

Reliability of Mass Timber Buildings in Fire: A performance-based design method and its application to office buildings

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Abstract

This paper proposes a probabilistic simulation approach to assess the fire reliability of a compartment with an exposed mass timber structure in a fire situation. A recently developed predictive method for contribution of protected and unprotected timber exposed to the development of natural fire in a compartment is utilized. A method for conducting parametric and stochastic studies to define the reliability for a given building typology is presented. The approach is predicated on the introduction of a number of parameters and criteria. These enable the Monte Carlo execution of fire simulation models, whilst also allowing for the consideration of active fire safety measures, including sprinkler systems and fire brigade intervention. The findings demonstrate how effective various fire safety measures are at enhancing reliability. They highlight the permissible percentage for the area of exposed timber in a compartment in accordance with the overall fire safety objective with a reliability according to the Structural Eurocode. This paper sets out the application of a method and the development of tools for determining the reliability of office buildings under fire load. The results pertaining to the attainment of tolerable risk objectives are discussed in this paper.

Keywords: performance-based design, exposed mass timber, passive and active protection, fire safety, natural fires, probabilistic, Monte Carlo, risk assessment, reliability

1. Introduction

Structural timber is increasingly used in mid-rise and high-rise buildings, partly due to its potential to reduce the embodied carbon of buildings and to support compliance with emerging environmental regulations and low-carbon policy objectives. Conversely, in light of the expansion of timber construction, prescriptive fire regulations with the required degree of passive (as encapsulation) and active (as sprinklers) protection of structural timber members can be detrimental to the economy of construction and the reduction of the carbon footprint. In France, this issue is particularly pertinent in the context of the new environmental regulations (RE2020) and the impending fire regulations, which will incorporate the use of new bio-sourced materials.

Performance-based fire design is frequently employed to introduce innovative concepts and/or to accommodate the specific configuration of a given project. This approach is also employed to demonstrate that certain provisions, which are not explicitly addressed by prescriptive regulations, can achieve the overall objectives of fire safety regulations. Fire is by nature a stochastic phenomenon depending mainly on the heat release rate (HRR) and quantity of movable fuel, which can be increased by the contribution of mass timber elements, initially protected or not. A probabilistic approach might be preferred to deterministic analysis allowing the execution of parametric studies on generic types of construction to achieve the required fire safety regulation objectives.

Since zero risk is unattainable, and ultimate-limit-state regulations such as the Structural Eurocode [1] are based on target reliability levels corresponding to tolerable risk, methods are needed to quantify the fire reliability of specific mass-timber building configurations. These methods can support performance-based decisions on design variables such as exposed timber area and sprinkler protection, rather than relying solely on prescriptive and sometime unnecessary restrictions.

2. Material and methods

The numerical tool developed to achieve this purpose consists of a program written in Python that reads an Excel file with a sample size of N compartments (simulations). Input parameters for a given simulation is selected using Monte Carlo techniques from the assigned statistical distributions for a given parameter. The tool then launches an iterative process to take into account the contribution of mass timber to fire dynamics, writes the results according to each criterion relating to the overall objective of fire safety regulations, and calculates reliability (*i.e.* the probability of each criterion being met).

The iterative process and calculation to predict fire development and char depth for one compartment are described below in subsection 2.1, the Monte Carlo simulation and reliability calculation are described in subsection 2.2.

2.1 Mass timber contribution to fire dynamics

Unprotected mass timber could influence the three development stages of a compartment fire (growth, fully developed and decay), highlighting the unique challenge this material presents in fire dynamics and fire safety. During the growth stage, exposed mass timber surfaces on walls and

ceiling may ignite if they are sufficiently exposed to heat and flaming, accelerating the fire growth rate. This increased growth rate might cause the flashover to occur earlier than in a compartment made with less combustible finish materials. While exposed, mass timber surfaces may not in all scenarios impact the growth stage, depending on the ignition source location, their contribution to the fully developed stage is undeniable. Contribution of the exposed timber surfaces increases the heat release rate, and the duration of the fully developed stage compared to scenarios using a noncombustible or fully protected construction. The additional heat release rate usually results in more intense flaming out of the openings, which could amplify the heat exposure to the façade and to adjacent buildings. During the decay stage, the exposed mass timber surfaces will eventually reach flaming extinction as the movable fuel load burns out and the ambient compartment temperature reduces. But in some situations, the amount of exposed timber – initially exposed or exposed due to char fall-off or encapsulation failure – could be sufficient to sustain its combustion after the complete combustion of the movable fuel load [2,3]. During the decay stage, the oxygen availability increases allowing the oxidation of the char layer, which releases additional heat that may prolong the duration of the decay stage.

The estimation of the increase in heat release rate due to the contribution of structural timber elements are pivotal parameters for performance-based fire design. Several methodologies have been proposed over the last decade to consider the contribution of structural timber to fire dynamics [4-6]. Based on those methods, the numerical tool developed initiates a simulation of the two-zone model B-RISK [7] and for each step of an iterative process the timber contribution to the fire load and subsequent fire development is explicitly considered according to the output of each simulation. The charring rate of the timber and its fuel contribution (the HRR of the timber elements) are calculated according to equations (12), (14) and (15) from Girompaire *et al.* [4] with the values of the total flux received by the timber elements and the oxygen concentration per mass of air given by B-RISK. The most recent improvement of B-RISK (2025.03) incorporates specific data exchange enhancements, including the addition of supplementary outputs to the standard Excel output file. The outputs encompass incident radiant fluxes, convective heat transfer coefficients, and the interface temperature between the surface lining materials and the substrate (in the event of both being present). Additionally, the nodal temperature data for the various surfaces (*e.g.* wall, ceiling) can be transferred to an Excel file following the simulation. These enhancements facilitate the automation of the entire iterative process, allowing for a quick stochastic calculation study. The tool enables the evaluation of the temperature of the upper (hot) and lower layer in the mass timber compartment, and the corresponding incident heat flux to structural timber elements, as well as the resulting char depths.

The contribution of the initially protected timber surfaces in the event of encapsulation material failure, is further discussed in subsection 2.1.1. The results of the predictive tool are then compared with a series of experiments that have been conducted around the world in subsection 2.1.2.

2.1.1 Contribution of protected timber elements

As demonstrated by Sultan [8], the process of fall off gypsum board (GB) occurs at temperatures that exceed the charring temperature (300°C) of the exposed side of the base layer (*i.e.* the interface between GB and timber). This assertion is further substantiated by a comparison of the temperature of the compartment, the time required for the interface between GB and timber to reach 300°C, and the GB fall-off time in experiments where a substantial contribution of protected timber to fire dynamics has been documented [14-17,29]. The timber, which is initially protected, does not

contribute to fire dynamics inside the compartment at the onset of its charring. However, its contribution increases with the interface temperature, the fall of the first layer, the initial flaming at the joint between panels, and finally, it fully contributes after the fall of the base layer.

In accordance with the observed behavior, the procedure for incorporating protected timber in the predictive tools presented in this paper is as follows:

- The protected timber contributes if the thickness of the protection is less than the minimum thickness, $h_{p,min}$, calculated according to the cumulative radiant energy model and as specified in Annex A of the 2025 version of EC5-1-2 [9].
- B-RISK provides the time history of temperatures at the interface between the protective and fire-facing sides of the timber. These temperatures are recorded for the ceiling, as well as the upper and lower parts (according to layers of zone model) of walls. In the case of the protected solid timber element under consideration, the HRR of the timber is first calculated in accordance with the contribution law of the method described above in 2.1. The calculation of the fuel contribution is then weighted by a reduction factor, the value of which is dependent on the interface temperature between the protection (GB) and the mass timber, $T_{interface}$. The following temperature-dependent percentage values have been empirically set to 0% for $T_{interface}$ no greater than 350°C, 10% for $T_{interface}$ between 350°C and 450°C, 50% between 450 and 550°C, 90% between 550 and 650°C, and 100% above 650°C.

In the configuration of B-RISK [7], material thermal properties are assumed to remain constant and are therefore not influenced by changes in compartment temperature. For gypsum-protected timber assemblies, this assumption resulted in an overestimation of temperatures at the interface between the unexposed side of the gypsum board and the timber. Consequently, equivalent constant thermal properties were calibrated to improve the accuracy of predicted interface temperatures with respect to experimental measurements.

The calibration procedure, adapted from the methodology described by Brandon [10], was performed using SAFIR [11,12] for heat transfer simulations. Thermal conductivity and specific heat were iteratively adjusted to minimize the error between experimentally measured temperatures and the corresponding temperatures predicted by the program SAFIR. The optimization was performed simultaneously across multiple experiments to obtain a single set of representative equivalent material properties.

For the calibration, plate thermometer measurements were used to define the thermal boundary conditions in the SAFIR models, while average temperatures measured at the gypsum-CLT interface or at interfaces between gypsum layers were used for comparison with SAFIR predictions. Data from seven flashover compartment fire tests with varying opening factors and fuel loads were included: Tests 1 and 3 from Zelinka *et al.*, [22] with two layers of 15.9mm gypsum board; Tests 1, 2, and 4 from Brandon *et al.* [25] 15.9mm gypsum with two layers for Test 1 and 4 and three layers for Test 2; and Tests 1-1 and 1-3 from Su *et al.* [16] 15.9mm gypsum with three layers for Test 1-1 and two layers for Test 1-3. Temperature predictions using the calibrated properties are set against experimental averages in Figure 1.

Best calibration result - iteration 21

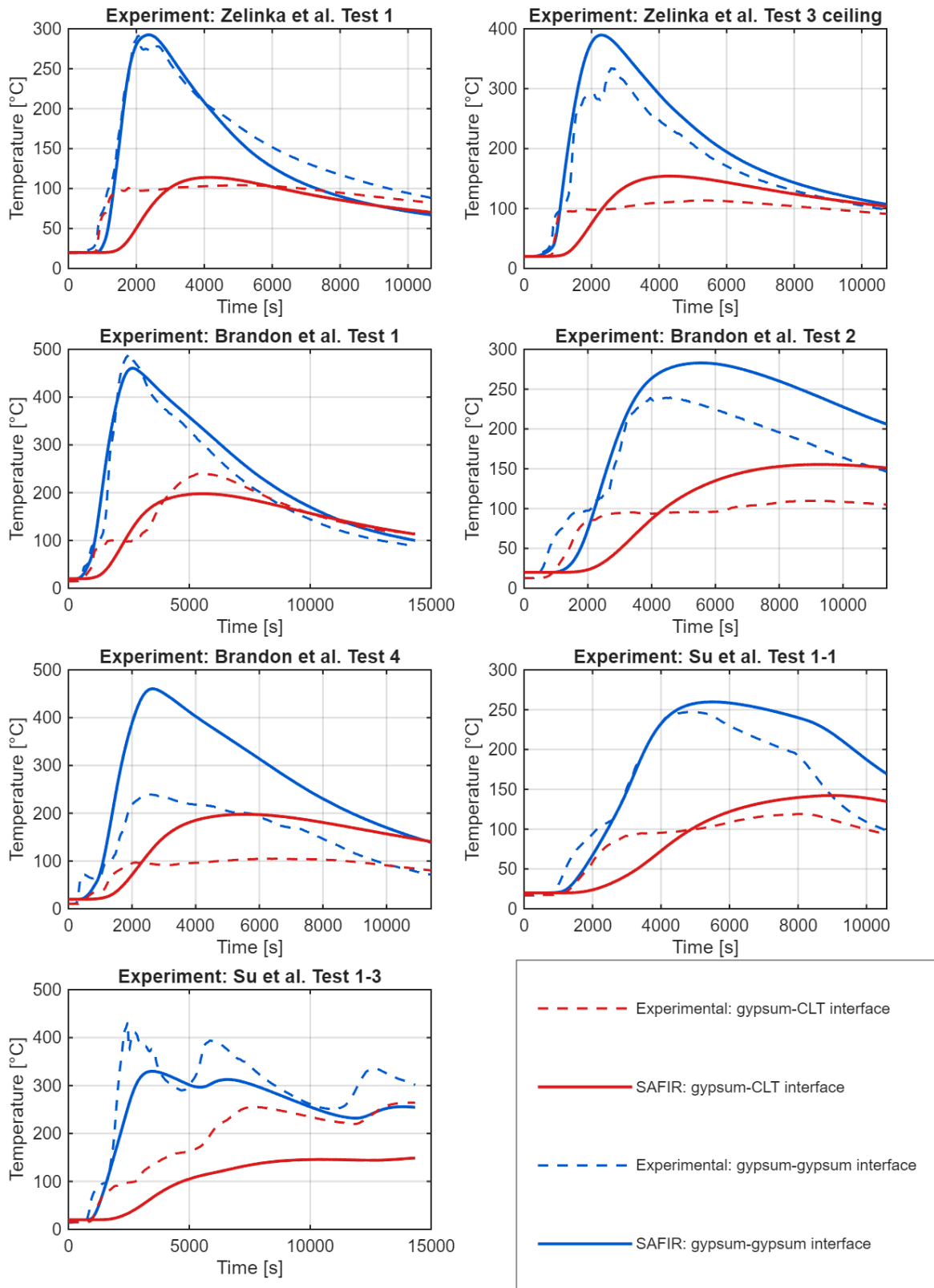


Figure 1: Comparison of temperature predictions and experimental averages at interfaces

The resulting equivalent gypsum board properties adopted in the B-RISK calculations were thermal conductivity = 0.0673 W/m·K, specific heat = 586.92 J/kg·K, and density = 896 kg/m³. Comparison of interface temperatures over time between the B-RISK calculations and experimental measurements demonstrated that the calibrated properties provided conservative predictions.

2.1.2 Predictive tools benchmark

From the review presented in Mitchell *et al.* [13] and from recent experiments with protected, partially or fully exposed timber elements, the results of 54 compartments fire tests [14-29], listed in appendix A (Table 2), have been used to evaluate the accuracy of the predictive tool. The experiments name column of this table list those used in the text and figure legend below. They are representative of the state-of-the-art worldwide and cover a wide range of realistic situations in terms of floor area (between 7.3 m² and 352.0 m²), movable fuel load density (between 15 MJ/m² and 1085 MJ/m²), opening factors (between 0.03 m^{1/2} and 0.27 m^{1/2}), ceiling height (between 2.4 m and 3.3 m) and exposed surface of mass timber (between 3% and 75% of the total enclosing area including floor, ceiling and openings, or between 9% and 134% of the surface of surrounding walls including the opening area).

From this list, 5 experiments fall outside the designed scope as characterized by the event of significant delamination (NRCC&NIST_4 and 5 from [16], Edimb_4 from [20], AdivBois_4 from [30]) or an opening factor greater than 0.2 (RISE_4 from [25]).

For 6 others experiments (NRCC&NIST_1 and 2 from [16], NRCC_Room_1 from [17], USDA_1 from [22], AdivBois_4 from [28], TIMPuls_0 from [29]), all structural timber was protected and did not exhibit timber contribution and char depth. The tool correctly predicted this behavior.

The comparison of the calculated char depth and the test measurement for the 43 remaining experiments are presented in Figure 2 **highlighting the conservative predictions of** the predictive tool (*i.e.* points are in conservative zone, above the 1:1 black line). These 43 experiments represent a total of 93 collections of char depth measurements whereby distinctions are made between walls, ceilings, floors, beams and columns.

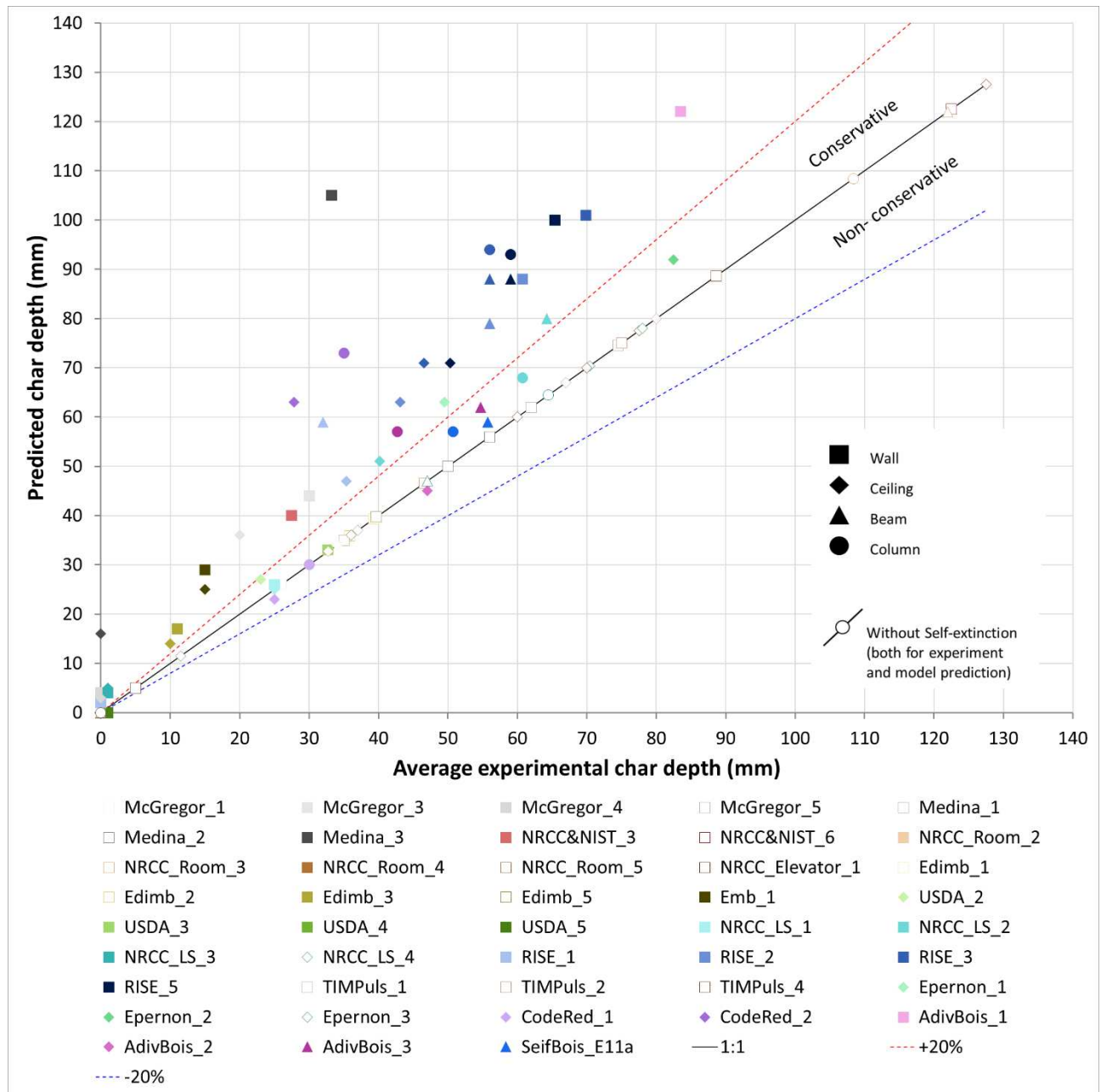


Figure 2: Comparison between calculated and measured values of char depth.

In the absence of self-extinction, the predicted char depth can become high, thereby affecting the scale of the y-axis. In order to address this issue, it was decided to position the series that well predicted no self-extinction on the 1:1 black line in Figure 2 (as successful values, see legend for "empty symbols").

The absence of self-extinguishing behavior of the timber surfaces was observed in 20 of the benchmark experiments presented in Appendix A (Table 2). This was attributed to the persistence of flaming, which resulted in manual extinguishment of the fire at the conclusion of the experiment. For each of these tests, the tool correctly predicted the absence of self-extinguishing behavior. In three other experiments, the tool predicted the absence of self-extinguishing behavior

(Medina 3 [15] - see black square symbol off-centre at coordinates 33,105 mm in Figure 2 -, NRCC_Room_2 and 4 [17]) despite this not being observed in the experimental setting. For NRCC_Room_2 and 4, the calculated values exceed the member depth (for an average experimental char depth of approximately 70mm) and are not displayed on the graphs in Figure 2.

2.2 Stochastic analysis approach

The method involves a stochastic calculation using Monte Carlo techniques of the **overall reliability** for a given typology of compartment with a **fixed** amount of **exposed mass timber** surfaces under fire development. Following Östman *et al.* [30] and Hietaniemi [31] the criteria to assess the tolerable risk is set to a probability (P_a) of $72.3 \cdot 10^{-6}$ per building lifetime corresponding to a safety index (β) of 3.8, as stipulated in Eurocode 0 [32]. The selected reliability index of 3.8 corresponds to a consequence class CC2. This specific class is consistent with the solutions assessed herein. Office buildings, including mid and high-rise structures, are typically designated as CC2 category. In the event where a structure designated as CC3 would be evaluated, the value of P_a would need to be adjusted accordingly.

The present case study, further described in subsection 2.2.1, is a compartment from an **office building with and without automatic sprinkler** systems.

2.2.1 Office case study

The case study was conducted using the floor area distributions, room heights, opening factors, as well as movable fuel loads summarized in Table 1. As discussed in Section 2.2.2, the number of Monte Carlo draws has been set to 15 000. The case study focuses on relatively small office space areas (with a mean value of 75 m²), determined based on a fixed width of the compartment of 7 m and varying lengths. Fire load density is defined according to French annex of Eurocode [33] for offices.

As proposed by Consigny *et al.* [34] the time lag between the initiation of a fire and the commencement of fire brigade intervention is calculated by adding the time of alarm t_{alarm} , the time of travel t_{travel} and the time of action of fire brigade since their arrival t_{action} . The value of t_{alarm} is taken as the time of flashover (taken as the time when the room upper layer temperature reaches 500°C and the window glass breaks). The time of travel follows the gamma distribution defined in Table 1 (where location, *i.e.* the minimal travel time is 11.2 min). The value of t_{action} is fixed at 7 minutes, which is also a conservative value from Särqvist [35]. This also takes into account the compartment access delay for mid-rise buildings.

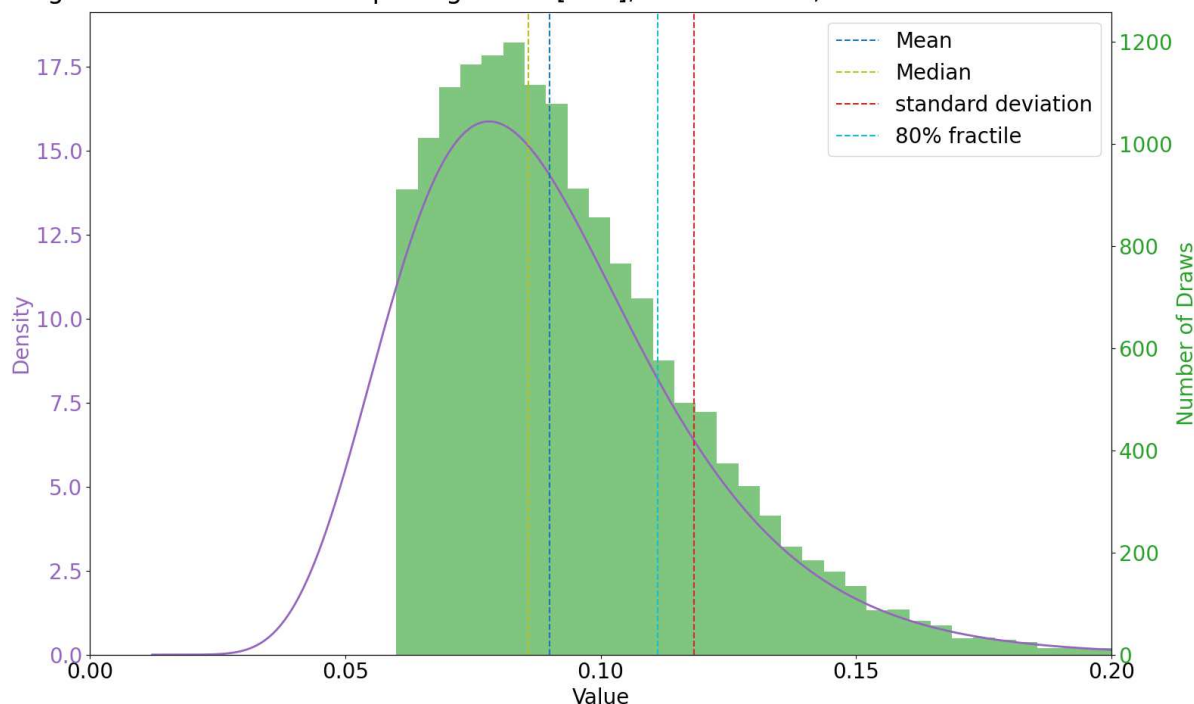
The probability of fire being extinguished by the fire brigade is linked to the HRR value at the time of firefighter intervention in the compartment. The relationship between the probability of successful firefighting and the fire heat release rate, decreasing from 1 for a 10MW fire to 0 for a 35 MW fire, is illustrated in Figure 121 in Hietaniemi *et al.* [36]. It can be highlighted that in our case, this probability of success of the fire brigade is contingent on the increased firepower resulting from the timber contribution. In the present case study in the event of unsuccessful firefighting operations, two new interventions by the fire brigade are introduced, with a 15-minute

230 interval between each attempt. The intervention may therefore fail if the intensity of the fire (the
 231 HRR) remains ‘too high’ by the third and final attempt.

232 Table 1: Parameters for the distributed scenarios

Parameter	Distribution	Value/characteristics
Room size	Normal	Height: mean 3.3m, standard deviation 0.1 Floor area: mean 75m ² standard deviation 7
Fire load density	Gumbel	Mean 450 MJ/m ² 90th percentile 740 MJ/m ²
Heat release rate per unit area HRRPUA	Triangular	(200, 250, 300) 250 kW/m ² +/- 20%
Fire growth time t_g	Triangular	(240, 300, 360) 300 s +/- 20%
Opening factor	Log Normal	Mean 0.09 m ^{1/2} , standard deviation 0.028 with minimum threshold at $A_f/A_v < 6$
Open windows	Bernouilli	$P_{\text{closed}} = 0.8$ (in B-RISK calculation, vent initially closed then opened at time of flashover), $P_{\text{open}} = 1 - P_{\text{closed}} = 0.2$
Fire Brigade travel time	Gamma	Mean 16.8 minutes with: Shape a: 2, width b: 2.8, location: 11.2 minutes
Sprinklers	Bernouilli	$P_{\text{fail}} = 0.12$; $P_{\text{controlled}} = 1 - P_{\text{fail}} = 0.88$

Log Normal distribution - Opening factor [m^{1/2}], Mean = 0.09, standard deviation = 0.028



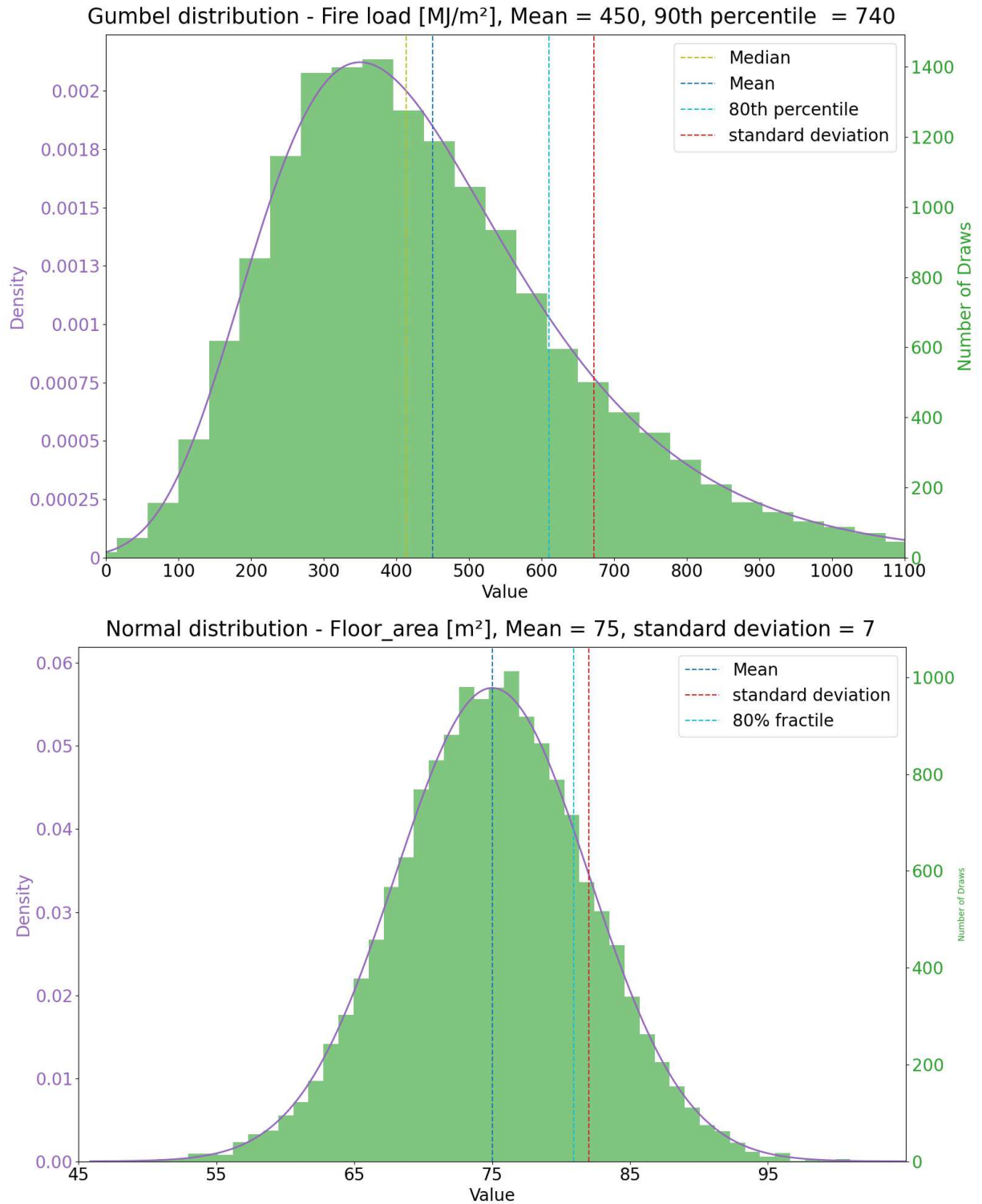


Figure 3: Overview (from top to bottom) of opening factor, fire load and floor area distributions used

According to Hietaniemi *et al.* [36], the probability of fire occurrence for office (in France) is taken as $P_{\text{occ}}=8.9 \cdot 10^{-6}$ /year/ m^2 and the probability of minor fire (or fire being detected and extinguished by the occupants) is taken as $P_{\text{occup}}=0.6$.

The system failure rate for solutions incorporating automatic sprinkler systems was set at 12%, based on surveys of sprinkler system failures. The data indicated an activation failure rate of 8% (and an ineffective activation rate of 3%) in the USA [37] and an activation failure rate of 11% (and an ineffective activation rate of 2%) in office buildings in Canada [38]. In the B-RISK model, sprinklers are incorporated using the default values for 'Standard Response Sprinklers'. These are defined by the following parameters: RTI 135 (ms)^{1/2}; activation temperature 68 °C; C_{factor} 0.85 (m/s)^{1/2}; distance below ceiling 25mm. In the event of effective activation, the sprinklers are assumed to control the heat release rate without extinguishing the fire. The number of sprinklers required is contingent upon the area and dimensions of the compartment ceiling. The arrangement of the sprinklers is in a regular grid, with a minimum distance of 0.2 m from the walls and a maximum distance between sprinklers of 4 m. This results in a ceiling surface for each sprinkler ranging from approximately 11 m² to 14 m². It is important to note that these characteristics and layout are conservative in that they fall short of those typically specified for a sprinkler system in a typical building. Tests on mass timber buildings were carried out in 2022 in the case of office use by Auguin *et al.* [39]. They demonstrated the ability to control, or even extinguish, the primary (movable) fire, and to significantly limit the contribution of structural timber for automatic water-based sprinkler systems sized for an OH1 risk (lower class of Ordinary Hazard according to NF EN 12845 [40]). As sprinkler systems are based on the movable fuel load depending on building occupancy, it seems that the likelihood of sprinkler being ineffective doesn't depend of the presence of mass timber (i.e. if sprinklers act, and movable fuel is controlled the heat flux received by the timber is also limited and it does not contribute to the fire). However, further investigation or guidance as proposed in [39] is likely to be required to ensure that this behavior is maintained.

In the present case study, the mass timber ceiling and walls are considered to be initially exposed. The allocation of exposed timber is determined by a set of criteria that governs the proportion between the ceiling and the walls. The considered rule stipulates that in instances where the total area of exposed timber is less than that of the ceiling, the entirety of the allocated timber is assigned to the ceiling. Conversely, in cases where the total area of exposed timber exceeds that of the ceiling, the remaining allocation is then distributed between the walls.

Three types of compartments were analyzed according to their structural fire-resistance requirements (R60, R90 or R120). The recently implemented French regulation [41] delineates the stipulated requirements for passive fire protection measures to be employed in the context of structural mass timber. The regulation stipulates that the timber must not contribute to the fire for a duration that is at least equivalent to the required fire-resistance duration according to ISO 834 fire, without being less than 30 minutes. It is also stated that if the composition and thickness of the plasterboards allow the interface temperature between the base layer and the timber to be limited to 250 °C after required structural resistance time (*i.e.*, 60, 90 or 120 minutes) of fire testing in accordance with ISO 834, this objective is deemed to have been achieved. Thus, the composition and thickness of the walls and ceiling, modelled for each configuration, were adapted to meet the requirements as follows:

- For a compartment with structural fire requirement R60: a passive protection of two 18 mm gypsum boards and a 175 mm-thick Cross-Laminated Timber (CLT).
- For a compartment with structural fire requirement R90: a passive protection of one 18 mm gypsum board and one 25 mm plasterboard, and a 220 mm-thick CLT.
- For a compartment with structural fire requirement R120: a passive protection of two 25 mm gypsum boards and a 260 mm-thick CLT.

This specification on thermal insulation of the gypsum board induces a global fire resistance of the complex of protection and structural mass timber higher than the required one. However, this does not rule out the possible contribution of the timber throughout the duration of the (natural) fire, depending on the extent of the movable fuel load, which is taken into account in the calculation, in accordance with section 2.1.1. The total modeling time (and final char depth calculation) is set to 3 hours.

2.2.2 Number of Monte Carlo draws

The Monte Carlo estimation method was historically the first simulation method used to estimate an expectation, and therefore, by extension, a failure probability. For a Monte Carlo of sample size N , in which each realization is independent and identically distributed, the coefficient of variation (CV) of the estimator of a failure probability (p_t) can be approximated as explained in Demange-Chryst [42] by:

$$CV = \sqrt{\frac{1-p_t}{Np_t}} \quad (1)$$

In the present case study, the probability of a developed fire (taking into account the probability that the fire is **not** extinguished by the occupants of $0.4 = 1 - P_{\text{occup}}$) during Eurocode building lifetime of 50 years is:

$P_{\text{fire}} = 8.9 \cdot 10^{-6} \text{ fires/m}^2/\text{year} \times 75 \text{ m}^2 \times 50 \text{ years} \times 0.4 = 1.34 \cdot 10^{-2}$ per lifetime. The probability p_t for this case study is $P_a/P_{\text{fire}} = 5.42 \cdot 10^{-3}$. In accordance with the stipulated parameters, a sample size N of 15,000 was selected, allowing an error of less than 12% (1).

2.2.3 Structural and Fire spread criteria

Structural failure criterion:

A simplified structural failure criterion is used for this case study. A draw fails if the calculated **char depth** at the end of the 3 hours (simulation time) is greater than the notional charring depth $d_{\text{char,n}}$ defined by EC5-1-2 [9]. In this manner, the criterion is formulated in such a way as to ensure that the mass timber structural element will withstand the loads to which it is required to bear in a fire situation for a period of time equivalent to the entire duration of the fire. It can be supposed that if the charring depth is found to be less than the conventional fire for which the mass structural timber structure was designed, then it can be assumed that the severity of the thermal action (which governs its stability) under the actual fire to which it was subjected will, in principle, also be lower. The notional charring rate (β_n) have been set to 0.7 mm/min which gives following criteria:

- For a compartment with structural fire requirement R60 the failure is given by a final char depth greater than 42 mm (*i.e.*, 0.70 mm/min x 60 min)
- For a compartment with structural fire requirement R90 the failure is given by a final char depth greater than 63 mm (*i.e.*, 0.70 mm/min x 90 min)
- For a compartment with structural fire requirement R120 the failure is given by a final char depth greater than 84 mm (*i.e.*, 0.70 mm/min x 120 min)

The value of the notional charring rate for softwood structural mass timber has been found to vary from 0.65mm/min to 0.78mm/min. The value of the theoretical char depth calculated at a rate of 0.7 mm/min has been considered, as a mean value. It can also be highlighted that the final implemented section size is generally greater than the required size, due to other calculations and/or constructive considerations (*e.g.* the size of the final section according to the standard thickness of the lamella).

Note: It is important to acknowledge a limitation of the study concerning the simplified charring criterion that was utilized. It is evident that the present criterion encompasses the decay phase, as it is applicable throughout the entire duration of the fire. However, the impact of the duration of this phase and the progression of the heat wave within the solid timber section have not been formally taken into account and should be the subject of further study.

Internal fire spread criterion (*i.e.* fire impacting areas beyond its room of origin):

The setting should be determined by verifying that, over the entire duration of the fire, the elevated temperature of the unexposed surface of each separating elements (*e.g.* walls, ceiling and floor) required to provide a fire-resistance rating remains below the average temperature rise criterion of 140°K typically used to assess the separating function of building assemblies. It should be noted that the configuration of the present case study involves solely mass timber (CLT), with some elements being protected and others unprotected. In this instance, the calculations demonstrate that, given the thermal inertia of mass timber, the elevation of unexposed surface temperature always remains below 50°C. Consequently, the internal fire spread criterion has not been implemented in the present case study.

External fire spread criterion (*i.e.* fire impacting areas beyond its building of origin):

The calculation of the emitted radiant heat flux is performed in accordance with the provisions set out in Annex B of EN1991-1-2, the upcoming Annex E of EN1995-1-2 which considers the structural fuel load) and the work by Law [43]. The criterion has been set at a heat flux no greater than 15 kW/m² at a horizontal distance of 12 m from the façade (value as defined for current operative building regulations in the Environment Buildings Decree of the Netherlands and in line with French national project of fire safety engineering [44]). This value is of the same order as the value of 12,5 kW/m² which is taken in North America as the critical heat flux for piloted ignition (*i.e.* with proximity of flame or hot spot as embers). A more detailed analysis of this limit value would be appropriate, given that the calculated value in this case corresponds to an instantaneous maximum peak. It is reasonable to assume that an average calculated over a few tens of seconds would provide a more accurate picture of the phenomenon.

Note: A limitation of this study is evident in the absence of consideration given to the potential for fire spread to upper floors by the façade of the compartment's building. Given that the calculation of the heat flux or temperature at a given vertical distance from the top of the opening has also been implemented in the predictive tool (in accordance with the provisions of Annex B of EN 1991-1-2), a target value and criteria should be defined and applied.

3. Results and discussion

The present paper assesses the overall risk of failure by verifying both the final calculated **char depth** and the external **spread** of fire, in accordance with the criteria described in Section 2.2.3.

In accordance with French prescriptive regulation [41], a maximum of 25% of the total surface area of walls, inclusive of openings that meet the stipulated fire resistance criteria, is permitted to be exposed on vertical surfaces or on certain linear mass timber structural elements (excluding exposed slabs on ceilings). This amount is established irrespective of the required fire resistance of the structure and the presence or absence of protection by sprinklers. The potential exists for this to be increased by means of performance-based design. As outlined in [45], in numerous European countries, mass timber structural elements are permitted in prescriptive requirements for residential buildings with a height of more than eight storeys, without the requirement for sprinkler systems. This assertion likewise pertains to office buildings, thus substantiating the scenarios with and without sprinkler systems. With the goal to determine the maximum permitted percentage of exposed timber in accordance with the general objectives for each of the three types of compartments (R60, R90 or R120), three configurations have been tested in a trial-and-error approach and are presented below.

3.1 R60 configurations

Three different configurations have been calculated for R60:

- 30% of A_{wall} of (initially) exposed mass timber without sprinklers
- 30% of A_{wall} of (initially) exposed mass timber with sprinklers
- 60% of A_{wall} of (initially) exposed mass timber with sprinklers

where: A_{wall} is the total surface of walls, including openings. The remaining area of mass timber for ceiling and walls being protected with gypsum board in accordance with the fire requirement of R 60.

The results of the study are summarized in Figure 4. In this case, the exterior fire spread criterion is not breached by any sample. For the case without sprinklers, the maximum (instantaneous time peak) heat flux received at a distance of 12 meters from the opening is 14 kW/m² (sample n°3084, with a fire load of 704 MJ/m², a floor surface area of 87.7 m² and an opening factor of 0.066 m^{1/2}). Therefore, the probability of failure (combined fire-resistance and fire spread criteria) is equivalent to the probability of failure of the R60 char criterion. That is to say, the probability that the char depth at the end of the fire duration exceed 42 mm (*i.e.*, 0.70 mm/min x 60 min).

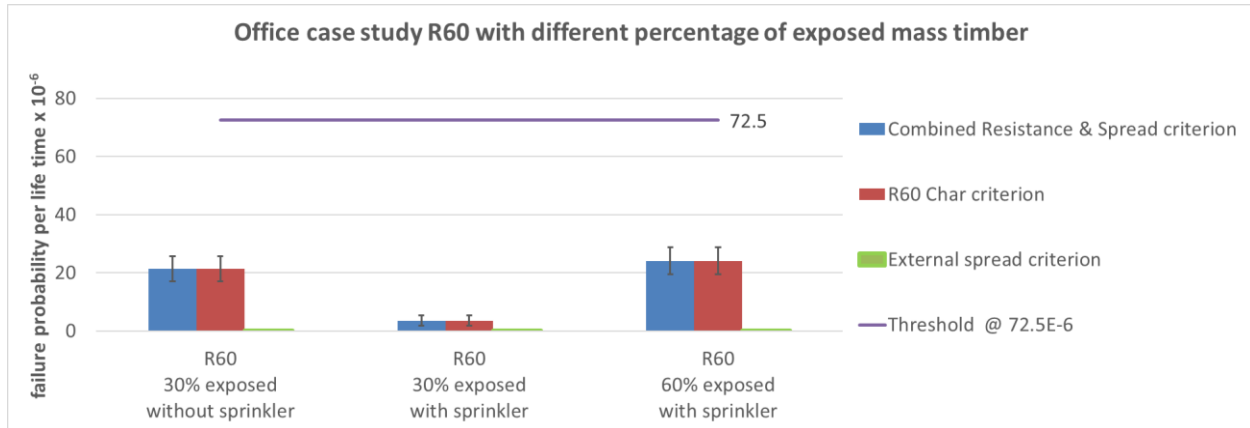


Figure 4: Failure probability for the case study of an office compartment with required resistance R60 with box and whiskers plot to estimate the error on the Monte-Carlo 15 000 N-sample according to formula (1)

3.2 R90 configurations

Three different configurations have been calculated for R90:

- 60% of A_{wall} of (initially) exposed mass timber without sprinklers
- 60% of A_{wall} of (initially) exposed mass timber with sprinklers
- 75% of A_{wall} of (initially) exposed mass timber with sprinklers

where: A_{wall} is the total surface of walls, including openings. The remaining area of mass timber for ceiling and walls being protected with gypsum board in accordance with the fire requirement of R 90.

The results of the study are summarized in Figure 5. Similarly to the results from the R60 analyses, the exterior fire spread criterion is not breached by any sample of all 3 configurations. Therefore, the probability of failure (combined fire-resistance and fire spread criteria) is equivalent to the probability of failure of the R90 char criterion.

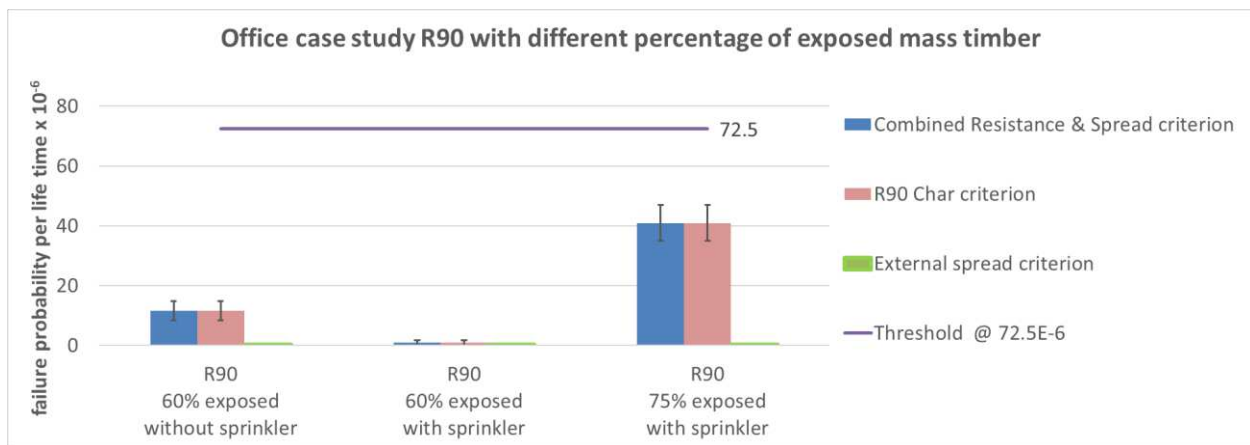


Figure 5: Failure probability for the case study of an office compartment with required resistance R90 with box and whiskers plot to estimate the error on the Monte-Carlo 15 000 N-sample according to formula (1)

3.3 R120 configurations

Such buildings are typically high-rise buildings greater than 12-16 storeys, depending on the applicable building code. At these heights, timber buildings are generally required to be protected by sprinklers. Nevertheless, the effect of the absence and presence of sprinklers is presented. Three different configurations have been calculated for R120:

- 75% of A_{wall} of (initially) exposed mass timber without sprinklers
- 75% of A_{wall} of (initially) exposed mass timber with sprinklers
- 90% of A_{wall} of (initially) exposed mass timber with sprinklers

where: A_{wall} is the total surface of walls, including openings. The remaining area of mass timber being protected with gypsum board in accordance with the fire requirement of R 120.

The results of the study are summarized in Figure 6. Here, with this level of exposed timber surfaces, the exterior fire spread criterion of 15 kW/m^2 is, sometimes, reached. For the case without sprinklers, the maximum (instantaneous time peak) heat flux received at a distance of 12 meters from the opening is 16.3 kW/m^2 (sample n°3477, with a fire load of 1078 MJ/m^2 , a floor surface area of 23.4 m^2 , an opening factor of $0.157 \text{ m}^{1/2}$ and a calculated char depth of 40 mm which is less than the R120 char criterion of $0.7 \text{ mm/min} \times 120 \text{ min} = 84 \text{ mm}$). Therefore, the probability of failure (combined fire-resistance and fire spread criterion) is greater than the probability of failure of the R120 char criterion. This value exceeds slightly the criterion ($85.7 \cdot 10^{-6}$ with the range of estimator error included for the limit of $72.5 \cdot 10^{-6}$). As the requirement R120 pertains essentially only to high-rise buildings, the criterion has been evaluated for a distance of 15 meters instead of the stipulated 12 meters, given that such buildings are typically not located in narrow streets. At a distance of 15 m, none of the samples exceeded the outdoor fire spread criterion. The probability of failure is therefore equivalent to that of exceeding the R120 char criterion. The calculated probability is $74.4 \cdot 10^{-6}$, including the estimator's margin of error, and is then close to the limit of $72.5 \cdot 10^{-6}$. In consideration of the foregoing discourse and the conservative assumptions employed in the present study, it can be deduced that a proportion of 75% of exposed mass timber surfaces is capable of attaining the overall objectives of fire safety regulations.

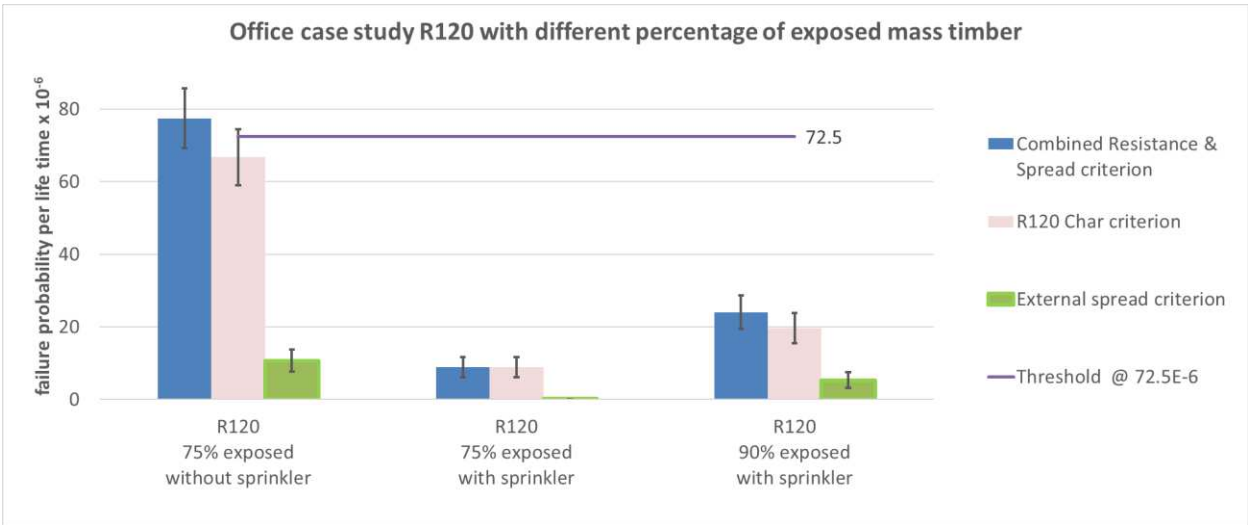


Figure 6: Failure probability for the case study of an office compartment with required resistance R120 with box and whiskers plot to estimate the error on the Monte-Carlo 15 000 N-sample according to formula (1)

4. Conclusions and perspectives

As part of the objective to develop methods and tools to calculate the reliability of a given configuration of mass timber mid- or high-rise buildings in fire situations, this paper presents a case study of a performance-based design and stochastic analysis approach. This approach confirms the feasibility of the project and provides initial results for medium surface area of office space with various surfaces of exposed structural timber that do not delaminate, with and without an automatic sprinkler system.

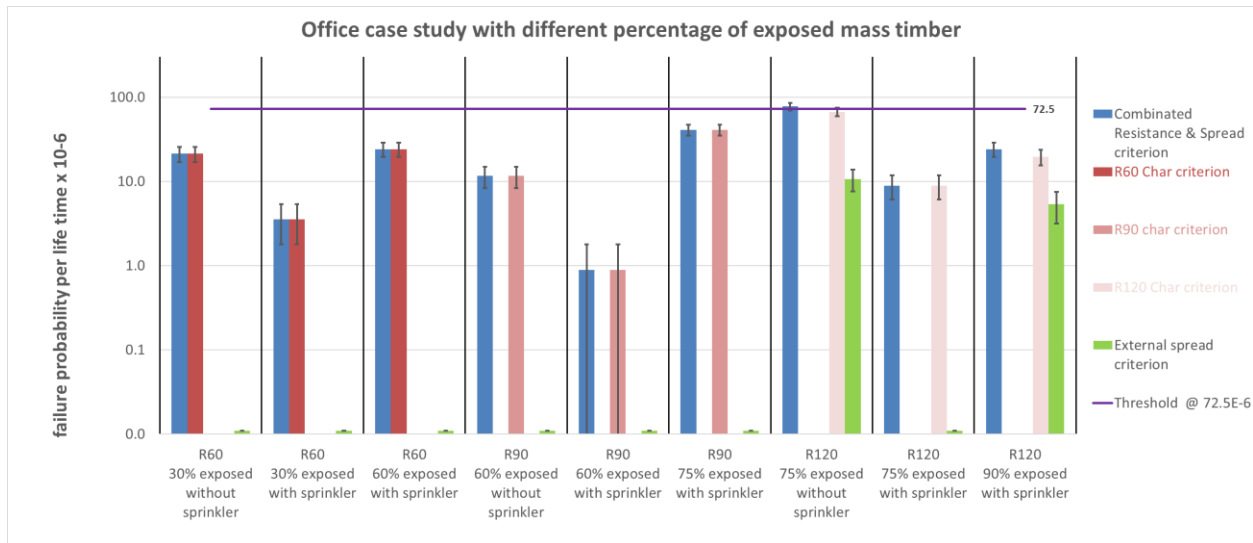


Figure 7: Synthesis of failure probability stochastic study. (Beware the logarithmic scale used here for summary purposes, which tends to blur the differences between the probabilities of failure)

As highlighted by Figure 7, for each typology and required design, the percentage of allowable exposed mass timber surface can be set according to the overall objectives of fire safety regulations by such studies as the method allows. This enables demonstration that these timber structures could withstand natural fires without internal or external fire propagation with a reliability corresponding to the Eurocodes values.

The case study demonstrated that the criterion for external fire spread should be incorporated and become significant for high values of percentage of initially exposed timber (75% of wall surface A_{wall} for the present case study).

The main finding of this study pertains to the acceptable proportion of unprotected timber that can be incorporated into the design of a structure's fire resistance and protection measures. In numerous regulatory frameworks, the permissible percentage of exposed timber reduces (up to the stipulation for complete encapsulation) in correlation with the increase height of the building. Given that increasing building height, due to the increased egress time, requires higher fire-resistance and protection time, this study shows that, for the same building consequence class, **the percentage of exposed timber for taller building could remain the same or even increase.**

This case study also demonstrates that this method and these tools could be used to **determine the maximum permitted percentage of exposed timber** in accordance with the general objectives

of fire safety regulations for building types **without active fire protection systems, as well as the increase in this percentage where such systems are present.**

However, in order to confirm these preliminary conclusions and before applying the method to different typologies (different use of buildings and different types of exposed surface of structural mass timber), the benchmarking of the model predictions highlighted six limitations and improvements that need to be made:

- The enhancement of char prediction accuracy could be achieved through the refinement of the reduction coefficient and contribution law, thereby ensuring more precise predictions. In particular, the implementation of the zone model should consider the temperature-dependent characteristics of the thermal properties of gypsum board. This will ensure that the interface temperature is less conservative, and the contribution law could be adapted accordingly.
- According to further functional requirement to be published in the actual revision of regulation in France, criterion spread via openings to other buildings could be reviewed.
- Furthermore, the criterion for fire spread to the upper compartment of the building by the facade should be implemented.
- Some of the assumptions were fixed more or less arbitrary (opening factor distribution and cut, action delay of the fire brigade according to the floor level of the sample compartment, number of try - and delay in between - of the fire brigade intervention), and so would need to be set with relevant parties or subjected to sensitivity studies.
- The resistance criteria need to be refined, particularly with regard to the “char equivalency method”. This method is to be demonstrated as conservative and refined (refine could be done, for example, through post-processing with finite element analysis according to the calculated time-dependent temperature and thermal impacts on the structural elements). In particular, the effect of thermal diffusion during the decay phase of a fire should be formally evaluated or sufficient overall conservatism should be demonstrated.
- Include additional parameters and their distribution law parameters as: timber characteristics (in conjunction with revised resistance criterion), wind speed and direction, distance to exterior building, level in the building of the compartment with the fire event allowing to adjust t_{action} the action delay of the fire brigade .

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Appendix A: Experiments benchmark

Columns in Table 2 are colored from the lower (green) to the higher value (red). For opening factors the color scale is inverted (from higher to lower), since lower opening factors result in under-ventilated fire, prolonging fire duration and increasing char depth.

Table 2: List of 54 experiments

Institution [Ref]	Experiment Name	$F_d^a)$ [MJ/m ²]	A_f [m ²]	$A_t^b)$ [m ²]	A_{exp}/A_t [%]	$O^b)$ [m ^{1/2}]
		fuel load density per floor area	Floor Area	Comp Area	Exposed timber	Opening factor
Carlton University [14]	McGregor_1	482	15.35	69.3	0%	0.044
	McGregor_3	182	15.75	71.5	75%	0.042
	McGregor_4	553	15.35	69.3	0%	0.044
	McGregor_5	529	15.75	71.5	75%	0.042
Carlton University [15]	Medina_1	532	15.55	70.03	28%	0.043
	Medina_2	532	15.52	69.98	31%	0.043
	Medina_3	532	15.64	71.14	16%	0.042
NRCC&NIST [16]	NRCC&NIST_1	549	41.86	157.7	0%	0.032
	NRCC&NIST_2	548	41.86	157.7	0%	0.065
	NRCC&NIST_3	556	41.86	157.7	16%	0.065
	NRCC&NIST_4	548	41.86	157.7	27%	0.032
	NRCC&NIST_5	556	41.86	157.7	16%	0.032
	NRCC&NIST_6	550	41.86	157.7	42%	0.032
NRCC_Room [17]	NRCC_Room_1	550	10.48	57.7	0%	0.037
	NRCC_Room_2		10.82	59.1	23%	0.036
	NRCC_Room_3		10.70	58.7	23%	0.037
	NRCC_Room_4		10.70	59.1	29%	0.036
	NRCC_Room_5		10.82	59.6	40%	0.036
NRCC Misc [18]	NRCC_Elevator	790	23.69	100.1	0%	0.064
Edinburgh University [20]	Edimb_1	132	7.26	44.4	34%	0.043
	Edimb_2		7.26	44.4	34%	0.043
	Edimb_3		7.33	44.7	33%	0.042
	Edimb_4		7.33	44.7	33%	0.042
	Edimb_5		7.26	44.4	50%	0.043
Edinburgh University [21]	Emb_1	100	11.98	60.3	35%	0.043

Institution [Ref]	Experiment Name	$F_d^a)$ [MJ/m ²]	A_f [m ²]	$A_t^b)$ [m ²]	A_{exp}/A_t [%]	$O^b)$ [m ^{1/2}]
USDA [22]	USDA_1	570	82.38	262.9	0%	0.106
	USDA_2		82.38	262.9	3%	0.106
	USDA_3		82.96	264.4	12%	0.106
	USDA_4		82.96	264.4	34%	0.106
	USDA_5		82.96	264.4	34%	0.106
Cerib [23]	Epernon_1	891	24.00	98.4	21%	0.144
	Epernon_2		24.00	98.4	21%	0.050
	Epernon_3		24.00	98.4	21%	0.032
NRCC_LS [24]	NRCC_LS_1	613	22.40	99.9	0%	0.072
	NRCC_LS_2		22.40	99.9	30%	0.072
	NRCC_LS_3	15	22.40	99.9	55%	0.072
	NRCC_LS_4	224	51.1	179.42	69%	0.116
	NRCC_LS_5	362	201.25	687.3	42%	0.107
RISE [25]	RISE_1	560	47.07	169.1	31%	0.063
	RISE_2				53%	
	RISE_3				59%	
	RISE_4				48%	0.267
	RISE_5				59%	0.063
Arup/Cerib [26] [27]	CodeRed_1	374	351.95	980.1	37%	0.070
	CodeRed_2	377	351.95	980.1	37%	0.039
AdivBois [28]	AdivBois_1	968	28.58	112.81	13%	0.059
	AdivBois_2	809	28.58	113.66	25%	0.131
	AdivBois_3	795	28.58	113.66	22%	0.131
	AdivBois_4	822	28.58	113.66	25%	0.131
Technical University Zurich [29]	TIMPuls_0	1085	20.25	83.70	0%	0.094
	TIMPuls_1	1085	20.25	83.70	24%	0.094
	TIMPuls_2	1085	20.25	83.70	26%	0.094
	TIMPuls_4	1085	40.50	145.80	43%	0.094
SEIFBois [30]	SeifBois_E11a	350	55.75	209.5	22%	0.063

^{a)} Fuel type cribs and/or furniture's except for experiments McGregor 1 and 3 where it is propane burner. NRCC LS 3 is a construction fire scenario with garbage bin fire source

^{b)} The opening factor is defined as $O = A_v \sqrt{H_v} / A_t$ where $A_v = \sum A_i$ is the sum of all openings areas (A_i , m²), $H_v = (\sum H_i A_i) / A_v$ is the sum of each opening height (H_i , m) multiply by their area divided by the total opening area, and the compartment boundary area A_t is the total enclosing area (including openings)