over the item first ignited, or by spreading to nearby objects. Later, a stage will be reached when the confinement will begin to influence the fire development. The increase in energy feedback from the surroundings will eventually lead to a rapid spread to all combustibles in the compartment. The transition is commonly referred to as flashover, and it is not an instantaneous event, but still passing. Following flashover, the fire will involve all combustibles in the compartment. More fuel is pyrolysed than can be burned with the oxygen available in the compartment, i.e. the fire is ventilation controlled. Unburned fuel will leave the openings and may ignite and burn outside the compartment.

The third stage above is of interest when studying the performance of structures in fire as the heat release rate reaches its maximum and the highest temperatures within the enclosure are observed. Therefore, it is necessary to fully understand the issues related to the transformation from a localised fire to full room involvement via flashover. The occurrence of flashover is commonly associated with either a temperature at the upper gas layer or a specific heat flux at floor level. Peacock et al. (1999) define that the onset of flashover will occur with an upper gas temperature of more than 600° C or a heat flux at floor level of more than 20 kW/m$^2$, a definition that is consistent with a broad range of experimental data. The authors recognise that there are significant uncertainties associated with materials involved and the room configuration.

The outline of the fire development from the ignition, via flashover, to a fully developed fire as described above could be interrupted and changed at any time. Both external and internal factors influence fire development. Such factors could be the ignition source, the fire location, fuel characteristics, location of nearby combustibles, ceiling height, floor area, construction material as well as various fire safety measures such as the presence of an extinguishing system or smoke ventilation. The commonly used MQH correlation (McCaffrey et al., 1981) is strongly influenced by the thermal properties of the compartment materials. E.g., if flashover is considered to occur at a heat release rate of 1000 kW in a compartment with concrete surfaces, it would only require 130 kW if the surfaces were made of fibre insulating board.
3.3.2  **Fires in large enclosures**

Several authors have recognised the need to provide a better understanding of the fire development in large enclosures that offer a more nuanced approach considering both pre-flashover and post-flashover exposure. Experiments carried out by the Fire Research Station in the U.K. concluded that a fully developed fire throughout the whole compartment is unlikely due to lack of oxygen away from the openings (Kirby et al., 1994). Even when a fire is ignited in the rear of a compartment concerning its openings, it will quite rapidly spread to combustible material near the openings, after which it will be starved of oxygen in the middle to the rear of the compartment. The fire will progress slowly back to the rear as the fuel in the front of the compartment is consumed. Temperature measurements indicate a difference of app. 400° C between the rear and the front of the compartment, a relationship that changes over time as the fire travels within the compartment.

The absence of a large fire compartment growth and spread model was recognised by a New Zealand research initiative where Clifton (1996) developed a model that used temperature-time curves from small enclosures and adopted these to be valid for large compartments by considering how the fully developed fire will spread throughout the compartment. The model uses a maximum area of a fully developed fire in which a small enclosure model was applicable and moving that area around in the fire compartment in a series of time steps. The small enclosure model adopted was like the parametric fire of the Eurocode where the temperature-time relationship is depending on the fuel load, available openings and the construction material. The spread of the fire was given a fixed rate of 0.5 or 1.0 m/minute, depending only on the opening factor, see Figure 3.7.

![Figure 3.7 Modelling a spreading fire within a large enclosure. The left picture represents conditions in the enclosure after some time, and the right picture illustrates the fire development after additional time has passed.](image)

Cadorin and Franssen (2003a and 2003b) proposed a similar concept to Clifton where a two-zone model was combined with a one-zone model to cover the transformation from an initial, localised fire to full room involvement, called “OZone V2”. The authors established a set of criteria that would initiate the switch of compartment fire model. These criteria relate to the onset of flashover, ignition of combustibles, the interface height and the fire area.
The purpose of the model is to develop more realistic fire scenarios for structural fire safety as it covers both localised fires and fully developed fires. OZone V2 has a similar area of applicability and detail as traditional two-zone models. Thus its capability to predict the fire development in large compartments is limited.

Clifton’s model was one of the earlier approaches to the concept of travelling fire later investigated by Stern-Gottfried and Rein (2012). Even though it was criticised for lacking support in experimental data, it did provide a useful theoretical background related to fire development in large enclosures that could be used in further model development such as which have been carried out by Stern-Gottfried and Rein. Their concept of travelling fires introduces ideas on near field and far field fire exposure. A fire exposes the structure to initial far-field heating, near-field heating as the fire travels by the structure and posterior far-field heating. The near-field temperature is assumed to be 1200° C to represent worst-case conditions as flames in compartment fires rarely exceeds this value. The duration of the near-field exposure is assessed to be app. 20 min by using typical values on fuel load density and heat release rate per unit area. Far-field exposure is estimated by using a ceiling jet correlation developed by Alpert (1972).

### 3.4 Implications and disadvantages

Naturally, there are several advantages associated with the current design practice on structural fire safety, and one of the significant benefits is the simplicity of the methods. A construction element can be exposed to a standard fire in a testing facility and hence qualify to be used in a building. The available calculation models are somewhat calibrated to result in a similar design as the result of a fire test. However, during the last decade questions have been raised in scientific publications regarding the validity of the methods and the drawbacks related to them. Section 3.4.1 to 3.4.3 will describe some practical implications with the current design practice.

The standard fire exposure forms the basis of most structural designs, even though it is considered unrepresentative of real fire conditions. Furthermore, when more realistic fire conditions are used, significant uncertainties regarding the input parameters, in particular, the magnitude of the fire load, are introduced and need to be treated. As the current design practice is mainly consequence-based, it is not common to explicitly consider risk, i.e. the combined effect of the frequency and the consequence of a specific scenario set. Thus, both the prescriptive and the analytical design approaches result in an unknown level of risk, which is an unwanted situation both for both designers and regulators. The designer asks for freedom regarding which method to use to fulfil the building requirements, and the regulator has an interest in a well-known safety level as well as a similar safety level within different types of buildings.

In the prescriptive approach, the risk is mainly controlled as a function of building height as the requirements on the load-bearing capacity are increased with the height of the building. The analytical approach gives an opportunity for a more flexible design as some building
characteristics such as the fire load density, the compartment size, the air supply and the construction material could be taken into consideration. Some building codes apply a safety factor (e.g. 1.5) to the design fire load for tall buildings implying that tall buildings need additional protection as they are exposed to potentially more substantial consequences. Designing for a larger fire load will result in less probability that the fire duration exceeds the fire rating of the construction. If the design fire load is increased, the structure is exposed to a higher maximum temperature and longer fire duration as shown in Figure 3.10. Active fire safety measures, such as an automatic sprinkler system, do allow for a reduction in design fire load or the possibility to design for lower structural requirements when using the prescriptive approach. However, the opportunities to apply an active approach to ensure that the fire is contained or that the temperatures do not reach a level that will cause mechanical distress to the structure are limited.

3.4.1 Temperature-time relationship

One of the most influential parameters in fire safety design of the structural members is the gas temperature surrounding the members of construction, as this temperature will decide the load-bearing capacity of the member when exposed to fire conditions. Uncertainties related to this parameter will, therefore, have a strong influence on the safety level. The designer could choose a heat exposure model from standard fire exposure, a time-equivalence concept, or a natural fire. All methods have several drawbacks that need to be considered. Purkiss (2007) describes some inherent disadvantages of the standard fire test related to the very nature of the test and in part due to the uses of the tests. Standard fire testing is expensive and time-consuming. The data obtained from a test are only applicable to that specific test. Test specimens are limited to size as well as the load conditions are simplified in relation to real-world conditions where, e.g., only axial loads are applied, but the most critical situation for columns is when it is subjected to moments (Purkiss, 2007). Interesting data on reproducibility has been published by Dottreppe et al. (1995) where the same column maintained its load-bearing capacity for 84 min in one test and 138 min in another. Platt (1994) summarises results from different sources on the actual performance of fire rated structures. E.g., the average value of the test failure time is app. 25 % higher than the specified fire rating of the structure. This is a logical consequence of the basis of the fire tests as the test often is interrupted when the desired fire rating is achieved. Thus, a fire test does not provide information on the actual performance in the event of a fire.

Natural fire is considered to have the best adaption to the specific conditions in the fire compartment. Nevertheless, several issues have been revoked on the application of such fires, e.g. the assumption of uniform temperature distribution and the discrepancies between the fire curves and full-scale tests. The temperature-time curve for a natural fire is assessed by using a one zone model of the fire compartment where the temperature is uniformly distributed within the room. Naturally, such an assumption has limited validity for large fire compartments, and consequently, the EN 1991-1-2 limits the use of the parametric fire to rooms with a floor area of maximum 500 m² and a ceiling height of maximum 4 m. However,
full-scale testing for a smaller fire compartment at Dalmarnock (Stern-Gottfried et al., 2010) indicates that the 80 % percentile of the temperature exceeds the mean value by 25 % and from the mean value. The time to reach the maximum value deviates similarly. Barnett (2007) shows that the parametric fire varies from experimental results and other computational models and Yii et al. (2006) illustrate the effect of fuel type and geometry of the compartment. It has been shown that the temperatures will be lower if the compartment has large openings to the outside or if it is well insulated. The result is the opposite for small openings and less insulation. Meanwhile, significant uncertainties relate to the actual opening conditions in the event of a fire as the common assumption is that all doors and windows that do not have a fire rating are open. The dependence of the parametric fire curve to the opening factor is illustrated in Figure 3.8, where the thermal inertia of the construction is $160 \text{ W s}^{0.5}/\text{m}^2 \text{K}$. Note that the growth phase of the temperature-time curve for an opening factor of 0.04 m$^{0.5}$ is very similar to the standard fire.

![Eurocode parametric fire curves, $q_{\text{f}} = 800 \text{ MJ/m}^2$](image)

Figure 3.8 The dependence of the parametric fire on the opening factor.

The parametric curve has its basis in the so-called Swedish fire curves introduced by Magnusson & Thelandersson (1970). However, concerns have been raised on the validity of the initial assumptions made by Magnusson & Thelandersson on ventilation-controlled fires with one vertical opening and wood-based fuel. Synthetic material has different burning behaviour and has shown to produce higher temperatures. The presence of more than one opening in a real fire will result in a non-uniform temperature distribution as a large part of the combustion takes place near the openings. Feasey and Buchanan (2002) propose some changes to the parametric fire in EN 1991-1-2 to get a better estimation of temperatures in post-flashover compartment fires. They also indicate a need for further research into post-flashover behaviour to deal with challenges related to, e.g. fuel geometry and the presence of other ventilation openings apart from the limitation on one vertical opening introduced by Magnuson & Thelandersson. Several authors criticise the decay rate of the parametric fire in
EN 1991-1-2 for not following a natural cooling curve (Barnett, 2007) and for being either too long or too short depending on the opening factor and the thermal properties (Feasey and Buchanan, 2002). Hertz (2005) shows that a structural element of concrete could have its load-bearing capacity reduced by 50 % during the growth phase of the temperature-time curve and reduced by another 25 % during the cooling phase. Thus, depending on construction material, the cooling phase is of great importance to the performance of the structural element in the event of a fire. Equation [1] in the introduction of this paper states that a fully-developed fire is required to put enough thermal stress to the structure to cause collapse. However, this assumption is questionable in larger compartments where flash-over is unlikely to occur, and the temperature in the upper gas layer is non-uniform. For such compartments, Stern-Gottfried and Rein (2012) have introduced a concept of travelling fires. They introduce ideas on near field and far field fire exposure and a fire that exposes structures to initial far-field heating, near-field heating as the fire travels by the structure and posterior far-field heating.

### 3.4.2 Fire load data

Most fire load data are 40-50 years old, and it is necessary to address the relevance of this data in relation to the fire loads today given the increasing use of synthetic materials in furnishing etc. Characteristic values on the fire load (80 % percentile) are given in EN 1991-1-2 for different groups of occupancies such as dwellings, hospitals, hotels, offices and shopping centres. EN 1991-1-2 also provides mean values of the fire load density and a statement that a Gumbel distribution is assumed for the fire load. Figure 3.9 illustrates the cumulative distribution of the fire load density in offices, shopping centres and dwellings. The distributions have been plotted by using data from EN 1991-1-2.

![Cumulative distributions of the fire load density.](image)

**Figure 3.9** Cumulative distributions of the fire load density.

A Swiss fire load survey by Thauvoye et al. (2008) compare fire load density in Eurocode with recent studies in shopping centres, hotels, hospitals and offices. It is concluded that data provided by EN 1991-1-2 on office buildings do not seem to be safe as the densities in the
survey are app. 40 % higher. The same conclusion is drawn for shopping centres. Opposite conditions apply on fire load densities in hospitals and fire load densities in hotels show good agreement with Eurocode data. Thauvoye et al. (2008) conclude that wood material continues to be a high proportion of the fire load and plastics are only present in small quantities. The generalisation of fire load densities to represent wide-range occupancy groups, e.g. shopping centres, may result in uncertainty whether the fire load is representative to a specific fire compartment within the building. The average fire load in shopping centres is 600 MJ/m² according to EN 1991-1-2, which is similar to 571 MJ/m² presented in the Swiss study. Although, when examining individual fire load densities presented by CIB (Kersken-Bradley, 2003) in a variety of occupancies within a shopping centre several types of occupancies are identified where the fire load exceeds the average value of the occupancy group. E.g., bookstores have a characteristic fire load density of app. 1 250 J/m² and the probability that the actual fire load will exceed the characteristic value in EN 1991-1-2 is 83 %, compared to 20 % which should be the result due to the definition of the characteristic fire load as a fire load which is expected not to be exceeded during 80 % of time.

3.4.3 Trade-offs between active and passive provisions

Several national building regulations allow for a reduction in load-bearing capacity when buildings are fitted with sprinklers. But, other active safety measures such as smoke ventilation, fire brigade response, and oxygen depletion systems are not provided with an equal opportunity. The critical question is to decide on the residual level of passive fire safety applied to the structure that when combined with sprinklers will result in the same safety level as the code required fire rating. A possibility to reduce the design fire load will result in a construction that is designed for lower maximum temperature and shorter fire duration, as illustrated in Figure 3.10. In Figure 3.10, $\beta_{qf}$ represents the partial factor in Equation [7], and under normal circumstances, it has a value of 1.0. If sprinklers are fitted in the building, a value of $\beta_{qf} = 0.61$ could be applied according to EN 1991-1-2. For illustrative purposes, the parametric fire for buildings taller than four stories ($\beta_{qf} = 1.5$) is shown in the figure.
Current practice balances the level of residual fire protection by allowing for a construction to be designed with less maximum temperature and shorter fire duration. Note that the rate of increase in the growth period is independent of the fire load and it could be questioned if this is an appropriate approach as fires in sprinklered buildings could have high, but short duration. Using $\beta_{q,f} = 0.61$ is although conservative compared to what has been proposed by the Natural fire Safety Concept where a minimum value $\beta_{q,f} = 0.13$ could be applied if the building has several active fire safety measures in place. Such a low value on $\beta_{q,f}$ results in practically no residual fire protection at all as the temperature only reaches a maximum of 160 °C, and a localised fire will be more severe.

Controlling risk only by changing the design fire load is strictly a probability-based approach that does not consider other aspects of risk than the likelihood of collapse. Neither the magnitude of the consequence nor when a failure occurs is considered, which is insufficient in the common practice of risk control.
4 Large enclosure fire development model

It is recognised that the size and shape of the fire compartment are influencing the onset of flashover and the transformation from localised burning to full room involvement. As the fire progressed, the energy feedback from the surroundings will have increased importance. Eventually, the energy feedback will reach a level where it becomes the dominant force of fire spread compared to flame radiation. This will result in a rapidly increasing area of burning as the fire extends beyond the first item ignited to adjacent surfaces and adjacent objects. Therefore, it would be of interest to illustrate how the size and shape of the compartment influence the fire development quantitatively. A correlation between the likelihood of flashover and the size and shape of the compartment could be used in the design of structural fire safety. For premises, where flashover is unlikely solely due to the configuration of the compartment, another set of design conditions than those traditionally used could be applied.

A model has been developed with the objective to analyse how the compartment itself influences the fire development regarding energy feedback to the initial fire. If the energy feedback is low, one might argue that there is less likelihood for an escalating fire development and thus the designer needs to use alternative methods when designing for structural fire safety such as the concept of localised fires. On the other hand, if the enclosure geometry results in high energy feedback, the designer is forced to consider a fully developed fire.

If a fire is free-burning without any influence from the surroundings, the heat flux to a target at an ambient distance from the flame front is a function of the flame temperature and the configuration factor (i.e. view factor) from the flame to the target. This configuration factor is decided by the distance to the target and the width and height of the flame. The fire itself only influences the propagation of flame. The enclosure boundaries will eventually affect fires occurring inside a building. Flames could impinge under the ceiling, causing an increase in radiation towards targets and there is also heat transfer from the upper gas layer that needs to be considered. Figure 4.1 illustrates how the net heat flux to a target ahead of the flame front is influenced by these two components, i.e. the upper gas layer and the flame itself.
4.1 Model description

A two-zone model has been developed to estimate the upper layer gas temperature in the early stages of an enclosure fire. The radiation from the upper layer, $q_{UL}$, will be used together with the emissive power from the flame, $q_f$, to quantify the net emissive power ($q_{net}$) to the floor:

$$q_{net} = q_{UL} + q_f$$

Equation [4.18]

A comparison between the heat flux from the flame and the total heat flux to the target indicates the importance of the enclosure on the fire development in the building. The two-zone model is made in a spreadsheet to make it possible to change input values and extract output data in a time-efficient way. The model is based on the plume equations by Heskestad (1982) and simple theory on the conservation of energy. The heat released by the fire is transferred to the enclosure boundaries through a one-dimensional heat conduction model, and the excess energy heats the upper gas layer to achieve a balance. Burning occurs within the model if there is oxygen available to maintain combustion. Thus, the maximum heat release rate is dependent on the enclosure volume.

Fire is assumed to spread if a pre-defined threshold value is exceeded. The threshold value is dependent on the type of combustible material that is exposed to radiation from the flame and the upper layer. A threshold value of 15 kW/m$^2$ is selected for the study as this value is representative for spontaneous ignition without the presence of a flame. A free-burning fire is not influenced by an enclosure. Thus, the emissive power of the flame is the parameter that could cause the fire to spread. But, if the fire is placed inside an enclosure, the emissive power from the upper layer will play an essential role in the rate of fire spread. Figure 4.2 below illustrates the addition of the enclosure influence to the free-burning radiation to the floor. The closer the area where the net emissive power exceeds the threshold is to the area where the emissive power from the flame exceeds the threshold, the less influence has the enclosure on the fire spread.
4.2 Model assumptions
The model is based upon the following assumptions:

- The building is assumed to have no openings to the surroundings, except for regular leaks (no pressure build-up).
- There is no exchange of gases to the outside.
- There is no mixing between the upper and lower gas layer.
- Calculations are stopped when the minimum oxygen concentration needed for combustion is reached.

4.3 Scenario characteristics
The model has been run for a total of 136 scenarios where different ceiling heights (3 to 10 m) and different floor areas (100 m² to 8100 m²) are combined. The heat release rate follows a time squared growth rate (0.044 kW/s²) and could be influenced by reduced oxygen availability within the compartment. The heat release rate per unit area is kept at a constant value of 500 kW/m². Thus the fire growth is simulated by an increase in the fire area. Compartment boundaries are assumed to be of concrete.

4.4 Results
Data is calculated for the early stage of the fire development and the results shown below are all from the point in time when the upper gas layer reaches the floor. The fire area can grow until the smoke layer interface reaches the floor. The heat release rate could be influenced by reduced oxygen availability according to the correlation provided by Peatross and Beyler (1997). Figure 4.3 below shows the maximum heat release rate at the end of the calculation. The maximum heat release rate is influenced by the enclosure geometry and ranges from 2 MW in a small 100 m² enclosure to 35 MW in a large 8100 m² enclosure.
Figure 4.3  Maximum heat release rate when the smoke layer interface reaches the floor.

The upper layer gas temperature is the output that is used to estimate the radiative heat flux from the upper layer to the floor. Figure 4.4 below indicates that the upper layer temperature is sensitive both to the ceiling height and the floor area. A large floor area has a higher maximum heat release rate and thus a higher upper layer gas temperature. A low ceiling height results in a higher temperature as there is less air entrainment in the plume, as well as the room volume, is smaller.

Figure 4.4  Upper layer gas temperature estimates.

The upper layer emissive power is based on the gas temperature and the configuration factor between the upper layer and the floor. It follows the same pattern as upper layer gas temperature and is illustrated in Figure 4.5.
Figure 4.5 Upper layer emissive power to floor estimates.

Figure 4.6 and Figure 4.7 illustrates how the ratio between the area where the flame emissive power exceeds the threshold and the area where the net emissive power exceeds the threshold (as shown in Figure 4.2). One could notice that the ratio has a strong dependence on the ceiling height. Ratios for ceiling heights of approximately 5 m or lower are remarkably higher than those for higher ceiling heights, which indicates that an accelerated fire growth would be more likely in these cases.

Figure 4.6 Importance of floor area (fixed ceiling height) on the exceedance of threshold for fire spread.
Figure 4.7 Importance of ceiling height (fixed floor area) on the exceedance of threshold for fire spread.

Figure 4.8 and Figure 4.9 are similar to the figures displaying ratios above, but they show the distance from the flame front to a point where the emissive power exceeds the pre-defined threshold. Combustible items usually are spaced within a building, but most buildings are likely to have less than a few meters of separation distance. Again, an accelerated fire growth is more likely the longer the distance to threshold exceedance is.

Figure 4.8 Importance of floor area (fixed ceiling height) on the distance to threshold exceedance.
Figure 4.9 Importance of ceiling height (fixed floor area) on the distance to threshold exceedance.
5 Balancing fire risk

Reliability and performance are essential parameters that need to be addressed when balancing fire risk. The more frequent a safety system operates and being effective, the more weight can be given to the system when verifying a trial design. This approach applies to passive as well as active safety provision although they have different failure modes. This chapter will discuss various aspects of reliability and introduce some design approaches where these aspects are illustrated.

5.1 Reliability and performance of safety provisions

The reliability of an active system, e.g. fire sprinklers is considered explicitly in the current design approach. Passive systems are, however, always assumed to perform as intended. E.g., neither any ageing effects of sprayed passive protection nor the variability in performance of a board system is considered. Furthermore, doors are assumed to be closed and dampers to shut. The probability that a passive system operates as intended is believed to be 100%, which of course is not true. Thus, there is an inherent imbalance within the system when performing trade-offs that favours passive provisions in front of active provisions that need to be addressed in future methodology development.

5.1.1 Aspects of reliability

Bukowski et al. (2002) discuss different aspects of the reliability of fire protection systems and how their definitions. They define reliability is an estimate of the probability that a system or component will operate as designed over some period. The term unconditional reliability is an estimate of the probability that a system will operate “on demand.” Conditional reliability is an estimate that two events of concern, i.e., a fire and a successful operation of a fire safety system occur at the same time.

Bukowski et al. (2002) use a term called operational reliability, i.e. a measure of the probability that a fire protection system will operate as intended when needed. The operation reliability is a measure of component or system operability, and it does not consider the possibility that system design does not match the fire hazards in the building. Therefore, there is need to provide additional information on the likelihood that the fire development is within the design boundaries. Such a measure of reliability is defined by Bukowski et al. (2002) as the “performance reliability”, i.e. a measure of the adequacy of the system design. A common approach to describe the performance of a sprinkler system is to use terms as Required Density Delivered (RDD) and Actual Density Delivered (ADD). If a sprinkler system ought to be successful, the ADD must exceed the RDD, as shown in Figure 5.1.
In fire safety design it is the combination of operational reliability and performance reliability that is of most interest. It is not possible to only study how often a sprinkler system operates as design as information on the performance in the actual fire is crucial to decide if the system has been successful or not. Ahrens (2017) combines measures of operational reliability (percent where equipment operated) with measures of performance reliability (percent effective of those that operated) to an overall measure of effectiveness (percent where equipment operated effectively), see Figure 5.2.

Passive provisions have other failure modes than active provisions regarding how failure occurs. E.g. delayed or partial failure is more likely than a complete breakdown of the barrier. Even if a building element cannot withstand the design thermal exposure and fail prior its design requirements are met, there is a likelihood that the capacity will be sufficient due to the variability in fire load. If a structural element is protected by other means than over-dimensioning, e.g. by spray-on systems, paint or by boards, there is increased uncertainty that the system will protect the structure with sufficient reliability. Intumescent paint is being exposed to ageing effects with a significant decrease in thermal resistance during the first service years (Zhang et al., 2014). The intumescent coating also performs differently depending on fire development (Cirpici et al., 2016). The standardised test will produce results on the safe side for slower fires, but unsafe results for more rapid fires.
Gypsum boards used to protect both structural and separating elements are also subject to uncertainty regarding performance. E.g. loss of attachment due to heat exposure is hard to predict in general terms and need to be specified by the manufacturers (Kolarkar and Mahendran, 2012).

5.1.2 Reliability data

Active provisions for fire safety, e.g. sprinklers show great record in minimising fire damage. Literature state a reliability of the system from a minimum of 70% to a maximum of 99.5% with most likely values in the range of 90% to 95% (Frank et al., 2013). Table 5.1 provides data on U.S. sprinkler reliability and effectiveness from 2010-2014. Effectiveness is calculated as shown in Figure 5.2. The U.S. experience with sprinklers states that flame damage was confined to the room of origin in 96% of fire when sprinklers were present, compared to 71% of fire without sprinklers (Ahrens, 2017). Thus, sprinkler systems do account for a statistically proven reduction in the probability of a severe fire that could be used when balancing active and passive safety provisions.

Table 5.1 U.S data on sprinkler reliability and effectiveness from 2010-2014 (Ahrens, 2017).

<table>
<thead>
<tr>
<th>Property use</th>
<th>Operation reliability</th>
<th>Performance reliability</th>
<th>Effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public assembly</td>
<td>90 %</td>
<td>94 %</td>
<td>85 %</td>
</tr>
<tr>
<td>Educational</td>
<td>87 %</td>
<td>96 %</td>
<td>84 %</td>
</tr>
<tr>
<td>Health care</td>
<td>85 %</td>
<td>97 %</td>
<td>82 %</td>
</tr>
<tr>
<td>Apartments</td>
<td>94 %</td>
<td>96 %</td>
<td>91 %</td>
</tr>
<tr>
<td>Hotels</td>
<td>90 %</td>
<td>98 %</td>
<td>89 %</td>
</tr>
<tr>
<td>Store/office</td>
<td>91 %</td>
<td>96 %</td>
<td>87 %</td>
</tr>
</tbody>
</table>

From a design point of view, a passive system would fail to operate if it does not withstand the pre-determined fire exposure. But, the performance might still be sufficient for escape and rescue service intervention. Hence, the failure might only be partial. This is not unique to passive systems as both fire sprinklers and smoke management system could fail partially having reduced performance compared to their design criteria. But, the performance still might be sufficient to control the fire and limit the upper layer temperature. Although, sprinkler systems are more likely to have complete failure as the dominant cause for sprinklers fail to operate is the water supply being shut off (Ahrens, 2017).

Available sources on reliability show remarkable variability in the likelihood of successful sprinkler operation. This wide range is troubling, and emphasis must be made to collect and report statistics in a transparent and fair way. The most likely cause of the flaws is the fact that the collection of statistics does not recognise whether the fire was large enough to activate the sprinkler system or if the sprinkler system failed to operate when the fire was large. U.S. statistics presented by Ahrens (2017) indicates that the fire is too small to active sprinkler
heads in 40 to 80 % of the fires. If this information is not considered in the collection of data, the reliability figures will be quite misleading. Jensen et al. (2010) provide evidence on the performance of sprinklers in fire by a compilation of accessible sources. The report addresses sprinklers, residential sprinklers and water mist for protection of residential, care, hospital, office, education as well as retail premises. The information provided by Jensen et al. (2010) could be used as a knowledge base for anyone interested in sprinkler performance in various situations.

It is quite challenging to find suitable reliability data on various fire safety measures, especially those related to doors, smoke vents and fire separating structures. BSI 7974:2003 part 7 (BSI, 2001) provides some data to be used for design purposes which are presented in Table 5.2 below.

### Table 5.2  Reliability data on passive fire systems

<table>
<thead>
<tr>
<th>Passive fire systems</th>
<th>Masonry walls</th>
<th>0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>The probability that fire-resisting structures will achieve at least 75 % of the designated fire resistance standard</td>
<td>Partition walls</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>Glazing</td>
<td>0.4</td>
</tr>
</tbody>
</table>

| The probability that fire doors are kept closed | General value | 0.7 |
| The probability of self-closing doors to close correctly on demand (excluding those blocked open) | General value | 0.8 |

A study from New Zealand (Platt, 1994) shows that there is a variance between documented fire resistance according to the standard fire tests and the measured performance. A construction performs app. 1.10-1.25 time better than its rating, with a coefficient of variation between 5 to 13 %. Higher fire ratings have a smaller coefficient of variation than lower ratings. Table 5.3 presents the findings by Platt (1994).

### Table 5.3  Statistical information on fire resistance.

<table>
<thead>
<tr>
<th>Fire rating</th>
<th>Measured performance</th>
<th>Coefficient of variation</th>
<th>Performance / rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>R 30</td>
<td>37.4 min</td>
<td>12.6 %</td>
<td>1.25</td>
</tr>
<tr>
<td>R 60</td>
<td>70.1 min</td>
<td>9.4 %</td>
<td>1.17</td>
</tr>
<tr>
<td>R 90</td>
<td>99.9 min</td>
<td>6.8 %</td>
<td>1.11</td>
</tr>
</tbody>
</table>

The information provided in Table 5.3 is enough to perform a statistical analysis on the probability that a particular fire rated structure does not withstand fire as long as its rating. Platt (1994) suggests the use of a log-normal distribution to describe the fire resistance, which gives the following results:
- The probability that a construction with a fire rating of 30 min has a performance that is less than its rating is 4.5%.
- The probability that a construction with a fire rating of 60 min has a performance that is less than its rating is 5.4%.
- The probability that a construction with a fire rating of 90 min has a performance that is less than its rating is 6.7%.

5.1.3 Analysis of effectiveness related to performance requirements

Section 2.1.3 lists performance requirements on fire safety in buildings and this section studies available data regarding sprinkler systems’ ability to assist in fulfilling these requirements on fire safety. This section is mainly for illustrative purposes, and two performance requirements are covered: development of fire and spread of fire inside the building. These performance requirements both relate to the functional requirement on “development and spread of fire and smoke in the building”.

The growth of fire within the room of origin could be limited by a number of fire safety features, e.g. by sprinklers. But, if the fire is not kept small, there is a high probability that the fire will spread outside the room of origin. There is limited information available on the performance of Swedish sprinkler systems to reduce the spread of fire. However, it is possible to derive the likelihood of fire spread beyond the room of origin from Swedish incident statistics. Johansson (2003) present a simplified event tree-based methodology (see Figure 5.3) for structuring incident statistics to derive the probability of various stages in the fire development.

![Figure 5.3 An event tree illustrating different fire scenarios (Johansson, 2003).](image)

A small fire is a fire that the incident statistics is considered as being either too small to become large, extinguished at an early stage or self-extinguished. If the fire becomes large, the fire is considered to reach flash-over and become fully developed given that it also spread beyond the room of origin. When this scenario occurs, the fire could either stay within the fire compartment or continue to spread to another fire compartment. Fire sprinklers can stop the fire from becoming fully developed and is therefore considered as an additional barrier as shown in Figure 5.4 below.
Figure 5.4 An event tree illustrating different fire scenarios with fire sprinklers.

Table 5.4 presents the probabilities for each scenario as defined in Figure 5.3 based on incident statistics from the past 20 years, i.e. from 1998 to 2017.

<table>
<thead>
<tr>
<th>Property use</th>
<th>Small fire (S 1)</th>
<th>No fire spread beyond room of origin (S 2)</th>
<th>No fire spread beyond fire compartment (S 3)</th>
<th>Fire spread to other fire compartments (S 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public assembly</td>
<td>35.3 %</td>
<td>20.5 %</td>
<td>24.8 %</td>
<td>19.4 %</td>
</tr>
<tr>
<td>Educational</td>
<td>47.3 %</td>
<td>21.1 %</td>
<td>18.7 %</td>
<td>13.0 %</td>
</tr>
<tr>
<td>Health care</td>
<td>67.3 %</td>
<td>13.9 %</td>
<td>15.2 %</td>
<td>3.6 %</td>
</tr>
<tr>
<td>Apartments</td>
<td>46.1 %</td>
<td>18.8 %</td>
<td>30.8 %</td>
<td>4.3 %</td>
</tr>
<tr>
<td>Hotels</td>
<td>55.8 %</td>
<td>16.2 %</td>
<td>16.6 %</td>
<td>11.4 %</td>
</tr>
<tr>
<td>Store/office</td>
<td>44.6 %</td>
<td>19.9 %</td>
<td>25.7 %</td>
<td>9.8 %</td>
</tr>
</tbody>
</table>

The average value of a fire not kept small is 47 %, i.e. approximately one out of two fires do not endanger either people or property. Hotels and health care premises both have better numbers than average. This could be explained by the requirements on fire alarm as well as the presence of staff. The cumulative probability that fires will be spread outside the fire compartment vary from 4 to 19 % where public assembly has the highest value and health care premises the lowest. Thus, the relative importance of the sprinkler system to limit fire development will be lower in some buildings compared to others. However, the fire sprinkler system is not aware of where it is installed, and such statements are not of interest when verifying fire safety. Although, the operational reliability and effectiveness is dependent on the building use and must be treated individually for the various building types. Information in Table 5.4 can be used to calculate the likelihood that the fire does not spread beyond the room of origin by adding the figures for S 1 and S 2. Consequently, the probability that the fire does not spread beyond the fire compartment is the sum of S 1 to S 3. Numerous factors are influencing whether a fire will end in any of the scenarios described above. Such factors
are fire separating structures as well as the response of the rescue service and building occupants. Sprinkler performance data in section 5.1.2 can be used to calculate estimated probabilities on fire spread in sprinklered buildings. The result is outlined in Table 5.5.

Table 5.5 Estimated probabilities of different fire scenarios, with or without fire sprinklers.

<table>
<thead>
<tr>
<th>Property use</th>
<th>No fire spread beyond the room of origin</th>
<th>No fire spread beyond the fire compartment of origin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No sprinklers</td>
<td>Sprinklers</td>
</tr>
<tr>
<td>Public assembly</td>
<td>55.8 %</td>
<td>93.4 %</td>
</tr>
<tr>
<td>Educational</td>
<td>68.3 %</td>
<td>94.9 %</td>
</tr>
<tr>
<td>Health care</td>
<td>81.2 %</td>
<td>96.6 %</td>
</tr>
<tr>
<td>Apartments</td>
<td>64.9 %</td>
<td>96.8 %</td>
</tr>
<tr>
<td>Hotels</td>
<td>72.0 %</td>
<td>96.9 %</td>
</tr>
<tr>
<td>Store/office</td>
<td>64.5 %</td>
<td>95.4 %</td>
</tr>
</tbody>
</table>

The figures in Table 5.5 indicates that traditional fire safety measures, based on prescriptive design, give a safety level that could be considered satisfactory regarding prevention of fire spread beyond the compartment of origin. Only four (4) of one hundred (100) fires in apartment buildings will spread to another fire compartment, even though there are no sprinklers present. Sprinklers, however, do provide additional safety with a probability of fire spread to another fire compartment in the range of 0.4 % to 3 %. This data could be used when assessing how effective sprinklers are in comparison with other safety measures when verifying design alternatives related to the functional requirements on limit fire spread and prevent structural collapse.

5.2 Design approaches

BSI (2008) states that a sprinkler system in most instances it will assist in controlling the fire. The fire resistance (both separating and load-bearing) of the compartment walls and floors can, therefore, be reduced in a sprinklered building or compartment. The statements on sprinkler influence on these barrier group presented in section 2.2.1 is that:

Sprinklers could replace other fire safety features in the “limit fire, and smoke spread within building” barrier group, given that the probability of sprinkler failure is less than the probability of failure of the replaced features. From a more global perspective, fire sprinklers would allow for lower ratings on fire separating and load-bearing structures. The “national” level of fire damage and building collapse must be kept within the range of acceptable risk.

Sprinkler system efficiency is estimated in section 5.1.3 where the probability of flashover within the room of fire origin could be quantified. When flashover is prevented, the thermal load on the separating structure will be too low to cause fire spread.
Eurocode EN 1991-1-2 (European Standard, 2002b) contains a calculation method to assess the equivalent time of fire exposure, which could be considered a possible solution to “translate” the fire load, material properties and ventilation factors in a specific room to an equivalent time related to the standard fire exposure. EN 1991-1-2 also provides information on the statistical distribution of the fire load in different occupancies which makes it possible to calculate a statistical distribution of the equivalent time of fire exposure. By analysing this distribution, it is possible to assess the probability that a fire in the occupancy will last longer than the fire-rating of the separating construction.

\[ t_{\text{equivalent}} = q_f \cdot k_b \cdot w_f \]  

Equation [5.20][5.1]

Where

- \( t_{\text{equivalent}} \) = equivalent time of fire exposure, min.
- \( q_f \) = the fire load, MJ/m\(^2\) floor area, see Table 5.6.
- \( k_b \) = material properties, 0.07 min m\(^2\)/MJ.
- \( w_f \) = ventilation factor, 1.5 (conservative estimate according to CIB (1986)).

There are known limitations to the time equivalence concept, and the method are not recognised as a design method in all countries, e.g. Sweden. Law (1973) developed the idea and stated that it could only be applied where a single temperature can characterise the structural element behaviour. Thus, it is acceptable for protected steelwork, unprotected steelwork and concrete where the fire performance is dependent only on the temperature of the reinforcement. The concept cannot be used for concrete columns or timber. Nevertheless, the method serves a purpose when illustrating how to use probabilistic methods for verifying safety.

Appendix E to Eurocode EN 1991-1-2 (European Standard, 2002b) present fire loads for different occupancies as shown in Table 5.6.

<table>
<thead>
<tr>
<th>Occupancy</th>
<th>Average</th>
<th>80 % percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwelling</td>
<td>780</td>
<td>948</td>
</tr>
<tr>
<td>Hospital (room)</td>
<td>230</td>
<td>280</td>
</tr>
<tr>
<td>Hotel (room)</td>
<td>310</td>
<td>377</td>
</tr>
<tr>
<td>Office</td>
<td>420</td>
<td>511</td>
</tr>
<tr>
<td>Classroom of a school</td>
<td>285</td>
<td>347</td>
</tr>
<tr>
<td>Shopping centre</td>
<td>600</td>
<td>730</td>
</tr>
</tbody>
</table>
The fire load is considered to belong to a Gumbel distribution\(^3\), and Figure 5.5 shows the complementary cumulative distribution function (CCDF) of the fire load for shopping centres.

\[
\frac{1}{\exp\left(\frac{t-x}{\alpha}\right) + 1} = 0.80 \\
\Rightarrow \frac{t-x}{\alpha} = \ln\left(\frac{1}{0.80} - 1\right) \\
\Rightarrow t = x + \alpha \ln\left(\frac{1}{0.80} - 1\right)
\]

\(\alpha = 730\) MJ/m\(^2\) floor area in this case.

When the statistical distribution of the fire load is used to calculate the equivalent time of fire exposure with Equation [5.20] it is possible to study the probability that fire duration will exceed the rating of the separating or load-bearing elements. The list below is an example valid for shopping centres.

- The probability that a real fire will have a duration exceeding the capability of a 30 min-rated structure is 99.99%.
- The probability that a real fire will have a duration exceeding the capability of a 60 min-rated structure is 83%.
- The probability that a real fire will have a duration exceeding the capability of a 90 min-rated structure is 31%.
- The probability that a real fire will have a duration exceeding the capability of a 120 min-rated structure is 7%.

\(\text{Figure 5.5 CCDF (showing the probability of } x \text{ MJ/m}^2 \text{ or higher) for the fire load in a shopping centre. Please note that the 80% percentile corresponds to the design fire load in the building (730 MJ/m}^2 \text{ floor area in this case).}\)

\(^3\) The Gumbel distribution is a type of extreme value distribution.
These probabilities are only valid if the fire development is uninterrupted. In reality, the fire service has great importance on the likelihood of fire spread. The calculated probability on fire spread in a shopping centre (fire rating of EI 60) is 83 %, which could be compared with the measured probability of 3 % according to data in section 5.1.3. Such difference between statistical data and models need to be addressed when establishing risk criteria.

A design would be considered to have adequate safety if the probability of collapse in a sprinklered building (with design alternative on the fire rating) is the same as in a non-sprinklered building with prescriptive requirements on fire ratings:

$$P_{\text{failure/sprinkled}\sim\text{EI XX}} = P_{\text{failure/no-sprinkled}\sim\text{EI YY}}$$  \hspace{1cm} \text{Equation [5.21]}

$$P_{\text{failure}} = P_{\text{flashover}} \cdot P(S > R)$$  \hspace{1cm} \text{Equation [5.22][5.3]}

The design approach will be illustrated in the example below related to lower requirements on separating as well as load-bearing constructions.

**Can fire sprinklers allow for a reduction from EI 60 to EI 30 in a shopping centre?**

The probability that the fire is not contained within the fire compartment protected by fire sprinklers and with a fire rating of EI 60 is calculated by using Equation [5.22] with data from Table 5.4.

$$P_{\text{failure}} = P_{\text{flashover}} \cdot P(S > R) = 1.2\% \cdot 83\% = 1.0\%$$

The probability that the fire is not contained within the fire compartment protected by fire sprinklers and with a fire rating of EI 30 is calculated by using Equation [5.22] with data from Table 5.4.

$$P_{\text{failure}} = P_{\text{flashover}} \cdot P(S > R) = 0.1\% \cdot 99.99\% = 0.1\%$$

Fire sprinkler and EI 30 have a performance that is app. 10 times better than a rating of EI 60 without fire sprinklers.

**Can fire sprinklers allow for a reduction from R 90 to R 60 in an office building?**

Let us consider an office with a floor area of approximately 100 m$^2$ with a ceiling height of 2.4 m. The opening factor is presumed to be 0.04. The fire load density in this office is given in Table 5.6, and by using Equation [5.20] it is possible to calculate the maximum fire load to prevent the fire duration from exceeding the fire rating.

- The fire load must not exceed 571 MJ/m$^2$ it the fire should have a duration shorter than 60 min (in the standard fire test).
- The fire load must not exceed 857 MJ/m$^2$ it the fire should have a duration shorter than 90 min (in the standard fire test).

The Gumbel distribution on the fire load in dwellings gives a probability that the fire load exceeds 571 MJ/m$^2$ (60 min fire duration) of 11.4 % and a probability of exceeding 857 MJ/m$^2$ (90 min fire duration) of 0.65 %. Their likelihood of failure is app. 17 times higher if the fire rating is lowered to R 60 compared to R 90. This must be compensated by the
reduced probability of flashover offered by the sprinkler system. The reliability of the sprinkler system in an office building is 96% given that the fire is large enough to activate the system.

Even though the fire becomes fully developed, other safety measures could prevent a collapse. The fire service could be successful in their attempt to control the fire, or the fire could run out of fuel. It is reasonable to assume that there are no differences between the studied buildings the possibilities of successful rescue service response, or that the fire will remain small. The event trees in Figure 5.6 and Figure 5.7 illustrates the design problem leading to collapse.

![Event tree on the collapse in a building with R 90 and no sprinkler system.](image)

**Figure 5.6**  Event tree on the collapse in a building with R 90 and no sprinkler system.

![Event tree on the failure in a building with R 60 and fire sprinklers.](image)

**Figure 5.7**  Event tree on the failure in a building with R 60 and fire sprinklers.

The probability of collapse, i.e. the likelihood that the fire duration exceeds the fire resistance time, in a building with a fire sprinkler system and R 60 ratings on load-bearing structures is 0.46%. This should be compared to 0.65% in a building without fire sprinklers and a rating on load-bearing structures of R 90. It is therefore verified that a building with fire sprinklers and R 60 offers at least the same amount of safety as a building with R 90 and no sprinkler system.

The approach is solidly theoretical, and the verification is performed within the same framework as the performance achieved when using results from standardised testing. The method has an implicit link to behaviour under real fire conditions. But, the relationship with the actual structural load under the event of a fire and the capacity of the structure is unclear. Thus, the uncertainty and variability of the system are not fully known.
6 Discussion

6.1 Future design concepts

The conceptual approach on a probability-based design guide on structural safety presented by CIB points out that the only consistent method available to treat the uncertainties related to the behaviour of structures in the event of a fire is a probability-based design approach. Some guidance on the use of a risk-based model is provided EN 1991-1-7 where it is stated that the risk of collapse could be assessed by the frequency of fire, the likelihood of severe fire and the likelihood that the fire duration of a severe fire exceeds the capacity of the structure. The risk of collapse due to fire could then be evaluated towards an acceptable level of safety. Thus, well-established target reliabilities are necessary to implement a probabilistic design code on structural safety. The target reliabilities must represent the current state of risk perception in the society, and it should be investigated how aspects on both individual risk and societal risk ought to be considered. It would be preferable if acceptable levels of risk could be based only upon the probability of collapse as there are several large uncertainties related to the estimation of the consequences of collapse, e.g. regarding time to failure and the number of people left in the building. Ditlvenen (1997) points out that a target reliability criterion must be accompanied by a reference to the specific code format by which it is defined as constant reliability in one code does not imply constant reliability in another code. Therefore, it is necessary to develop a model code in conjunction with the establishment of target reliabilities.

Design strategies for accidental loads in ISO 2394 allow for a reduction of the probability of the action, a decrease of the action intensity as well as a reduction of the effect of the action by limiting the amount of damage or making the structure strong enough. From a philosophical point of view, it should be arbitrary to the society whether the safety of a structure is based on a preventive or a protective approach. However, special attention must be given to the differences between active and passive fire safety features and their failure modes. Time to failure is of great interest, and there are fundamental differences between, e.g. sprinkler water being shut off and insufficient coating of structural members.

The review of the current design practice and its practical implications identified several areas related to the heat exposure model (see Figure 3.6) that need to be developed and considered in a future probabilistic model code on structural fire safety. The magnitude of the fire load is of interest as this variable has significant uncertainties. Fire load data are collected for different types of occupancies, and the characteristic value of the variable is chosen to represent the 80 % percentile of the statistical distribution. However, it has been shown that the fire load varies in great extent within a specified occupancy type (e.g. bookstores in shopping centres). Consequently, the validity of using “generalised” fire load data in combination with “local” variables (e.g. thermal properties and ventilation characteristics) when assessing the temperature-time curve must be questioned.
Fire load data, fuel type and fire compartment geometry are all variables that influence the outcome of the heat exposure model. Thermal properties of the structural elements are considered to have a significant influence on the thermal action of fire as they impact the net heat flow to the construction. The approach with several partial factors related to fire severity, danger of fire and active fire safety measures introduced in the Natural Fire Safety Concept is promising and could form a basis for further development of the heat exposure model. However, additional partial factors must be added related to the variability and uncertainty in fire load data and model uncertainties. It is also necessary to investigate at what phase in the heat exposure model that the partial factors should be applied. Adjusting only the fire load will most likely neglect some essential aspects used to quantify fire severity.

### 6.2 Nuances of risk

The probabilistic design equation provided by CIB (Kersken-Bradley et al., 2003) has a few limitations:

\[ P_{\text{failure}} = P_{\text{failure|flashover}} \cdot P_{\text{flashover|fire}} \cdot P_{\text{fire}} \]  

Equation [3.4]

By studying Equation [3.4], one realises that the probability of failure given a fully developed fire could be increased with the same factor as the probability of flashover given fire is decreased. However, this approach does not consider the consequence of a failure any other way than that a failure occurs. From a societal point of view, it is of interest to extend Equation [3.4], with additional variables describing the effect of the failure. Such variables could be the probability that failure occurs before successful escape or the likelihood that occupants and rescue service personnel will be notified on the imminent failure in due time. The sensitivity of the design solution to common error could also be considered. Usually, active provisions are subject to more frequent inspections than passive provisions. Less effort is taken to ensure that self-closing doors are not blocked and that services passing through compartment walls or floors are adequately fire-stopped.

One other aspect that Equation [3.4] not explicitly consider is the number of barriers in place to prevent an initiating event from progressing to an unwanted event, e.g. failure of a structural element. Figure 6.1 illustrates two safety system.

![Figure 6.1 Two safety systems that are providing the same risk of the unwanted event.](image)

The first safety system has one barrier with a probability of failure of 0.001. The second safety system has three independent barriers each having a probability of failure of 0.1. The second safety system thus has the same total probability of failure as the first (i.e. \(0.1^3 = 0.001\)). But, could the performance of the two safety systems in Figure 6.1 be considered equal? If measuring only the probability of failure, the answer is yes. A failure of 0.001 with one barrier...
is similar to the failure of three barriers having the same combined probability of failure. But if evaluating, e.g. the time until failure, the result could differ a lot. If the barrier in the single barrier system is of on/off-type, then it either operates with 100% effectiveness or it does not operate at all. Compare such a barrier to the multiple-barrier safety system, where failure does not occur until all three barriers have failed. Such a system has a failure time that most likely is longer than what the single barrier system would have. From this point of view, these systems are not equal, despite having the same probability of failure.

The example illustrates one of the crucial factors that need to be considered when combining design alternatives. Naturally, one could express risk as a probability distribution of the failure time and compare these distributions between the two safety systems. Such a procedure would result in an expected time until failure and not just a probability that the collapse will occur. The possibility to reduce ratings on load-bearing structures in sprinklered buildings is a question similar to the one discussed above. In a building without fire sprinklers, the load-bearing structure will keep their capacity for a specific time. This time is relatively unknown as ratings are based on exposure in a standardised test method. Nevertheless, it is assumed that people will escape safely before the occurrence of collapse.

If the fire ratings are reduced in a sprinklered building, there will be two different scenarios. The first, when the sprinkler system operates effectively will have an infinite load-bearing capacity. The second, when the sprinkler system is unavailable will have a load-bearing capacity that is lower than the prescribed solution. How small could be determined by either the time required for escape and rescue or the rating required having the same total level of collapse? There is no straightforward answer on how to combine design alternatives. The most appropriate approach, given the current level of knowledge and experience, is to follow the procedure described by Lundin (2005).

When two risk profiles are compared, it is not always evident which of them that has the lowest risk. If the curves do not cross each other, the lowest of them is the preferable alternative. Figure 6.2 shows two design options. Alternative A is a prescriptive design solution which has a much higher risk than Alternative B, where an active system has been introduced allowing for a reduction of some passive measures. Alternative B performs better than Alternative A with the exemption that the maximum consequence is higher. If the risk is evaluated towards comparative criteria, we must reject Alternative B. But, wouldn’t that be to make perfect the enemy of the good? Instead, Lundin (2005) proposes that the average risk should be used to decide which of them that is the safest.
Figure 6.2 Overlapping risk profiles.

Figure 6.3 illustrates two risk profiles with vastly different characteristics. Alternative B has a high frequency, but a low consequence. Alternative (A) is quite the opposite. Low frequency of failure, but high consequence. In this case, the average risk could be the same, but they have very different risk profiles. Such differences need to be addressed when acceptance criteria are to be established.

Figure 6.3 Risk profiles with vastly different characteristics.
7 Conclusions

A passive system, as well as an active system for fire safety, should both be considered as appropriate provisions to achieve adequate safety. Even though there is support of trade-offs between passive and active provisions, current regulations and guidance, as well as practice, do not treat the different aspect of risk related to these systems. By only considering the probability of collapse, the design could deviate from overall societal requirements on avoiding catastrophes or principles of robustness stating that consequences should not be disproportionate to their cause.

Traditionally, passive systems are assumed more robust. These findings are probably related to the concepts where target reliabilities are evaluated as the system is designed. Sprinklers are, on the other hand, assigned a probability of successful operation based on decades of statistics. This is an unfair comparison between the systems as a properly design sprinkler system always would prevent a fully developed fire, thus requiring no specific fire resistance on separating and structural elements. Naturally, this is not the path forward as the failure modes of both types of systems must be treated and understood. Active systems could be argued to be more forgiving as they do not care what mistakes are made to cause a fire, neither do they care if occupants act as planned or not. E.g., passive systems are more sensitive to building use when doors are kept open.

Future performance criteria and risk acceptance criteria should not focus solely on probabilities. Emphasis must be put on establishing criteria that measure the risk of the unwanted event considering the initiating the event, number of barriers, expected consequence, the possibility of damage control, etc. The full potential of performance-based fire safety design cannot be utilised until such criteria are available.

It has been shown that upper layer temperature is the most important variable when evaluating the importance of enclosure geometry on the fire development. The higher upper layer temperature, the more heating of fuel packages and the quicker the fire spread. There is a strong link between the upper layer temperature and both the ceiling height and the floor area. Low ceiling height will result in less air entrainment in the plume resulting in higher upper layer temperatures. Compared to floor area the ceiling height has the most substantial influence on the upper layer temperature. When the ceiling height is 6 m or higher, the size of the enclosure has relatively small importance for the fire development. The dependence between the fire development and the floor area is weak. The fire development in such enclosures would most likely be better represented by a localised fire or a travelling fire.
8 References


CAENZ, see New Zealand Centre for Advanced Engineering.


Ditlevsen, O., *Structural reliability codes for probabilistic design - a debate paper based on elementary reliability and decision analysis concepts*, Structural Safety Vol. 19, No. 3, 1997


The Swedish Fire Research Board, Brandforsk, is a non-profit body, formed in collaboration between insurance companies, industry, associations, government agencies and local municipalities. The purpose of Brandforsk is to initiate and fund research and knowledge development within the field of fire safety in order to reduce the negative social and economic impact of fire.

The work is under the leadership of the board of directors and is undertaken in the form of projects at universities, institutes of technology, research organisations, government agencies and industrial enterprises. The Secretariat of Brandforsk shares the premises of the Swedish Fire Protection Association, SFPA, which is also the principal organization.