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COMPARATIVE RISK ANALYSIS

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This report has a technical-comparative nature and aims to analyse the fire performance of reinforced concrete and timber structures on the basis of regulatory references, scientific literature and documented case studies. The assessments and conclusions presented refer to project scenarios and reference conditions, developed on real reinforced concrete structures and on timber solutions considered solely at the design level, and do not replace the detailed checks required for individual buildings or specific real situations

The comparison between the construction solutions examined does not claim to cover all possible fire scenarios, nor to represent the uniqueness of behaviours under real conditions, which may vary depending on design choices, construction quality, maintenance, and operational factors. The conclusions should therefore be interpreted as general indications rather than performance guarantees for specific applications. Therefore, no responsibility is assumed for the use of the information contained in this report for design, construction, or decision-making purposes without appropriate project-specific checks, nor for any consequences arising from interpretations or applications that are inconsistent with the intended context.

Section 1: Scientific Comparison Report

1. Introduction

1.1 Centrality of Fire Safety in Building Design

Fire safety today represents one of the most central and critical aspects in the design and management of buildings, particularly in complex urban contexts and in structures with strategic functions or high occupant density. Fire is an exceptional but potentially devastating event, capable of simultaneously compromising occupants' safety, the structural integrity of the building, and the continuity of its functions, with significant economic, social, and environmental consequences.

At European level, fire safety has progressively assumed a central role in building design, evolving from a predominantly prescriptive approach toward a performance-based and risk-oriented framework. This evolution is embedded in the broader regulatory structure established by the Construction Products Regulation (EU No. 305/2011, 3110/2024) and the system of structural Eurocodes, which define the essential requirements related to mechanical resistance, stability and safety in case of fire. Within this harmonised framework, Member States adopt national fire regulations that integrate prescriptive provisions with performance-based and risk-informed methodologies. For example, in Italy, the "*Codice di Prevenzione Incendi*" *(D.M. 03/08/2015 and subsequent amendments)*, in line with the structural Eurocodes, places the control of fire consequences at the core of fire-safety design, requiring that buildings be conceived to limit the probability of structural collapse, ensure acceptable evacuation conditions, and allow rescue teams to operate safely. In France, the "sécurité incendie" requirements for ERP[1] and IGH[2], regulated by the "*Code de la construction et de l'habitation and the related Arrêtés*", require structures to guarantee fire resistance for a specified duration, effective compartmentation, and limitation of fire spread, with growing attention to engineering-based methods. In this context as well, the choice of structural materials and their classification in terms of combustibility and fire resistance are key elements in defining safety measures, influencing both structural design and the extent of required fire protection.

Within this framework, the fire behaviour of structural materials plays a decisive role. Intrinsic material properties, such as combustibility, degradation of mechanical performance with temperature, ability to retain residual strength, and predictability of fire response, directly affect the severity of the fire scenario and its consequences. The choice of the structural system therefore influences not only performance under normal conditions but becomes a key factor in fire-risk management and in the overall resilience of the building.

[1] ERP: Établissements Recevant du Public, buildings or facilities intended for public use.
[2] IGH: Immeubles de Grande Hauteur, high-rise buildings subject to specific fire-safety regulations.

The growing focus on sustainability and innovative construction methods has also encouraged the introduction and dissemination of new structural solutions, making a critical and rigorous approach to fire safety even more essential. In this context, the comparative assessment of different structural materials cannot be limited to verifying compliance with minimum regulatory requirements but must extend to the analysis of performance under severe fire scenarios and to post-event consequences, in terms of safety, structural damage, and the feasibility of restoration.

1.2 Objectives of the Report and Scope of Application

This report aims to provide a technical and scientific comparison between combustible structural material and non-combustible one, analysing their behaviour exclusively from the standpoint of fire protection and safety and the consequences associated with the development of the fire. The analysis is deliberately limited to the effects of fire on the building and on its recoverability. It does not address life safety, nor multidisciplinary evaluations which, although relevant (environmental sustainability, costs, construction time), fall outside the scope of this document.

In particular, the report aims to:

- Describe the physical and thermo-mechanical mechanisms governing the response of the two structural systems to fire exposure.
- Compare the loss of load-bearing capacity as a function of temperature and fire duration, and the condition of the structure at the end of the exposure.
- Examine how the structural material interacts with the fire-safety strategy of the building, with reference to compartmentation, passive and active protection, and the maintenance of these measures over the service life.
- Assess, through five case studies, the consequences of fire in terms of Property Damage, Business Interruption and post-fire recoverability, including indirect damage caused by smoke, soot and firefighting water.
- Identify the conditions under which the choice of the structural material materially affects the outcome, and those under which it does not.

The scope of the report concerns civil, tertiary and industrial buildings, with particular attention to multi-story structures and buildings of medium to high complexity, for which fire protection and safety plays a decisive role in design and management choices. The comparison is developed with reference to realistic fire scenarios consistent with current design practice.

The document adopts a predominantly performance-based approach, supported by regulatory references, experimental evidence, and consolidated scientific literature. The objective is not to establish an absolute hierarchy between materials, but to provide the reader with objective and technically grounded elements to understand how different structural solutions respond to fire and what the related consequences are in terms of risk and safety. From an engineering perspective, fire is classified as an exceptional event, characterised by high uncertainty and strong dependence on multiple factors: fire load, occupancy, ventilation, compartment geometry, and active and passive protection systems.

Unlike static or seismic actions, fire evolves over time and space, generating complex thermal and mechanical effects. Elevated temperatures induce degradation of mechanical properties, thermal expansion, stiffness loss, and, in the most critical cases, structural collapse. For this reason, the assessment of a structure's fire response cannot be limited to its initial resistance but must consider the overall behaviour of the building–fire system.

1.3 Role of Reinforced Concrete in Structural Fire Design

Reinforced concrete benefits from a well-established framework for fire design. EN 1992-1-2 provides tabulated data, simplified calculation methods, and advanced calculation models, supported by an extensive body of standard fire test results (*EN 1992-1-2; fib Bulletin 38, 2007; fib Bulletin 46, 2008*). Complementary national fire-safety provisions and regulatory frameworks exist in various countries, for example through the "*Norme Tecniche per le Costruzioni*" (NTC) and the "*Codice di Prevenzione Incendi*" (D.M. 3 August 2015 and subsequent amendments) in Italy; the "*Approved Document B to the Building Regulations*" (United Kingdom); the "C*ode de la construction et de l'habitation and related fire-safety decrees*" in France; and the "*Boverkets byggregler*" (BBR) in Sweden, and, in Austria, the OIB-Richtlinien issued by the Österreichisches Institut für Bautechnik, in particular OIB-Richtlinie 2 (Brandschutz) and OIB-Richtlinie 2.1 (Brandschutz bei Betriebsbauten), complemented by the TRVB technical guidelines and the ÖNORM standards.

From a fire-protection perspective, reinforced concrete combines three measurable properties: non-combustibility (Euroclass A1 to EN 13501-1), high thermal inertia, and low thermal conductivity. The material does not contribute to the fire load, so that fire development depends on contents and surface linings only, while the thermal behaviour of the cover produces a gradual heating of the reinforcement, delaying the loss of load-bearing capacity.

The mechanical degradation of concrete and reinforcing steel with increasing temperature is a well-known and extensively studied phenomenon, described in EN 1992-1-2 through temperature-dependent reduction factors for strength and stiffness. These relationships allow the residual load-bearing capacity to be computed for a given fire duration, and the resulting response is generally characterised by a progressive reduction in performance rather than by sudden loss of capacity.

A specific critical issue for reinforced concrete under fire conditions is the phenomenon of spalling, discussed in detail later, which may lead to the loss of concrete cover and the direct exposure of reinforcement. Its occurrence depends on moisture content, permeability, compressive strength, and heating rate, and remains difficult to predict quantitatively. Established mitigation measures exist, including limits on moisture content, the use of polypropylene fibres, and additional passive protection.

Reinforced concrete therefore combines codified design procedures (*EN 1992-1-2*), a documented degradation behaviour, and one critical mechanism requiring specific measures. These aspects define the terms on which alternative structural solutions can be compared from a fire-safety perspective, since fire-safety design pursues three main objectives, of which this report addresses the second and the third:

- Protection of human life, ensuring adequate evacuation times and environmental conditions compatible with occupant survivability.
- Limitation of structural damage, preventing progressive collapse and ensuring sufficient load-bearing capacity during and after the fire.
- Reduction of economic and functional consequences, promoting building resilience and the feasibility of post-fire recovery.

These objectives are strongly influenced by the structural typology and the materials employed. The comparison between reinforced concrete and timber must therefore be conducted not only in terms of combustibility, but above all by considering the systemic consequences of fire on the entire building.

1.4 Spread of timber constructions and main fire prevention issues

Over the past two decades, the construction sector has seen a growing diffusion of timber structures *(Fig. 1)*, particularly in mass-timber configurations, such as glued laminated timber (GLT), and cross-laminated timber panels (CLT). This trend has been driven by a combination of environmental, regulatory and construction-process factors, and by the progressive adaptation of the European and international regulatory framework. At European level, the structural fire design of timber is specifically addressed by Eurocode 5 - EN 1995-1-2, which provides calculation models for charring rates, residual cross-sections and fire resistance verification. At national level, these provisions are implemented through building regulations that include dedicated requirements for combustible structural materials, such as the "*Norme Tecniche per le Costruzioni"* (Italy), "*Approved Document B to the Building Regulations"* (United Kingdom), the French *"Code de la construction et de l'habitation"*, and the Swedish *"Boverkets byggregler" (BBR)*. These regulations permit the use of timber in multi-storey buildings, subject to compliance with specific fire performance criteria and, in many cases, additional protective measures.

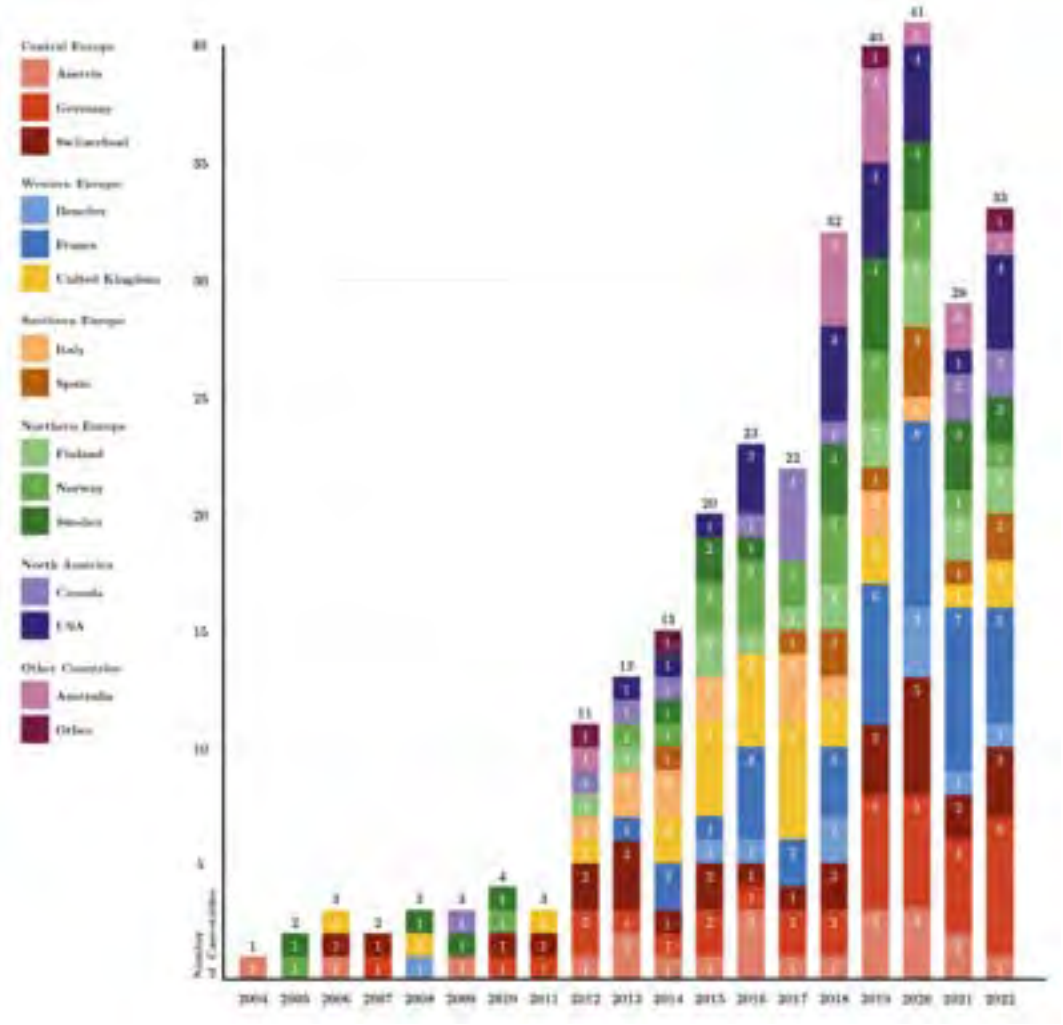


Fig. 1, Construction of Multi-Storey Timber Buildings (TU Wien - Vittorio Salvadori, 2023)

From a fire-protection perspective, timber is a combustible material, typically Euroclass D according to EN 13501-1, with higher classes achievable for dense species or fire-retardant-treated products, that participates in combustion and contributes to the fire load of the compartment.

Its fire behaviour is governed by the phenomenon of surface charring, which leads to a progressive reduction of the load-bearing cross-section and, consequently, of the structural capacity of the elements. EN 1995-1-2 describes this process through tabulated charring rates, which allow the residual cross-section to be computed for a given fire duration. The loss of material is, however, irreversible, and it affects both the load-bearing capacity during the fire and the residual capacity of the elements in the post-fire phase.

Required fire-resistance ratings for timber elements can be achieved through a combination of member sizing, sacrificial charring and passive protection, such as gypsum-board linings or other protective systems, depending on the design strategy. Structural performance is therefore conditional on the design, installation, and durability of these systems, since damage, installation discontinuities, or degradation over time may lead to premature exposure of the timber and to direct involvement of the structural elements in the fire.

Exposed timber surfaces contribute to the heat release rate (HRR) of the compartment. In full-scale compartment tests with fully exposed mass timber, the measured heat release was approximately 80% higher than in comparable tests with protected timber or non-combustible construction, and in one test series the timber panels accounted for about 63% of the total energy released (*McGregor, 2013; Brandon & Östman, 2018*). Under ventilation-controlled conditions, exposed surfaces can also promote external flaming through openings, with implications for fire spread and for firefighting operations. In engineered timber products, the performance of adhesives at high temperature may lead to delamination, that is, the detachment of the charred layer and the exposure of unburnt material underneath, which can prolong the burning phase or prevent self-extinction. Current research and fire-safety provisions increasingly recognise adhesive performance at elevated temperatures as an important factor in controlling delamination, although the prediction of delamination remains an area of ongoing research.

For example, within the framework of the Italian "*Codice di Prevenzione Incendi*" or the UK "*Approved Document B to the Building Regulations"*, the adoption of timber as a primary structural material often requires more articulated fire-safety strategies and compensatory measures compared with solutions based on non-combustible materials. This results in a greater sensitivity of the building-structure system to design assumptions, operating conditions, and long-term maintenance. In this context, while acknowledging the technological and regulatory advances that have expanded the applicability of timber structures, their fire performance is more strongly dependent on the interaction between structural design, protection, material configuration, and fire exposure conditions. This dependency introduces additional sources of uncertainty that should be explicitly considered when comparing timber with reinforced concrete, particularly under severe fire scenarios and when assessing post-fire structural performance.

1.5 Structure of the Document and Comparison Methodology

This report is structured with the objective of providing a technical and consistent comparison between reinforced-concrete structures and timber structures, limited to fire-safety aspects and to the consequences of fire on the building, its occupants, and the continuity of use. The adopted approach is performance-based and engineering-oriented, avoiding generic or purely prescriptive evaluations and focusing instead on the actual response of materials and structural systems under significant fire scenarios.

The document is organised into two sections: a theoretical comparison and the development of five case-studies. The initial theoretical comparison recalls the main fire protection and safety regulatory references at European and international level, with particular attention to reaction-to-fire and fire-resistance classification criteria (EN 13501, NFPA 220) and their impact on design choices. On this regulatory basis, the behaviour of structural materials during a fire is analysed, separately developing the characteristics of reinforced concrete and timber.

For reinforced concrete, the analysis focuses on the non-combustible nature of the material, the progressive degradation of mechanical properties with increasing temperature, the phenomenon of spalling, and the role of intrinsic and extrinsic protection, such as concrete cover and protective plasters. Attention is given to behavioural predictability, residual load-bearing capacity, and implications for global safety and post-fire recoverability.

For timber structures, the comparison examines the combustibility of the material, charring mechanisms, the reduction of the effective cross-section, and the resulting loss of load-bearing capacity. Particular emphasis is placed on the dependence of fire performance on passive-protection systems (linings, intumescent systems) and on the variability of behaviour as a function of fire-exposure conditions, construction methods, and the durability of protection systems.

Subsequently, the report addresses fire-safety strategies at the building-system level, developing a comparison between the two structural typologies with respect to compartmentation, passive and active protection, and long-term maintainability. This analysis is conducted with a consequence-oriented approach, assessing not only the achievement of design performance but also the overall robustness of the system and its sensitivity to design and management assumptions.

The theoretical section concludes with a critical synthesis of the findings and with a comparative summary table, in which reinforced concrete and timber are assessed against a common set of criteria, covering, for example, reaction to fire and contribution to fire growth, the thermal evolution of the cross-section and the resulting residual load-bearing capacity, the critical phenomena specific to each material as detailed on Chapter 3. Applying the same criteria to both systems allows the differences to be attributed to specific mechanisms rather than to overall judgements of material performance.

The second part of the report focuses on five real case studies, appropriately anonymized, concerning different types of reinforced-concrete buildings. For these configurations, a performance-based comparison is developed, assessing how fire behaviour and global performance would vary if the same buildings were constructed using a timber structural system. The comparison is developed through the definition of fire scenarios and the assessment of the resulting losses, following the methodology described in Section 4.

2. Reinforced Concrete vs. Timber: Theoretical Comparison

2.1 Fire-Safety Regulatory Framework: EN 13501

Fire safety in European construction is governed by a harmonised regulatory system that clearly distinguishes between reaction to fire of materials and fire resistance of construction and structural elements. This distinction is essential for understanding the performance differences between reinforced concrete and timber structures, not only during the development of the fire but, above all, in terms of structural consequences, fire spread, and emergency management.

At European level, the main reference is the EN 13501 series, which forms the basis for the classification of fire-performance characteristics of products and construction elements. In particular:

- EN 13501-1 regulates materials reaction to fire.
- EN 13501-2 concerns the fire resistance of construction elements, expressed in terms of load-bearing capacity (R), integrity (E), and thermal insulation (I), for predefined durations (30, 60, 90, 120 minutes and beyond).

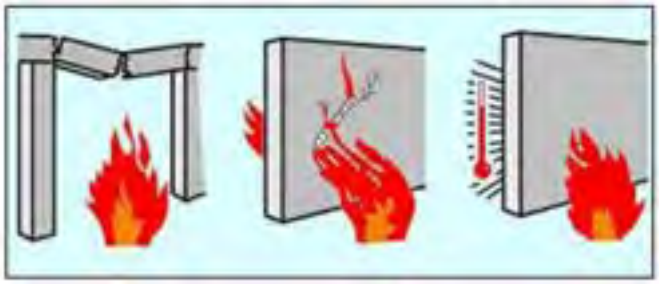


Fig. 2, Loss of load-bearing capacity (R), loss of integrity (E) and loss of insulation (I)

At national level, these classifications are implemented within domestic building regulations. For example, in the United Kingdom, the "*Approved Document B* to the Building Regulations" adopts the EN 13501 classification system and integrates it into a performance-based framework that defines minimum fire-resistance periods, reaction-to-fire requirements for linings and façades, and provisions aimed at limiting structural collapse and fire spread.

Reaction to fire measures the contribution of a material to ignition and fire growth. The European classification system defines classes ranging from A1 (non-combustible) to F (easily combustible). Within this regulatory framework, reinforced concrete consistently falls into classes A1 or A2, being a non-combustible material that does not participate in combustion nor contribute to the fire load. Timber and timber-based products, unless specifically treated, are instead classified in classes C-D-E and are therefore combustible materials capable of actively contributing to fire development; the durability of such treatments over the service life remains the subject of ongoing investigation (Johansson et al., 2026).

In Italy the “Codice di Prevenzione Incendi” and several decrees, such as D.M. 26/08/1992 for school buildings, explicitly limit the use of combustible materials in escape routes, compartmentation elements, and high-occupancy spaces, precisely to reduce the risk of fire spread and flashover. In these contexts, A1/A2-class materials are structurally and functionally more consistent with safety objectives.

In international construction-classification standards, as defined for example by the National Fire Protection Association (NFPA) and the International Building Code (IBC), structures built with non-combustible materials (such as reinforced concrete) typically fall within Type I or Type II categories, which are associated with the highest levels of fire resistance and fire-spread control. Conversely, buildings based on structural timber elements are classified in categories such as Type IV (Heavy Timber) or Type V (Wood Frame), which are combustible construction types and require additional protection to achieve comparable fire-resistance ratings *(NFPA 220)*.

Fire resistance represents the ability of a structural element to maintain its load-bearing function during a fire for a predefined period, thereby ensuring the protection of people, property, and the environment, and thus enabling:

- the evacuation of occupants and the safe intervention of rescue teams.
- the limitation of the risk of progressive collapse.
- the reduction of environmental impacts associated with the fire, by limiting the production of smoke, combustion gases, and potentially harmful residues resulting from the involvement of structural materials.

From a regulatory standpoint, the non-combustible classification of concrete (Euroclass A1 to EN 13501-1) means that the fire-safety verification is limited to fire resistance, without the additional demonstrations that regulations require for combustible structural materials. EN 1992-1-2 allows this verification to be carried out through minimum cross-sectional dimensions and axis distance, so that in many cases the required rating is achieved without additional protective systems.

Timber structures, by contrast, achieve the required fire-resistance classes through a combination of member sizing, sacrificial charring, and passive protection, such as encapsulation with gypsum boards, protective claddings, or intumescent coatings. Where protective systems are used, the achieved performance depends on their installation and on their condition over the service life of the building, which introduces sensitivity to local damage, installation defects, and long-term degradation.

A comparable regulatory philosophy can be observed in Germany, where the “*Musterbauordnung” (MBO)* and the corresponding state building codes distinguish clearly between combustible and non-combustible construction systems and require explicit demonstration of compliance when combustible structural materials are used beyond conventional limits. The same distinction applies in Austria, where OIB-Richtlinie 2 links reaction-to-fire and fire-resistance requirements to the building class, with OIB-Richtlinie 2.1 setting the corresponding provisions for industrial and storage buildings.

Within this framework, the adoption of non-combustible materials, such as reinforced concrete, reduces the extent of compensatory measures required by the regulations.

Recent regulatory openings toward taller timber buildings do not alter this fundamental principle, as they are the result of experimental verification and advanced modelling, but they require rigorous control of construction details, appropriate inspection and maintenance of fire-protection systems, and a comprehensive assessment of the fire scenarios relevant to the specific building configuration.

2.2 Regulatory Frameworks for Structural Fire Design

Structural fire design within the European regulatory framework is governed by the provisions of the Eurocodes, which provide specific methodologies for assessing the structural response of materials exposed to fire conditions. In particular, reinforced concrete structures are addressed within Eurocode 2 - EN 1992-1-2, while timber structures are covered by Eurocode 5 - EN 1995-1-2. Although both standards pursue the common objective of ensuring structural stability for the required fire resistance period, the underlying physical assumptions and modelling approaches differ substantially.

The fire design methodology for reinforced concrete structures is primarily based on the progressive reduction of material mechanical properties as a function of temperature. According to EN 1992-1-2, structural verification in fire conditions may be performed through several approaches, including simplified tabulated methods, simplified calculation models, or advanced numerical analysis. The simplified design approach relies on experimentally validated relationships describing the degradation of concrete compressive strength and reinforcing steel yield strength at elevated temperatures, combined with heat transfer models that account for the relatively low thermal conductivity and high thermal inertia of concrete.

In practical design applications, the standard frequently allows verification through tabulated data that relate fire resistance periods to minimum member dimensions, concrete cover thickness, and reinforcement detailing. These tabulated values are based on experimental results accumulated over several decades of furnace testing, full-scale structural tests, and post-fire investigations.

A key aspect of reinforced concrete behaviour in fire conditions is that the material itself does not contribute to the fire load. Concrete is classified as a non-combustible material (A1 according to EN 13501-1), and therefore the structural system does not participate in the combustion process. Fire exposure primarily affects the structural elements through heat transfer and progressive thermal degradation of mechanical properties, while the structural mass and thermal inertia generally contribute to slowing down temperature penetration into the cross-section. Even in severe fire events, a significant portion of the cross-section may remain below critical temperatures for extended periods, allowing a residual load-bearing capacity to be maintained.

Conversely, the fire design approach for timber structures, as described in EN 1995-1-2, is based on a fundamentally different physical mechanism. Structural resistance during

fire exposure is determined by modelling the progressive charring of timber elements subjected to fire. The design methodology assumes that the outer layers of timber are progressively converted into a char layer that no longer contributes to structural resistance, while the remaining internal core retains its mechanical properties. Structural verification is therefore performed by reducing the effective cross-section according to a predefined charring rate and evaluating the load-bearing capacity of the residual section.

While this simplified approach provides a practical design methodology, it relies on several assumptions regarding the uniformity and stability of the charring process. In real fire conditions, the behaviour of timber structural assemblies can be influenced by multiple additional factors that are not always fully represented within simplified design models. These factors include the performance of protective claddings, the integrity of connections, the behaviour of glued laminated or cross-laminated products under elevated temperatures, and possible delamination phenomena that may expose fresh timber surfaces to direct fire attack. These simplifications are intentional. The nominal charring rates and the reduced cross-section method are calibrated to provide a safe design outcome across the natural variability of timber products and are not intended to reproduce the behaviour of a specific element in a specific fire.

A further element highlighting the evolving nature of the timber fire design framework concerns the treatment of the contribution of combustible structural materials to fire development. In the current provisions of EN 1995-1-2, the structural design approach is primarily focused on the verification of residual load-bearing capacity through charring models, while the potential contribution of exposed timber elements to the overall fire load is not explicitly incorporated within the standard calculation procedures.
Recent developments in the revision of EN 1995-1-2, published in 2025 and expected to enter into force in the coming years, introduce an informative annex providing guidance on how the contribution of timber structural elements may be considered within parametric fire analyses. The introduction of this annex reflects the growing recognition within the fire engineering community that combustible structural materials may significantly influence fire development, particularly in configurations where large, exposed timber surfaces are present.

The need for such provisions highlights a limitation of earlier design approaches, which generally assumed that the structural system would not materially influence the fire scenario considered in the analysis. In configurations where large timber surfaces are exposed, this assumption may lead to an underestimation of potential fire severity and duration.

The practical consequences differ at two levels. The first concerns the fire scenario itself. The concrete model is applied to a fire whose severity is governed by the contents of the compartment, whereas in configurations with large exposed timber surfaces the structure is also a source of energy, so the exposure assumed in the verification and the exposure that develops in the compartment are not fully independent. The second concerns the condition of the structure once the fire is over, which is what governs damage assessment and repair. In reinforced concrete the section normally retains its geometry and is

thermally damaged, so residual capacity is largely a matter of determining the depth affected by heat, unless spalling has removed part of the cover or of the cross-section. In timber the section is physically smaller, and the charred material does not return, so residual capacity is governed by the geometry that remains. Both models are conservative design tools rather than descriptions of real fire behaviour.

Both standards therefore provide recognised design procedures, based on different physical mechanisms and supported by experimental databases of different extent and maturity. The verification carried out under either standard establishes performance under standard fire exposure, and the limits of that exposure with respect to natural fire conditions are discussed in the following sections.

2.3 Materials behaviour

The behaviour of structural materials under fire conditions represents one of the central aspects of building fire protection and safety, as it directly influences both the evolution of the fire event and the associated structural and environmental consequences. Unlike static and seismic actions, fire is characterised by high spatial and temporal variability, with thermal effects that significantly affect the physical and mechanical properties of construction materials. Technical and scientific literature shows that exposure to high temperatures leads to a progressive degradation of structural performance, governed by mechanisms that differ according to the nature of the material. In particular, combustibility, thermal conductivity, heat capacity, chemical stability, and the production of combustion effluents are key parameters in defining the fire response of a structural system *(Buchanan & Abu, Structural Design for Fire Safety, 2017; SFPE, Handbook of Fire Protection Engineering, 2016)*.

The structural Eurocodes for fire conditions, EN 1992-1-2 for reinforced concrete and EN 1995-1-2 for timber, adopt simplified but differentiated models to describe the loss of strength and stiffness of materials as a function of temperature. These models reflect conceptually distinct approaches: on one side, non-combustible materials whose response is dominated by heat transfer and thermo-mechanical degradation; on the other, combustible materials that can actively contribute to fire development and experience a reduction of the load-bearing cross-section due to combustion.

Numerous experimental studies and post-fire analyses have also shown that material behaviour influences not only structural stability during the event, but also system robustness, fire spread, smoke and gas production, and the repairability of the structure after the fire *(FIB, Bulletin 38, 2007; SFPE, 2016)*. As a result, the choice of structural material plays a decisive role in fire-risk management and in the assessment of the overall consequences of the event.

The following sections therefore analyse separately the behaviour of reinforced concrete and structural timber under fire conditions, highlighting their dominant physical mechanisms, regulatory implications, and consequences in terms of safety, reliability, and consequence control.

2.3.1 Reinforced Concrete

Reinforced concrete is widely used in civil, industrial and infrastructure applications owing to its non-combustibility, its high thermal mass, and a loss of strength that develops progressively with temperature and is described by codified thermo-mechanical models.

International technical literature highlights that the response of reinforced concrete to thermal action is characterised by progressive phenomena that can be analysed through consolidated thermo-mechanical models and codified calculation approaches *(Buchanan & Abu, 2017; FIB, Bulletin 38, 2007; SFPE, 2016)*. This predictability has enabled the development of reliable verification methods incorporated into European and international standards, including Eurocode 2 – EN 1992-1-2.

More than a century of use in high-occupancy buildings, critical infrastructure, and industrial facilities has produced an extensive record of real fire events, which complements the results of large-scale experimental campaigns. Both sources underpin the calibration of the design criteria in EN 1992-1-2 and allow calculation models to be validated against observed structural behaviour, including cases of prolonged or ventilation-controlled fires that fall outside standard test conditions.

A particularly relevant aspect, often emphasized in post-fire studies, is the ability of reinforced-concrete structures to retain significant residual strength even after fire exposure. In the absence of severe damage or local collapse, numerous experimental investigations have shown that such structures can be assessed through non-destructive testing, subjected to localized repair interventions, and subsequently reused *(Kodur, 2014; FIB, Bulletin 46, 2008)*.

This behaviour directly affects overall fire-risk management, with important economic and environmental implications in terms of reduced demolition, lower waste production, and limited downtime of activities. Within the framework of fire-safety engineering, these characteristics allow the fire performance of reinforced concrete elements to be verified through the procedures of EN 1992-1-2, on the basis of member dimensions, concrete cover and the temperature-dependent properties of the materials.

2.3.1.1 Non-Combustible behaviour

From a reaction-to-fire perspective, the first fundamental aspect to consider is the intrinsic nature of the material and its potential contribution to fire development. In this context, reinforced concrete stands out for its non-combustible behaviour, as it does not participate in the combustion process in any form, neither as a heat source nor as a fuel. According to the European classification of construction products for reaction to fire (EN 13501-1), concrete falls within Class A1, the highest class, reserved for materials that do not contribute to the fire at any stage of its development. This classification is assigned to materials that do not generate significant heat, do not produce flames, and do not release smoke or flaming droplets under standardised fire-test conditions. This characteristic has significant implications for fire safety. First of all, the absence of combustible contribution means that the fire load of a compartment is not increased by the presence of reinforced concrete structural elements, remaining confined to contents, furnishings and surface linings. Numerous fire-engineering studies highlight that fire severity is strongly correlated with the available fire load and its distribution, making the selection of structural materials that do not participate in combustion a strategic design choice (SFPE, Handbook of Fire Protection Engineering, 2016).

Moreover, the non-combustibility of concrete directly contributes to limiting fire spread, both within the same compartment and towards adjacent ones. In the absence of combustion phenomena involving the structural material, fire propagation is primarily governed by ventilation conditions and the distribution of combustible materials, simplifying the analysis of fire scenarios and increasing the reliability of the design assumptions adopted.

At national level, this classification has direct implications for fire-safety design. In Italy, the “Codice di Prevenzione Incendi” (D.M. 3 August 2015 and subsequent amendments) incorporates the European reaction-to-fire system and sets requirements that favour non-combustible materials in compartmentation and fire-resistance strategies. Similarly, the French “Code de la construction et de l’habitation”, aligned with the European classification framework, treats A1 materials as non-contributing to fire development, thereby simplifying design assumptions related to fire load and flame spread. The non-combustibility of reinforced concrete therefore means that the material does not feed the fire, does not accelerate its development, and does not introduce uncertainties related to the participation of the structural system in the combustion process. This aspect represents the starting point for analysing the behaviour of concrete under fire conditions, which will be further examined in the following sections in terms of mechanical response and structural performance.

2.3.1.2 Mechanical degradation

During a fire, reinforced concrete is subjected to a progressive increase in temperature that leads to a reduction in its mechanical properties and in those of the embedded steel reinforcement. This phenomenon is not associated with combustion processes but rather with physical and chemical transformations of its constituents, which affect the strength and stiffness of the material. It is extensively studied and formalised in the normative models of EN 1992-1-2, which provides temperature-strength relationships for both materials. Understanding these mechanisms is essential for correctly assessing the residual load-bearing capacity of fire-exposed structures.

Numerous experimental studies have shown that the compressive strength of concrete decreases as a function of the temperature reached, with a gradual trend well documented in the literature and expressed through the reduction factor $k_c(\Theta)$, yielding: $f_{ck}(\Theta) = k_c(\Theta) \cdot f_{ck}(°C)$. In particular, up to approximately 300 - 400 °C, the loss of strength is generally limited, whereas more significant reductions occur at higher temperatures, coinciding with the decomposition of cement hydration products and the increase in internal microcracking *(CEB, Bulletin 208, 1991; FIB, Model Code 2010)*.

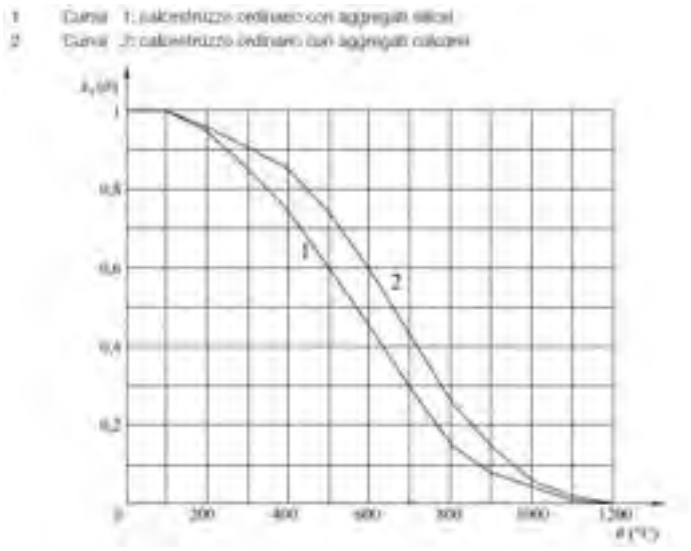


Fig. 3, Trend of the coeff. Kc(Θ) as a function of temperature Θ (EN 1992-1-2:2005)

The behaviour of concrete under fire conditions is systematically described in the structural Eurocodes, particularly EN 1992-1-2, which provides simplified models and reduction diagrams for mechanical properties as a function of temperature. These models, based on an extensive experimental database, allow reliable estimation of the residual strength of structural elements, facilitating design and verification in fire situations.

A relevant aspect highlighted in scientific literature is the progressive nature of mechanical degradation in concrete. Unlike sudden or unstable phenomena, the loss of strength occurs gradually and continuously as temperature increases, allowing a certain degree of stress redistribution within the structure. This progressive behaviour is considered a key factor for structural robustness under fire conditions and for preventing sudden collapse *(Buchanan & Abu, 2017)*. It should also be noted that the mechanical response of concrete is strongly influenced by the mass and thickness of structural elements. The material's low thermal conductivity results in significant temperature gradients between the exposed surface and the inner core, which may remain at relatively low temperatures even during long-duration fires. The consequence is the preservation of a substantial portion of the overall load-bearing capacity, as confirmed by numerous full-scale tests *(Kodur, 2014)*.

Therefore, the mechanical degradation of reinforced concrete under fire conditions is a well-known, modelled, and extensively regulated phenomenon. The availability of consolidated calculation models, combined with the progressive nature of strength loss and the material's ability to limit heat penetration, enables a reliable assessment of structural performance during and after the fire event

2.3.1.3 Spalling

Spalling is a phenomenon that may occur in concrete exposed to high temperatures and consists of the violent detachment of surface layers of material, with consequent exposure of the inner portions. This phenomenon is generally associated with the increase in vapour pressure within the cementitious matrix and with high thermal gradients between the fire-exposed surface and the core of the structural element.

Scientific literature distinguishes several types of spalling, including explosive spalling, progressive spalling, and surface spalling. Among these, explosive spalling has attracted the greatest attention, as it may lead to a rapid reduction of the effective thickness of the element and the possible exposure of reinforcement. However, numerous experimental studies have shown that this phenomenon is neither systematic nor inevitable but depends on a combination of factors related to the material, geometry, and fire-exposure conditions *(Hertz, 2003; Kodur, 2014)*. The main parameters influencing the probability of spalling include the water-to-cement ratio, concrete permeability, degree of saturation, heating rate, and the stress state of the element. In particular, high-strength and low-porosity concretes are more sensitive to the phenomenon due to the greater difficulty in dissipating water vapour generated at high temperatures. Conversely, ordinary concretes and thick structural members generally exhibit a lower propensity for explosive spalling *(FIB, Bulletin 38, 2007; CEB, Bulletin 208, 1991)*.

From a design perspective, it is important to note that the Eurocodes, particularly EN 1992-1-2, consider the possible occurrence of spalling through precautionary approaches that ensure structural safety even in the presence of limited surface material loss. Several European countries, such as Italy and Germany, incorporate these provisions into their

national regulations, promoting a performance-based approach focused on the global assessment of structural behaviour in fire rather than on assumptions of localized damage.

It is also important to emphasise that, in most real fires analysed in the literature, spalling does not automatically lead to structural collapse. Post-fire investigations show that even when localized concrete cover detachment occurs, reinforced concrete structures often retain sufficient residual load-bearing capacity to prevent global collapse, allowing firefighting and evacuation operations to proceed safely *(Buchanan & Abu, 2017)*.

Modern fire-design practice for reinforced concrete includes specific mitigation measures aimed at reducing the probability of critical phenomena under fire conditions. These include the correct design of concrete cover, calibrated according to the required fire-resistance class, the selection of concretes with controlled composition and adequate permeability, and the use of polypropylene fibers, widely documented in the literature as an effective solution to facilitate vapour pressure dissipation within the cementitious matrix during heating *(FIB, Bulletin 38, 2007; Hertz, 2003)*.

Fig. 4, Some effects of spalling (Innocenzo Mastronardi)

Spalling therefore represents a potentially critical but manageable phenomenon, whose occurrence depends on well-identified and extensively studied variables. Its proper consideration during design and safety assessment makes it possible to avoid excessively conservative interpretations while recognising, at the same time, the ability of concrete to provide reliable structural performance even under severe fire conditions.

2.3.1.4 Additional Protection Measures (Concrete Cover, Protective Plasters)

In reinforced concrete structures, fire resistance is not entrusted solely to applied protection systems but is largely ensured by the intrinsic configuration of the structural element, particularly by the thickness of the concrete cover and the overall mass of the section. Additional protection systems therefore play a role of optimization and performance enhancement rather than representing an essential requirement for achieving the prescribed safety levels.

Concrete cover represents the first and most important form of protection for reinforcement against thermal action. Its function is twofold: on the one hand, it delays the temperature rise in the steel; on the other, it contributes to the stability of the section even in the presence of localized surface degradation. EN 1992-1-2 provides precise indications on the minimum cover thicknesses required to ensure specific fire-resistance classes, depending on the type of structural element, the applied loads, and the duration of fire exposure. The French Code incorporates these criteria, making them an integral part of standard design practice. In addition to concrete cover, protective plasters or fire-resistant coatings may be used in specific situations to further increase fire-resistance time or to compensate for geometric limitations. These solutions are typically employed in retrofitting, refurbishment, or existing-structure interventions rather than in new construction, where the required fire resistance is often achieved through the structural section alone.

Technical literature highlights that the effectiveness of additional protection systems applied to concrete is generally high, owing to the physical and chemical compatibility between the substrate and the protective materials. Unlike other systems, the fire behaviour of concrete does not critically depend on the integrity of a thin protective layer; even in the event of partial damage to the coating, the mass of the structural element continues to provide significant thermal inertia, limiting the heating rate of the inner core *(Kodur, 2014; FIB, Model Code 2010)*.

Another relevant aspect concerns the long-term durability of protection systems. Concrete cover, being an integral part of the structural section, does not require specific maintenance to preserve fire-safety performance. Similarly, traditional plasters applied to concrete exhibit good resistance to environmental and mechanical degradation, reducing the dependence of fire safety on periodic inspection and repair activities.

In conclusion, for reinforced concrete structures, the required fire resistance derives from the concrete cover and the mass of the section, and additional protection systems extend the fire-resistance time achieved by the section itself. This characteristic allows high levels of fire safety to be achieved through robust design solutions that are minimally sensitive to operating conditions and have limited impact on maintenance activities throughout the service life of the structure.

2.3.2 Timber

Structural timber, whether used in solid form or as engineered wood products such as glued laminated timber and cross-laminated timber (CLT/X-Lam), exhibits a fire behaviour that differs substantially from that of non-combustible structural materials. This behaviour is governed by the simultaneous occurrence of physic-chemical, thermal, and mechanical phenomena, which develop in an interdependent manner throughout the fire event.

From a fire safety perspective, timber must be regarded as a reactive material when exposed to fire, as it undergoes thermal decomposition and combustion processes that directly influence both the evolution of the fire and the structural response of the element. Consequently, the fire performance of timber structures cannot be assessed solely on the basis of the material's mechanical properties at ambient temperature; instead, it requires an integrated analysis of degradation mechanisms and fire-exposure conditions.

In Europe, structural fire design is regulated by EN 1995-1-2 (Eurocode 5), which adopts a performance-based approach primarily centred on the progressive reduction of the load-bearing section due to charring. This approach enables the modelling of material behaviour through simplified methods, assuming defined fire scenarios and exposure conditions. However, scientific literature highlights that the actual response of timber structures is strongly influenced by variables such as the type of timber product, the geometric configuration of the elements, compartment ventilation, and the degree of exposure of structural surfaces *(SFPE, 2016; Buchanan & Abu, 2017)*.

In recent years, full-scale experimental research programs have significantly improved the understanding of the fire behaviour of timber structures, particularly in multi-storey buildings. These studies have shown that fire performance can vary considerably depending on the adopted design and construction choices, underscoring the importance of a careful assessment of material degradation mechanisms and their associated structural consequences *(Fire Protection Research Foundation, 2020)*.

In light of these considerations, the fire behaviour of structural timber must be interpreted as the outcome of a complex system in which the final response depends on the interaction between the material, the construction system, and the fire scenario. This framework forms the basis for the analysis of the individual mechanisms governing structural fire performance, which are discussed in the following sections.

2.3.2.1 Combustibility and Charring behaviour

The fire behaviour of structural timber is governed by physic-chemical processes of thermal decomposition that begin well before the onset of visible flaming. As temperature rises, wood undergoes pyrolysis, involving the breakdown of its constituent

polymer chains (cellulose, hemicellulose, and lignin) and the formation of combustible gases, vapours, and carbonaceous solid residues. These processes start at temperatures in the range of approximately 200–250 °C and precede the flaming combustion phase *(Drysdale, An Introduction to Fire Dynamics, 2011)*. Because timber is a combustible material, it does not merely degrade under heat exposure; it actively interacts with the fire, feeding the combustion process through the release of pyrolysis gases. The quantity and rate at which these gases are released depend on factors such as wood species, density, moisture content, and the applied heat flux, making the phenomenon inherently variable and strongly dependent on the fire scenario *(SFPE, 2016)*.

Charring represents the macroscopic outcome of these processes, whereby the outer layer of the timber is converted into char, a brittle and non-load-bearing material with significantly lower thermal conductivity than virgin wood. Although this char layer can slow heat transfer into the element, its formation is a direct consequence of combustion and therefore corresponds to an irreversible loss of mass and load-bearing cross-section *(Buchanan & Abu, 2017)*.

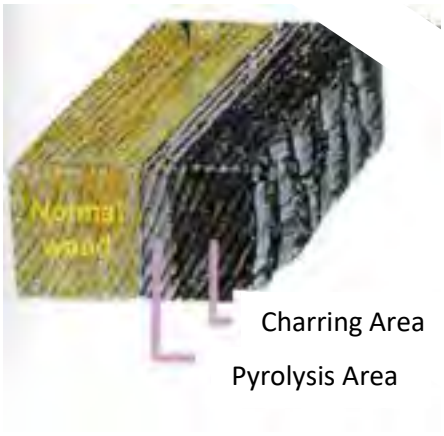


Fig. 5, Charring on a wood sample

Full-scale compartment fire tests have shown that, when structural timber surfaces are exposed, the combustion of the wood contributes to the overall energy balance of the fire, influencing both the heat release rate and the duration of the event. In particular, the Fire Protection Research Foundation has highlighted that timber's contribution can be substantial during the fully developed and decay phases of a fire, especially under controlled or limited ventilation conditions (FPRF, 2020; Hadden et al., 2017).

It is important to emphasise that charring does not constitute a form of "self-protection" in a structural sense; rather, it is a by-product of combustion whose development is closely tied to the intensity and duration of fire exposure. The fire response of timber must therefore be understood as the result of a dynamic balance between heat generation, material loss, and the insulating effect of the char layer, a balance that can shift significantly depending on the fire conditions.

2.3.2.2 Fire Load contribution

The fire load is the thermal energy potentially released per unit of gross floor area, expressed in MJ/m², and includes all combustible materials present: contents, finishes, and, where applicable, construction elements *(EN 1991-1-2)*.
For buildings with a timber load-bearing structure, it is necessary to distinguish between:

- fire load associated with the contents (furniture, plastic materials, textiles, etc.).
- fire load associated with finishes and linings.
- any contribution from the timber structure itself, when it is exposed or becomes exposed during the fire

According to Eurocode 1 – EN 1991-1-2, the contribution of combustible structural elements may also be considered in the determination of the thermal action, if they participate in the combustion process. The effective contribution depends on the exposure conditions: where the elements are fully encapsulated, their involvement is delayed or limited; where protection is absent or fails through detachment, damage or degradation over time, the timber surface begins to contribute to the available energy. Experimental literature shows that, when large and exposed timber surfaces are present, wood can participate in the post-flashover phase, contributing to the duration and intensity of the fire, albeit with relatively predictable charring rates *(Buchanan & Abu, 2017; Frangi et al., 2008)*. Studies on mass-timber buildings have shown that, for some products, delamination and char-layer fall-off can increase the exposed timber surface and consequently the heat release (*Brandon et al., 2018; Awadallah et al., 2024).*

Recent research indicates that this behaviour is strongly product-specific, with significant differences depending on adhesive formulation, lamella thickness, lay-up and fire exposure conditions (*RISE, 2021; Wiesner et al., 2022*). Consequently, delamination or char-layer fall-off should not be regarded as an inherent characteristic of CLT, but rather as a phenomenon requiring assessment for the specific product and adhesive system under consideration. For fire safety purposes timber is therefore not a single material. Product type, exposure configuration, adhesive system and protection strategy each change the outcome, so the contribution of the structure to the fire load is not a fixed quantity and a statement about mass timber in fire holds only for the combination of these four being considered. A single exposed wall is not equivalent to several exposed walls combined with an exposed ceiling, and the geometry of the compartment matters as much as the extent of the exposure: in one of the natural fire tests, the position of the opening produced markedly asymmetric charring on opposite sides of the same column, attributed to differences in local oxygen concentration rather than temperature (*Robert et al., 2023*). EN 1995-1-2 and EN 1991-1-2 provide the design methods through which these variables are considered, while the conditions under which timber structures are admitted in multi-storey buildings are set by national building regulations.
This material-related characteristic does not necessarily limit the ability to achieve specific fire-resistance ratings, but it may influence the duration of a natural fire and the assessment of post-event consequences in severe scenarios.

2.3.2.3 Charring Rate and Effective Cross-Section

In Europe, the structural fire design of timber elements is based on the assessment of the charring rate and the resulting determination of the residual effective cross-section. EN 1995-1-2 adopts a simplified model in which the loss of load-bearing capacity is directly linked to the progression of the char front over time.

The standard provides nominal charring rates (β_0), differentiated according to the type of timber product (solid timber, glued laminated timber, CLT panels) and the fire-exposure conditions. Typical nominal charring rates range between 0.7 and 0.9 mm/min, while the mechanical properties of the uncharred core remain essentially unaffected by elevated temperatures. These values are consistent with measurements under standard exposure, where 0.67 mm/min was recorded over the first 10 mm of GLT columns tested under the ISO 834 curve. Under natural fire exposure, the same sections showed rates between 1.52 and 2.00 mm/min over the first 10 mm across all seven compartment tests, two to three times the standard value, decreasing progressively towards the decay phase (*Robert et al., 2023*). To these nominal values the standard adds an additional thickness, the zero-strength layer, representing material that, although not fully charred, is considered unable to contribute to the load-bearing capacity (EN 1995-1-2). It is not a physical boundary observed in tests but a design allowance, calibrated so that the verification remains on the safe side across the range of conditions covered by the standard.

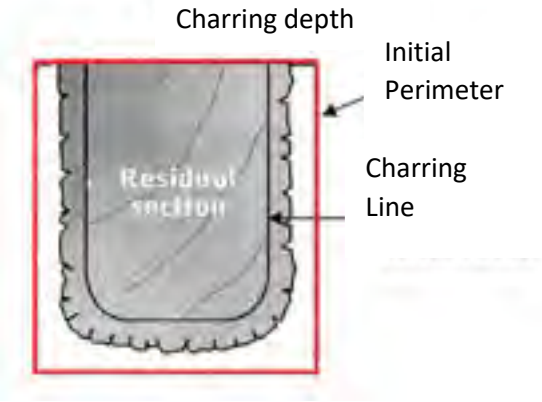


Fig. 6, Charring behaviour and Effective Cross Section

The simplified design approach treats the problem as a geometric reduction of the load-bearing cross-section, allowing the use of calculation methods analogous to those applied at ambient temperature. The idealisations on which it rests, a uniform char front and a constant charring rate (*Buchanan & Abu, 2017*), are deliberate. Timber is a natural material whose density, moisture content and defect distribution vary within a single species and within a single element, and the standard responds to this variability by adopting nominal values calibrated on the upper range of observed behaviour, so that the design outcome remains conservative without requiring a case-by-case reconstruction of the charring process. The model is therefore a safe design method rather than a predictive description of a specific element in a specific fire, and the same distinction applies to the simplified provisions of EN 1992-1-2.

A substantial body of experimental research has shown that the charring rate can vary as a function of parameters not explicitly accounted for in simplified design models, such as fire intensity, compartment ventilation, multi sided exposure, and the presence of construction discontinuities *(SFPE, 2016)*. In particular, under non standardised real fire scenarios, the incident heat flux may differ significantly from that associated with the ISO 834 curve, thereby influencing the development of charring.

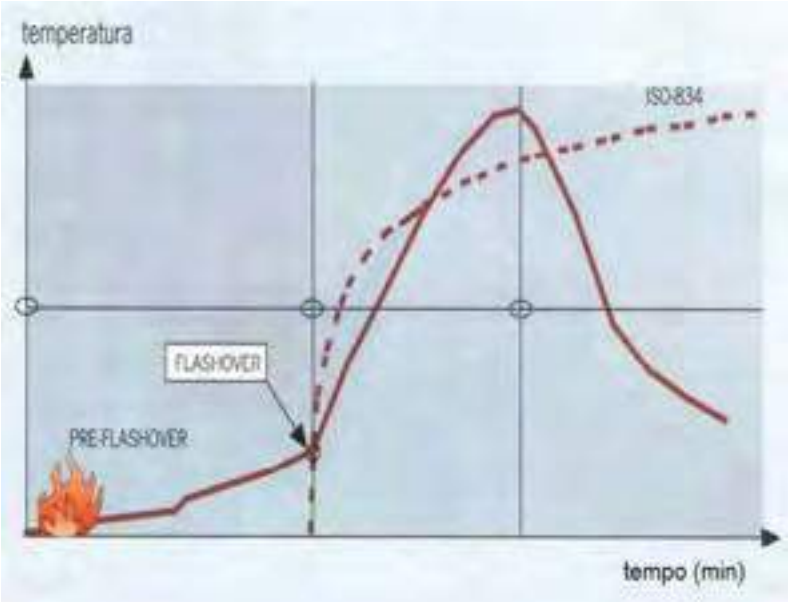


Fig. 7, Natural fire curves compared with the ISO 834 standard fire curve (Ing. G. Biffarella, 2014)

For glued engineered wood products, additional layers of complexity arise from the behaviour of adhesive bond lines. The literature documents how delamination phenomena can alter the effective geometry of the load-bearing section during fire exposure, resulting in a char front that progresses neither continuously nor uniformly, contrary to design assumptions *(Lange et al., 2014; Frangi et al., 2018)*. Under such conditions, the determination of the residual effective cross-section becomes highly sensitive to the assumptions adopted.

From an engineering standpoint, the reduction of the effective cross-section represents an irreversible loss of load-bearing material, increasing with the duration of fire exposure. Within the range of conditions covered by the standard, the nominal charring rates and the zero-strength layer provide a design margin against this loss. The same tests also showed that the zero-strength layer does not advance as a layer of constant depth under natural fire exposure, so a design method for such fires cannot be obtained by simply adapting the two constant values of the simplified method (*Robert et al., 2023*). Outside that range, for example under prolonged exposure, multi-sided exposure or where delamination exposes fresh timber, the extent to which the design margin remains available should be verified against the specific fire scenario and, where relevant, against product-specific test evidence (*Fire Protection Research Foundation, 2020*).

2.3.2.4 Residual Load-Bearing Capacity and Predictability of Structural Behaviour

The residual load-bearing capacity of timber structures under fire conditions results from the combined effect of the remaining effective cross-section and the degradation of the mechanical properties of the uncharred material, which is progressively heated. Unlike structural design at ambient temperature, assessing fire resistance requires considering a continuously evolving system in which the load-bearing capacity decreases over time as a function of thermal exposure.

EN 1995-1-2 allows the residual capacity to be estimated by verifying the effective cross-section, assuming that the remaining material retains constant mechanical properties equal to the design values at ambient temperature. While consistent with the objective of normative simplification, this approach introduces an additional idealized assumption, as it neglects the progressive reduction of mechanical properties in the heated inner layers of the timber *(Buchanan & Abu, 2017)*. In real fire scenarios the temperature distribution within the cross-section may be non-uniform, so that the relationship between residual cross-section and load-bearing capacity can deviate from the predictions of simplified models.

From a quantitative standpoint, the load-bearing capacity of an element with a uniform cross-section depends non-linearly on its geometric dimensions. For rectangular sections in bending, for example, the elastic section modulus is proportional to the product of the width and the square of the height ($b \times h^2$). Consequently, even a modest reduction in dimensions due to charring can lead to a substantial decrease in capacity. As an illustrative example, for a rectangular timber member exposed to fire on three sides, a 10% reduction in both width and height (initial dimensions normalised to 1; reduced to 0.9×0.9^2) results in an approximate 30% reduction of the section modulus, while a 15% reduction leads to a decrease of around 40%. Whether this reduction exhausts the margin available at the ultimate limit state depends on the utilisation ratio of the element in the fire design situation. The relationship is illustrative rather than generally applicable, since the actual loss depends on the governing failure mechanism, whether bending, compression, tension, shear or stability, on the cross-sectional geometry and on the loading conditions. In a five-layer vertical CLT panel, for instance, a 40% reduction in thickness corresponding to the loss of two layers reduces the radius of gyration and increases slenderness, so that capacity becomes governed by stability rather than by strength, particularly under eccentric vertical loads. These examples illustrate the sensitivity of residual capacity to the reduction of the effective cross-section.

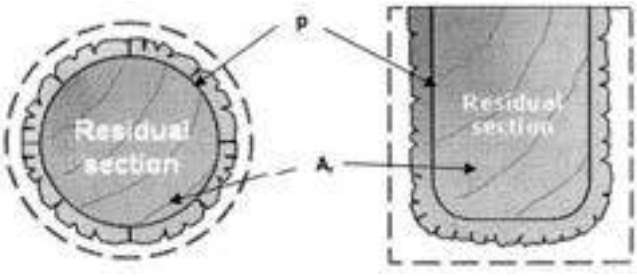


Fig. 8, Examples of Residual Cross-Sections for Circular and Rectangular Sample

For glued engineered wood products, the predictability of the residual load-bearing capacity is further affected by the behaviour of adhesives at elevated temperatures. Loss of bond phenomena can trigger non-progressive changes in the structural response that cannot be attributed to the geometric reduction of the section alone, and studies on CLT panels have shown sudden drops in the global load-bearing capacity of the element, introducing discontinuities during fire exposure (*Lange et al., 2014; Frangi et al., 2018*).

The fire performance of a mass timber assembly depends on the complete construction system and not on the main elements alone. Wall-to-floor joints, corner joints, service penetrations and glulam and CLT connections are not covered by standardised test methods to the same extent as the panels themselves, and the documentation available for these details is correspondingly more limited. Fire resistance established for an element therefore does not transfer automatically to the assembly in which it is installed.

A further difference concerns the fire itself. In a standard fire resistance test the thermal action is imposed and independent of the specimen, whereas in a building with exposed timber the structure adds fuel to the compartment, so that the severity of the fire is in part a consequence of the structure being assessed. The rating therefore describes the response of an element to a defined exposure, not the exposure that will actually develop.

Another critical aspect concerns the post-flashover phase and potential cooling periods. The Fire Protection Research Foundation has highlighted that, in long-duration fires, the residual load-bearing capacity may be influenced by complex thermal cycles in which partial cooling phases are followed by renewed heating, with cumulative effects on material degradation *(FPRF, 2020)*. Recent experimental research further highlights the relevance of structural behaviour during the cooling phase of a fire. The Burnout Resistance Project comprised furnace tests on concrete columns at Liège University and on GLT columns at TU Braunschweig, under both the ISO 834 curve and controlled heating-cooling exposures, followed by natural fire tests on GLT columns at CERIB. The results show that the structural response of timber elements cannot be assessed based on their behaviour during the heating phase alone.

Numerical analyses indicate that the duration of the heating phase (DHP) leading to structural failure ranges between 20% and 50% of the standard fire resistance time (*Gernay, 2021*). Full-scale furnace tests confirmed the lower end of that range: 280 x 280 mm GLT columns rated 55-58 minutes failed after a heating phase of only 15 minutes, while identical columns heated for 10 minutes survived, giving a measured DHP of 18-27% (*Robert et al., 2023*). A member classified as R60 may therefore collapse during or after the decay phase.

The same studies demonstrate that timber elements may experience delayed failure mechanisms associated with the progressive degradation of the residual cross section and the continued thermal penetration into the core during the cooling phase.
One of the mechanisms sustaining this process is smouldering combustion, a slow flameless oxidation that can continue long after a fire appears to be extinguished. It persists at oxygen levels too low to sustain flaming, and flaming reappears only when the

smouldering breaches the panel and opens the charred surface to the atmosphere. In a full-scale test on an encapsulated CLT compartment, smoke was observed at the wall-to-floor interface, one of the details discussed above, two hours after ignition, visible flaming occurred after twelve hours, and smouldering had spread to the roof approximately ninety hours after ignition (*Lennon & Lalu, 2025*), with water applied repeatedly over that period. The same test showed that the compartment maintained overall stability and compartmentation through burnout of the moveable fire load, so the issue concerns the period that follows rather than the rated performance itself. Encapsulation delays ignition but does not prevent smouldering, which can spread beneath the protective layers and is difficult to detect without infrared imaging, so that post-fire inspection cannot rely on visual assessment alone (*Lennon & Lalu, 2025*).

Self-extinction is therefore not a predictable or inherent property of mass timber. Whether it occurs depends on ventilation, incident heat flux, exposed surface area, delamination and adhesive performance, and the cessation of visible flaming does not imply that charring or structural degradation has stopped. In five of the seven natural fire tests the columns failed during the cooling phase, in one case 71 minutes after ignition with compartment temperatures already down to 200-300 °C, and the authors conclude that the fact that an element displays some self-extinction does not mean that its stability is ensured (*Robert et al., 2023*). Structural instability may develop at a later stage, when internal stresses, reduced material strength and geometric weakening combine under decreasing but still critical thermal conditions. This is particularly relevant in natural fire scenarios where heating and cooling cycles deviate from standardised fire curves and where, as quantified in Section 2.3.2.3, the charring rate is not constant over time. These findings confirm that the assessment of residual load-bearing capacity cannot be limited to peak temperature conditions but must consider the full thermal history of the fire, including cooling phases.

Overall, the residual load-bearing capacity of timber structures in fire is closely tied to the validity of the simplified models and to their application within the limits for which they were developed.

2.3.2.5 Importance of Passive Fire Protection (Claddings, Intumescent Coatings)

In timber structures, achieving the fire-resistance performance required by regulations generally depends on the use of passive protection systems, such as gypsum board claddings, protective panels, or intumescent coatings. These solutions do not alter the intrinsic behaviour of the material; rather, they delay the direct exposure of wood to fire, limiting the onset of pyrolysis and charring processes.

EN 1995-1-2 allows the protective effect of claddings to be considered through models that introduce an effective protection time (t_p), during which the timber element is not directly exposed to fire. Once this interval has elapsed, the behaviour of the wood is assessed according to standard charring models. This approach implies that the fire performance of the structure is critically dependent on the continuity and integrity of the adopted protective system.

Scientific literature and test reports show that the effectiveness of passive protection can be influenced by multiple factors, including installation quality, mechanical resistance of the cladding, the presence of joints, technological service penetrations, and construction discontinuities *(SFPE, 2016)*. For example, inspections carried out by the Fire Protection Research Foundation found that approximately 70% of fire-stopping for service penetrations showed installation deficiencies or deviations from tested configurations. In addition, experimental studies conducted by the National Institute of Standards and Technology demonstrate that improper application or damage to sprayed fire-resistive materials can significantly reduce their effective fire resistance. This highlights the importance of installation quality and inspection regimes, as the fire performance achieved in laboratory tests may not always be fully replicated under real construction conditions. In cases of detachment, cracking, or local failure of the protective layer, the underlying wood may become suddenly exposed to fire, accelerating degradation processes compared with design assumptions.

A particularly relevant aspect concerns the long-term durability of passive protection systems. Several studies highlight that the effectiveness of claddings and intumescent systems can be sensitive to service conditions, maintenance interventions, and changes in building use. Accidental damage, impacts, subsequent perforations, or performance decay due to material ageing may significantly compromise the fire response of the structural system *(Fire Protection Research Foundation, 2020)*.

From an engineering perspective, this means that the fire performance of timber structures is not determined solely by the properties of the structural material but is strongly dependent on the reliability of the protective systems throughout the entire service life of the building. The literature consistently recognises this dependency as a critical factor in fire-safety assessment, as it introduces a higher sensitivity to real-world usage and maintenance conditions compared with structural systems that achieve the required fire resistance through the section itself, without applied protective layers.

2.4 Fire Safety Strategies

Fire safety strategies represent the coordinated set of design, technological, and management measures aimed at preventing ignition, limiting fire spread, ensuring structural stability for an adequate duration, and reducing consequences for people, property, and the environment. These strategies cannot be considered independently of the adopted structural system, as the physical properties and fire behaviour of materials directly influence the overall effectiveness of fire-safety solutions.

The European regulatory framework (EU Regulation No. 305/2011, 3110/2024, EN 13501) promotes a performance-based approach to fire-safety design, in which the adopted strategies must be consistent with the risk profile of the activity and with the construction characteristics of the building. In this context, structural materials with predictable fire behaviour, non-combustible or limited combustibility, high thermal inertia, and reduced contribution to fire development allow for the implementation of more robust strategies, less dependent on auxiliary systems or on particularly controlled operating conditions.

Among fire-safety strategies, the following sections will address compartmentation measures, passive and active protection, and long-term maintenance. Each of these components is strongly conditioned by the behaviour of the structural material under fire exposure, influencing both design choices and the resilience of the building throughout its service life and in post-fire management. We will observe how different construction solutions interact with these strategies and how certain structural typologies inherently offer more favourable conditions for limiting damage, safeguarding human life, and reducing the economic and environmental consequences of a fire event.

2.4.1 Compartmentation

Fire compartmentation is a primary preventive measure aimed at limiting the spread of fire, smoke, and heat within a building, ensuring adequate time for occupant evacuation and for the intervention of emergency teams. From a regulatory standpoint, compartmentation is governed at the European level by EN 13501-2, which defines the fire-resistance performance of separating elements, and at the national level by specific fire safety frameworks adopted by individual countries. For example, Italy regulates compartmentation through its "*Codice di Prevenzione Incendi*" (Ministerial Decree 3 August 2015 and subsequent amendments), while countries such as Germany and France apply their own national provisions, respectively the "*Musterbauordnung"* (MBO) and associated technical guidelines, and the French "*Code de la Construction et de l'Habitation"* together with the "*Règlement de sécurité contre l'incendi",* which define requirements according to the building type and risk profile.

In reinforced concrete structures, compartmentation benefits from the non-combustible nature of the material and its high thermal inertia. Walls, slabs, and shear walls made of reinforced concrete can simultaneously serve structural and separating functions, providing high fire-resistance ratings (REI 90, REI 120 and beyond) even without additional protective layers, provided they are properly designed in accordance with EN 1992-1-2. This allows for greater integration between structural design and fire-safety design,

reducing reliance on applied systems and simplifying long-term control of compartment continuity.

In timber structures, compartmentation requires a more articulated approach, as structural elements generally cannot be exposed when they are also required to perform a fire-separating function. Compartmentation performance is typically achieved through multilayer systems, such as gypsum board claddings or protective panels, designed to delay ignition and charring of the timber. The literature highlights that the effectiveness of such systems is strongly dependent on the continuity of the cladding and on installation quality, making compartmentation more sensitive to construction defects, service penetrations, and degradation over time *(Frangi et al., 2018; FPRF, 2020)*.

Studies on real fires and full-scale tests show that, in buildings with reinforced concrete structures, compartmentation generally retains its function under severe fire conditions, so that fire spread beyond the compartment of origin is limited for the rated period and global structural involvement is less likely. In several fire incidents in multi-storey concrete buildings, structural damage was found to be localised and compatible with targeted repair interventions (*Buchanan & Abu, 2017*). In timber buildings, where the separating function relies on protective claddings, damage to or discontinuity of those claddings during the fire can lead to earlier loss of the separating function, with fire spread and damage extending to a larger portion of the building.

Another relevant aspect concerns the robustness of compartmentation under non-ideal scenarios. The Italian “Codice di Prevenzione Incendi” emphasises the importance of solutions that maintain performance even in the presence of operational uncertainties or suboptimal maintenance. In this regard, compartmentation achieved with massive concrete elements is less dependent on perfect operating conditions, whereas solutions based on applied protective systems, typical of timber structures, require a higher level of control and maintenance to ensure long-term performance.

Fire compartmentation can be effectively achieved in both reinforced concrete and timber structures, but through different design approaches. In the former, the separating function is often intrinsic to the structural element; in the latter, it is predominantly entrusted to additional systems. This difference affects the overall robustness of the fire-safety strategy and the expected consequences in the event of a real fire, underscoring the central role of integrated design and proper execution.

2.4.2 Passive Fire Protection

Passive fire protection is a fire safety strategy applied across all structural materials, with measures that differ according to the material, the required fire resistance rating and the overall fire safety concept. Steel structures generally rely on applied protection such as boards, sprayed materials or intumescent coatings. Timber elements achieve the required rating through sacrificial charring of an oversized cross-section, through encapsulation, or through a combination of the two. Reinforced concrete derives its rating from the cover and the mass of the section, with applied protection used to extend it further. These measures are intended to ensure, without the intervention of active systems, that structural and compartmentation elements maintain their fire-resistance performance for a prescribed duration. Their performance does not depend on electrical power supply, automatic activation or human intervention.

Within the European regulatory framework, passive protection is closely linked to the fire-resistance classification of construction elements according to EN 13501-2 and to the determination of performance through standardized testing (EN 1363, EN 1365). At the national level, the French regulatory system, primarily defined by the "*Code de la Construction et de l'Habitation* and the *Règlement de sécurité contre l'incendie",* assigns passive protection a central role in achieving the objectives of life safety, structural stability, and damage limitation.

The fire performance of a structural element depends on how many conditions have to remain satisfied for the rated performance to be available. Where resistance derives from the material and the cross-section itself, fewer components are involved; where it derives from applied layers, performance depends on their installation quality, continuity and condition over time (*Buchanan & Abu, 2017; SFPE, 2016*).

Commonly used passive protection systems include fire-resistant plasters, dry claddings (such as gypsum-based boards), intumescent coatings, and multilayer systems. When properly designed and maintained, these solutions can provide high fire-resistance performance; however, numerous experimental studies and post-fire analyses have shown that loss of cladding continuity or premature detachment can lead to rapid exposure of the structural material to thermal action, resulting in a reduction of the expected performance *(Frangi et al., 2018; FPRF, 2020)*.

Another relevant aspect concerns the durability of passive protection. National fire safety frameworks adopted by individual countries emphasise the need for the selected solutions to maintain their declared performance over time, taking into account service conditions and maintenance requirements. In this sense, the sensitivity of a protection system to ageing, environmental degradation and alterations resulting from building use is part of its performance.

Finally, in terms of fire consequences, passive protection limits the extent of structural damage and reduces the likelihood of local or progressive collapse, facilitating firefighting operations and subsequent repair activities. The Fire Protection Research Foundation notes that buildings characterised by robust passive protection systems, and less

dependent on ideal operating conditions, exhibit lower damage levels under comparable fire scenarios *(FPRF, 2020).*

2.4.3 Active Fire Protection

Active fire protection comprises the set of systems that require automatic or manual activation to detect, control or suppress a fire. This category includes, among others, fire detection and alarm systems, smoke and heat control systems, sprinkler installations, and hydrant networks. Within the UK regulatory framework, these systems are governed by the relevant fire safety legislation, primarily the Regulatory Reform (Fire Safety) Order 2005 and the associated Approved Documents and British Standards, which define their role within the overall safety strategy in accordance with the objectives of life safety, asset protection, and environmental safeguarding. These systems perform three distinct functions. Detection systems provide early warning but neither control nor extinguish the fire. Conventional sprinklers are designed as fire control systems, limiting fire growth and spread rather than guaranteeing extinguishment. Only systems designed for suppression are intended to extinguish it. Their necessity and design requirements depend on occupancy, building height, compartmentation and risk profile, and for some occupancies they are prescribed by regulation.

In both reinforced concrete and timber buildings, active protection systems play an essential role in limiting fire growth and reducing the severity of design scenarios. However, fire engineering literature highlights that the overall effectiveness of active protection depends significantly on the passive and structural behaviour of the building, which constitutes its operational context *(SFPE, 2016)*.

In buildings with reinforced concrete structures, active protection generally operates in an environment characterised by non-combustible structural elements and robust compartmentation. Under such conditions, the activation of systems such as sprinklers or smoke control installations tends to be more effective in containing the fire within the compartment of origin, reducing the likelihood of spread and enabling a more predictable management of the event. Analyses of real fires show that, in massive buildings, the contribution of active systems often results in damage being limited to contents and surface linings with minimal impact on the load-bearing structure *(Buchanan & Abu, 2017)*.

In timber structures, active protection often assumes an even more central role within the fire-safety strategy, as it is required to compensate for the combustible nature of the structural material and for the greater sensitivity of performance to damage affecting passive protection systems. In this context, the literature emphasises that the reliability of active systems becomes a critical factor, particularly in scenarios characterised by fast-growing fires or unfavourable ventilation conditions *(FPRF, 2020)*. Failure or delayed activation of such systems may lead to a rapid increase in fire severity, with direct effects on the extent of structural damage.

Another point of comparison concerns the dependence of overall safety on the correct functioning of active systems. The Italian “Codice di Prevenzione Incendi” reiterates that

active protection must never be considered as a standalone measure, but rather as part of an integrated system that includes compartmentation and fire resistance. In buildings where structural stability and compartmentation are primarily ensured by the intrinsic characteristics of the materials, active protection serves as a risk-mitigation and optimisation measure. Conversely, in solutions heavily dependent on active systems, overall reliability becomes more sensitive to failures, maintenance deficiencies, or non-ideal operating conditions.

From a post-fire perspective, comparative studies indicate that buildings in which active protection operates in synergy with structures and compartments that are intrinsically fire-resistant exhibit, under comparable scenarios, a higher likelihood of limiting damage and maintaining structural serviceability after the event *(SFPE, 2016; FPRF, 2020)*. This makes clear that active fire protection must be evaluated as part of the building's global fire-safety performance.

2.4.4 Maintainability Over Time

The long-term maintainability of fire-safety performance is often underestimated, yet it plays a crucial role in the overall assessment of fire risk and its potential consequences. Fire-prevention regulations, particularly the German fire safety framework, defined by the "*Musterbauordnung"* (MBO), the associated "*Länderbauordnungen"*, and the relevant technical standards such as DIN 4102 and EN 13501, emphasise that achieving safety objectives requires preserving design conditions throughout the building's life cycle, highlighting the importance of management and maintenance activities.

In reinforced concrete structures, fire resistance is provided mainly by the mass and thickness of the elements and by the concrete cover and therefore does not rely on applied protective layers in most configurations. Maintenance is nonetheless required, since carbonation, reinforcement corrosion, cracking and loss of concrete cover progressively reduce the protection of the reinforcement and, with it, the fire performance assumed in design. These mechanisms develop over long time scales, are addressed by the durability provisions of EN 1992-1-1, and can be assessed through measurable geometric parameters such as cover thickness.

In timber structures, fire performance frequently depends on the integrity of applied protection systems, such as gypsum-board linings, plasters and surface treatments, and on the sealing of service penetrations. These components are sensitive to impact, moisture, modifications to building services and uncontrolled interventions, and their degradation or partial removal can reduce the fire performance verified at commissioning (*FPRF, 2020; Frangi et al., 2018*). The difference with respect to reinforced concrete therefore concerns the type of component to be maintained and the time scale over which its condition can change, rather than the existence of a maintenance requirement, which applies to both systems.

Another point of comparison concerns the traceability and assessability of performance over time. In reinforced concrete buildings, verifying fire-safety characteristics generally relies on measurable geometric and construction parameters, such as thicknesses and

concrete cover, which can be checked even years after construction. Conversely, in systems based on applied protections, assessing the state of conservation and actual effectiveness is more complex and may require frequent visual inspections or invasive investigations.

From a post-fire perspective, maintainability directly influences the building's resilience. Structures that preserve robust fire-safety performance over time and are less dependent on routine maintenance tend to exhibit more limited damage and a higher likelihood of functional recovery after a fire event. In contrast, buildings whose fire safety relies heavily on systems susceptible to degradation may experience more severe outcomes, with significant impacts on repair costs and downtime. Empirical evidence from the insurance sector and fire engineering research indicates that non-combustible structural systems tend to experience more limited fire spread and improved post-fire recoverability. For example, studies referenced by RISC Authority indicate that only about 4% of fires in concrete buildings lead to extensive structural damage (>100 m^2). Furthermore, reinforced concrete elements can often, after exposure to fire and post-fire curing, recover up to ~75% of the original resistance *(Tawfik, T.A. et al., 2025)*.

Recent experimental research conducted by Halliwell Fire Research on behalf of the NFPA Fire Protection Research Foundation highlights that, in sprinkler-protected mass timber buildings, post-fire damage may be significantly influenced also by water exposure rather than by direct fire effects. Full-scale fire tests on CLT assemblies have shown that, although structural damage due to fire remains limited under controlled conditions, large volumes of water discharged during suppression can penetrate structural connections and become trapped within hidden voids. This may lead to prolonged moisture retention, complex drying processes, and potentially invasive repair interventions. These findings suggest that, in timber structures, post-fire recovery may be governed not only by fire severity but also by water-induced damage mechanisms, with direct implications for repair costs and downtime.

The maintainability of fire-safety performance therefore constitutes an essential criterion in the selection of structural and construction solutions. A design approach oriented toward durability and long-term robustness reduces exposure to fire risk and limits the economic and functional consequences associated with fire events, reinforcing the importance of an integrated perspective encompassing design, management, and the entire life cycle of the building.

3. Executive Summary: Fire Performance of Reinforced Concrete vs. Timber

The comparative assessment presented in this section highlights a number of fundamental differences between reinforced concrete and timber structural systems in relation to fire behaviour and post-fire performance. As summarized in the table below, reinforced concrete is a non-combustible material that does not contribute to the fire load and therefore does not participate in the combustion process during a fire event. In such conditions, the development and duration of the fire are primarily governed by the amount and distribution of combustible materials stored within the building, and the fire naturally decays once the available fuel load is consumed.

Conversely, structural configurations incorporating timber elements introduce additional combustible material within the compartment. Under prolonged fire exposure, timber components may progressively char and continue to contribute to the fire load, potentially sustaining the combustion process even after the initial involvement of stored goods. This characteristic may influence both the duration of the fire and the potential for fire propagation across structural elements.

Operational aspects are also affected by these material characteristics. Reinforced concrete structures generally maintain stable structural conditions during fire exposure due to their non-combustibility and thermal inertia, which may facilitate firefighting intervention and limit the likelihood of progressive structural involvement. Timber structures, while capable of maintaining load-bearing capacity through charring mechanisms, may instead present conditions where the involvement of combustible structural elements can accelerate fire spread and increase the complexity of suppression activities.

These differences also have implications for post-fire recovery. Reinforced concrete structures frequently retain a significant portion of their residual load-bearing capacity even after severe fire exposure, allowing localized repair interventions and relatively faster reinstatement of operations. In contrast, damage affecting combustible structural elements may require more extensive structural reconstruction, potentially resulting in longer recovery periods and increased exposure to Business Interruption losses.

The extent of these differences is not uniform. As the case studies in Section 2 show, it depends on the degree to which the load-bearing structure also forms the compartment boundaries, and it is limited where the structure performs no separating function and the fire load is governed by the contents of the building.

The main parameters influencing these aspects are summarized in the following comparative table.

Analysed Parameter	Reinforced Concrete	Timber
Reaction to Fire	Non-combustible material, classified A1 according to EN 13501-1; does not ignite or contribute to fire load	Combustible material; ignition from approximately 300 °C, contributes to fire load
Contribution to Fire Growth	Does not participate in the combustion process at any stage	Participates in combustion; contribution depends on exposure and protection
Thermal Evolution of the Cross-Section	Slow heating due to high thermal inertia and low conductivity	Progressive reduction of the cross-section due to charring of outer layers
Behaviour Predictability	Codified models available (EN 1992-1-2); progressive mechanical degradation	Charring rate is highly reproducible, but delamination and protection continuity introduce uncertainty
Residual Load-Bearing Capacity	Residual strength generally significant even after severe fires, thanks to mass and stress redistribution	Residual capacity dependent on the remaining effective section after charring for light fires; in severe or prolonged fires compromised load-bearing capacity due to the burning of the structural elements
Critical Phenomena	Possible spalling, a known phenomenon mitigable through design measures	Charring; Possible delamination in glued products; Local instability
Dependence on Additional Protective Systems	Limited; fire resistance often ensured by sizing alone	High; performance strongly dependent on effectiveness and continuity of protective systems
Performance during Fire Events	Behaviour generally consistent with design assumptions	More sensitive to deviations from design conditions and to local damage
Maintainability of Fire-Safety Performance	Intrinsic and stable performance over time; low maintenance needs	Requires inspection and maintenance of passive protection systems
Post-Fire Consequences	Damage often limited to surface degradation; Structural recovery frequently possible	Only for very light fires structural elements may suffer limited section loss due to combustion; for severe or prolonged fires the timber structural elements completely burn
Regulatory Reliability	Broad and consolidated regulatory and experimental basis at EU and national level	Evolving regulatory framework; greater dependence on scenarios and specific assumptions

Section 2: Analysis of Fire Risk Scenarios

4. MFL & NLE scenarios

The fire scenarios developed in this study are based on an integrated engineering and risk-assessment framework combining internationally recognized fire protection standards with established industrial loss evaluation methodologies.

The technical definition of fire initiation, fire growth, compartment development, fire spread mechanisms, and structural thermal exposure is derived from consolidated fire engineering principles and from the design and protection criteria established by the National Fire Protection Association (NFPA). In particular, the assumptions adopted for ignition sources, commodity classification, storage configurations, sprinkler performance, detection systems, and fire brigade intervention are consistent with the general methodologies provided by standards such as NFPA 13 and NFPA 72, together with the broader performance-based approach commonly adopted in modern fire safety engineering and industrial risk assessment practice.

The National Fire Protection Association (NFPA) is an internationally recognized organization in the field of fire safety and fire protection engineering. NFPA standards and guidelines are extensively adopted worldwide for the design of fire protection systems, fire risk assessment, and performance-based fire engineering analyses across industrial, commercial, and residential applications. Their relevance derives from decades of scientific research, large-scale fire testing, post-fire investigations, and continuous technical development conducted through multidisciplinary expert committees. The adoption of NFPA-based methodologies within this study provides a technically recognized framework for the definition of fire scenarios, suppression assumptions, fire growth conditions, and structural exposure under fire, ensuring consistency with internationally accepted fire engineering practice.

The development of the fire scenarios follows a deterministic and scenario-based methodology widely used in fire engineering practice. The analysed scenarios do not represent probabilistic predictions of fire occurrence, but rather credible design fire events selected to evaluate the potential structural and economic consequences under predefined boundary conditions. In this context, the scenarios are intentionally developed using conservative assumptions regarding fire growth, suppression effectiveness, and fire spread potential, in order to ensure methodological consistency and direct comparability between the investigated structural configurations.

The classification into Maximum Foreseeable Loss (MFL) and Normal Loss Expectancy (NLE) scenarios derives from industrial risk engineering and property insurance practice rather than directly from NFPA standards. These concepts are used in a comparable form by nearly all property insurers and risk engineering organizations, including FM Global, for the assessment of property damage risks and potential loss scenarios. Related concepts such as Maximum Possible Loss (MPL), Probable Maximum Loss (PML) and other kinds of scenarios are equally common, and the definitions adopted differ between organizations.

All of them are built on the same set of inputs: building characteristics and construction materials, compartmentation, fire resistance ratings, active protection systems, insured values and business interruption exposure. Those applied in this study are stated below.

FM Global is among the leading international industrial property insurers and is widely recognized for its engineering-based approach to fire and natural hazard risk assessment. Over decades of large-loss analysis, experimental research, and industrial investigations, FM Global has developed methodologies specifically aimed at evaluating potential property damage and business interruption associated with severe fire events. The adoption of these methodologies in the present study allows the analysis to extend beyond purely structural fire resistance considerations, incorporating also the economic consequences of fire scenarios, including operational downtime, recoverability, and overall loss magnitude.

From a scientific perspective, the adopted methodology is consistent with contemporary performance-based fire engineering practice, where scenario definition is based on physically credible fire development, thermally consistent structural exposure, and engineering judgement supported by experimental research, fire dynamics theory, and real-loss experience. The objective of the study is therefore not to predict the exact evolution of a future fire event, but to compare, under consistent and technically justified conditions, the relative vulnerability, damage propagation potential, residual structural stability, and economic consequences associated with different structural systems. The study therefore combines two distinct frameworks. Fire development is described using performance-based fire engineering assumptions consistent with NFPA guidance, while the fire consequences, including Property Damage (PD) and Business Interruption (BI) impacts, are classified and quantified using loss-assessment concepts drawn from industrial risk engineering practice.

4.1 Maximum Foreseeable Loss (MFL) Scenario

MFL is the largest monetary loss (including Property Damage and Business Interruption) that could occur as a result of a fire when the most unfavourable circumstances are combined. It assumes that fire protection systems such as automatic sprinklers and fire detection are ineffective or unavailable, that fire separations fail or provide limited resistance and that fire brigade intervention is delayed or ineffective. As a consequence, the fire is ultimately stopped by impassable obstacles or by lack of sustenance.

4.2 Normal Loss Expectancy (NLE) Scenario

NLE represents the expected level of monetary loss resulting from a fire developing in accordance with the available combustible load and under normal operating conditions. If active fire protection systems are installed (such as automatic detection or extinguishing systems), these are expected to work properly and in accordance with their design specifications. Fire separations perform according to their actual fire rating, and the local fire brigade will be able to respond within realistic timeframes based on travel distance and availability.

5. Comparative design assumptions

For the purpose of the comparative analyses developed in this study, the alternative timber configurations are defined according to a simplified substitution methodology intended to isolate the influence of material behaviour under fire while maintaining comparable architectural and structural layouts between the investigated solutions.
In particular, the comparative scenarios are developed assuming equivalent global geometry, building volume, structural arrangement, and load distribution between the reinforced concrete and timber configurations. The position of structural elements, spans, storey heights, compartmentation layout, and overall building dimensions are therefore maintained unchanged to ensure direct comparability of fire development, fire spread mechanisms, etc.
Within this approach, the substitution from reinforced concrete to timber does not imply a complete structural redesign of the building. Differences in required member sizing, cross-sectional dimensions, connection detailing, and stiffness typically associated with real timber structural design are intentionally not investigated in detail. Structural elements are therefore assumed to occupy equivalent geometric configurations in both solutions, while the material composing the load-bearing system is varied for comparative fire-engineering purposes.
This assumption allows the analysis to focus specifically on the different fire-related behaviour associated with combustible and non-combustible structural materials, avoiding distortions introduced by major geometric or architectural modifications that would otherwise alter compartment characteristics, fire dynamics, ventilation conditions, and exposed surface areas.

Where timber configurations are considered, engineered wood systems such as CLT and glulam are assumed to be protected, as required by national codes, through conventional passive fire-protection measures (e.g. gypsum-based encapsulation systems or sacrificial charring layers) consistent with current fire design practice. However, the detailed dimensioning of protective layers and structural connections is beyond the scope of the present comparative assessment and is therefore treated through generalized engineering assumptions consistent with contemporary timber fire design methodologies. From a methodological standpoint, this simplified equivalency approach does not aim to represent a final structural design solution. Rather, it provides a controlled comparative framework allowing the study to evaluate, under consistent boundary conditions, the relative influence of structural material combustibility on fire growth, property damage, business interruption, and post-fire recoverability.

Consistently with this approach, the reconstruction value of timber configurations is assumed to be equal to that of the corresponding reinforced concrete baseline in each case study. While a timber structural system, together with the passive fire-protection measures required to achieve equivalent fire-resistance classes, would in practice involve a higher construction cost, generally in the order of 5% to 15% above the reinforced concrete solution, this differential is intentionally not reflected in the monetary baseline. The adoption of an identical reconstruction value ensures that the comparison of property damage between the two configurations depends solely on the fire behaviour of the structural material and not on a pre-existing difference in asset value.

The damage percentages reported in the scenario tables are not independent assumptions but the quantified outcome of the physical scenario defined for each case. For every scenario, the analysis first determines, on the basis of the fire dynamics and the expected compartmentation performance, the extent of fire spread, identifying the elements affected by the fire, whether compartment boundaries remain effective or are breached, and whether the structural load-bearing system becomes involved. This physical outcome is then translated into damage ranges, expressed as percentages of the replacement value of the affected assets and reported separately for the building structure and its contents. The use of percentage intervals, rather than single values, reflects the inherent variability of fire development and the associated variability in the resulting damage.

The monetary values reported alongside the percentages are obtained directly by applying these damage ranges to the reconstruction and contents values established in the facility description of each case study. Consequently, the Property Damage values expressed in euros are derived quantities, inherently consistent with both the corresponding damage percentages and the asset valuations, rather than independent estimates. Business Interruption is evaluated separately according to the occupancy characteristics of each facility, taking account of industrial profit, rental income or continuity of public service, as described in the relevant case study.

The resulting values should therefore be regarded as indicative technical estimates developed in accordance with established Normal Loss Expectancy (NLE) and Maximum Foreseeable Loss (MFL) methodologies, within the uncertainty bounds discussed in the limitations of this report. Their primary purpose is to provide a consistent basis for comparison rather than an exact prediction of financial loss. Because the same methodology, scenario definition and valuation framework are applied systematically to both the reinforced concrete and timber structural configurations in every case study, the comparative assessment between the two structural solutions remains robust despite the residual uncertainty associated with any individual estimate.

6. Case Study #1: Industrial Building - Automated Warehouse

6.1 Facility Description

The building under analysis is a newly constructed industrial automated warehouse intended for high-density storage of consumer goods, decorative items, artificial plants, seasonal products, and related materials. The occupancy is classified as an automated high-rack storage warehouse containing mixed commodities with significant packaging materials. Based on NFPA storage classification criteria, the stored materials can be conservatively assimilated to Class III–IV commodities, with a possible fraction of Group A plastics due to packaging components.

The total gross floor area of the facility is approximately 7.125 m², of which 6.464 m² are dedicated to the ground-floor warehouse and 595 m² to a mezzanine storage level. An additional office area of approximately 554 m² is located on the first floor.

The building reaches a maximum internal height of 12 m in the main storage area, allowing vertical optimization of storage capacity through industrial rack systems. A photovoltaic system with a capacity of 410 kWp is installed on the roof. The facility also includes a dedicated forklift charging room, technical areas, sanitary facilities, and loading/unloading bays equipped with multiple industrial doors.

6.1.1 Actual – Concrete Structure

Structurally, the building is entirely realized in reinforced concrete. Foundations consist of deep piles. The vertical load-bearing system is composed of reinforced concrete columns and shear walls designed to resist both gravity and seismic actions in accordance with current structural regulations. Horizontal structures are formed by precast reinforced concrete beams and hollow-core or ribbed slabs, while the roof structure consists of reinforced concrete beams and shed-type precast elements with mineral wool insulation, contributing to both thermal performance and non-combustible envelope behaviour. Internal compartmentation between warehouse, mezzanine, offices, and technical areas is achieved through reinforced concrete or fire-rated partition systems. The main structural frame is designed to achieve a fire resistance rating of R120, while separating elements and compartmentation walls are rated REI 120.

From a fire protection perspective, the building is equipped with automatic fire detection, manual alarm systems, sprinkler protection, internal hydrants, and a dedicated fire water storage tank with a useful capacity of approximately 300 m³. Smoke management measures and fire-resistant doors are implemented in accordance with the applicable fire safety regulations. The building analysed in this study constitutes a single fire area.

The reconstruction value of the building is estimated at approximately €11.4 million, while the value of stored goods and automated handling equipment is estimated at approximately €8 million, resulting in a total exposed asset value exceeding €19 million, excluding indirect economic impacts.

Items	Replacement value in Euro (€)
Civil works	8,500,000
Mechanical system	1,500,000
Electrical system	900,000
Technical costs: commissioning, construction supervision…	500,000
Machinery and Goods	8,000,000
Total	19,400,000

Overall, the facility represents a high-value industrial asset characterized by significant combustible storage concentration, advanced operational logistics, and a structurally robust reinforced concrete load-bearing system designed to ensure fire resistance, compartmentalization, and structural stability under fire exposure.

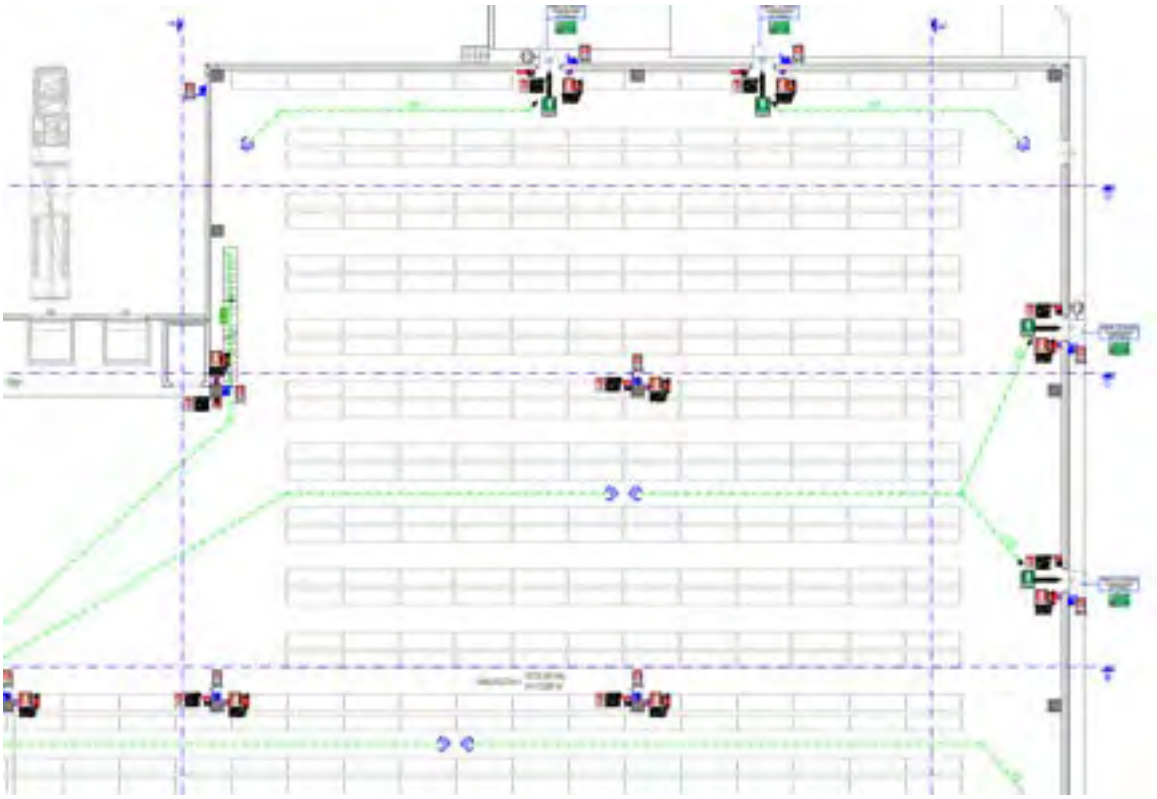


Fig. 9, Detail of the automated warehouse plant

6.1.2 Simulated – Hybrid Timber Structure

In order to ensure a technically consistent comparison between different construction solutions, the first alternative configuration considered in this study does not involve a complete replacement of the reinforced concrete structural system. Instead, a partial substitution scenario has been developed, in which the primary load-bearing structure of the building remains in reinforced concrete while roof structure and selected secondary elements are assumed to be realised in engineered timber. In this configuration, the main structural frame of the warehouse, including columns, primary beams and the elements responsible for the global stability of the building, is assumed to remain unchanged and therefore constructed in reinforced concrete. This choice reflects common industrial construction practice, where reinforced concrete is frequently adopted for the primary structure due to its robustness, stiffness and durability, particularly in buildings characterised by large spans, significant vertical loads and high storage racks.

The hypothetical timber variant instead concerns the roof structure and selected non-primary vertical enclosure elements. In this scenario, the roof system is assumed to be realised using engineered timber components such as glulam beams and cross-laminated timber (CLT) panels, replacing the original non-combustible construction layers. Similarly, some internal partition walls or enclosure elements are assumed to be realised using timber-based systems.

From a fire-engineering perspective, this modification introduces relevant differences in the potential behaviour of the building during a fire event. While the reinforced concrete primary structure remains non-combustible and therefore does not contribute to the fire load, the introduction of timber components within the roof and enclosure systems potentially adds combustible material to the compartment. As widely recognised in fire-engineering literature, structural or semi-structural timber elements may contribute to the overall fire load of a compartment once protective layers are damaged or once the timber surface becomes exposed to sustained thermal radiation.

For this reason, the following fire scenarios consider not only the structural response of the reinforced concrete frame but also the possible involvement of timber roof and enclosure elements in the fire development process. This approach allows a more comprehensive evaluation of the potential differences in fire growth, structural performance and recovery conditions between the original reinforced concrete configuration and the hybrid solution including timber components.

For the purpose of the comparative analysis, the reconstruction value of the hybrid timber configuration has been assumed to be equal to that of the reinforced concrete baseline. Although the adoption of a timber structural system, together with the additional passive fire-protection measures, would in practice entail a higher reconstruction cost, this difference has deliberately not been reflected in the monetary baseline, so as to isolate the influence of structural material behaviour under fire from any cost differential between the two solutions.

6.2 Maximum Foreseeable Loss (MFL) Scenarios

6.2.1 Reinforced Concrete MFL Scenario

In the automated warehouse under analysis, the MFL scenario assumes ignition within a densely loaded rack aisle, at intermediate storage height, in the presence of significant combustible packaging materials. The sprinkler system, although designed in accordance with the standards of the National Fire Protection Association, is assumed to be impaired and therefore ineffective in controlling the fire during its early development phase. Detection may occur, but without immediate suppression capability, the fire grows uncontrolled.

The fire develops following a fast growth rate, typical of rack storage configurations. Vertical flame spread is accelerated by the chimney effect within storage aisles, rapidly involving multiple pallet levels. As hot gases accumulate beneath the roof, flashover conditions are reached within the initial fire sector. Radiative heat transfer promotes horizontal spread across adjacent rack arrays. Given the absence of effective compartmentation capable of halting propagation at an early stage, the fire progressively involves a substantial portion of the storage area.

Fig. 10, Simulated image of an early stage of the fire under MFL conditions

Fig. 11, Simulated image of a fully developed fire through the racks

Peak heat release rates may reach several tens of megawatts before structural degradation or fuel depletion begin to limit further escalation. Gas layer temperatures in the upper zone are expected to approach 900-1000°C, with sustained high thermal exposure lasting well beyond one hour. The fire continues to propagate until it encounters either areas devoid of combustible storage or structural boundaries capable of resisting full penetration.

From a structural perspective, the reinforced concrete frame does not contribute to fire load and does not participate in combustion. However, it is subjected to severe thermal exposure. Surface

layers of slabs, beams, and columns experience significant temperature rise, leading to reduction of compressive strength and stiffness in accordance with temperature-dependent material degradation models. Reinforcement embedded within the concrete progressively loses yield strength as steel temperatures exceed 400–500°C. Thermal gradients develop between exposed surfaces and the cooler core, generating internal stresses and localized cracking. In heavily exposed zones, concrete cover spalling may occur, further exposing reinforcement to elevated temperatures.

Despite these mechanisms, the intrinsic characteristics of reinforced concrete, namely its non-combustibility, high thermal inertia, and low thermal conductivity, limit the depth of heat penetration. The degradation process remains progressive rather than sudden. Load redistribution within the structural system mitigates the risk of disproportionate collapse. While localized structural failure of secondary elements or roof portions cannot be excluded in the most exposed sectors, global structural collapse of the entire building is not considered a foreseeable outcome. The fire is ultimately arrested by the lack of additional combustible material and by the persistence of primary structural stability.

Under these conditions, property damage is extensive. A significant portion of the warehouse floor area, estimated between 70% and 80%, may be directly affected by fire, heat, smoke, and firefighting water. Structural elements in the most severely exposed bays require demolition and reconstruction due to loss of mechanical capacity and excessive cracking or spalling. Roof systems, façade panels, mechanical installations, and electrical distribution networks within the affected area require complete replacement.

Considering a declared reconstruction value of 11.4 million euros for the building, structural and building-related damage may reasonably reach 70% of replacement value. In extreme but still foreseeable circumstances, this figure could approach higher percentages if structural demolition extends beyond the initially involved bays.

Damage to contents and automation systems is even more substantial. The automated storage equipment, rack systems, control units, and stored goods within the affected area are assumed to be largely destroyed. Smoke contamination and heat exposure may compromise additional stock beyond the directly burned zones. Given a declared value of approximately 8 million euros for machinery and goods, damage in the range of 80% to 90% of this value is plausible.

The combined direct property damage under MFL conditions may therefore reach approximately 16 million euros, potentially approaching total asset value in the most unfavourable configuration where the majority of storage sectors are involved.

The Business Interruption component becomes particularly significant in this scenario. The extensive structural repairs, demolition and reconstruction of multiple bays, replacement of automation systems, reinstallation of mechanical and electrical infrastructure, and subsequent commissioning activities result in a prolonged period of operational shutdown. Even if parts of the structure remain standing, the high level of automation typical of such facilities implies strong interdependence between storage sectors, making partial operation technically difficult during reconstruction. The total period required for full reinstatement is reasonably estimated in 12 months, with gradual restart of operations after 9 months, exposing to overall profit losses of

about 75%. Assuming annual profit in the range of 30 to 40 million euros, a closure period of 12 months exposes between 20 and 30 million euros. This duration includes structural assessment, engineering redesign where necessary, procurement of specialized automated systems, reconstruction works, and full operational testing.

In conclusion, under Maximum Foreseeable Loss conditions, the automated warehouse in reinforced concrete configuration may sustain a total monetary loss potentially approaching or exceeding the combined value of the building and its contents. Nevertheless, the structural system does not act as a contributing factor to fire escalation. On the contrary, the non-combustible and thermally robust nature of reinforced concrete limits the probability of instantaneous collapse and provides residual structural stability even under severe thermal exposure. The ultimate extent of loss is therefore governed primarily by fuel load, suppression impairment, and operational dependency rather than by structural combustibility.

MFL Reinforced Concrete Scenario		
	Involved Area	**% Damage**
Property Damage	Entire Building	70% of Building replacement cost 80-90% of Machinery & Goods
Business Interruption[3]		75% for 12 months

Note:
The percentages reported do not account for potential mitigation measures such as rent an additional facility and/or temporarily relocating operations to third-party premises.

6.2.2 Timber MFL Scenario

Under the Maximum Foreseeable Loss (MFL) scenario, the fire is assumed to originate within the automated storage area of the warehouse, in conditions identical to those previously described for the reinforced concrete configuration. Ignition occurs within a storage rack as a consequence of an electrical fault affecting one of the automated handling systems.

In accordance with the MFL assumptions, automatic suppression and detection systems are considered unavailable or ineffective. The fire therefore develops freely within the storage array, rapidly involving the combustible goods and packaging materials stored on the racks. Vertical flame spread occurs along the rack structure and within the stored commodities, leading to a rapid increase in heat release rate.

Within approximately 15-20 minutes the fire reaches a fully developed stage inside the storage area. Flames propagate horizontally to adjacent racks through radiation and flame spread, while hot smoke accumulates beneath the roof. In the hybrid timber configuration considered for this

[3] For recovery periods up to 12 months, the BI percentage represents the estimated annual profit loss or loss-of-rent over a 12 month reference horizon, while the reported recovery period indicates the time required to return to full operational capacity. For recovery periods exceeding 12 months, the BI percentage represents the total profit loss over the stated recovery period, while the reported months indicate the time required to progressively restore operations to 100% capacity.

study, parts of the enclosure system, specifically the roof structure and portions of the wall assemblies, are assumed to be realised using engineered timber elements. Under prolonged fire exposure and in the absence of effective suppression, these elements may progressively become involved in the fire.

Unlike reinforced concrete, timber is a combustible material and may contribute to the fire load once its protective layers are compromised or when it is directly exposed to flames. As the fire continues to develop within the storage compartment, the high temperatures reached in the upper smoke layer progressively affect the timber roof elements.

Engineered timber structures typically develop a protective char layer when exposed to fire, which slows down further degradation of the cross-section. However, under severe fire conditions such as those assumed in the MFL scenario, characterised by high heat release rates and prolonged exposure, the progressive loss of effective cross-section may significantly reduce the load-bearing capacity of the timber elements. In addition, connections and roof components may experience accelerated degradation when exposed to elevated temperatures. As a consequence, after prolonged fire exposure the stability of roof elements may become increasingly uncertain, particularly in areas where fire intensity is highest. Localised collapse of roof portions may therefore occur during the later stages of the fire. Such events can introduce additional oxygen into the compartment, potentially intensifying combustion and facilitating further fire spread within the building.

In the hybrid configuration, prolonged fire exposure affects the timber roof and wall assemblies once their protective layers are breached, while the reinforced concrete frame and foundations retain their load-bearing function. Damage is therefore concentrated in the enclosure system and may extend across multiple bays, requiring demolition and reconstruction of the timber elements and of the building envelope, together with repair of the concrete elements affected by the fire. Combined with the loss of contents and equipment, the overall property damage could approach the full replacement cost of the asset, estimated at approximately €11.4 million in the most adverse configuration.

Under MFL conditions, the automated storage equipment, rack structures, control units and goods located within the impacted sectors would be considered non-recoverable. In addition to direct fire damage, extensive smoke migration and elevated temperatures are likely to compromise electronic components and stored goods in adjacent areas. Considering the declared value of approximately 8 million euros for machinery and goods, losses affecting 100% of this value may reasonably occur where several storage aisles are involved and automation infrastructure is severely damaged.

Operational impacts are expected to be substantial. The reconstruction of damaged structural elements, installation of new storage racks, replacement of automated handling systems and reinstallation of mechanical and electrical infrastructure would require a complex and time-consuming recovery process. In highly automated facilities, the interdependence of storage sectors typically prevents meaningful partial operation during reconstruction works. Taking these factors into account, the full reinstatement period is estimated at approximately 15-18 months, including structural demolition, engineering redesign, procurement of specialized automation equipment, reconstruction works and final commissioning. Limited operational recovery may occur after around 15 months, while the prolonged shutdown could extend over approximately 18 months. Assessed on the same annual profit basis of 30 to 40 million euros adopted for the reinforced concrete configuration and reflecting an almost complete loss of operation over that period, the resulting Business Interruption reaches approximately €55 million.

MFL Timber Scenario		
	Involved Area	**% Damage**
Property Damage	Entire Building	100% of building replacement cost 100% of Machinery & Goods
Business Interruption[3]		90% for 18 months

Note:
The percentages reported do not account for potential mitigation measures such as rent an additional facility and/or temporarily relocating operations to third-party premises.

6.3 Normal Loss Expectancy (NLE) Scenarios

6.3.1 Reinforced Concrete NLE Scenario

The Normal Loss Expectancy (NLE) scenario for the automated warehouse is developed in accordance with a performance-based fire engineering approach consistent with the analytical framework adopted by the National Fire Protection Association (NFPA). The scenario reflects a credible and statistically frequent loss event in which ignition occurs within stored commodities and all active fire protection systems operate as designed, without impairment or failure.

The fire is assumed to originate at intermediate rack height within a storage aisle, representing a realistic ignition location associated with electrical faults, mechanical overheating, or accidental ignition sources linked to automated handling systems.

The building is protected by an automatic sprinkler system designed in accordance with NFPA 13 criteria for storage occupancies. The system is assumed to be hydraulically adequate for the rack height and commodity class present, with reliable water supply and no obstruction to discharge patterns. Detection and alarm systems operate in line with NFPA 72 principles, ensuring timely notification and fire brigade response.

Under these assumptions, ignition leads to localized flame development within the rack array. Thermal plume formation results in progressive ceiling layer heating, with sprinkler activation expected within approximately 4 to 6 minutes from ignition, depending on ceiling height and the response time. Following activation, discharge density is sufficient to control the fire plume and prevent vertical and horizontal propagation beyond the initial rack zone. Full flashover conditions within the entire compartment are not reached, and fire spread remains confined to a limited storage sector.

Thermal exposure to structural elements is therefore localized and time limited. Upper layer gas temperatures remain significantly below those associated with post-flashover fully developed compartment fires, and the duration of elevated temperature exposure is restricted to the period preceding suppression stabilization. For reinforced concrete elements, surface temperatures may locally approach values in the range of 400–500°C in directly exposed zones, but the limited exposure duration and the material's low thermal conductivity result in steep temperature gradients and relatively low core temperatures.

The structural frame consists of reinforced concrete elements designed for a nominal fire resistance rating of R120. As a non-combustible material, concrete does not contribute to the fire load and does not participate in combustion processes. Mechanical degradation under elevated temperature follows the reduction relationships defined in EN 1992-1-2; however, given the localized and short-duration thermal exposure assumed in the NLE scenario, no significant reduction in global load-bearing capacity is expected. The structural system maintains stability throughout the event, and no progressive collapse mechanisms are triggered.

Damage mechanisms are primarily associated with direct flame impingement on stored goods, thermal damage to automation equipment, sprinkler water discharge, and smoke contamination. Structural damage, if present, is limited to superficial cracking, minor spalling in directly exposed areas, and localized repairable damage to the concrete cover. No structural replacement of primary load-bearing elements is anticipated.

From a quantitative standpoint, building damage is expected to remain within approximately 2-4% of replacement value, reflecting localized repair interventions. Contents damage is estimated in the range of 10-15% of stored value, driven by direct fire involvement and smoke contamination within the affected rack sector. The resulting total loss under NLE conditions is therefore consistent with a controlled fire event, representing a limited fraction of the total asset exposure.

Business interruption impacts are expected to remain relatively contained, as the structural system remains unaffected and the event is confined to a limited operational area. Temporary disruption associated with clean-up, equipment replacement and localized reinstatement could

result in approximately 5% of annual profit over a period of around three months, reflecting partial operational constraints rather than full site shutdown.

NLE Reinforced Concrete Scenario		
	Involved Area	**% Damage**
Property Damage	Some racks in the warehouse area	4% of building replacement cost 10%-15% of Machinery & Goods
Business Interruption[3]		5% for 3 months

Note:
The percentages reported do not account for potential mitigation measures such as rent an additional facility and/or temporarily relocating operations to third-party premises.

6.3.2 Timber NLE Scenario

For the purpose of the comparative analysis, a second scenario has been developed assuming a hybrid structural configuration in which the primary load-bearing system remains in reinforced concrete while the roof assembly and selected secondary elements, particularly internal partitions, are realised in engineered timber.

The fire is assumed to originate within the automated storage area of the warehouse, where stored goods and packaging materials constitute the primary combustible load. As in the previous scenario, the ignition source is assumed to be associated with an electrical fault within automated handling equipment located within the rack storage system.

In the early stage of the fire, the combustion process is driven primarily by the stored goods, packaging materials and plastic components typically present in automated warehouses. Heat release rates progressively increase as the fire spreads vertically within the storage racks, generating significant thermal radiation toward the upper portions of the compartment.

Under normal expected loss conditions, the building fire-protection systems are assumed to operate as designed. The automatic sprinkler system activates following detection of elevated temperatures near the ceiling, initiating water discharge aimed at controlling fire growth within the storage area. The fire detection system also triggers the alarm, allowing the notification of emergency response services.

However, in the hybrid configuration, the presence of timber roof elements introduces an additional potential interaction with the fire plume. As the fire develops within the storage racks, hot gases accumulate beneath the roof level, increasing the thermal exposure of the roof structural components. If protective linings or encapsulation layers are present, these initially limit direct thermal exposure to the timber elements. Nevertheless, sustained heat exposure may progressively degrade these protective layers. Should portions of the timber structure become exposed, the wood elements may begin to undergo pyrolysis and surface charring. Although engineered timber exhibits a relatively predictable charring behaviour, its combustible nature means that it may locally contribute to the fire load once exposed to sufficient thermal radiation.

This additional fuel contribution may slightly increase the duration of the fire phase before suppression is fully achieved.

In the NLE scenario, however, the sprinkler system is assumed to successfully control the fire before it develops into a fully compartment-involved event. Fire brigade intervention further supports the suppression phase, limiting the spread of flames beyond the initial rack area.

Consequently, the reinforced concrete primary structure remains largely unaffected from a structural standpoint, while the timber roof elements may experience limited surface charring in areas directly exposed to the hottest gases. Localised replacement of roof components and repair of fire-damaged sections may therefore be required during the recovery phase. From an operational perspective, the presence of combustible roof and secondary elements may lead to slightly more extensive smoke contamination and minor structural repair requirements compared with the fully non-combustible configuration. Nevertheless, under normal expected loss conditions, the damage remains primarily confined to the ignition zone and to limited portions of the roof assembly directly above the fire area.

From a quantitative standpoint, building damage is expected to remain under 10% of replacement value, reflecting localized repair interventions. Contents damage is estimated to be the same of the previous NLE scenario. The resulting total loss under NLE conditions is therefore consistent with a controlled fire event, representing a limited fraction of the total asset exposure.

Business interruption impacts are expected to remain relatively contained, as the structural system remains unaffected and the event is confined to a limited operational area. Temporary disruption associated with clean-up, equipment replacement and localized reinstatement could result in approximately 10% of annual profit over a period of around four months.

NLE Timber Scenario		
	Involved Area	**% Damage**
Property Damage	Timber roof and some racks in the warehouse area	10% of building replacement cost 10-15% of Machinery & Goods
Business Interruption[3]		10% for 4 months

Note:
The percentages reported do not account for potential mitigation measures such as rent an additional facility and/or temporarily relocating operations to third-party premises.

Although the primary reinforced concrete structure ensures structural stability in both configurations, the introduction of combustible roof and secondary elements may increase both the extent of building damage and the recovery time. In particular, the presence of timber roof elements may require partial structural replacement following fire exposure, resulting in longer repair operations and increased business interruption compared with the fully non-combustible reinforced concrete configuration.

6.4 Scenario Comparison - Case Study #1

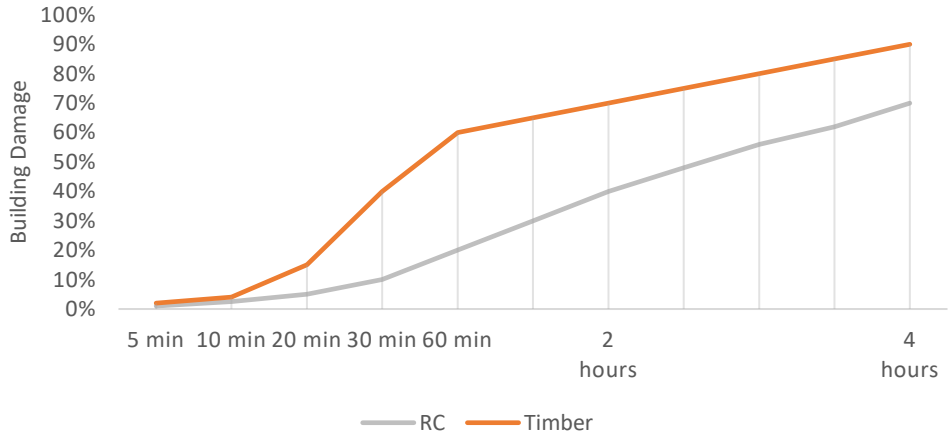
The comparative analysis of the four scenarios highlights that differences between the two structural configurations remain relatively limited under Normal Loss Expectancy (NLE) conditions. When fire protection systems are assumed to operate correctly and are designed in accordance with NFPA 13, fire development is rapidly controlled and remains confined to a limited storage sector. Under these circumstances, both structural configurations maintain overall stability and damage is mainly restricted to stored goods, rack systems and localized building components. As a result, property damage remains contained and business interruption is relatively short, with only minor differences between the reinforced concrete and the hybrid timber configuration.

A more significant divergence emerges under Maximum Foreseeable Loss (MFL) conditions, where the fire protection systems are assumed to be ineffective and the fire develops into a fully involved compartment event. In this scenario, the reinforced concrete configuration benefits from the intrinsic non-combustibility and thermal inertia of the structural system, which is expected to maintain overall stability even under severe fire exposure. Consequently, recovery operations can focus primarily on replacing damaged equipment and rebuilding localized structural elements, allowing a shorter reinstatement period and a comparatively lower Business Interruption exposure. In contrast, the hybrid configuration incorporating timber roof elements may experience additional structural degradation under prolonged fire exposure, requiring more extensive demolition and reconstruction works. This condition increases both the extent of structural repairs, from 12 to 18 months, and the complexity of the recovery process, resulting in longer reinstatement periods and Business Interruption losses that are €25-35 million higher than those associated with the reinforced concrete configuration.

	Building Damage		Mach. & Goods Damage		Total Property Damage	Business Interruption Damage		Total PD + BI
MFL - RC	70%	~€8 M	90%	~€7 M	~€15 M	75% for 12 months	~€25 M	~€40 M
MFL - Timber	100%	~€11,4 M	100%	~€8 M	~€19,4 M	90% for 18 months	~€55 M	~€74,5 M
NLE - RC	4%	~€0,5 M	10-15%	~€1 M	~€1,5 M	5% for 3 months	~€1,5 M	~€3 M
NLE - Timber	10%	~€1,1 M	10-15%	~€1 M	~€2,1 M	10% for 4 months	~€3,5 M	~€5,7 M

Overall, while fire protection systems remain the primary factor controlling loss magnitude under normal operating conditions, the structural configuration becomes a critical determinant of recovery time and economic impact in extreme fire scenarios, particularly in highly automated facilities where operational continuity strongly depends on the rapid restoration of both structural and technological systems.

So, this first comparison highlights how the intrinsic non-combustibility and thermal stability of reinforced concrete contribute to maintaining structural integrity even under extreme fire conditions. Conversely, when combustible structural materials are involved, the fire may progressively affect the structural system itself, increasing the extent of damage and the complexity of post-fire recovery operations.



Graph 1, Building Damage comparison between RC and Timber under MFL scenario

Graph 2, Property Damage and Business Interruption under the MFL scenario, Case Study #1

7. Case Study #2: Residential Building

7.1 Facility Description

The second case study concerns a residential development consisting of the construction of four attached housing units (row houses), designed as a low-rise multi-family configuration. The building is characterized by a repetitive modular layout, limited vertical development, and a relatively low occupancy load compared to large-scale residential or commercial buildings.
Each unit is functionally independent, with dedicated access and limited shared infrastructure. The building can therefore be classified as a low-rise residential occupancy with inherent compartmentation between units, which plays a key role in fire development and limitation.

From a geometric standpoint, each unit develops over multiple levels (basement, ground floor, first floor and attic), with a total gross floor area of approximately 656 m² and a total enclosed volume of about 1,998 m³ for the entire complex. The net usable surface of each dwelling is approximately 124 m², consistent with low-density residential housing.
The architectural configuration follows a row typology, where adjacent units share vertical separating walls. This compact configuration has direct implications for fire scenarios, particularly in relation to horizontal fire spread between units, façade fire propagation, and the role of compartmentation.

Compared to the previously analysed industrial case, fire loads are significantly lower and more distributed, while fire scenarios are generally more localized. However, the presence of combustible materials within building envelopes and roof assemblies may influence fire development under severe conditions, particularly in the absence of suppression systems.

The building is equipped with standard residential fire protection measures, including smoke detection systems, alarm devices, and passive fire protection elements. Automatic sprinkler systems are not assumed to be present, in line with common European residential practice for low-rise buildings.

Overall, the case study represents a typical contemporary residential development, characterized by moderate fire loads, effective compartmentation, and limited reliance on active fire protection systems. In this context, fire behaviour is primarily governed by compartment dynamics and material response under fire exposure.

Fig. 12, View of the entrance facade

7.1.1 Actual – Reinforced Concrete Structure with Timber roof

Structurally, the building is realized through a mixed construction system, combining reinforced concrete structural elements with lightweight and partially combustible (mainly timber) components. The foundation system consists of reinforced concrete strip footings and/or slab-on-grade solutions. The vertical load-bearing system is primarily composed of reinforced concrete walls and slabs, providing both gravity load resistance and global structural stability. Horizontal structures are formed by cast-in-place reinforced concrete slabs, with typical thicknesses up to approximately 20 cm, ensuring adequate stiffness and effective fire compartmentation between storeys.

The roof structure is characterized by a lightweight timber assembly, consisting of wooden structural elements combined with insulation layers (e.g. cellulose insulation) and waterproofing systems. This configuration introduces combustible materials at the uppermost level of the building envelope, which may become involved in fire scenarios under prolonged thermal exposure.

External walls are realized using multilayer systems, including masonry or concrete elements combined with thermal insulation (e.g. EPS), while internal compartmentation between residential units is achieved through separating walls designed to ensure fire resistance.

From a fire engineering perspective, the structural system is predominantly non-combustible, with the exception of the roof assembly. This configuration provides a robust compartmentation framework, limiting fire spread and ensuring structural stability even under severe fire exposure

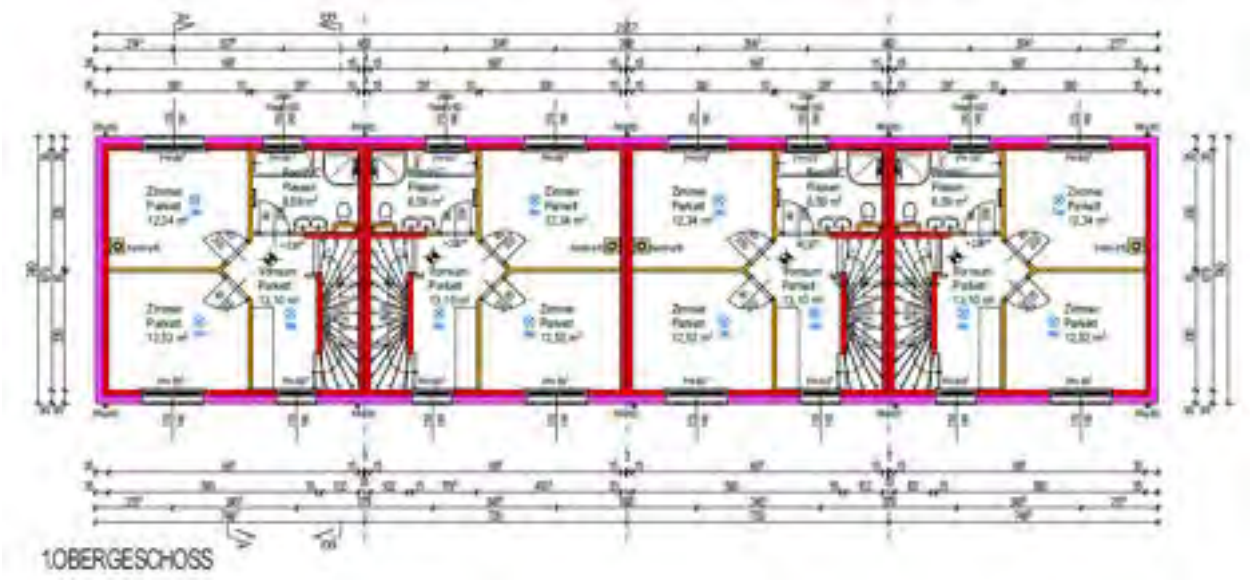


Fig. 13, Detail of the first floor

The reconstruction value of the complex is estimated at approximately €1.2 million, without taking into consideration interior doors, floor covering, furnishings and the value of stored goods, resulting in a total exposed asset value about €2 million, excluding indirect economic impacts.

7.1.2 Simulated – Timber Structure

In the alternative design scenario, the building is assumed to be realized using a timber-based structural system, representative of modern engineered wood construction for residential applications.

The foundation system remains in reinforced concrete, as typically required for durability and ground interface conditions, while the superstructure is entirely composed of timber elements. The vertical load-bearing system consists of cross-laminated timber (CLT) walls, providing both load-bearing capacity and in-plane stiffness for global stability. Horizontal structures (floors) are realized using CLT panels or engineered timber elements (e.g. glulam beams with timber decking), designed to transfer vertical loads. The roof configuration is assumed to be equivalent to the actual case.

Compartmentation between units is achieved through multi-layer timber assemblies, incorporating additional protective layers (e.g. gypsum boards) designed to meet fire resistance requirements. The performance of such systems is strongly dependent on the integrity of protective layers, detailing of joints and connection behaviour under fire exposure.

Structural fire design is carried out in accordance with EN 1995-1-2, based on the progressive reduction of the effective cross-section due to charring. While engineered timber exhibits predictable charring behaviour, its combustible nature implies that, in the event of exposure of structural elements, the structure itself may contribute to the fire load.

Compared to the reinforced concrete configuration, the timber structure is characterized by lower mass, lower thermal inertia, and potential participation in the combustion process under severe fire exposure conditions.

7.2 Maximum Foreseeable Loss (MFL) Scenarios

7.2.1 Reinforced Concrete MFL Scenario

The MFL scenario assumes a severe, uncontrolled fire originating in the kitchen/living area at ground floor level of a central residential unit, without the contribution of active fire protection systems and in the absence of fire brigade intervention. Under these conditions, the fire is assumed to develop until complete burnout, i.e. until the available combustible material is exhausted.

The ignition is assumed to be associated with typical residential sources (e.g. cooking-related events or electrical faults), involving furniture, appliances, and plastic components. The fire develops rapidly and likely leads to flashover within the compartment of origin within a short time frame. Post-flashover conditions result in full involvement of the ground floor, followed by vertical fire spread through internal openings and the stairwell, progressively involving the entire unit.

Peak gas temperatures are expected to reach values in the range of 800–1000°C. All combustible contents within the affected unit are assumed to be destroyed. Fire spread to adjacent units may occur through façade openings due to flame ejection and window breakage. However, due to the

presence of reinforced concrete separating walls and floor slabs, horizontal fire spread remains limited and does not typically result in full involvement of multiple units.

The reinforced concrete structural system plays a key role in limiting the extent of the fire. Due to its non-combustible nature and inherent fire resistance, the structure does not contribute to the fire load and acts as an effective barrier to fire spread. Structural elements of adjacent buildings, including slabs and separating walls, are expected to maintain their load-bearing function throughout the fire, with damage generally limited to superficial degradation phenomena such as localized spalling and reduction of concrete cover in the most exposed areas. Global structural instability is not expected under the assumed conditions, and the fire is ultimately governed by the available fuel within the affected compartments.

In this configuration, the MFL scenario is characterized by the total loss of the unit of origin and partial damage to adjacent units, while the remaining portions of the building remain structurally intact.

From an economic standpoint, total losses are estimated in the range of 40-50% of the total building complex value, about €0.6 million. The recovery process is primarily driven by internal refurbishment rather than structural reconstruction, resulting in an estimated reinstatement period of 6 to 9 months.

MFL Reinforced Concrete Scenario		
	Involved Area	**% Damage**
Property Damage	Central Unit and adjacent ones	40-50% of 4 units replacement cost 100% of 1 Unit' Internal Value
Business Interruption[3]		100% of one unit for 6 to 9 months

Note:
The percentages reported do not account for additional costs related to temporary accommodation, such as renting alternative housing units during the period of unavailability of the affected dwelling.

7.2.2 Timber MFL Scenario

The MFL scenario is defined assuming the same ignition conditions as the reinforced concrete case, ensuring full comparability between the two configurations.

Following ignition and flashover within the unit of origin, the fire develops into a fully compartment-involved event. As in the previous case, the initial fire growth is driven by movable fire load (furniture, finishes, and household contents). However, in the timber configuration, the structural system may progressively interact with the fire as exposure conditions become more severe. The behaviour of the structure is strongly dependent on the performance of protective linings and the integrity of connections.

In the early stages, protective layers (e.g. gypsum boards) delay the involvement of timber elements. Under prolonged exposure, degradation or failure of these layers may locally expose structural timber surfaces. Once exposed, timber undergoes pyrolysis and charring. While the formation of a char layer provides a degree of protection, prolonged thermal exposure may result in progressive reduction of the effective cross-section. In certain conditions, phenomena such as delamination or joint opening may lead to renewed exposure of fresh timber surfaces, potentially sustaining combustion over an extended period.

As a consequence, the fire duration may be longer compared to the reinforced concrete configuration, and the decay phase may be significantly delayed.

Fire spread is no longer limited to compartment boundaries. Through a combination of internal propagation, façade flame spread, and continued availability of combustible structural material, the fire is expected to extend to adjacent units. Given the continuity of timber structural elements and the absence of effective passive barriers equivalent to reinforced concrete walls, progressive fire spread between units becomes likely.

Under these conditions, the fire evolves from a compartment-controlled event to a structure-involved fire scenario, in which the building itself acts as fuel. The combustion process continues until a substantial portion of both contents and structural timber elements is consumed. This leads to a significantly longer fire duration compared to the reinforced concrete case and may result in partial or global structural collapse, particularly of floor systems and load-bearing walls, as cross-sections are progressively reduced by charring.

From a loss estimation perspective, property damage approaches a potentially full replacement in the most adverse scenario, with the loss of the total building value, about €1.2 million, not accounting for the four units' internal value.

The recovery process is significantly influenced by the need to replace structural timber elements, verify residual capacity, and reconstruct affected portions of the building. This results in a longer and more complex reinstatement phase, typically estimated in the range of 12 to 18 months.

MFL Timber Scenario		
	Involved Area	**% Damage**
Property Damage	The entire complex	100% of 4 units replacement cost 100% of 4 Units' Internal Value
Business Interruption[3]		100% for 18 months

Note:
The percentages reported do not account for additional costs related to temporary accommodation, such as renting alternative housing units during the period of unavailability of the affected dwelling.

7.3 Normal Loss Expectancy (NLE) Scenarios

7.3.1 Reinforced Concrete NLE Scenario

The NLE scenario considers a relatively frequent and realistic fire event, characterized by early detection, limited growth, and intervention by occupants and/or the fire brigade. The ignition is assumed to occur in the kitchen of a residential unit, one of the most common fire sources in residential buildings (e.g. unattended cooking or small appliance malfunction). The fire initially develops locally, involving cooking equipment and nearby combustible materials. Due to smoke detectors, occupants are alerted early, enabling prompt response actions such as manual extinguishment.

Before reaching flashover, the fire is partially controlled either by occupants or fire brigade intervention. As a result, fire spread remains confined to the room of origin, with limited extension to adjacent spaces. Peak temperatures remain significantly lower than in MFL scenarios, and the fire is mainly fuel-controlled, involving movable fire loads and limited portions of fixed materials.

The reinforced concrete structural system is not affected, due to limited thermal exposure and the non-combustible nature of the materials. Internal partitions (gypsum board systems) may experience localized damage but do not cause significant fire propagation. The timber roof structure is not involved, as the fire does not reach upper levels.

Smoke production is the main source of damage, affecting the room of origin and adjacent spaces within the unit. Soot deposition and contamination may require cleaning and partial refurbishment. The expected damage level under NLE conditions is limited. Structural damage is negligible, 0-5%, due to the non-combustible reinforced concrete and limited thermal exposure. Damage to contents and finishes is more significant, mainly due to direct fire impact and smoke spread. Total content loss at unit level is estimated at 15-30%, with severe damage in the kitchen and minor smoke contamination in adjacent rooms. Loss of use is expected to range between 1 and 2 months, depending on the extent of smoke damage and the time required for cleaning and refurbishment.

NLE Reinforced Concrete Scenario		
	Involved Area	**% Damage**
Property Damage	Room of fire origin (kitchen)	0-5% of one unit replacement cost 15%-30% of Internal Unit Value
Business Interruption[3]		100% for 1 to 2 months

Note:

The percentages reported do not account for additional costs related to temporary accommodation, such as renting alternative housing units during the period of unavailability of the affected dwelling.

7.3.2 Timber NLE Scenario

The NLE scenario is defined assuming the same ignition conditions and detection mechanisms as the reinforced concrete reference case, with a localized fire originating in the kitchen area of a single residential unit and early intervention limiting fire development. The key difference lies in the structural system, which in this case is entirely composed of timber elements.

Early detection is ensured by smoke detectors, enabling prompt occupant response and fire brigade intervention. However, compared to the reinforced concrete configuration, the presence of combustible structural elements introduces additional fire dynamics. In the early stages, fire growth remains primarily fuel-controlled, but partial degradation or localized failure of protective linings (e.g. gypsum boards) may expose timber elements. This can lead to involvement of structural components, contributing additional fuel to the fire and slightly increasing fire severity compared to the actual case. Nevertheless, due to timely intervention, the fire does not transition into a fully developed structure-involved scenario.

Fire spread remains mostly confined to the room of origin, with only minor extension to adjacent spaces. Compartmentation between units remains effective under NLE conditions, preventing inter-unit fire spread. The timber roof structure is not directly involved, although minor smoke contamination may reach upper levels.

Smoke production plays a significant role, affecting a larger portion of the unit compared to the reinforced concrete case due to slightly higher fire severity and material contribution. Under NLE conditions, remains moderate but higher than in the reinforced concrete case, due to partial involvement of combustible structural elements. Structural damage is limited but not negligible, below 20%, mainly due to localized charring of timber components and damage to protective linings requiring repair or replacement. Water damage from firefighting operations may also contribute substantially to overall losses, particularly affecting finishes and adjacent areas.

Damage to contents and finishes is more significant, driven by both direct fire impact in the room of origin and increased smoke production. Total content loss at the unit level is estimated at approximately 20-35%. The loss of use is expected to range between 2 and 4 months, depending on the extent of smoke contamination and the need for inspection and repair of timber structural elements.

NLE Timber Scenario		
	Involved Area	**% Damage**
Property Damage	Room of fire origin (kitchen)	10-20% of one unit replacement cost 20-35% of one Unit' Internal Value
Business Interruption[3]		100% for 2 to 4 months

Note:
The percentages reported do not account for additional costs related to temporary accommodation, such as renting alternative housing units during the period of unavailability of the affected dwelling.

7.4 Scenario Comparison - Case Study #2

In contrast to the reinforced concrete configuration, the timber MFL scenario leads to a structure-involved fire, where the building itself contributes to fire development. This results in significantly increased fire duration, uncontrolled fire spread across multiple units, and extensive structural damage. Consequently, the MFL scenario is characterized by near-total loss of the building and substantially longer recovery times. Direct damages in the timber configuration are consistently higher, reaching values up to approximately two times those observed in the reinforced concrete scenario under comparable conditions, highlighting the severe economic impact associated with the combustibility of the structural system.

It must be emphasised that, in all MFL scenarios, the dominant driver of loss is the absence of active fire suppression and external intervention. Under these conditions, the structural system primarily influences the progression of the fire and the post-fire recoverability of the building, rather than the ignition or early fire development.

Even under NLE conditions, timber structures exhibit higher vulnerability due to their intrinsic combustibility. In this case, direct damages are also significantly higher, almost double compared to the reinforced concrete scenario, mainly due to the absence of protection systems within residential units, which delays fire containment and makes the intervention of the fire brigade the primary mitigation measure.

	Building Damage		Contents & Equip. Damage		Total Property Damage	Business Interruption (Loss of Use) Damage		Total PD + BI
MFL - RC	40-50%	~€0,6 M	100%	~€0,2 M	~€0,8 M	100% for 9 months	N/A	~€0,8 M
MFL - Timber	100%	~€1,2 M	100%	~€0,8 M	~€2 M	100% for 18 months	N/A	~€2 M
NLE - RC	5%	~€0,03 M	15-30%	~€0,04 M	~€0,07 M	100% 1 to 2 months	N/A	~€0,07 M
NLE - Timber	10-20%	~€0,12 M	20-35%	~€0,06 M	~€0,18 M	100% 2 to 4 months	N/A	~€0,18 M

8. Case Study #3: Warehouse

8.1 Facility Description

The third case study concerns an industrial warehouse used for the storage of goods, designed as a single-storey building with a functional layout optimized for logistics and storage operations. The facility is characterized by a regular structural grid and an open internal configuration, allowing efficient material handling and storage management.

The building is organized as a single fire compartment, with no internal subdivision into multiple fire areas. The storage layout is based on continuous vertical racking systems extending across the warehouse floor, enabling high-density storage. Stored materials consist of mixed commodities, including palletized goods, packaging materials, and plastic components, resulting in a significant and uniformly distributed fire load.

The warehouse has a gross floor area of approximately 5,000 m² and an internal clear height of 9 m, allowing vertical storage while maintaining operational accessibility. The building includes loading and unloading bays equipped with industrial doors, as well as limited ancillary areas such as technical rooms and service spaces located along the perimeter.

Fire protection systems include automatic fire detection, manual alarm systems, and an automatic sprinkler system designed for storage occupancies. These systems ensure early detection and control of fire events under normal operating conditions.

From an operational standpoint, the warehouse is continuously utilized, with high occupancy of the storage racks and a rapid rotation of goods. The facility forms part of a multi-site operation, and the annual turnover attributable to its activity, used as the reference value for the quantification of Business Interruption, is in the order of €3 million. The reconstruction value of the building amounts to approximately €4.5 million, of which the civil and structural works represent €3.0 million, while the value of stored goods, racking and handling equipment is estimated at approximately €2.5 million, resulting in a total exposed asset value of approximately €7.0 million, excluding indirect economic impacts.

Items	Replacement value in Euro (€)
Civil works	3,000,000
Mechanical system	900,000
Electrical system	400,000
Technical costs: commissioning, construction supervision…	200,000
Machinery and Goods	2,500,000
Total	7,000,000

Overall, the facility represents a modern, high-value logistics asset characterized by a significant combustible storage concentration within a single large compartment, a fully precast and non-combustible load-bearing system, a documented EI 120 internal separation protecting the office and technical wing, and an active protection concept based on automatic suppression, early detection and external intervention.

8.1.1 Actual – Reinforced Concrete Structure

The building is realized using a reinforced concrete structural system. The foundation system consists of reinforced concrete foundations designed to support vertical and horizontal loads. The vertical load-bearing system is composed of reinforced concrete columns arranged according to a regular structural grid.

The roof system is realized using non-combustible prefabricated elements, combined with insulation layers and waterproofing membranes. External walls consist of precast concrete panels, providing a robust and non-combustible building envelope.

The building envelope consists of precast concrete sandwich panels with the insulation core fully encased between two concrete leaves, so that both faces are non-combustible. Within the two-storey wing, the mezzanine floor is formed by prestressed concrete elements certified REI 60. The fire resistance declared for the principal load-bearing elements of the hall is R 60. The internal separation between the storage hall and the wing, described in Section 8.1, is realized by full-height precast reinforced concrete walls classified EI 120, constituting physical, non-combustible fire barriers integral to the structural system, independent of applied linings or maintenance-sensitive components.

From a fire-engineering perspective, the structural system is entirely non-combustible (reaction-to-fire class A1) and does not contribute to the fire load of the compartments. Fire development is therefore governed exclusively by the stored contents, while the structure acts as a stabilizing, non-participating element whose degradation mechanisms under fire are those described in Section 2.3.1.

8.1.2 Simulated – Timber Structure

In the alternative configuration, the warehouse is realized using a timber-based structural system, consistently with the comparative design assumptions set out in Section 5, this configuration is developed as a controlled material substitution. The timber configuration is assumed to be a complete mass-timber building. The vertical load-bearing system consists of glulam columns, the roof structure is formed by double-pitched glulam girders of equivalent span supporting a roof deck of cross-laminated timber (CLT) panels carrying the same insulation and waterproofing build-up, and the mezzanine floor and stair core of the wing are likewise assumed in CLT. The building envelope is realized with prefabricated timber-based wall elements of equivalent insulation performance, and the internal EI 120 separation between the storage hall and the wing is realized by encapsulated CLT panels nominally achieving the same classification. The foundation system remains in reinforced concrete, as is standard practice in timber buildings, and has no influence on the fire scenarios analysed.

From a fire engineering perspective, the structural system is combustible and may actively participate in the fire scenario. Under fire exposure, timber elements start charring, leading to a progressive reduction of the effective cross-section and a corresponding decrease in load-bearing capacity.

The structural fire design of the timber configuration is assumed to be carried out in accordance with EN 1995-1-2, based on the verification of the residual effective cross-section through the charring models discussed in Section 2.3.2. In order to nominally achieve the fire-resistance classes documented for the actual building, the load-bearing elements and the compartment walls are assumed to be protected by gypsum-board encapsulation, complemented where necessary by sacrificial charring layers. The comparison therefore does not assume bare, unprotected timber, but a code-compliant building in which the required ratings are met at the design stage through the combination of charring resistance and protective linings.

For the purpose of the comparative analysis, in keeping with the methodology set out in Section 5, the reconstruction value of the timber configuration is taken to be equal to that of the reinforced concrete building. A mass-timber solution achieving the same fire-resistance classes would, in real construction practice, carry a higher cost than the precast concrete baseline, principally on account of the structural system and of the gypsum-board encapsulation and sacrificial layers required to protect the load-bearing elements. The value of stored goods, racking and handling equipment, the storage layout and the active protection systems remain unchanged with respect to the actual building.

8.2 Maximum Foreseeable Loss (MFL) Scenarios

8.2.1 Reinforced Concrete MFL Scenario

The Maximum Foreseeable Loss scenario considers a severe, uncontrolled fire affecting a single-storey industrial warehouse used for storage purposes. The building is assumed to be realized with a reinforced concrete structural system, including columns, beams, and roof elements, providing high fire resistance and non-combustible behaviour.

The fire is assumed to originate within a storage area due to typical industrial ignition sources (e.g. electrical faults, overheating equipment, or accidental ignition of stored goods). Given the storage function, the fire load is primarily associated with the type and arrangement of stored materials (e.g. palletized goods, packaging materials, plastics), which may result in a high and concentrated fuel load. Under MFL assumptions, no active fire protection systems are considered effective (e.g. sprinkler system failure), and no fire brigade intervention takes place. The fire is therefore allowed to develop until complete burnout of all present fire load. Following ignition, the fire spreads rapidly within the storage area due to the presence of combustible goods and possible vertical storage configurations. Fire dynamics are strongly influenced by storage geometry, ventilation conditions, and fire load density.
Despite the severity of the fire, the reinforced concrete structural system does not contribute to the fire load and plays a key role in limiting structural consequences. Load-bearing elements are expected to maintain their stability for a significant duration due to their inherent fire resistance. However, under prolonged exposure to high temperatures, local damage may occur, including: spalling of concrete cover, reduction of mechanical properties and localized degradation of structural elements. In extreme conditions, partial structural damage or localized roof collapse cannot be excluded, particularly in areas subjected to the highest thermal exposure. However, a global structural collapse is generally not expected. At the end of the fire, damage is primarily governed by the loss of stored goods and internal equipment, while the structural frame is expected to remain partially recoverable, depending on the severity and duration of exposure.

Under these conditions, property damage is severe but confined to the storage hall. The stored goods, the racking systems and the handling equipment within the hall are assumed to be destroyed or unrecoverable, with damage estimated at 85-90% of the insured value of machinery and goods, corresponding approximately to €2.2 million. Building damage is governed by the demolition and reconstruction of the roof structure of the most exposed bays, the replacement of deformed or spalled elements, the reinstatement of the facade panels in the fire-affected sectors and the complete replacement of the internal installations of the hall, while the wing requires only cleaning and minor reinstatement works. Building-related damage is estimated at 50-70% of the building replacement value, corresponding approximately to €2.7 million.

Business interruption is expected to be substantial, with a complete halt of operations, 70%, for an estimated period of 6 to 9 months. The associated financial impact, including loss of revenue and additional operational costs, can be estimated in the range of € 2 million.

MFL Reinforced Concrete Scenario		
	Involved Area	**% Damage**
Property Damage	Entire Building	50-70% of Building replacement cost 85-90% of Machinery & Goods
Business Interruption[3]		70% for 6 to 9 months

Note:
The percentages reported do not account for potential mitigation measures such as rent an additional facility and/or temporarily relocating operations to third-party premises.

8.2.2 Timber MFL Scenario

The MFL scenario is defined under the same boundary conditions described for the reinforced concrete case, with a severe fire originating within the storage area of the warehouse and developing in the absence of active fire protection systems and fire brigade intervention. The building, as previously introduced, is assumed to be entirely realized with a timber structural system, including load-bearing elements and internal components.

The warehouse is characterized by high-density vertical storage, with continuous racking systems and significant fire load associated with stored goods and packaging materials. Following ignition, the fire rapidly involves the stored materials, leading to fast horizontal and vertical fire spread throughout the storage area.

Due to the timber structural system, the fire is not limited to the movable fire load. After enough time, structural elements actively contribute to fire development. The progressive degradation of timber members through charring, combined with the failure of connections and the opening of joints, continuously exposes fresh combustible surfaces, sustaining and intensifying the fire.

Fire propagation extends rapidly across the entire building through a combination of involvement of stored goods, structural fire contribution, continuity of combustible elements, lack of effective compartmentation.

As the fire progresses, the load-bearing capacity of the timber structure is progressively reduced due to section loss caused by charring. This degradation leads to increasing structural instability, initially at local level and subsequently extending to multiple structural elements, ultimately resulting in partial and then global collapse of the building. The collapse further contributes to fire development by exposing additional combustible surfaces and increasing ventilation conditions within the compartment.

From a structural perspective, the failure process is not necessarily sudden. During the decay and cooling phase, residual thermal gradients, combined with the already reduced cross-sections of timber elements, may trigger delayed collapse mechanisms or further structural degradation. These effects can occur even after the peak fire phase, contributing to the overall instability of the structure.

At the end of the event, the fire evolves into a fully structure-involved scenario, in which the building itself acts as fuel. As a consequence, the warehouse is assumed to be completely destroyed, with no recoverable structural elements.

From a quantitative loss perspective, the MFL scenario results in the total loss of the facility. Property damage is estimated at 100% of the building replacement cost, corresponding approximately to € 4.5 million.

Stored goods are assumed to be almost completely destroyed 100% of stored value, with an estimated loss in the order of € 2.5 million, reflecting the high storage density and full fire involvement.

Business interruption is expected to be total 100%, with a prolonged recovery period due to full reconstruction requirements. The downtime is estimated at 12-15 months, with associated financial losses above € 3 million, depending on the scale of operations and reconstruction timeline and without take into consideration the possibility to rent an additional facility and/or temporarily relocating operations to third-party premises.

MFL Timber Scenario		
	Involved Area	**% Damage**
Property Damage	Entire Building	100% of Building replacement cost 100% of Machinery & Goods
Business Interruption[3]		100% for 12 to 15 months

Note:
The percentages reported do not account for potential mitigation measures such as rent an additional facility and/or temporarily relocating operations to third-party premises.

8.3 Normal Loss Expectancy (NLE) Scenarios

8.3.1 Reinforced Concrete NLE Scenario

The NLE scenario assumes a localized fire originating within the storage area, under the same boundary conditions previously defined, with the additional assumption of a fully effective automatic sprinkler system. The warehouse is characterized by high-density vertical storage, resulting in a significant but concentrated fire load.

Following ignition, the fire is rapidly detected and controlled by the sprinkler system, which limits fire growth and prevents flashover. Fire development remains confined to the immediate area of origin, with only a limited number of storage racks involved.

The reinforced concrete structural system is not affected in terms of load-bearing capacity, with thermal exposure remaining insufficient to produce any structural damage.

At the end of the event, damage is restricted to a small portion of stored goods and localized areas of the warehouse, with no impact on structural integrity and only minor restoration activities required.

From a quantitative perspective, the NLE scenario results in minor and highly localized damage. Property damage is estimated in the range of 2-3% of the total building replacement cost, corresponding approximately to € 0.1 million.

Stored goods are partially affected within the area of origin, with losses estimated in the range of 5-10% of the stored value, equivalent to approximately € 0.1 to 0.3 million.

Business interruption is expected to be limited, with operational disruption estimated at 5-10% for a duration of 4 weeks, mainly due to cleanup, replacement of damaged goods, and localized system checks. The associated financial impact is estimated in the range of € 0.15 to 0.3 million.

NLE Reinforced Concrete Scenario		
	Involved Area	**% Damage**
Property Damage	Entire Building	2-3% of Building replacement cost 5-10% of Machinery & Goods
Business Interruption[3]		5-10% for 1 month

Note:
The percentages reported do not account for potential mitigation measures such as rent an additional facility and/or temporarily relocating operations to third-party premises.

8.3.2 Timber NLE Scenario

The NLE scenario for the timber warehouse is defined under the same boundary conditions as the reinforced concrete configuration, ensuring full comparability in terms of ignition source, fire load, and effectiveness of fire protection systems. The fire is assumed to originate within the storage area, in a high-density vertical rack configuration, with automatic sprinkler systems operating as designed.

Following ignition, fire development is initially driven by the stored goods and packaging materials. Due to the high storage density, flame spread within the first rack levels occurs rapidly; however, sprinkler activation takes place within a short time frame, limiting further vertical and horizontal propagation. As a result, the fire remains confined to a limited number of storage bays, preventing the transition to a fully developed compartment fire.

In contrast to the reinforced concrete configuration, the timber structural system introduces a potential interaction with the fire, even under controlled conditions. During the early stages, structural elements remain protected by encapsulation layers; however, localized degradation of these layers may expose timber surfaces to elevated temperatures. Where exposure occurs, limited charring may develop, leading to minor involvement of structural elements without transitioning into a structure-involved fire.

In addition to thermal effects, sprinkler discharge represents a relevant damage mechanism in timber structures. Water penetration into connections, joints, and concealed cavities may lead to moisture accumulation that is not immediately detectable, requiring targeted inspection, drying, and, in some cases, localized replacement of affected elements.

At the end of the event, damage is primarily confined to a limited number of storage racks, portions of the timber structural system directly above the fire area, and zones affected by smoke and water.

From a quantitative loss perspective, building damage is estimated in the range of 8-12% of the total replacement cost, corresponding approximately to € 0.4 - 0.6 million. Stored goods are partially affected within the area of origin, with losses estimated in the range of 10-15% of the total stored value, corresponding approximately to € 0.3 - 0.4 million.

Business interruption remains limited but slightly higher compared to the reinforced concrete configuration, due to additional time required for inspection, drying, and repair of timber structural components. Operational disruption is estimated at 10-15% for a duration of 1 to 2 months, corresponding approximately to € 0.3 to 0.45 million.

NLE Timber Scenario		
	Involved Area	**% Damage**
Property Damage	Entire Building	8-12% of Building replacement cost 10-15% of Machinery & Goods
Business Interruption[3]		10-15% for 1 to 2 months

Note:
The percentages reported do not account for potential mitigation measures such as rent an additional facility and/or temporarily relocating operations to third-party premises.

8.4 Scenario Comparison - Case Study #3

The comparative assessment between the reinforced concrete (RC) and timber structural configurations confirms that the differences in loss performance are limited under Normal Loss Expectancy (NLE) conditions, while becoming significantly more pronounced under Maximum Foreseeable Loss (MFL) scenarios. When fire protection systems are assumed to operate effectively, including early detection and automatic sprinkler activation in accordance with NFPA 13 design principles, fire development remains controlled and confined to the area of origin. In both structural configurations, the event does not progress, and damage is primarily restricted to stored goods, localized rack systems, and limited building parts. Under these conditions, the structural systems do not experience meaningful thermal degradation, and overall stability is fully preserved. As a result, differences between the two configurations remain marginal, with slightly higher impacts observed in the timber solution due mainly to localized water exposure effects and more extensive post-event inspection requirements. It has to be noted that, without the presence of automatic fire extinguishing systems, the difference between the two NLE scenarios would be significantly more in favour of the actual case (reinforced concrete scenario).

A substantially different behaviour emerges under MFL conditions, where fire protection systems are assumed to be ineffective and no external firefighting intervention is considered. In this context, the reinforced concrete structure demonstrates a high degree of inherent fire resistance due to its non-combustible nature and thermal inertia. Although localized spalling and material degradation may occur under prolonged high-temperature exposure, the global structural system is expected to remain largely stable for a significant duration. This limits the fire to a fuel-driven event governed primarily by the stored goods, resulting in a high but comparatively contained loss scenario. The consequence is a partial recoverability of the structural frame and a more efficient post-fire reconstruction process, with shorter overall downtime and reduced Business Interruption exposure.

In contrast, the timber-based configuration exhibits a markedly different fire response under the same MFL conditions. The combustible nature of the structural system leads to progressive involvement of load-bearing elements with charring, connection failure, and loss of section capacity driving a continuous escalation of fire severity. This structural participation in the fire results in a self-sustaining combustion process, ultimately leading to total collapse of the building. The collapse further accelerates fire development by exposing additional combustible surfaces and increasing ventilation conditions.

From a loss perspective, this structural behaviour translates into significantly higher severity outcomes compared to the reinforced concrete case. Property damage reaches total replacement of the building, while Business Interruption is substantially extended due to full demolition and reconstruction requirements. Overall, the analysis confirms that while performance under controlled fire conditions remains broadly comparable, the choice of structural system becomes a critical differentiating factor in extreme loss scenarios, with reinforced concrete providing a substantially more resilient framework in terms of fire-induced collapse prevention, loss limitation, and recovery time.

	Building Damage		Mach. & Goods Damage		Total Property Damage	Business Interruption Damage		Total PD + BI
MFL - RC	50-70%	~€2,7 M	85-90%	~€2,2 M	~€4,9 M	70% for 6 to 9 months	~€2,1 M	~€7 M
MFL - Timber	100%	~€4,5 M	100%	~€2,5 M	~€7 M	100% for 15 months	~€3 M	~€10 M
NLE - RC	2-3%	~€0,1 M	5-10%	~€0,2 M	~€0,3 M	5-10% for 1 month	~€0,2 M	~€0,5 M
NLE - Timber	8-12%	~€0,5 M	10-15%	~€0,3 M	~€0,8 M	10-15% for 1 to 2 months	~€0,4 M	~€1,2 M

9. Case Study #4: School Building

9.1 Facility Description

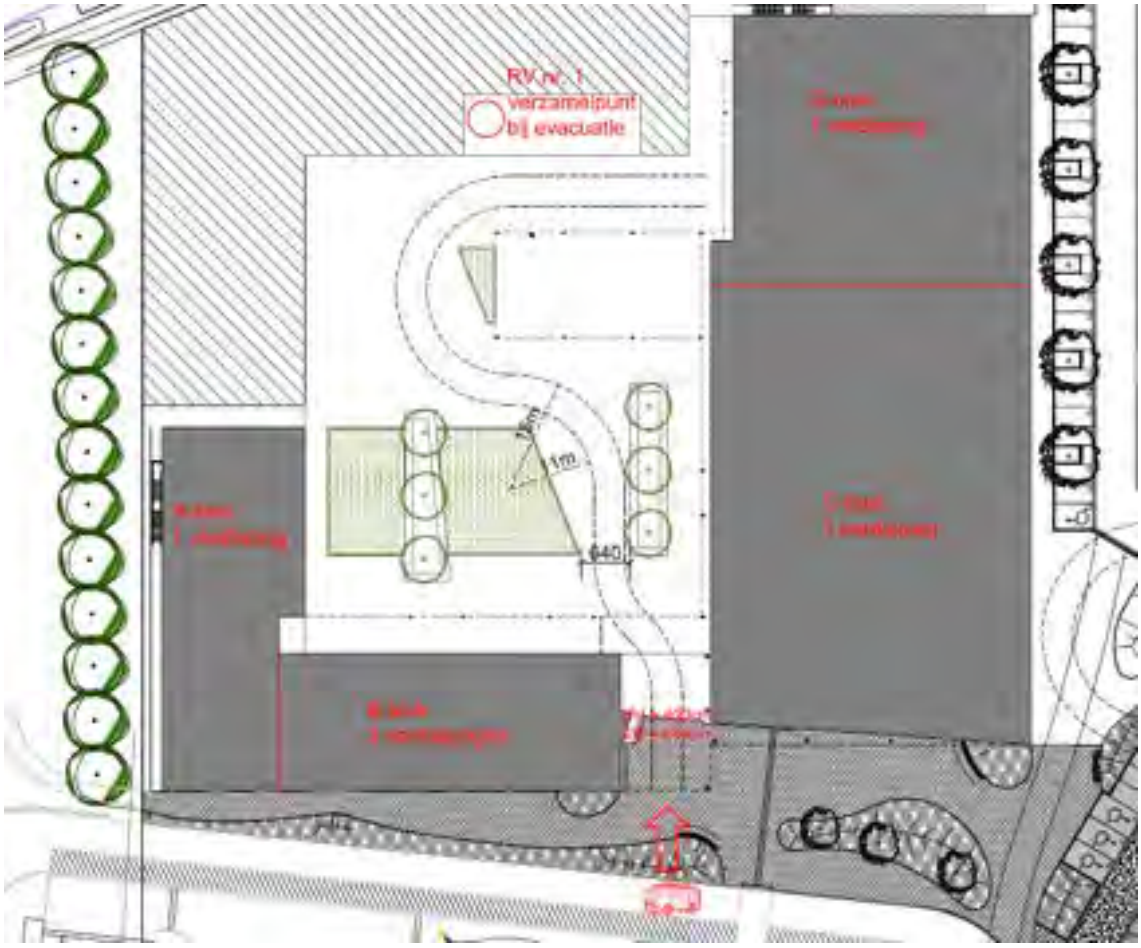
The fourth case study concerns a secondary technical school located in Belgium, built between 2014 and 2016 within the framework of a public DBFM school-building programme and documented through a complete set of as-built architectural and structural drawings. The campus configuration, the certified fire performance of its structural elements, and the presence of technical workshops make this facility particularly representative for the scope of the project.

The school is organized as a campus of four interconnected blocks (A, B, C and D) arranged around a central courtyard, with two designated external assembly points. Block A (ground + 1 storey) accommodates the refectory, a large single-volume dining hall of approximately 468 m², together with teachers' rooms and sanitary facilities. Block B (ground + 2 storeys) hosts the general classrooms and, at ground level, an auditorium and student services; its typical floor is a single fire compartment of approximately 890-1,030 m². Blocks C and D (ground + 1 storey, with a high single-volume ground floor) contain the technical heart of the school: the metal and welding workshops (a single compartment of approximately 1,588 m², the largest of the entire complex), the wood workshops (approximately 1,398 m²) and the related storage and technical areas. The first floor of blocks C and D accommodates additional teaching spaces (compartments of 1,141 m² and 600 m²).

The total gross floor area of the complex is approximately 9,500-10,000 m². Typical storey height is 3.85 m in the classroom blocks while the workshop hall reaches an internal height of approximately 4.9 m with a roof level at +9.40 m. The workshop roof incorporates a repetitive array of polycarbonate rooflights (approximately 9.00 × 2.40 m each) providing natural daylight to the production areas, and a rooftop photovoltaic system of approximately 131 kWp.

From an occupancy standpoint, the building is a medium-density educational facility with a design population in the order of 1,800-2,000 persons distributed across the compartments. Fire loads are moderate and distributed in the classroom blocks (furniture, teaching materials, IT equipment) and significantly higher and more concentrated in the workshop blocks, where machinery, raw materials (timber sections, steel plates), finished works, lubricants and packaging are present.

A distinctive feature of this facility is the presence of special technical risks typically associated with technical education: a dedicated welding centre at the ground floor of block C, equipped with welding booths, local fume-extraction systems and a fixed gas-distribution network supplied from a separate gas room and an external gas-cylinder store; wood-dust extraction systems serving the machine park of the wood workshops (blocks C and D); and a compressed-air distribution network. These installations, fully documented in the as-built MEP drawings, represent both credible ignition sources and factors capable of influencing fire development in severe scenarios.



From a fire protection perspective, the building is equipped with a complete automatic fire-detection system, optical and ionization smoke detectors throughout, supplemented by gas detectors with local warning lamps in the workshop and gas areas, manual call points behind break-glass, alarm sounders and a fire-brigade interface. First-intervention means consist of wall-mounted fire-hose reels housed in fire-rated niches and ABC portable extinguishers; natural smoke-vent hatches are provided. In line with common European practice for school buildings, no automatic sprinkler protection is installed. The local fire brigade response time is about 8 minutes, a parameter that plays a central role in the Normal Loss Expectancy scenarios developed below. The building's fire-safety concept therefore relies on the combination of early detection, rapid external intervention, and a robust passive compartmentation strategy.

The reconstruction value of the building is estimated at approximately €20 million, while the insured value of the building contents (furniture, workshop machinery, teaching and IT equipment) amounts to almost €4,5 million resulting in a total exposed asset value of approximately €24,5 million, excluding indirect economic impacts.

Items	Replacement value in Euro (€)
Civil works	15,500,000
Mechanical system	2,200,000
Electrical system	1,500,000
Technical costs: commissioning, construction supervision…	800,000
Contents and equipment	4,400,000
Total	24,400,000

Overall, the facility represents a modern, high-quality public educational asset characterized by a clear separation between high-occupancy teaching areas and high-fire-load workshop areas, a documented and certified passive fire-protection strategy, and an active protection concept based on detection and external intervention rather than automatic suppression. This combination makes the case study particularly suitable for assessing how the choice of the structural material influences fire development, damage extent and recovery time in a building use destination (schools) where mass-timber solutions are experiencing their fastest market growth across Europe.

9.1.1 Actual – Reinforced Concrete Structure

The building is realized through a fully precast reinforced concrete structural system. The vertical load-bearing system consists of precast reinforced concrete columns and precast core walls at the stair and technical shafts, complemented by load-bearing precast wall panels. Horizontal structures are formed by prestressed hollow-core slabs completed with a cast-in-place reinforced structural topping, providing diaphragm action and effective horizontal compartmentation between storeys. Roof structures over the long-span volumes are realized with deeper prestressed hollow-core units of the SPHS 320 and SPHS 400 series, achieving spans in the order of 10.6 m over the workshop halls. Precast prestressed beams of rectangular and ledger type complete the frame, with depths up to 1,335 mm and individual lengths of up to 17.8 m in the workshop bays. Concrete strength classes are C30/37 for columns and wall elements and C50/60 to C60/75 for the prestressed units. Limited structural steel members are present only in secondary positions, such as lintels and canopy supports, together with detached light steel structures serving ancillary functions.

From a fire-resistance standpoint, the as-built structural drawings of all blocks explicitly declare a fire resistance of the structure of 1 hour (R60), and the production tables of the precast elements report the 60-minute fire rating at the level of the individual unit. The fire performance of the load-bearing system is therefore not merely a design assumption but a certified characteristic of the supplied products, achieved through the intrinsic properties of the elements (concrete cover, cross-sectional mass and the low thermal conductivity of concrete) without reliance on applied protective systems, consistently with the framework discussed in Section 2.

A particularly relevant feature of this facility is the materialization of the internal compartment lines within the workshop block. The separation between the main workshop compartments is achieved through dedicated precast reinforced concrete fire walls, 140 mm thick, extending over the full height of the building up to the roof level (+9.40 m). These walls constitute physical, non-combustible fire barriers, integral to the load-bearing system that do not depend on linings, on joints sealing performed on site or on maintenance-sensitive components. Together with the REI60 internal compartment walls, fire-rated doors and the fire-rated glazed screen protecting the internal void, they implement the compartmentation layout described in Section 9.1.

The building envelope consists of precast concrete sandwich panels, for which the as-built drawings declare a fire resistance of 30 minutes. The external faces of the envelope are therefore non-combustible concrete surfaces, limiting the contribution of the façades to external fire spread. The only significant combustible components of the envelope are the polycarbonate rooflights distributed over the workshop roofs and the polycarbonate canopies of the external covered areas; these elements act as preferential failure points for smoke and flame venting through the roof in severe scenarios, but they do not compromise the load-bearing function of the hollow-core roof structure beneath.

From a fire-engineering perspective, the structural system is entirely non-combustible (reaction-to-fire class A1) and does not contribute to the fire load of the compartments. Fire development is therefore governed exclusively by the contents while the structure acts as a stabilizing, non-participating element whose degradation mechanisms under fire are those described in Section 2.3.1: progressive and predictable reduction of mechanical properties with temperature, high thermal inertia of the massive prestressed sections and possible localized spalling, without sudden loss of load-bearing capacity. The combination of an R60 certified frame, full-height concrete fire walls in the highest-fire-load area, and storey-by-storey separation provided by the hollow-core floors creates a robust passive framework, capable of confining even a severe fire to the compartment of origin and of preserving the global stability of the campus, conditions that directly influence both the expected damage extent and the post-fire recoverability assessed in the following scenarios.

9.1.2 Simulated – Timber Structure

In the alternative configuration, the school is assumed to be realized using a fully timber-based structural system, representative of contemporary engineered-wood construction for educational buildings. Consistently with the comparative design assumptions set out in Section 5, this configuration is developed as a controlled material substitution: the building retains the same global geometry, volumes, storey heights, structural grid, span layout, compartmentation lines and overall dimensions as the actual precast reinforced concrete building. Only the material composing the load-bearing system is varied, so that the comparison isolates the influence of the structural material's behaviour under fire.

The scope and the limits of this assumption must be clear from the outset. The objective of this study is not to develop a final structural design of the timber school, nor to optimize member sizing, connection detailing, stiffness, dynamic behaviour or foundation loads. Such aspects, which would legitimately differ between a concrete and a timber building, are intentionally not

investigated. The substitution is a fire-engineering modelling device: two geometrically identical buildings are compared solely to observe how a fire of equivalent origin and fuel develops when the surrounding load-bearing structure is non-combustible in one case and combustible in the other. The geometric equivalence is a deliberate boundary condition of the analysis, not a claim that the two structures are mechanically interchangeable, and it is adopted precisely to keep compartment volumes, ventilation conditions and exposed surface areas constant between the two configurations.

The timber configuration is assumed to be a complete mass-timber building. The vertical load-bearing system consists of cross-laminated timber (CLT) wall panels, providing both gravity load capacity and in-plane stiffness for global stability. The intermediate floors and the long-span roofs of the workshop and dining volumes are assumed to be realized with CLT floor panels and glulam beams and columns, dimensioned within the ranges typical of engineered-wood construction for the spans involved and the stair and shaft cores are likewise assumed in CLT. The foundation system remain in reinforced concrete, as is standard practice in timber buildings, and it is the only element common to both configurations and has no influence on the fire scenarios analysed.

The structural fire design of the timber configuration is assumed to be carried out in accordance with EN 1995-1-2, based on the verification of the residual effective cross-section through the charring models discussed in Section 2.3.2. In order to achieve the fire-resistance classes documented for the actual building, the timber elements are assumed to be protected by passive fire-protection systems consistent with current timber fire-design practice, principally gypsum-board encapsulation of the load-bearing elements and of the compartment walls, complemented where necessary by sacrificial charring layers. The comparison does not assume bare, unprotected timber, but a code-compliant building in which the required ratings are nominally met at the design stage through the combination of charring resistance and protective linings.

The detailed dimensioning of the protective layers, the design of the connections and the joint detailing are beyond the scope of this comparative assessment and are treated through generalized engineering assumptions consistent with contemporary mass-timber fire-design methodologies. The configuration so defined provides a controlled and methodologically transparent framework: a geometrically identical, code-compliant, fully encapsulated timber school, compared against the actual precast concrete school, for the sole purpose of evaluating the influence of structural combustibility on fire development, damage extent, property damage, business interruption and post-fire recoverability.

9.2 Maximum Foreseeable Loss (MFL) Scenarios

9.2.1 Reinforced Concrete MFL Scenario

In the school building under analysis, the MFL scenario is developed in accordance with the deterministic, conservative methodology defined in Section 4, combining NFPA-based fire-engineering assumptions for fire initiation and development with the FM Global loss-evaluation logic for Property Damage and Business Interruption. Consistently with the MFL definition, all active and operational mitigation layers are assumed to be unavailable or ineffective. So, the automatic detection and alarm system does not result in timely intervention, the fire-hose reels

and portable extinguishers are not effectively deployed, and the eight-minute fire-brigade response does not lead to early control of the fire during its critical growth phase. The fire is therefore assumed to develop freely until it is arrested by the boundaries of the compartment of origin or by the exhaustion of the available fuel.

The compartment of origin is assumed to be the metal and welding workshop at the ground floor of block C, which constitutes the largest single fire compartment of the complex (approximately 1,588 m²) and the area with the highest and most adverse fire load. Ignition is assumed to occur as a consequence of hot-work activity in the welding centre, a credible and well-documented ignition source given the fixed gas-distribution network, the welding booths and the presence of combustible materials, lubricants and packaging in the immediate vicinity. This selection places the fire in the compartment with the greatest fuel load, the greatest exposed area and the highest concentration of value, and it is consistent with the special-risk profile identified in the as-built documentation.

Following ignition, the fire develops with a fast growth rate, supported by the combustible contents of the workshop (timber stock and finished works, plastics, packaging, lubricants) and locally accelerated by the gas-distribution network feeding the welding stations. Hot gases accumulate beneath the roof and, in the absence of effective suppression, flashover conditions are reached within the compartment of origin with upper-layer temperatures approaching 900-1000 °C and sustained thermal exposure lasting well beyond one hour. The polycarbonate rooflights fail early, venting smoke and hot gases through the roof and admitting additional oxygen that sustains the fully developed fire. The fire continues until the combustible contents of the workshop are substantially consumed.

From a structural standpoint, the precast reinforced concrete frame does not contribute to the fire load and does not participate in combustion at any stage, although it is subjected to severe thermal exposure. The surface layers of columns, beams and hollow-core roof units lose strength and stiffness in accordance with the degradation models of EN 1992-1-2 discussed in Section 2.3.1. The prestressing and reinforcing steel progressively lose yield strength where steel temperatures exceed approximately 400-500 °C, and concrete cover spalling may occur in the most heavily exposed zones. These mechanisms develop progressively rather than suddenly. The high thermal inertia of the massive sections limits the depth of heat penetration, a substantial portion of each cross-section remains below critical temperatures, and the static indeterminacy of the precast frame allows stress redistribution. While limited, localized collapse of individual hollow-core roof units in the hottest zone is a foreseeable outcome, the global structural stability of block C, and of the campus as a whole, is not compromised.

The decisive feature of this configuration is the behaviour of the compartmentation. The 140 mm full-height precast concrete fire walls separating the workshop compartments, together with the compartment walls, the hollow-core floors with structural topping and the fire-rated doors, are intrinsic, non-combustible barriers that do not depend on the integrity of applied linings. Under MFL conditions they maintain their separating function for the duration of the fully developed fire, confining the event to the compartment of origin and preventing horizontal propagation to the adjacent wood workshops and vertical propagation to the upper teaching floors. The fire is ultimately arrested by the combination of fuel exhaustion and the persistence of the surrounding

non-combustible compartmentation. The remaining blocks of the school (A, B and the upper levels of C and D) remain structurally intact and unaffected by direct fire action, with damage limited, at most, to smoke migration through unsealed penetrations.

Under these conditions, property damage is severe but confined. The workshop contents works are assumed to be destroyed, and the directly exposed structural elements (the hollow-core roof of block C and the most exposed beams and column heads) require demolition and reconstruction. Beyond the compartment of origin, building damage is limited to localized smoke contamination. On this basis, building-related damage is estimated at approximately 25-30% of the building replacement value, reflecting the reconstruction of the workshop compartment roof and structure together with clean-up and reinstatement of smoke-affected finishes elsewhere. Damage to contents is estimated at approximately 35-40% of the insured contents value, concentrated in the high-value workshop machinery and equipment of block C.

The Business Interruption component for a school building is expressed in terms of the time required to reinstate full operational use, rather than as a loss of revenue. The structural damage is confined to a single block, and the modular campus layout allows the teaching activity to continue in the unaffected blocks while the workshop block is reconstructed. The full reinstatement of the workshop block with structural assessment, demolition, reconstruction, reinstallation of the technical networks (gas, fume and dust extraction, compressed air, electrical) and re-equipment, is estimated to require a period in the order of 9 to 12 months.

The non-combustible structure is therefore not a contributing factor to the escalation of the event. Its non-combustibility, thermal robustness and intrinsic compartmentation confine the loss to the compartment of origin, preserve the global stability of the campus, and govern a recovery process driven primarily by the reinstatement of a single block rather than by reconstruction of the building as a whole.

MFL Reinforced Concrete Scenario		
	Involved Area	**% Damage**
Property Damage	Block C – metal & welding area	25-30% of Building replacement cost 35-40% of Contents & Equipment
Business Interruption[3]		100% of the area for 9 to 12 months

Note:
The percentages do not account for the additional costs related to the temporary relocation of the teaching activity (e.g. rental and installation of temporary classroom modules, transport and logistics).

9.2.2 Timber MFL Scenario

The Maximum Foreseeable Loss scenario for the timber configuration is developed under assumptions strictly identical to those adopted in Section 9.2.1. Ignition occurs as a consequence of hot-work activity in the welding centre at the ground floor of block C.

The compartment of origin is the same metal and welding workshop of approximately 1,588 m², and the combustible contents, the ventilation conditions are unchanged, and all active and operational mitigation layers are assumed to be unavailable or ineffective. The only variable is the load-bearing structure which, in accordance with Section 9.1.2, consists of CLT timber wall and floor panels and glulam beams and columns, protected by gypsum-board encapsulation dimensioned to nominally achieve the R60 rating documented for the actual building.

The initial phase of the fire is, by construction, identical to that described in Section 9.2.1: fast growth across the workshop floor, sustained by the combustible contents, with hot gases accumulate beneath the roof, flashover conditions are reached within the compartment of origin, upper-layer temperatures approach 900-1000 °C, and early failure of the polycarbonate rooflights. During this phase the encapsulation performs its intended function, and the event remains, temporarily, a contents-governed fire.

The decisive evolution of the scenario occurs as the fully developed phase extends beyond the nominal protection period of the linings. Under sustained post-flashover exposure well in excess of one hour, the gypsum boards progressively calcinate, shrink and crack, and board fall-off initiates at joints, fixings and edges, the known weak points of any applied protective system as discussed in Section 2.3.2.

Since the MFL does not credit protection layers whose performance depends on installation quality, continuity and maintenance, the local breach of the encapsulation must be regarded as a foreseeable event. Wherever the linings are lost, the timber surfaces ignite and begin to char, and the progression of the char front to the adhesive interfaces of the cross-laminated panels can trigger the delamination of charred lamellae, exposing fresh wood and producing the step-wise regeneration of fuel described in Section 2.3.2.

From this point onwards the load-bearing structure itself becomes part of the available fuel. The exposed wall, ceiling and beam surfaces add a substantial and distributed fuel load to that of the contents, increasing the burning area, the radiation within the compartment and the overall heat-release rate. The condition of fuel exhaustion, which would otherwise terminate a contents-governed fire within the compartment of origin is deferred, and the fully developed phase is prolonged precisely during the period in which the compartmentation is called upon to perform. External flaming through the failed rooflight openings further exposes the timber roof elements directly, adding an external propagation path over the workshop roof.

The decisive consequence concerns the compartmentation. The internal compartment lines of the workshop wing are realized by encapsulated CLT panels whose separating function is conditional on the integrity of the linings. Once the protective boards are lost on the fire side, the separating elements themselves ignite and lose section, while panel joints, connection zones and service penetrations constitute preferential paths for hot gases and flames.

The loss of the separating function is therefore a foreseeable outcome, and the fire propagates horizontally into the adjacent wood workshops (approximately 1,398 m²), where the stored timber, the machine park and the wood-dust extraction systems offer an exceptionally favourable secondary fuel bed, and vertically through the wall-floor junctions and concealed cavities to the first-floor teaching compartments of blocks C and D (approximately 1,141 m² and 600 m²). The involvement of the entire workshop wing must therefore be assumed. Given the interconnection of the four blocks around the courtyard, blocks A and B are at minimum subjected to severe smoke and heat propagation, and an extension of the fire at the interfaces cannot be excluded.

Partial collapses of floor and roof elements within the fire-involved compartments are a foreseeable, and the global stability of the workshop wing is compromised. Consistently with the burnout behaviour discussed in Section 2.3.2, the structure remains vulnerable during and after the decay phase: smouldering combustion persists within the char layers, the concealed cavities and the adhesive interfaces, and delayed structural failures during the cooling phase are a documented possibility. These phenomena keep the fire-brigade operations defensive, prevent a safe interior overhaul, entail a concrete risk of re-ignition, and ultimately impose the demolition of the fire-affected timber structure, since the residual capacity of charred and delaminated elements and connections cannot be reliably verified or economically recovered.

Property damage extends far beyond the compartment of origin. The contents of the entire workshop wing are destroyed, the contents of the remaining blocks suffer widespread smoke and heat contamination, the timber structure of blocks C and D requires complete demolition and reconstruction, and the remaining blocks require extensive remediation of finishes, linings and installations. On this basis, building-related damage is estimated at approximately 75-85% of the building replacement value, approaching, in the most unfavourable but still foreseeable case, the threshold of complete reconstruction of the school. Damage to contents is estimated at approximately 85-90% of the insured contents value, reflecting the destruction of the high-value workshop equipment of blocks C and D and the contamination of teaching contents and IT equipment throughout the remaining blocks.

The Business Interruption component is correspondingly extended. The loss of the entire workshop wing, the contamination of the remaining blocks and the transformation of the whole site into a demolition and reconstruction yard largely suppress the per-block operational continuity that the campus layout would otherwise afford.

Full reinstatement, comprising the structural demolition of blocks C and D under the safety constraints imposed by a partially collapsed and smouldering-prone structure, the redesign and reconstruction of the wing, the reinstallation of the technical networks, the re-equipment of the workshops and the remediation of blocks A and B, is estimated to require 18 to 24 months.

The combustible structure is therefore a determining factor in the escalation of the event: it feeds the fire after the contents are consumed, it converts the compartment boundaries into consumable elements, and it transfers the MFL termination condition from the scale of the compartment of origin to the scale of the building wing.

MFL Timber Scenario		
	Involved Area	**% Damage**
Property Damage	Entire Building	75-85% of Building replacement cost 85-90% of Contents & Equipment
Business Interruption[3]		100% for 18 to 24 months

Note:
The percentages do not account for the additional costs related to the temporary relocation of the teaching activity (e.g. rental and installation of temporary classroom modules, transport and logistics).

9.3 Normal Loss Expectancy (NLE) Scenarios

9.3.1 Reinforced Concrete NLE Scenario

The Normal Loss Expectancy scenario describes the credible, statistically representative fire event for the facility, evaluated in accordance with the methodology of Section 4 under the assumption that all protection layers perform as designed. The ignition source and the compartment of origin are the same adopted for the MFL scenarios, namely a hot-work ignition in the welding centre of the metal and welding workshop at the ground floor of block C, so that the comparison between scenarios isolates the effect of the mitigation layers rather than of the ignition hypothesis.

In this configuration the event unfolds as a contained incident. The fire involves combustible materials in the immediate vicinity of the welding station and grows locally during its incipient phase. The automatic detection system, supported in this area by gas detectors, identifies the fire within minutes of ignition and activates the alarm and the fire-brigade interface.

Trained personnel intervene with the wall-mounted hose reels and portable extinguishers, limiting fire growth, while the fire brigade reaches the site within its documented response time of eight minutes and completes extinguishment during the growth phase, well before flashover conditions can develop in the 1,588 m² compartment. The natural smoke-vent hatches limit smoke logging within the workshop volume.

The structural and compartmentation systems are not significantly challenged. The thermal exposure remains localized and of short duration, far below the R60 capacity of the precast frame, and the surfaces of columns, beams and hollow-core units in the affected zone suffer at most superficial soot deposition and minor local damage, with no loss of mechanical capacity and no need for structural replacement.

The non-combustible concrete surfaces can be inspected, cleaned and reinstated without invasive works, and the compartment boundaries are not called upon to perform beyond ordinary smoke separation. Damage is therefore dominated by the contents and by smoke. The welding booth of origin and the equipment and materials in its vicinity are lost or require reconditioning, and smoke deposition affects part of the workshop contents, the finishes and the exposed installations of the compartment, including localized cleaning of the ventilation and extraction networks. On this basis, building-related damage is estimated at approximately below 5% of the building replacement value, essentially associated with the cleaning and reinstatement of finishes, services and local repairs within the compartment of origin. Damage to contents is estimated at approximately 5-10% of the insured contents value, concentrated in the welding area and in the smoke-affected equipment of the workshop.

The Business Interruption is limited and spatially confined. Teaching activity in blocks A, B and D, and at the upper levels of block C, can resume immediately after the event, since neither fire nor significant smoke propagates beyond the compartment of origin.

The reinstatement of the metal and welding workshop, comprising cleaning, repair of finishes and services, replacement of the damaged equipment and recommissioning of the gas and extraction networks, is estimated to require approximately 1 to 2 months. The event remains, in insurance terms, an ordinary and fully recoverable loss, consistent with the combination of early detection, rapid external intervention and a non-combustible structure that neither contributes to the fire nor requires post-fire structural works.

NLE Reinforced Concrete Scenario		
	Involved Area	**% Damage**
Property Damage	Block C – metal & welding area	0-5% of Building replacement cost 5-10% of Contents & Equipment
Business Interruption[3]		100% of the area for 1 to 2 months

Note:
The percentages do not account for the additional costs related to the temporary relocation of the teaching activity (e.g. rental and installation of temporary classroom modules, transport and logistics).

9.3.2 Timber NLE Scenario

The Normal Loss Expectancy scenario for the timber configuration is developed under the same assumptions adopted in Section 9.3.1. The ignition source and the compartment of origin are unchanged, all protection layers perform as designed, and the sequence of the event is identical: detection within the incipient phase, first intervention with hose reels and extinguishers, arrival of the fire brigade within eight minutes and extinguishment during the growth phase, well before flashover conditions can develop in the workshop compartment.

In a correctly protected mass-timber building, an event controlled at this stage does not engage the load-bearing function of the structure, and the gypsum-board encapsulation is expected to keep the timber elements out of the fire for the limited duration of the exposure.

The difference with respect to the actual building concerns the post-fire condition of the structure and the extent of the reinstatement works. The encapsulation in the area of origin is exposed to direct flame impingement, localized heat and mechanical action during firefighting, and is wetted by the extinguishing water. Even where the linings have performed correctly, their protective capacity in the affected zone can no longer be assumed, and the moisture absorbed by the boards and by the underlying panels must be addressed to prevent dimensional and durability problems in the timber. Furthermore, the load-bearing elements behind the damaged linings cannot be declared unaffected by visual inspection alone. The boards in and around the area of origin must be removed to verify the absence of localized charring and of smouldering pockets at joints, service penetrations and concealed cavities, a verification that has no equivalent in a non-combustible structure and that extends the intervention beyond the directly damaged surfaces. Where superficial charring is found, the affected layers are repaired or the panel faces locally reinstated, and the complete encapsulation system is then rebuilt to restore the certified fire performance of the compartment.

Fire and smoke damage to the contents is essentially the same as in the reinforced concrete configuration, since the event is identical in extent: the welding booth of origin and the nearby equipment are lost or require reconditioning, and smoke deposition affects part of the workshop contents and installations. Building-related damage, however, is moderately higher, as it includes the stripping, verification, drying and reconstruction of the encapsulation and the local repair of timber surfaces, in addition to the cleaning and reinstatement of finishes and services common to both configurations. On this basis, building-related damage is estimated at approximately 5-10% of the building replacement value, and damage to contents at approximately 5-10% of the insured contents value.

The Business Interruption follows the same logic. Teaching activity in the unaffected blocks resumes immediately, while the reinstatement of the metal and welding workshop must accommodate, in addition to cleaning, repairs and re-equipment, the opening and verification of the encapsulated structure, the drying of the wetted elements and the certified reconstruction of the protective linings. The time required to reinstate full operational use of the affected workshop is estimated at approximately 1 to 3 months. The event remains an ordinary and fully recoverable loss in both configurations; in the timber building, however, even a successfully controlled fire generates a verification and reinstatement burden on the structure itself, which is reflected in the moderately higher property damage and in the longer reinstatement period.

NLE Timber Scenario		
	Involved Area	**% Damage**
Property Damage	Block C – metal & welding area	5-10% of Building replacement cost 5-10% of Contents & Equipment
Business Interruption[3]		100% of the area for 1 to 3 months

Note:
The percentages do not account for the additional costs related to the temporary relocation of the teaching activity (e.g. rental and installation of temporary classroom modules, transport and logistics).

9.4 Scenario Comparison - Case Study #4

The substantive difference between the two structural solutions, which the scenarios above were designed to explore, lies in the nature of their fire resistance. In the reinforced concrete building, the fire-resistance ratings and compartment boundaries are intrinsic, non-combustible properties of the structure itself, represented, for example, by the 140 mm full-height precast concrete fire walls enclosing the workshop block. In the timber alternative, equivalent fire-resistance ratings are achieved through an encapsulation strategy applied to a combustible structural system. The load-bearing structure satisfies the prescribed R60 requirements only while the protective linings remain continuous, correctly installed, and effective throughout the design fire exposure.

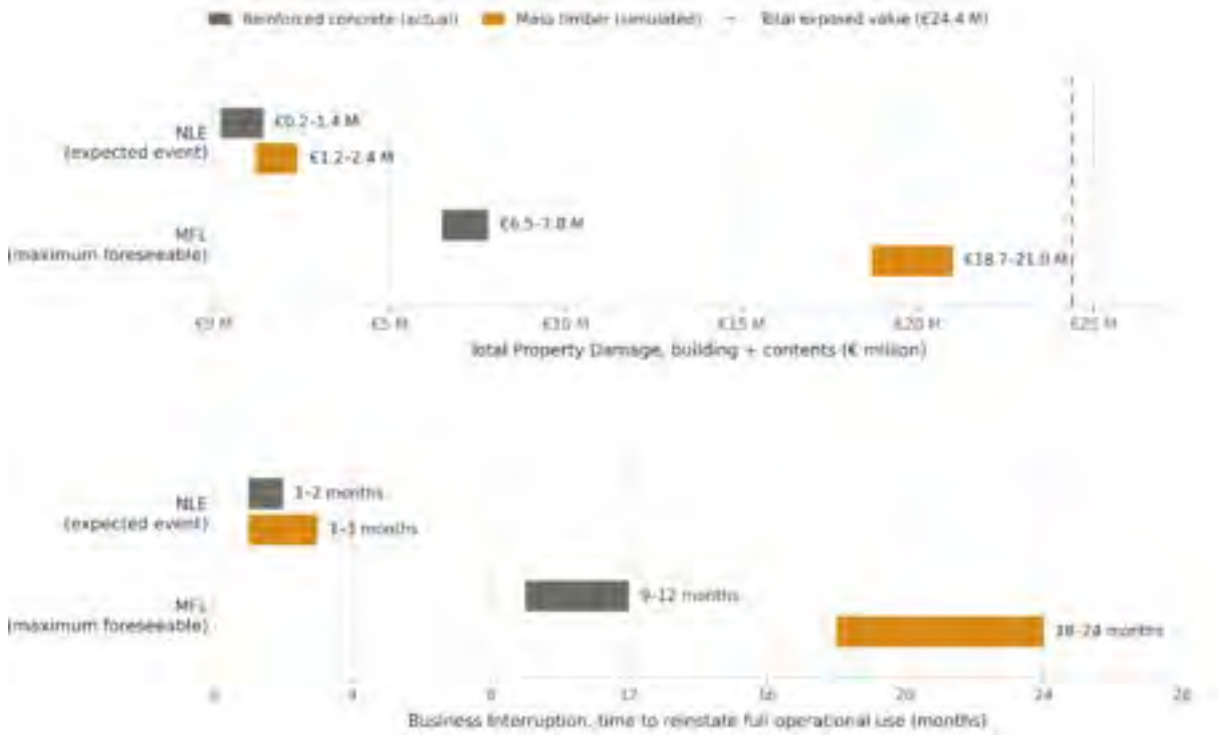
The fire performance of the timber solution therefore depends on the integrity of the protection system and on the validity of the assumed charring behaviour following any breach of that protection. As discussed in Sections 2.3.2 and 2.4, this dependency represents the fundamental distinction between the two structural systems under fire conditions.

The four scenarios differ by only one controlled variable: the structural material. Building geometry, compartmentation, occupancy, ignition source and protection strategy remain identical in every case, allowing any differences in outcome to be attributed solely to the behaviour of the load-bearing system during fire exposure. The results follow a consistent pattern: the two alternatives perform almost equivalently while the protection layers remain effective, but diverge markedly once those layers fail.

Under MFL conditions, where no active protection limits fire development, the structural material becomes the determining factor governing the magnitude of the loss through two distinct mechanisms.

The first mechanism concerns the available fuel. In the reinforced concrete building, the combustible fuel is limited to the compartment contents, allowing the fire to decay once that fuel has been consumed. In the timber structure, by contrast, the load-bearing system itself becomes an additional source of fuel after failure of the encapsulation. Fuel exhaustion is therefore delayed, prolonging the fully developed fire precisely when the compartment boundaries are required to maintain their separating function.

The second mechanism concerns compartmentation. In the existing building, the critical compartment boundary consists of a 140 mm full-height precast concrete fire wall, an inherently non-combustible barrier whose performance does not depend on applied protection systems or maintenance-sensitive components. In the timber alternative, the corresponding boundary is formed by an encapsulated CLT wall whose fire-separating function remains dependent on the integrity of the protective linings and which itself becomes combustible after their failure. Consequently, the fire that remains confined within a single 1,588 m² compartment in the reinforced concrete building propagates throughout the entire workshop wing in the timber solution, leading to collapse of the fire-exposed structural elements, residual structural vulnerability during the cooling phase, and the subsequent demolition of the affected portion of the building.



Graph 3, Ranges from the MFL and NLE scenarios (Case Study #4), applied to the provisional building replacement value of €20M and to the insured contents value of €4.4 M. Durations and percentages exclude temporary relocation costs

A further consideration concerns the geometry of the case-study building. The school is arranged horizontally across four interconnected blocks, a layout that limits vertical fire spread and confines the event, in the reinforced concrete structure, to a single compartment. Most schools, however, are multi-storey buildings, where the disadvantage of a combustible structural system would be considerably greater. If load-bearing walls and floors also form the compartment boundaries between storeys, failure of the encapsulation would create a vertical fire path through the structure itself, allowing the building to sustain the fire as it spreads upwards. The configuration examined here therefore represents a comparatively favourable case for the timber solution rather than a worst-case scenario.

The same geometry also limits the secondary effects of the fire. Beyond the direct effects of combustion, smoke contamination and firefighting water would produce considerably greater damage in a multi-storey timber building. Water discharged during suppression would migrate through floor junctions, panel joints and service penetrations, accumulating within the timber assemblies of the lower storeys and extending both drying operations and reinstatement works. In a predominantly horizontal building, these effects remain largely confined to the floor of origin.

Under NLE conditions, the fire is controlled during the growth phase in both structural solutions, and losses remain limited and fully recoverable. Damage to contents is identical because the extent of fire involvement is the same in both cases. The timber solution nevertheless incurs slightly greater building damage, since reinstatement requires removal of the encapsulation, verification of concealed charring and smouldering, drying of water-damaged timber elements, and reconstruction of the protective linings. Consequently, building damage increases to 5-10%, compared with 0-5% for the reinforced concrete solution, while reinstatement extends to 1-3 months instead of 1-2 months.

The quantitative implications are summarized below by applying the scenario percentages to a building replacement value of €20 million and a contents value of approximately €4.4 million.

	Building Damage		Contents & Equip. Damage		Total Property Damage	Business Interruption Damage		Total PD + BI
MFL - RC	25-30%	~€5,5 M	35-40%	~€1,6 M	~€7,1 M	100% of Block C for 9 to 12 months	N/A	~€7,1 M
MFL - Timber	75-85%	~€16 M	85-90%	~€3,8 M	~€19,8 M	100% Entire Build. for 18 to 24 months	N/A	~€19,8 M
NLE - RC	0-5%	~€1 M	5-10%	~€0,3 M	~€1,3 M	100% of Block C 1 to 2 months	N/A	~€1,3 M
NLE - Timber	5-10%	~€1,5 M	5-10%	~€0,3 M	~€1,8 M	100% of Block C 1 to 3 months	N/A	~€1,8 M

10. Case Study #5: Multi-Storey Apartment Building

10.1 Facility Description

The fifth case study concerns a multi-storey residential building located in Finland, and operated as rental housing, documented through the complete structural design basis and architectural drawings. The building belongs to fire class P1, the most demanding class of the Finnish classification, in which the structure is required to survive the complete fire without collapse, and is realized through a fully precast reinforced concrete wall-frame system, a configuration representative of contemporary Nordic residential construction. With respect to the previous case studies, the facility introduces a different risk profile, a sleeping occupancy distributed over a large number of small, individually compartmented units, in which the protection concept relies on passive compartmentation and early warning rather than on automatic suppression.

The building comprises eight storeys and a basement, with a total height of 23.2 m above ground and a gross floor area of 4,340 m². Two staircases, each served by a lift, divide the building into two sections of seven and six residential floors respectively, for a total of 52 apartments. The basement accommodates the common facilities, a club room, sauna and laundry rooms, technical rooms and the tenant storage rooms, part of which are located within the S1-class civil defence shelter, while pram and equipment stores are located at entrance level. Car parking is provided in a separate facility outside the building, so that no vehicle fire load is present within the premises. The apartments are provided with glazed balconies on the main facades.

About the fire compartmentation strategy, each apartment constitutes an independent EI 60 compartment, the basement is separated at EI 60, the tenant storage rooms are enclosed at EI 90, the balconies are separated at EI 30 and the staircase service enclosures at EI 30. The design fire load is standard throughout the building, rising above the standard only in the tenant storage rooms, where the load-bearing structures are correspondingly rated R 120 against the general requirement of R 60. Service penetrations through the compartment boundaries are sealed with certified fire-stopping systems rated EI 60 to EI 120.

The only combustible element of the construction is the roof. Above the reinforced concrete top-floor slab, the water roof is carried by timber trusses supporting a continuous board deck and a double-layer bituminous membrane, while the thermal insulation laid on the slab consists of non-combustible blown glass wool. The resulting cold attic is subdivided by EI 30 firebreak partitions, and the roof is structurally prepared for a future photovoltaic installation, although no system is installed at the date of this assessment.

The active protection concept reflects the national requirements for this occupancy. The building is not equipped with an automatic sprinkler system. Early warning is provided by mains-powered, battery-backed smoke alarms in every apartment, at a density of one detector per 60 m², and smoke ventilation is arranged through dedicated openable devices at the head of both staircases and through smoke exhaust shafts serving the tenant storage rooms and the shelter. The municipal fire brigade operates from the urban area, with a response time of approximately 15 minutes.

The building is fully let and continuously occupied. The reconstruction value is estimated at approximately €9.2 million, the value of the residents' property and of the common equipment at approximately €1.8 million, for a total exposed asset value of approximately €11 million, while the loss-of-rent exposure relevant to Business Interruption corresponds to an annual rental income of approximately €0.45 million, to which the costs of rehousing the affected households must be added.

Items	Replacement value in Euro (€)
Civil works	7,070,000
Mechanical system	1,120,000
Electrical system	600,000
Technical costs: commissioning, construction supervision…	430,000
Contents and equipment	1,800,000
Total	11,020,000

10.1.1 Actual – Reinforced Concrete Structure with Timber roof

The building is realized through a fully precast reinforced concrete wall-frame system. Vertical loads are carried by precast concrete walls, which also separate the apartments from one another and from the common spaces, and the floors consist of solid reinforced concrete slabs. The same elements that carry the building therefore also constitute its compartment boundaries, so that the cellular subdivision into EI 60 units described in Section 10.1 is achieved by the load-bearing structure itself rather than by applied partitions. The external walls are precast sandwich panels with a non-combustible mineral wool core encased between two concrete leaves, the staircases are precast concrete elements, and the basement, including the storage rooms and the shelter, is enclosed by heavier reinforced concrete walls rated up to R 120 where the higher fire load requires it.

The only combustible part of the construction is the roof. Above the continuous reinforced concrete slab covering the top floor, the water roof is carried by timber trusses supporting a board deck and a double-layer bituminous membrane, while the insulation laid on the slab is non-combustible glass wool. The resulting cold attic lies entirely outside the habitable volume, separated from it by the concrete slab, and is subdivided by EI 30 firebreak partitions that limit the horizontal extent of any fire developing within it.

From a fire-engineering perspective, the load-bearing system within the occupied volume is entirely non-combustible and contributes nothing to the fire load, so that any fire is governed by the contents of the compartment of origin, typically a single apartment with a fire load below 600 MJ/m². The degradation of the concrete elements under fire follows the progressive and predictable mechanisms described in Section 2.3.1, and the cellular wall-slab configuration provides a high degree of redundancy and robustness against local damage. The combustible roof structure represents the single deviation from this profile, and its position above the concrete slab, combined with the attic firebreaks, confines its relevance to scenarios in which the fire reaches or originates in the attic itself, a point that the loss estimate scenarios will examine explicitly.

10.1.2 Simulated – Timber Structure

In the alternative configuration, the building is assumed to be realized using a mass-timber structural system representative of contemporary multi-storey timber residential construction. Consistently with the comparative method set out in Section 5, the substitution is purely material. The building retains the same geometry, the same number of storeys and apartments, the same cellular compartment layout, the same staircase arrangement and the same protection concept, based on compartmentation and early warning without automatic suppression, so that the differences in outcome can be attributed to the structural material alone.

The load-bearing walls separating the apartments, the floor slabs, the staircase cores and the external wall elements are assumed in cross-laminated timber (CLT), while the roof retains the timber truss configuration of the actual building. The foundations, the basement and the civil defence shelter remain in reinforced concrete, as required for below-grade construction, and have no influence on the scenarios analysed. The structural fire design is assumed to be carried out in accordance with EN 1995-1-2, with the load-bearing elements protected by gypsum-board encapsulation, complemented where necessary by sacrificial charring layers, so as to nominally achieve the same classifications as the actual building, R 60 and EI 60 in general and R 120 with EI 90 enclosures in the storage areas. The comparison therefore assumes a code-compliant timber building, not an unprotected one.

The substitution nevertheless changes the nature of the compartment boundaries. In this building the separating elements coincide with the load-bearing structure, and in the timber configuration every apartment wall, floor and stair enclosure becomes a combustible element whose separating and load-bearing functions are conditional on the integrity of the applied linings, with joints between panels and service penetrations acting as potential weak points of an otherwise nominally equivalent system. For the comparative purposes of this study, both

configurations share the same reconstruction value, equal to that established for the actual reinforced concrete building, approximately € 9.2 million. The choice deliberately sets aside the cost premium that a real mass-timber alternative would carry, where the load-bearing elements must be safeguarded through gypsum-board encapsulation and sacrificial layers to reach equivalent fire-resistance classes. Contents and the rental income basis are likewise held constant.

10.2 Maximum Foreseeable Loss (MFL) Scenarios

10.2.1 Reinforced Concrete MFL Scenario

In the apartment building under analysis the Maximum Foreseeable Loss scenario is developed in accordance with the deterministic and conservative methodology defined in Section 4. Consistently with the MFL definition, every active and operational mitigation layer is assumed to be unavailable or ineffective. The building is not provided with automatic suppression, the mains powered smoke alarms do not translate into timely intervention, and the fire brigade does not achieve control of the fire during its critical growth phase. The fire is therefore assumed to develop freely until it is arrested either by the boundaries of an impassable, non-combustible compartment or by the exhaustion of the available fuel.

The compartment of origin is assumed to be a single apartment on one of the uppermost residential floors, a selection that places the fire close to the only combustible element of the construction, the timber roof, and that allows the scenario to examine both the vertical propagation potential and the interaction with the attic. Ignition is assumed to arise from a typical residential source within the dwelling, and the early development is governed by the movable fire load of the apartment, with furniture, finishes and household contents. In the absence of any suppressive action the fire grows for the time necessary to consume the contents of the dwelling.

The decisive feature of this configuration is the nature of the fuel available to the fire. The precast reinforced concrete wall frame is non-combustible, classified A1 according to EN 13501-1, and contributes nothing to the fire load at any stage. The walls that carry the building and that separate the apartment of origin from its neighbours, together with the solid reinforced concrete floor slabs above and below, do not participate in combustion and do not add to the energy released. The available fuel therefore coincides exclusively with the contents of the compartment, and the fully developed fire tends towards the burnout condition within the dwelling of origin once those contents are consumed.

Fire spread beyond the apartment of origin is governed by the external route rather than by the structure. As the windows fail and the glazed balconies, separated at EI 30, lose their integrity, flames eject through the openings and impinge on the façade and on the apartments immediately above and adjacent. Through window breakage and external flaming the fire can enter the dwellings on the floor above and, to a lesser extent, those laterally adjacent on the same level, producing severe contents fires in those units. The internal compartment lines, however, hold. Because the separating walls and the floor slabs are the load-bearing reinforced concrete elements themselves, the boundaries between apartments behave as intrinsic, non-combustible barriers whose performance does not depend on applied linings, on the sealing of

joints carried out on site or on maintenance sensitive components. Horizontal propagation through the party walls and vertical propagation through the slabs do not occur, and the event resolves into a cluster of individually burning compartments rather than a single continuous fire involving the whole building.

The interaction with the timber roof is examined explicitly, since the fire originates near the top of the building. Above the uppermost apartments the continuous reinforced concrete slab separates the habitable volume from the cold attic, where the only combustible structural elements of the construction are located, namely the timber trusses, the board deck and the bituminous membrane laid over non-combustible glass wool insulation. For the fire to involve the roof it must first defeat or bypass the concrete slab, through unsealed penetrations or at the perimeter, and reach the attic space. Should this occur, the timber roof over the affected portion ignites and burns, and the attic firebreak partitions rated EI 30 limit the horizontal extent of the involvement to the sector above the fire. The consequence of this involvement is confined to the roof package itself. The trusses and the deck char and may collapse, but they collapse onto the reinforced concrete slab beneath, which continues to protect the apartments below. The loss of the combustible roof, while economically relevant, does not propagate into the occupied volume and does not compromise the stability of the structural frame.

From a structural standpoint the precast reinforced concrete frame is subjected to severe thermal exposure in the involved compartments but behaves in accordance with the progressive and predictable mechanisms described in Section 2.3.1. The surface layers of the walls and slabs lose strength and stiffness following the temperature dependent degradation models of EN 1992-1-2, the reinforcement progressively loses yield strength where steel temperatures exceed approximately 400 to 500 °C, and localised concrete cover spalling may occur in the most heavily exposed zones. These mechanisms develop gradually rather than suddenly. The high thermal inertia and low conductivity of the massive precast sections limit the depth of heat penetration, so that a substantial portion of each cross section remains below critical temperatures, and the redundancy of the cellular wall slab arrangement allows the loads to be redistributed around any locally weakened element. The behaviour observed is precisely that required by the Finnish P1 classification, under which the structure must survive the complete burnout of the fire without collapse. Global structural instability is not a foreseeable outcome, and no progressive collapse mechanism is triggered at any stage of the event.

The fire is ultimately arrested by the combination of fuel exhaustion and the persistence of the surrounding non-combustible compartmentation. Once the contents of the involved apartments and the combustible roof over the affected sector are consumed, no further sustenance is available to the fire, and the reinforced concrete boundaries that were never breached continue to confine the residues of the event. The remaining apartments of the building, served by the two staircases and protected by their own EI 60 boundaries, remain structurally intact and are affected at most by smoke migration through unsealed penetrations and through the common circulation spaces.

Under these conditions the property damage is severe but spatially contained. The apartment of origin is completely destroyed, the apartments immediately above and adjacent suffer severe fire, heat and smoke damage, and the timber roof over the affected sector is lost, while smoke

and the products of combustion contaminate a broader portion of the building through the staircases and the service penetrations. On this basis the building related damage is estimated at approximately 25 to 30% of the building replacement value, reflecting the reconstruction of the involved apartments and of the affected roof sector together with the cleaning and reinstatement of the smoke affected finishes and services elsewhere. Damage to the contents and to the common equipment is estimated at approximately 15 to 20% of the insured contents value, combining the total loss within the directly involved dwellings with widespread smoke contamination across the building.

The Business Interruption for this occupancy is measured through the loss of rental income during the period required to reinstate the affected portion of the building, to which the cost of rehousing the affected households must be added. Because the structural frame remains intact and the damage is confined to a limited number of apartments and to the roof, the reinstatement is driven by internal refurbishment and by the reconstruction of the roof package rather than by structural works, and is estimated to require a period in the order of 6 to 9 months for the affected units, while the remaining apartments can be re-let as soon as the smoke remediation of the common areas is completed. The non-combustible structure is therefore not a contributing factor to the escalation of the event. Its non-combustibility, its thermal robustness and the intrinsic compartmentation provided by the load-bearing walls and slabs confine the loss to the apartments directly reached by the fire, preserve the global stability of the building in accordance with its P1 classification, and govern a recovery process driven by the reinstatement of a limited sector rather than by the reconstruction of the building as a whole.

MFL Reinforced Concrete Scenario		
	Involved Area	**% Damage**
Property Damage	Apartment of origin, adjacent units, roof	25-30% of Building replacement cost 15-20% of Contents & Equipment
Business Interruption[3]		75% for 6 to 9 months

Note:
The percentages reported do not account for potential mitigation measures, nor for the additional costs related to the temporary rehousing of the affected households during the period of unavailability of the dwellings.

10.2.2 Timber MFL Scenario

The Maximum Foreseeable Loss scenario for the timber configuration is developed under assumptions strictly identical to those adopted in Section 10.2.1. The compartment of origin is the same apartment on one of the uppermost residential floors, the ignition source and the movable fire load of the dwelling are unchanged, and every active and operational mitigation layer is assumed to be unavailable or ineffective. The only variable is the load-bearing structure which, in accordance with Section 10.1.2, consists of cross laminated timber wall and floor panels and stair cores, protected by gypsum board encapsulation dimensioned to nominally achieve the R 60 and EI 60 classifications documented for the building.

The initial phase of the fire develops within the apartment of origin, sustained by the furniture, the finishes and the household contents, and grows into a fully developed compartment fire with upper layer temperatures approaching 900 to 1000 °C. During this phase the encapsulation performs its intended function, the timber surfaces remain shielded and the event is, temporarily, a contents governed fire.

The turning point comes once the fire outlasts the protection afforded by the encapsulation. With no suppression to arrest it, the gypsum lining is gradually consumed from the exposed face, losing cohesion at the board junctions and fixing lines before detaching altogether, so that the timber it was shielding is laid open to the compartment fire in the manner described in Section 2.3.2. Wherever the linings are lost the timber surfaces ignite and begin to char, and as the char front reaches the adhesive interfaces of the cross-laminated panels it can trigger delamination of the charred lamellae, exposing fresh timber beneath and producing the stepwise regeneration of fuel that defers burnout rather than bringing it closer.

From this point onwards the structure itself becomes part of the available fuel, and its role in this configuration is critical because the elements that carry the loads are the same elements that separate the apartments. The walls that bound the dwelling and the floor slabs above and below are load-bearing and separating at once, and once the encapsulation is breached each of them becomes simultaneously a combustible surface and a structural element losing section. Both functions, the separation between the compartments and the support of the building, are therefore conditional on a protective layer that the MFL does not credit beyond its nominal duration.

The loss of the separating function governs the propagation. Once the linings fail on the fire side, the party walls and the floor panels ignite and lose integrity, while the joints between panels, the wall to floor junctions and the service penetrations constitute preferential paths for hot gases and flames. The fire propagates through the structure, horizontally into the apartments adjacent on the same floor and, more significantly, vertically through the floor junctions into the dwellings above. Because the building develops over eight storeys, the vertical path is the dominant one, and the fire climbs from one residential level to the next along the very elements intended to separate them, exposing the upper apartments in sequence as the structure that encloses them is consumed. The timber roof, reached from below by a fire now advancing through the structure, is drawn into the same event and adds a continuous combustible path at the top of the building.

The structural consequence is the central feature of the scenario. As the cross laminated panels lose section through charring, the floor slabs of the involved levels approach the loss of their load-bearing capacity, and the failure of a floor transfers its load and its burning debris onto the level below, already weakened by the fire climbing the structure. The conditions for a progressive vertical collapse of the affected section are therefore established, in which the loss of one level precipitates the loss of those beneath it.

Consistently with the burnout behaviour discussed in Section 2.3.2, the structure remains vulnerable during and after the decay phase, since smouldering combustion persists within the char layers, the wall to floor junctions and the concealed cavities, and delayed structural failures during the cooling phase are a documented possibility. The persistence of these phenomena entails a concrete risk of re-ignition and ultimately imposes the demolition of the fire involved timber structure, since the residual capacity of charred and delaminated panels and of their connections cannot be reliably verified nor economically recovered.

Property damage extends far beyond the compartment of origin. The apartment of origin and the dwellings reached by the vertical and horizontal propagation are destroyed, the structure of the involved section requires complete demolition and reconstruction following the partial collapse and the residual vulnerability of the charred elements, the timber roof over the affected area is lost, and the remaining apartments suffer widespread smoke, heat and water contamination through the staircases and the service penetrations. On this basis the building related damage is estimated at approximately 90 to 100% of the building replacement value, approaching, in the most unfavourable but still foreseeable case, the threshold of complete reconstruction of the building. Damage to the contents and to the common equipment is estimated at approximately 100% of the insured contents value, reflecting the destruction within the directly involved dwellings and the extensive contamination of the remaining units.

The Business Interruption is correspondingly extended. The involvement of the building as a whole, the structural demolition imposed by the collapse and by the impossibility of verifying the residual capacity of the timber elements, and the loss or contamination of the dwellings beyond the directly burnt section suppress entirely the dwelling-by-dwelling recovery that the cellular layout would otherwise afford. The reinstatement amounts in practice to the reconstruction of the building, comprising the demolition of the fire involved structure under the safety constraints imposed by a partially collapsed and smouldering prone timber frame, the rebuilding of the load-bearing system, the reinstatement of the technical networks and the finishing of the dwellings, and is estimated to require a period in the order 24 to 30 months, during which the loss of rental income extends to the entire building and the rehousing of all the affected households is correspondingly prolonged.

MFL Timber Scenario		
	Involved Area	**% Damage**
Property Damage	Entire Building	90-100% of Building replacement cost 100% of Contents & Equipment
Business Interruption[3]		100% for 24 to 30 months

Note:

The percentages reported do not account for potential mitigation measures, nor for the additional costs related to the temporary rehousing of the affected households during the period of unavailability of the dwellings.

10.3 Normal Loss Expectancy (NLE) Scenarios

10.3.1 Reinforced Concrete NLE Scenario

The Normal Loss Expectancy scenario assumes the same apartment of origin as the MFL case, so that the difference in outcome reflects the mitigation layers alone, with the protection concept now performing as designed. The fire originates from a typical residential source and develops within the dwelling, sustained by its movable fire load. The mains powered smoke alarms operate at the design density of one detector per sixty square metres and provide early warning, alerting the occupants and prompting the notification of the municipal fire brigade, which reaches the site within its documented response time. The intervention takes place during the growth phase of the fire, before the dwelling becomes fully involved, and the fire is controlled and extinguished within the apartment of origin.

The thermal exposure of the structure is therefore limited in both intensity and duration. The precast reinforced concrete walls and the solid floor slabs bounding the apartment, designed for an R 60 resistance well in excess of the demand imposed by a fire controlled in its growth phase, suffer at most superficial heating, with surface temperatures locally rising but core temperatures remaining low on account of the high thermal inertia and low conductivity of the sections, consistently with the progressive mechanisms described in Section 2.3.1. No reduction of load-bearing capacity occurs, the compartment boundaries are not called upon to perform beyond ordinary separation, and the structural and compartmentation systems are not significantly challenged.

The damage is consequently dominated by the contents of the apartment of origin and by smoke. The furniture and finishes within the dwelling are damaged or destroyed by the direct fire, and smoke deposition affects the adjacent rooms of the same apartment, and, to a limited extent, the common circulation spaces reached through the entrance door, requiring cleaning and partial refurbishment. The non-combustible concrete surfaces can be inspected, cleaned and reinstated without invasive works.

On this basis the building related damage is estimated at approximately 0 to 2% of the building replacement value, essentially associated with the cleaning and reinstatement of finishes and services within and immediately around the compartment of origin. Damage to the contents and to the common equipment is estimated at approximately 1 to 4% of the insured contents value, concentrated in the apartment of origin with limited smoke contamination beyond it.

The Business Interruption is limited and spatially confined. The remaining apartments of the building are not affected beyond minor smoke deposition in the common areas and remain occupied or immediately re lettable, so that the loss of rental income concerns the single dwelling of origin during the period required to clean, repair and refurbish it, estimated in the order of 1 to 2 months. The event remains, in insurance terms, an ordinary and fully recoverable loss, governed by the early operation of the detection and warning system and by the rapid external intervention, and bounded by a non-combustible structure that neither contributes to the fire nor requires post fire structural works.

NLE Reinforced Concrete Scenario		
	Involved Area	**% Damage**
Property Damage	One Apartment	0-2% of Building replacement cost 1-4% of Contents & Equipment
Business Interruption[3]		2% for 1 to 2 months

Note:
The percentages reported do not account for potential mitigation measures, nor for the additional costs related to the temporary rehousing of the affected households during the period of unavailability of the dwellings.

10.3.2 Timber NLE Scenario

The Normal Loss Expectancy scenario for the timber configuration assumes the same apartment of origin and the same protection concept performing as designed, so that the sequence of the event is identical to that of Section 10.3.1. The fire originates within the dwelling, the smoke alarms provide early warning, and the municipal fire brigade reaches the site within its documented response time, controlling and extinguishing the fire during its growth phase, before the apartment becomes fully involved.

Controlled at this stage, the fire does not engage the load-bearing function of the structure. The gypsum board encapsulation, exposed only to a limited and short duration thermal action, keeps the cross laminated timber elements shielded throughout the event, so that the walls and floor bounding the apartment retain their section and their separating capacity, and propagation beyond the dwelling of origin does not occur.

The damage is dominated by the contents of the apartment and by smoke, as in any controlled residential fire. The distinguishing feature of the timber configuration lies in the post fire condition of the structure. The encapsulation in the area directly exposed to the fire is subjected to flame impingement, to localised heating and to the mechanical action of the firefighting operations and is wetted by the extinguishing water. Even where the linings have performed correctly, their protective capacity in the affected zone can no longer be assumed, and the moisture absorbed by the boards and by the timber behind them must be addressed to prevent the dimensional and durability problems to which wood is sensitive.

The load-bearing elements behind the damaged linings cannot be declared unaffected by visual inspection alone. The boards in and around the area of origin must be removed to verify the absence of localised charring and of smouldering pockets at the panel joints, the wall to floor junctions and the concealed cavities, a verification that has no equivalent in a non-combustible structure and that extends the intervention beyond the directly damaged surfaces, consistently with the dependence on the integrity of the protection discussed in Section 2.4. Where superficial charring is found the affected layers are repaired or the panel faces locally reinstated, and the complete encapsulation system is then rebuilt to restore the certified fire performance of the compartment.

On this basis the building related damage is estimated at approximately 2 to 5% of the building replacement value, comprising the stripping, verification, drying and certified reconstruction of the encapsulation and the local repair of the timber surfaces, in addition to the cleaning and reinstatement of finishes and services within and around the compartment of origin. Damage to the contents and to the common equipment is estimated at approximately 1 to 4% of the insured contents value, concentrated in the apartment of origin with limited smoke contamination beyond it.

The Business Interruption follows the same logic. The loss of rental income concerns the apartment of origin, whose reinstatement must accommodate, in addition to the cleaning, the repairs and the refurbishment, the opening and verification of the encapsulated structure, the drying of the wetted elements and the certified reconstruction of the protective linings. The period required to return the dwelling to use is estimated in the order of 2 to 3 months. The event remains an ordinary and fully recoverable loss, in which even a successfully controlled fire generates a verification and reinstatement burden on the structure itself, reflected in the building damage and in the duration of the reinstatement.

NLE Timber Scenario		
	Involved Area	**% Damage**
Property Damage	One Apartment	2-5% of Building replacement cost 1-4% of Contents & Equipment
Business Interruption[3]		2-5% for 2 to 3 months

Note:

The percentages reported do not account for potential mitigation measures, nor for the additional costs related to the temporary rehousing of the affected households during the period of unavailability of the dwellings.

10.4 Scenario Comparison - Case Study #5

The four scenarios isolate a single controlled variable. The building geometry, the subdivision into fifty-two dwellings, the contents, the ignition source and the fire protection strategy based on compartmentation and early warning remain unchanged; only the material of the load-bearing system varies. Unlike the previous case studies, however, this residential building relies on the same elements for both structural support and compartmentation. The reinforced concrete walls and floor slabs are simultaneously the load-bearing structure and the fire-resisting boundaries separating adjacent dwellings and storeys. Replacing reinforced concrete with timber therefore modifies not only the structural system but also the effectiveness of the compartment boundaries, making this dual function the key factor governing the different fire outcomes.

Under NLE conditions, the two structural solutions perform similarly. The fire is controlled during its growth phase, before the apartment of origin becomes fully involved, and the load-bearing system is not significantly affected. Damage to contents is identical because fire involvement remains confined to the dwelling of origin, with only limited smoke contamination beyond it. The timber solution nevertheless incurs a modest increase in building damage. Even after successful suppression, reinstatement requires removal and inspection of the encapsulation, verification of concealed charring and smouldering, drying of water-damaged timber elements, and certified reconstruction of the protective linings, operations that have no equivalent in a non-combustible structure. Consequently, building damage increases to 2-5%, compared with 0-2% for the reinforced concrete solution, while reinstatement of the affected dwelling extends to 2-3 months instead of 1-2 months. In both cases, however, the event remains an ordinary and fully recoverable loss.

The difference becomes fundamental under MFL conditions, where no active protection limits fire development and the encapsulation is not assumed to remain effective beyond its nominal fire-resistance period. Two mechanisms then govern the divergence. First, the structural system contributes differently to the available fuel. In the reinforced concrete building, combustion is limited to the dwelling contents, and the fire naturally decays once this fuel is consumed. In the timber building, by contrast, the structure itself becomes an additional fuel source after failure of the encapsulation. As the char front reaches the adhesive interfaces of the cross-laminated timber panels, delamination exposes fresh timber surfaces, delaying burnout and prolonging the fully developed fire.

The second mechanism concerns compartmentation. In the reinforced concrete building, the walls and floor slabs form inherently non-combustible barriers whose fire-separating capacity is independent of applied protection systems or maintenance-sensitive components. Fire therefore remains confined to a limited cluster of dwellings, without propagation through the structural frame. In the timber solution, the same elements simultaneously provide structural support and fire separation. Once the encapsulation fails, they become both combustible and progressively weakened, causing the load-bearing and compartmentation functions to deteriorate together.

The consequences are amplified by the geometry of the building, distinguishing this case study from the previously analysed horizontal school. Here the structure extends vertically over eight storeys, so fire propagation primarily affects the floor assemblies connecting successive residential levels. In the reinforced concrete building, the floor slabs retain their integrity, preventing vertical fire spread. Even the combustible timber roof collapses onto the upper concrete slab without involving the apartments below, allowing the structure to survive complete burnout, consistent with the objectives of the Finnish P1 classification.

In the timber solution, however, the floor assemblies are both combustible and load-bearing. Fire propagates vertically through the structural elements intended to separate successive storeys, while failure of a floor transfers both load and burning debris onto the weakened level below. These conditions create the potential for progressive vertical collapse of the affected portion of the building. The timber structure therefore satisfies the P1 objective only while the encapsulation remains effective; under MFL conditions this assumption no longer applies, making compliance conditional rather than intrinsic.

This difference is reflected most clearly in post-fire recoverability. In the reinforced concrete building, damage remains localized to a limited number of dwellings, allowing the unaffected apartments to remain structurally intact and to return to service after remediation of the common areas. Recovery is therefore based on refurbishment of a defined portion of the building rather than complete reconstruction. In contrast, once fire propagates through the timber structure, the event becomes a building-wide loss. Partial collapse and the inability to verify the residual capacity of charred and delaminated structural elements and their connections necessitate demolition of the affected building.

The vertical arrangement also increases secondary damage. Smoke and firefighting water migrate through floor junctions, panel joints and service penetrations into the lower storeys, accumulating within the timber assemblies and extending both drying operations and reinstatement works. Compared with the horizontal school examined previously, the vertical configuration therefore combines more severe fire development with substantially greater smoke and water damage.

Business Interruption in this occupancy consists primarily of lost rental income together with the cost of rehousing displaced tenants. Unlike the industrial case studies, annual rental income is relatively small compared with the reconstruction value, so Business Interruption remains substantially lower than Property Damage in monetary terms, particularly under NLE conditions. The more meaningful indicator is therefore the number of dwellings withdrawn from use and the duration of their unavailability. Under NLE conditions, the dwelling of origin remains unavailable for 1 to 3 months in both structural solutions. In the timber building, the verification and reinstatement of the encapsulation in the units adjacent to the one affected may extend the loss of use to a small number of neighbouring dwellings, slightly increasing the share of accommodation temporarily withdrawn from service.

Under Maximum Foreseeable Loss conditions, although the physical damage in the reinforced concrete building is confined to a cluster of dwellings, the reinstatement of that cluster, together with the temporary closure of the affected stair core, the shared services and the dwellings exposed to smoke and water, withdraws the major part of the building from use for approximately 6 to 9 months. Only the dwellings served by the unaffected stair core and untouched by the event return to use earlier. The timber solution, by contrast, loses the rental income of the entire building during the 24 to 30 months required for reconstruction.

The quantitative implications are summarised below by applying the scenario percentages to a building reconstruction value of approximately €9.2 million and a contents value of approximately €1.8 million.

	Building Damage		Contents & Equip. Damage		Total Property Damage	Business Interruption Damage		Total PD + BI
MFL - RC	25-30%	~€2,5 M	15-20%	~€0,3 M	~€2,8 M	75% of Entire Build. for 6 to 9 months	~€0,3 M	~€3,1 M
MFL - Timber	90-100%	~€8,8 M	100%	~€1,8 M	~€10,6 M	100% Entire Build. for 24 to 30 months	~€1 M	~€11,6 M
NLE - RC	0-2%	~€0,1 M	1-4%	~€0,05 M	~€0,15 M	2% of Entire Build. 1 to 2 months	~€1 k	~€0,15 M
NLE - Timber	2-5%	~€0,3 M	1-4%	~€0,05 M	~€0,35 M	2-5% of Entire Build. 2 to 3 months	~€2 k	~€0,35 M

11. Comparative discussion through the 5 cases and Conclusions

11.1 Cross-case comparative analysis

The five case studies were conceived not as independent illustrations but as a structured sample of the European building stock, selected so that general conclusions could be drawn from their comparison rather than observations valid only for the individual building. They span industrial, residential and educational occupancies, single-storey and multi-storey configurations up to eight floors, open single-compartment layouts and finely cellular ones, and protection concepts ranging from full automatic suppression to detection and external intervention alone. Read together rather than in sequence, they permit the behaviour of the two structural materials to be separated from the particular circumstances of each building. The following table summarises the outcome of each case along the dimensions that the discussion will develop.

Case study	Occupancy	NLE outcome	MFL outcome	RC recoverability	Timber recoverability	Dominant driver
CS#1 Automated warehouse	Industrial	Comparable	Severe in both, higher in timber	Repair and re-equipment	Demolition and reconstruction	Operational dependency and structural fuel
CS#2 Residential row houses	Housing	Comparable	Divergent	Partial repair, units retained	Total reconstruction	Loss of inter-unit compartmentation
CS#3 Storage warehouse	Industrial	Comparable	High in both, total in timber	Partial frame reuse, repair	Full demolition	Structural fuel in a single compartment
CS#4 School campus	Educational	Comparable	Large divergence	Compartment repair	Wing reconstruction	Intrinsic versus conditional compartmentation
CS#5 Apartment building	Residential	Comparable	Extreme divergence	Sector refurbishment	Building reconstruction	Vertical propagation, structure as boundary

Although the five case studies involve different occupancies, geometries, contents and fire scenarios, a consistent pattern emerges across all of them. Under the NLE scenario the two materials behave alike, and under the MFL scenario they diverge, by an amount that is not constant but varies with the type of building. The remainder of this chapter establishes that this pattern is governed by the role of the structural material in the fire, demonstrates why its magnitude depends on occupancy and geometry, and draws the consequences for property loss, business interruption and post-fire recoverability.

11.2 The role of the structural material

The comparative analysis demonstrates that the discriminating factor between the two structural solutions is neither the building type, its occupancy nor its contents, all of which were held constant within each case study, but the role played by the structural material in the development and consequences of fire. Across all five case studies, this influence is consistently expressed through four recurring mechanisms.

The first mechanism concerns the available fuel. Reinforced concrete, classified as A1 according to EN 13501-1, is non-combustible and does not contribute to the fire load. Fire development therefore depends exclusively on the compartment contents and naturally progresses towards burnout once that fuel is exhausted. In contrast, once the encapsulation of a timber structure is compromised, the structural system itself becomes an additional source of fuel. Charring progressively reaches the adhesive interfaces of engineered wood products, where delamination may expose fresh combustible surfaces, prolonging combustion and delaying burnout. As a result, the fire in the reinforced concrete building remains limited by a fixed quantity of fuel, whereas in the timber building the structure itself contributes to sustaining fire growth.

The second mechanism concerns compartmentation. In three of the five case studies, the load-bearing elements also define the compartment boundaries. Replacing reinforced concrete with timber therefore alters not only the structural system but also the nature of the fire barriers. In the reinforced concrete solution, compartmentation is an intrinsic property of the structure itself. In the timber solution, equivalent fire-resistance ratings rely on the continued integrity of the encapsulation. Once this protection is lost, the structural and separating functions deteriorate simultaneously, and the equivalence between the two systems no longer exists.

The third mechanism is structural robustness and its predictability. The behaviour of reinforced concrete under fire is progressive, well characterised by EN 1992-1-2 and supported by extensive experimental evidence, resulting in a gradual reduction of structural capacity. The residual capacity of timber, however, depends on assumptions regarding charring rates, adhesive performance, connection behaviour and the effectiveness of passive protection. These mechanisms are represented in design through simplified models whose validity depends on the actual fire scenario. Moreover, timber structures remain vulnerable during the cooling phase, when delayed failure mechanisms may continue to develop after the visible fire has decayed.

The fourth mechanism concerns post-fire recoverability. Reinforced concrete structures that survive severe fire exposure generally retain sufficient residual capacity to permit repair of the affected areas. Timber structures that have burned beyond the effectiveness of their protective systems, by contrast, often cannot be reliably assessed for continued service because of concealed damage, extensive charring and uncertainty regarding the residual capacity of structural elements and their connections. Consequently, recovery frequently shifts from repair to demolition and reconstruction. This distinction is not merely a consequence of different repair strategies, but the direct economic outcome of the preceding three mechanisms.

11.3 Influence of occupancy

While the underlying fire mechanisms remain unchanged, the way in which the loss presents itself depends on the use of the building, and the five cases show that the dominant component of the loss shifts with occupancy. In the industrial cases the value and the vulnerability are concentrated in the operation rather than in the fabric, so that the interruption of activity can rival or exceed the physical damage, most markedly in the highly automated warehouse, where the interdependence of the storage and handling systems makes partial operation impracticable during reconstruction and drives the business interruption above the property damage. In the residential cases the exposure is concentrated in the building and the contents, while the income basis is small in relation to the reconstruction value, so that the property damage dominates and the interruption, expressed as loss of rent, remains structurally an order of magnitude below it. The educational case (school) occupies an intermediate position in which the relevant measure is neither profit nor rent but the continuity of a public service, so that the interruption is properly expressed as the time and the extent over which teaching is displaced rather than as a monetary figure.

This dependence on occupancy does not weaken the comparison but refines it. The choice of structural material acts on the same four mechanisms in every building, but the consequences of those mechanisms are read on different accounts depending on use, and an assessment confined to property damage alone would understate the effect in the industrial buildings and would misrepresent its nature in the institutional one.

11.4 Influence of geometry

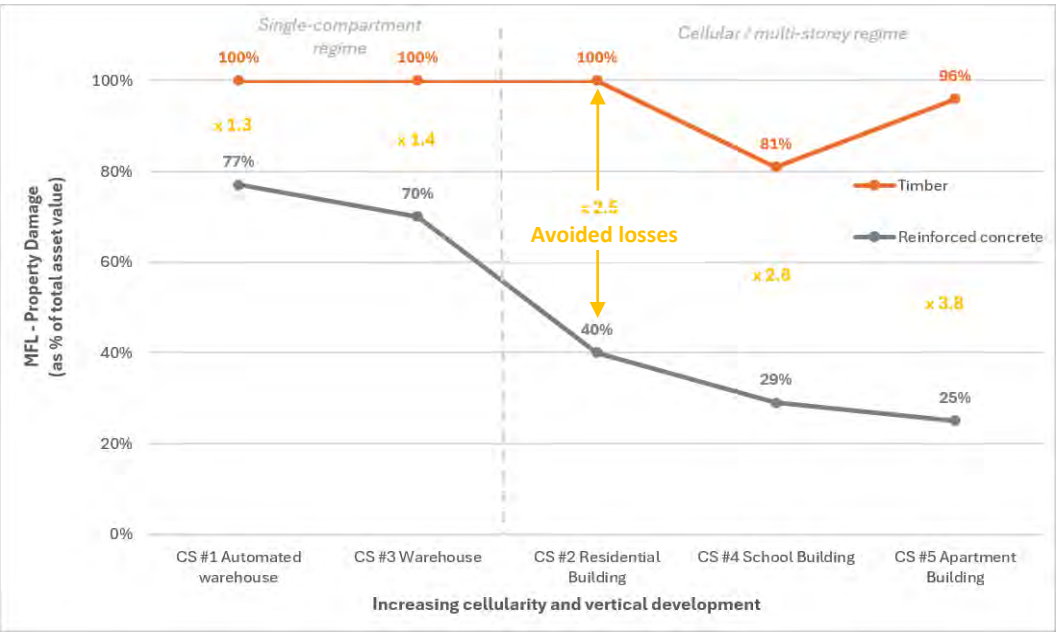
The comparison demonstrates that the divergence between reinforced concrete and timber structures under Maximum Foreseeable Loss is governed primarily by building geometry rather than occupancy. More specifically, it increases with the extent to which the load-bearing system also provides the compartment boundaries.

Across all five case studies, the timber configurations consistently produce Property Damage between approximately 80% and 100% of the insured asset under MFL conditions, largely irrespective of occupancy or building height. The reinforced concrete solutions, by contrast, range from approximately 75% of the asset in the open warehouse to only 25% in the highly compartmented multi-storey residential building. The benefit of the non-combustible structure therefore lies not in preventing ignition or limiting the early stages of fire development, where both structural solutions perform similarly, but in preserving compartmentation during fully developed fire and thereby limiting the proportion of the building affected.

Case study	Building geometry	Compartment strategy	RC Property Damage (% asset)	Timber Property Damage (% asset)	Timber/RC ratio
CS#1 Automated warehouse	Single-storey, open plan	Single fire area	~77%	~100%	1.3
CS#2 Residential row houses	Low-rise cellular	Party walls	~40%	~100%	2.5
CS#3 Storage warehouse	Single-storey	Single compartment	~70%	~100%	1.4
CS#4 School campus	Horizontal, highly compartmented	Full-height fire walls	~29%	~81%	2.8
CS#5 Apartment building	Eight-storey cellular	Structure coincident with compartment boundaries	~25%	~96%	3.8

The percentages reported in this table express the total Property Damage (building damage and contents damage combined) as a share of the total exposed asset value stated in the description of each case study, that is, the sum of the building reconstruction value and the insured value of the contents.

The ratio between the two structural solutions is lowest in large open industrial buildings, where the fire develops within a single compartment and the dominant fuel is the stored commodity rather than the structure itself, so that reinforced concrete offers only a limited reduction in Property Damage and its principal advantage lies instead in structural stability and post-fire recoverability. As compartmentation becomes more effective, the difference increases markedly. Reinforced concrete preserves the integrity of the fire barriers, restricting damage to a limited portion of the building, whereas the combustible structural system progressively compromises those same barriers and allows fire to spread beyond the compartment of origin. The greatest divergence occurs in vertically developed buildings, where the floor assemblies simultaneously provide structural support and compartmentation, and their failure not only permits vertical fire spread but also creates the conditions for progressive collapse. Across the five cases the ratio of the timber loss to the reinforced concrete loss therefore rises from approximately 1.3 in the open warehouse to nearly 4 in the eight-storey apartment building, as illustrated in the graph below. The same geometry also amplifies secondary damage, as smoke and firefighting water migrate through floor junctions and service penetrations into the storeys below, prolonging drying and reinstatement works.



Graph 4, MFL: timber versus reinforced concrete across the five case studies

This finding extends beyond the individual case studies. It indicates that the advantage of a non-combustible structural system is smallest in large open industrial buildings, where compartmentation plays only a limited role, and greatest in highly compartmented and multi-storey buildings, where the structural system also defines the fire compartments. These are also the building typologies in which mass timber construction is currently expanding most rapidly, making the relationship between structural material, geometry and compartmentation particularly relevant to future fire risk assessments.

11.5 Property Damage versus Business Interruption

The two components of the loss do not move together, and their relationship carries a distinct meaning for the insurance reading of the results. In the residential and institutional buildings the property damage governs the total, and the interruption, whether measured as loss of rent or as displacement of a public service, remains comparatively small. In the highly automated industrial facility the relationship can reverse, and the interruption becomes the larger component, because the recovery is constrained by the time required to procure and recommission specialised systems rather than by the physical reinstatement of the fabric.

A further and less obvious consequence concerns the correlation of the loss within a single risk. In the cellular concrete building the maximum foreseeable event is a set of independent compartment losses, decorrelated by the intrinsic boundaries, so that the loss to the risk is a fraction of its total value. In the timber configuration the dissolution of those boundaries converts the same event into a single correlated loss approaching the full insured value, raising the probable maximum loss of the individual risk towards its total exposure. For a portfolio composed of such risks, the distinction is material, because it affects not only the expected loss but the tail of the aggregate distribution against which capital is held.

11.6 Engineering implications

The analysis does not suggest that timber buildings cannot achieve the prescribed fire-resistance classes. Within the assumptions adopted, the timber configurations were taken to be code-compliant and fully encapsulated, and under the expected fire they performed accordingly. What the study shows is that identical fire-resistance ratings do not necessarily imply equivalent fire performance under severe fire scenarios. A reinforced concrete element and an encapsulated timber element may both satisfy the same R or REI classification. However, the fire resistance of reinforced concrete is an intrinsic property of the structural material, whereas that of the timber solution depends on the continued effectiveness of an applied protection system. Maximum Foreseeable Loss scenarios explicitly represent conditions under which this assumption can no longer be relied upon.

The comparison therefore indicates that identical regulatory classifications may correspond to substantially different levels of property loss, business interruption and post-fire recoverability. This should not be interpreted as a limitation of the current regulatory framework, nor as an argument against timber construction. Rather, it highlights that fire-resistance classifications describe compliance with prescribed design requirements, but do not fully characterise the robustness of structural performance when fire conditions exceed the assumptions adopted during design. From a risk engineering perspective, the structural material should therefore be regarded as an independent determinant of severe-loss outcomes rather than as a neutral variable once equivalent fire-resistance ratings have been demonstrated.

11.7 Limitations

The findings of this study should be interpreted within the scope of the adopted methodology. Timber configurations were developed using a simplified material-substitution approach that preserves the geometry, building volume, compartment layout, occupancy, contents and fire protection strategy of the original reinforced concrete buildings while varying only the structural material. No structural redesign was undertaken, and differences in member dimensions, connection detailing and global stiffness that would normally arise in a purpose-designed timber building were intentionally excluded in order to isolate the influence of structural material on fire behaviour.

The scenarios are deterministic and represent credible bounding events rather than probabilistic predictions. Consequently, the estimated Property Damage and Business Interruption values are based on engineering judgement, established fire-engineering principles and insurance loss-assessment practice rather than on statistical frequency analysis. The assessment is limited to Property Damage and Business Interruption. It does not address life safety, evacuation, firefighter intervention, environmental impacts, or the embodied carbon associated with post-fire reconstruction.

In addition, Business Interruption is evaluated using occupancy-specific metrics, namely industrial profit, rental income and continuity of public service. While these measures are appropriate for each case study, they are not directly comparable across occupancies. For this reason, the cross-case comparison is based primarily on Property Damage, with Business Interruption interpreted within the context of each building type.

These limitations affect the precision of the numerical estimates but not the consistency of the underlying trends. Across all five case studies, the same relationships between structural material, fire development, compartmentation, recoverability and economic loss emerge despite the differences in occupancy, geometry and valuation methodology, supporting the general validity of the comparative conclusions within the assumptions adopted.

11.8 Conclusions

This study compared the fire performance of reinforced concrete and code-compliant encapsulated timber structures from the perspective of Property Damage, Business Interruption and post-fire recoverability. Using a controlled material-substitution methodology applied to five representative European case studies, the analysis isolated the influence of the structural material while maintaining equivalent building geometry, occupancy, fire scenarios and protection strategies. Losses were evaluated using an established insurance engineering framework based on the distinction between Normal Loss Expectancy (NLE) and Maximum Foreseeable Loss (MFL).

The two structural systems respond to fire exposure through different mechanisms, and each is verified through design models built on those mechanisms. In reinforced concrete the section retains its geometry and loses strength progressively with temperature, so residual load-bearing capacity remains available and can be assessed after cooling, unless spalling has removed part of the cover or of the cross-section. In encapsulated timber the section is progressively reduced by charring wherever the protection is lost, and the material removed does not return. Both design models are conservative and are calibrated on standard fire exposure, which is the reference condition for classification rather than a representation of a natural fire.

The interaction between the structural material and the fire-safety strategy of the building was found to depend on the extent to which the structure also performs the compartmentation function. Where structural and separating elements coincide, the performance of the compartment depends on the performance of the structure. In both systems performance has to be maintained over the service life, the difference lying in the number and type of components whose condition has to be preserved, from the concrete cover and the sealing of service penetrations in one case, to protective linings, encapsulation systems and the same sealing in the other.

Across all five case studies, the two solutions exhibited broadly comparable performance under NLE conditions. Under MFL conditions their behaviour diverged consistently, because the structural material influenced four aspects of fire performance, namely the fuel available in the compartment, the robustness of compartmentation, structural stability and post-fire recoverability. The divergence increased systematically with the degree to which the structural system also performed the compartmentation function, reaching its maximum in the multi-storey residential building, where floor assemblies simultaneously provided structural support and fire separation, and its minimum in the large open industrial building, where the fire develops within a single compartment and the dominant fuel is the stored content.

The results therefore indicate that the equivalence established by identical fire-resistance ratings holds under the conditions assumed in the rating and is not necessarily maintained once those conditions are no longer satisfied. Within the assumptions adopted in this study, the reinforced concrete solution was not associated with higher Property Damage or Business Interruption than the corresponding timber solution in any of the five cases, and the difference was concentrated in the severe-loss scenarios of the highly compartmented buildings. Where the structure performs no separating function and the fire load is governed by the contents, the choice of structural material had a limited effect on the outcome.

The principal difference between the two solutions therefore lies not in their expected performance during ordinary fire events, but in the severity and recoverability of extreme losses once the assumptions underlying the fire-resistance design are no longer satisfied. From a fire engineering and insurance perspective, assessing the resilience of a building requires consideration not only of whether a prescribed fire-resistance class is achieved, but also of how many conditions have to remain satisfied for that performance to be available when a real fire departs from the design scenario.

Assumptions and Limitations of the study

The data and evaluations presented in this document are based on the information available at the time of the analysis, on the characteristics of the building under examination, and on the scenario assumptions adopted. Any changes in values, building configuration, stored goods, or operational conditions may result in variations in the estimated outcomes.

The loss assessments and scenarios have been developed in accordance and with the definitions generally applied to Normal Loss Expectancy (NLE) and Maximum Foreseeable Loss (MFL) scenarios. Consequently, the results should be interpreted as indicative technical estimates expressing orders of magnitude, and not as point valuations.

This document is intended solely for analytical and comparative purposes and does not constitute an insurance appraisal nor a guarantee of the losses that could actually occur in the event of a real fire incident. Accordingly, the authors disclaim any responsibility for discrepancies between the estimates presented and the losses that may arise from real-world circumstances or from changes in the conditions considered.

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