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A PERFORMANCE-BASED DESIGN AND STOCHASTIC ANALYSIS APPROACH FOR DETERMINING THE ALLOWABLE PERCENTAGE OF EXPOSED STRUCTURAL MASS TIMBER IN BUILDING.

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ABSTRACT: Use of structural timber in buildings, including in mid-rise and high-rise buildings, is a major lever for decarbonising the building sector and, in fact, an important way of complying with new environmental regulations and meeting global and national low carbon pathways. Conversely, in light of the expansion of timber construction, prescriptive fire regulations, with the required degree of passive and active protection and encapsulation of structural timber members can counter to the economy of construction and the reduction of the carbon footprint. Using a recently developed predictive method for the stability of exposed mass timber exposed to natural fire in buildings, a method for conducting parametric an stochastic studies to define, for a given type of construction, a percentage of exposed structural timber reaching tolerable risk objective is presented. The definition of absolute value targets based on the level of reliability required by Eurocodes and relative value targets (deemed-to-satisfy solutions) are discussed. The construction of scenarios, the parameters and their distribution, and the calculation of total probability failure by lifetime for the relevant criteria are defined. The Implementation of the method for a given typology of construction, allowing compliance with the requirements of performance-based building codes, is discussed.

KEYWORDS: Performance-based design, exposed mass timber, fire safety, probabilistic, monte carlo

1. INTRODUCTION

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 objective of fire safety regulations. The introduction of a probabilistic approach to fire simulation for exposed mass timber construction (fire is by nature a stochastic phenomenon depending on the value of the movable fuel, which is increased by the contribution of the exposed mass timber) allows for the running of parametric studies on generic types of construction and the evaluation of which one reaches the required goals.

It is well established that exposed mass timber in a building may contribute to the growth, severity and spread of a compartment fire. Given that zero risk does not exist, and that ultimate-states based regulations, such as the Strutural Eurocode, are driven by a reliability factor designed to cover a non-zero but tolerable risk, tools are needed to calculate the level of reliability for a given configuration of mass timber building (e.g. with a given percentage of exposed unprotected timber, with or without an active sprinkler system) in order to avoid ”de facto ban” on timber structures resulting from the application of several prescriptive regulations.

2. PROJECT DESCRIPTION

The European research projects RISK REI Hietaniemi (2005) [1] and FireInTimber (Fire Resistance of Innovative Timber structures) Mikkola (2010) [2] developed a probabilistic approach to assess fire safety in a performance-based design. This project, based on these works and an application example [3] [4], has adapted and extended the stochastic analysis method by adding a parametric study for a generic compartment typology with exposed mass timber in order to evaluate the allowable percentage of unprotected timber elements.

As underlined in [5]: “In general terms, a prescriptive code states how a building is to be constructed whereas a

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performance-based code states how a building is to perform under a wide range of conditions". There is a large body of literature on the performance-based approach, and readers unfamiliar with these concepts (absolute or relative basis, deemed-to-satisfy solution -DTS-, etc.) are invited to consult it, particularly [2] [5] in the context of timber buildings.

However, it is worth noting that the overall safety objectives in this study focus on structural stability and fire spread within the building and to adjacent areas or buildings. The presence of structural timber does not present particular difficulties in terms of smoke limitation and evacuation of people, and these objectives can be met through the 'business as usual' application of prescriptive codes as well as a performance-based approach.

3. PERFORMANCE-BASED DESIGN PROCESS

As for [2] [3] the absolute value to assess the tolerable risk is set to the probabilyt $\mathbb{P}_a = 72.3.10^{-6}$ per building lifetime corresponding to the safety index β=3,8 as stipulated in Eurocode 0 [6].

The overall method is based on the following assumptions and steps:

1. Choosing of a given typology, covering:
    - Use of the building: residential, office, industrial and storage etc.
    - Type of structure and exposed timber: CLT wall and/or ceiling, GLT post and/or beam, lightweight wood frame (LWF), composed structure etc.
    - Fire category of the building and REI requirements (30,60,90, 120 minutes or more)
    - Surface of exposed timber (unprotected) set as a percentage of the exposed structural timber area under the total enclosure area A_t (sum of floor, ceiling and wall area including openings)
    - Type and characteristics of fire detectors
    - Presence (or not) and type and characteristics of active system (sprinklers)
2. Selecting the relevant parameters and their distribution. Readers may find example of the following in [2], [7] and [11]:
    - The size of the compartment
    - The opening factor and configuration of the opening (closed / open, type of glass)
    - The environmental conditions (temperature, wind pressure and direction)
    - The design fire (fire load density, fire growth, rate of heat release, position of ignition)
    - If any, from their characteriscs, sensivity and reliability of sprinklers system
    - Characteristics of fire protection. As per structural timber but adding a distribution law on effective surface and thickness to take in account lifetime degradation of the protection (as loss of a part of the total surface of protection by 'vandalism' of the occupant of the dwelling or low quality of works)
    - The mechanical and thermal (density, heat of combustion) properties of structural timber
    - The dimensioning load combination for each structural members including permanent and variable action (G, Q) according to Eurocode [6] [12]
3. Failure probability for the typology is proceeded by:
    - The calculation of the probability $\mathbb{P}_{fire}$ of a developed fire with timber contribution using an **event tree method** (further description)
    - Monte Carlo simulation for the parameters and their distributions from point 2 above, with each of the draws: calculation of the time-dependent temperatures, flux and charring depth of the structural timber (initially protected or not). From these values, the fire resistance duration of the structural elements t_{res}, and the time of propagation (internal $t_{p,int}$ and external $t_{p,ext}$) are deduced regarding the three **performance criteria** (further description).
    - Therefore, for a specified time t_d and for each variable X_i (the i^th fire event in compartment draw) the probability of failure can be calculated. This is 1 if t_d is greater than the time value for the three types of failure, and 0 otherwise. The probability of failure for X_i and t_d is thus given by

      $$\mathbb{P}_{fail}(X_i,t_d)=\begin{cases}1\ for\ t_d > \mathrm{Min}(t_{res}, t_{p,int}, t_{p,ext})\\ 0\ for\ t_d \leq \mathrm{Min}(t_{res}, t_{p,int}, t_{p,ext})\end{cases}$$

      For the draw of N variables X_i the probability of failure is given by:

      $$\mathbb{P}_{fail}(t_d) = \frac{\sum_{i=1}^{i=N} P_{fail}(X_i,t_d)}{N}$$
4. Finally, for a given time t_d (60, 90, 120minutes or whole fire duration):
   Comparison of the overall probability of failure $\mathbb{P}(t_d) = \mathbb{P}_{fire} * \mathbb{P}_{fail}(t_d)$) of the typology with the absolute value $\mathbb{P}_a$ and/or DTS probability $\mathbb{P}_{dts}(t_d)$ calculated as for the given methodology (i.e for the same parameters and their distributions).

Calculation of time-dependent curves in step 3 are made via an iterative process taking in account the structural

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timber contribution of protected and unprotected members to fire as describe in [9].

Event tree method methods make it possible to determine the probability of a fire developing when the undesirable event of a fire occurs. The basic idea of the method is to analyse the fire event by dividing its progress into a relatively small number of discrete time intervals. At each time interval, an event tree is constructed to describe the fire-related processes and potential actions (by humans or by automatic systems) to detect and fight the fire, as illustrated on *Figure 1* [8].

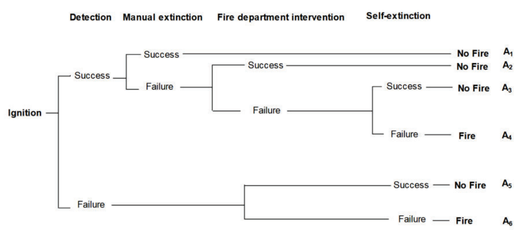

Figure 1: Event Tree to analyse the fire incident at a specific time.

A1,	*No fire:*	*Detected, Extinguished manually*
A2	*No fire:*	*Detected Extinguished by the fire department*
A3	*No fire:*	*Detected, Fire burned out*
A4	*Fire:*	*Detected,*
A5	*No fire:*	*Not detected, Firre burned out*
A6	*Fire:*	*Not detected*

The details of the progress of the fire incident are described by the branching probabilities of the event trees. For the case of *Figure 1* the probability of no fire is $\mathbb{P}_{\text{no-fire}} = \mathbb{P}(A_1 \cup A_2 \cup A_3 \cup A_5)$. The probability of fire with timber contribution is then given by multiplying the probability that any fire occurs for the choosen typology by the probablity that this fire growth (i.e. is not extinguished by occupants or fire brigade) $\mathbb{P}_{\text{fire}} = \mathbb{P}_{\text{fire\_event}} * (1 - \mathbb{P}_{\text{no-fire}})$. There are several levels of analysis via the event tree method with increasing complexity and number of parameters considered as described in [1], [3] and [8]. For the method of the present project, this "pre-process" only deals with the parameters of *Figure 1*. As time-dependent curves are calculated with ‘advanced’ two-zone model (BRISK or CFAST) [9], the effect of the active system as sprinklers (if any) is taken into account in the calculation of $\mathbb{P}_{\text{fail}}(t_d)$ via this model setting the parameters of the sprinkler given by the Monte Carlo draw.

<u>Nota:</u> In the same way an alternative to the preprocessing with an event tree method to calculate the probability of fire extinguished by occupants or fire brigade is under evaluation. This could be made with adding in the two-zone calculation ‘virtual sprinklers’ representing the occupant or fire brigade intervention according to distribution law of such events (occupied hours, delay time of fire brigade…)

The three **performance criteria** above are set as:

1. Structural failure:
   Members mechanical resistance shall be verified for the given duration of fire exposure t as required by Eurocode 5-1.2 [12] formula (4.2): $E_{d,fi} \leq R_{d,fi,t}$ where $E_{d,fi}$ is the design value of the effect of the actions for the fire situation, determined in accordance with EN 1991-1-2, $R_{d,fi,t}$ is the corresponding design resistance in the fire situation. The value t_{res} in step 3. above is then calculated following advanced design methods of Eurocode [12] using time-dependent temperatures from the concerning draw .
   As this method impose to chain a post-processing of thermo mechanical calculation which can be time consuming, two simplified method are under evaluation:
   - Application of the future Annex “Design of timber structures exposed to physically based design fires” of EC5-1-2 currently under study by CEN/TC 250/SC 5 "Eurocode 5: Design of timber structures" including a simplified method to calculate the effective cross section (taking in account decay phase of fire development).
   - Simplified ‘char equivalency method’ by setting the time t_{res} as the time at which the charring depth of the draw is less (with a margin allowing for a conservative assumption that it covers the thermo-mechanical effect of the real time-dependent temperature curve on the member) than the charring depth calculated for the dimensioning under fire of the members according to Eurocode (i.e. one used for the initial verification of formula (4.2) see 1 above). It is important to note that, even if this method proves to be too conservative, it could be used at the very least for the number of thermo-mechanical calculations required.
2. Internal propagation (i.e. propagation to other compartment of the building):
   By checking that during the fire until t_d the increased temperature of the unexposed face of each seprating element (i.e. wall; ceiling, or floor is less than the limit used for EI characterisation of 140 K)
3. External propagation (i.e. propagation to others buildings). Two possibilities are considered for this criterion:

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- If this value is given by the two-zone model, the criterion is met if the total flux at the opening remains less than 45 kW/m² during the time limited by t_d.
- Calculation according to Annex B of EN1991-1-2 (and the future Annex E of EN1995-1-2 taking into account the structural fuel load) of the flux verticaly at the façade at 1.2m above level N+1 and horizontally 8m from the façade and verification that the flux remains below 15kW/m².

4. CASE STUDY

To illustrate the method, a case study was carried out with 1000 draws of Monte Carlo and a reduced number of variable parameters (with distribution) with respect to those described in 3.

The variable parameters and their distribution (which have been set to be close from those used for similar studies in [3] [7] and [11]) are as follows:

1. Floor area:
   Following a normal distribution with a mean of 50m² and a standard deviation of 7.
2. Compartment heigth:
   Following a normal distribution with a mean of 2.9m and a standard deviation of 0.1.
3. Opening factor
   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 opening areas (A_i, m^2), $H_v = (\sum H_i\ A_i)/A_v$ is the sum of each opening height (H_i, m) multiply by its area divided by the total opening area, and A_t is the total enclosing area (including openings). The distribution is a lognormal with a mean of 0.06 and a standard deviation of 0.001. As the case study is for dwellings, a lower cut has been made in the distribution in order to obtain ratio A_v/A_f > 1/6 (allowing to have sufficient light in the dwelling and as required by the French regulation). In the case of a high opening factor, if the façade surface is not sufficient for the resulting opening area, openings are created on the opposite wall creating through-ventilation configuration (16% of the draws in the present case study)
4. Fuel load:
   The initial fuel load and corresponding HRR (Heat Released Rate) have been set following method describe in [9] with a fixed HRRPUA of 250kW/m² and a fire load following a Gumbel distribution with a mean of 509MJ/m² and a and a standard deviation of 92 (corresponding to a 80% fractile of 575) as proposed in [7]

The char depth was then calculated using an iterative process taking into account the movable fuel load and contribution of structural timber using the 'Flux' method as described in [9]. For all draws, fire duration of 180 min (three hours for the duration of the initial fuel load HRR, including decay and for the calulation of timber contribution), whole fire duration of four hours (end time of char depth calculation) and a fixed ratio of exposed timber to total enclosure area A_t of 30% were used. As the dimensions of the compartment and the opening vary between draws, the ratio of the opening area to the rest of the surface area varies as shown in *Figure 2*. However, it should be noted that this value of 30% of tthe total enclosure area is quite large (approximately 110% of the floor area and 80% of the wall area). As a hypothesis for this case study, it has been assumed that this 30% of exposed timber is dispach with 22.5% on the wall, 5% on the beams and 2.5% on the columns. The unexposed timber was protected with two layers of 15.9mm of gypsum board type X(5/8in).

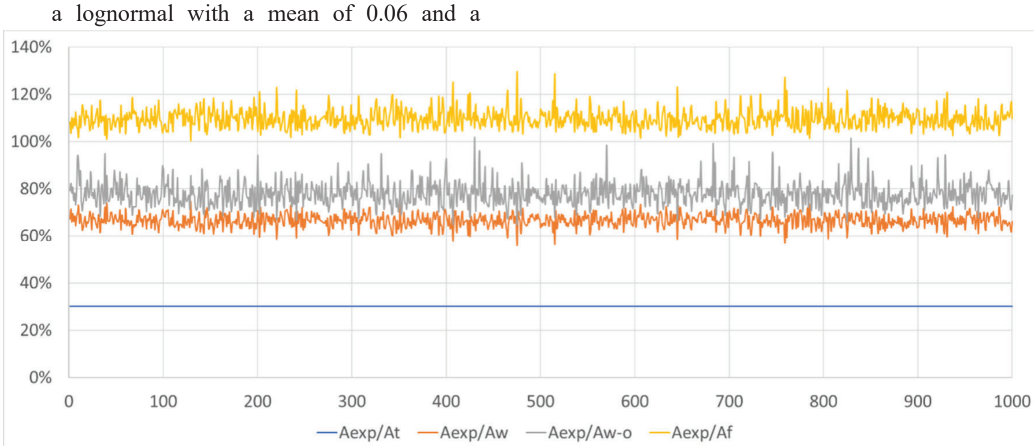

Figure 2: variation of ratio of exposed timber d surface on: wall surface (Aw), wall surface excluding openings (Aw-o) and floor surface (Af) with a fixed ratio of exposed wood surface on At of 30%

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5. RESULTS

The distribution result of the case study is shown in *Figure 3* in terms of char depths. It can be noted that, as for large scale compartments (see [9]) of such a ratio of total exposed timber, the mean value of char depth for walls is higher than for columns and beams. In this case study, this can be explained by the fact that we have set a constant parameter of wood density with a higher value for beams and columns (as glulam members), than for walls (as CLT), resulting in a slightly lower char rate for linear members. In the following discussion of failure criteria, only walls are then considered.

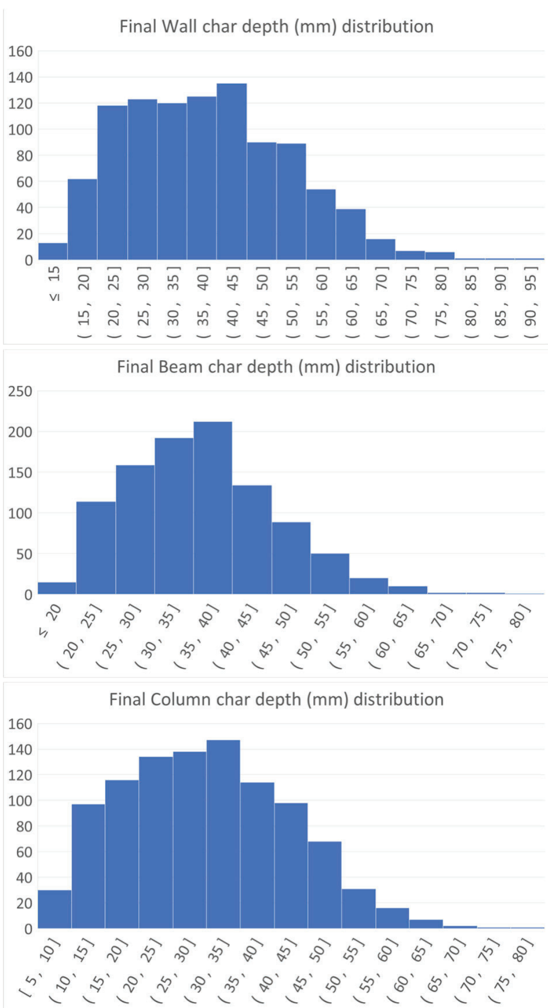

Figure 3: distribution (numbers of draws by step of 5mm char) under 1000 draws for Walls, Beams and Columns

As **an illustration of how to get the probability** of structural failure for the whole fire duration (four hours in this case) and to have an idea of the order of magnitudes of the values following assumptions are made:

1. According to [1] the frequency of fire occurrence for dwellings in France is $21.2\ 10^{-6}/(\text{m}^2\ \text{year})$. Hietamini [3] for a similar study " assign a probability of 1% to the design fire, i.e., we assume that only one fire out of 100 fires reported to the fire brigades has the potential of growing as severe as our design fire". Even if the severity of the design fire in the present case study (with a constant HRRPUA of 250kW/m²) is higher than in [3] (Weibull distribution of HRR with a median of 227MW and a standard deviation of 87MW leading to a maximum HRR of 292MW and a HRRPUA, for 1700m², of 172kW/m²), there are no statistical data for France to corroborate this important assumption. Nevertheless, as a simplified assumption, the same value of 0.01 is used to cover the probability of such a severe fire **and** the probability of the fire being detected and extinguished by the occupants or the fire brigade (i.e. the value of $(1 - P_{no\text{-}fire})$). For an average area of 50 m², as used in this case study, this gives:

   $P_{fire}=21.2\ 10^{-6}$ *50m² * 50year * 0.01= $5.3\ 10^{-4}$ per life time.
2. Simplified char equivalency hypothesis: Generaly structural members are design according to Eurocode and formula (4.2) by the effective cross-section method using the effective charring depth given by formula (7.3):

   $d_{ef} = d_{char,n}+d_0$ where d_{ef} is the effective charring depth and d_0 is the zero-strength layer taking in account the loss of strength of the member due to thermal agression of fire. $d_{char,n}$ is given for each fire resistance (R 60, R 90, R 120) as sumarized in *Table 1* according to a charing rate of approximativly 0.7mm/min. Even if this formula (7.3) and this charring rate is only valid for use regarding the standard fire exposure and not with other temperature- timecurves as "natural" fires, the following aproximation is made: if is the total char depth calculated at time t_d is less than the design value $d_{char,n}$ it is assumed that the member will withstand the design value of effect of actions for the fire situation. With this smplified assumption, values for a fire resistance R 90, as the distribution gives 43 draws with a final char depth superior to 63mm (= 90min*0.7mm/min), the coresponding P_{fail} take the value of 43/1000 = 0.043 (see *Table 1*)

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In view of these simplified assumptions, the distribution result gives the following table for the total fire duration and for each hypothesis of wooden wall design (R60, R90 or R120):

Table 1: Approximation[(a)] of case study failure probability

R [min]	$d_{char,n}$ [mm]	P_{fire}	P_{fail}	P	$<P_{a=}$ $72.3\ 10^{-6}$
60	42	$5.3\ 10^{-4}$	0.386	$205\ 10^{-6}$	NO
90	63	$5.3\ 10^{-4}$	0.043	$23\ 10^{-6}$	YES
120	84	$5.3\ 10^{-4}$	0.002	$1\ 10^{-6}$	YES

[(a)]It should be pointed out that these values are formed like described in the text. There could be significant uncertainty with the presented values.These values should be updated with the overall calculation described in 3

6. FIRST CONCLUSIONS AND FURTHER STEPS

In the context of the objective to develop methods and tools for calculating the reliability of a given configuration of mass timber buildings in fire situation, this paper presents the method and a case study of a performance-based design and stochastic analysis approach that confirms the feasibility of the project. However, before the method can be applied to different typologies (building use, timber structure and passive and/or active protections), further steps must be taken. These include:

- An enhancement to the brick of calcul of fire development and timber contribution, as outlined in [9], to ensure a more accurate representation of actual conditions which are probably too conservative
- The selection of (and implementation of the method for) a DTS solution (deamy-to-satisfy solution)
- The finalisation of the failure criteria, as discussed in 3 (in particular the simplified 'char equivalency method' which should be consolidated), and the configuration of the program to record results for each draw accordingly.
- Pursue bibliographic research and interviews to collect more data with the goal of improving the distribution law of all parameters (e.g. intervention time, probability of fire event by typology, fuel load, HRR and HRRPUA…).

CONFLICT OF INTERESTS

The authors declare that they have no conflicting interests concerning the publication of this article.

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