Development of a Bayesian framework for the post-fire assessment of concrete structures

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ABSTRACT:

Fire can have a significant impact on concrete structures, including the reduction of their structural capacity. A post-fire assessment must be conducted to determine the condition of the structure, which is based on a series of techniques and expert knowledge. To accurately assess the reliability of the structure, uncertainties from each step of the assessment should be incorporated into the analysis. Hence, a Bayesian framework for the post-fire assessment of concrete structures is presented. This paper focuses on three assessment techniques: visual inspection, reinforcement sample testing, and concrete core discolouration. A synthetic dataset of these results is generated and the prior uncertainty of the parameters influencing fire exposure and material behaviour is modelled based on literature data. The updated parameters are used for a probabilistic assessment of the residual capacity of a concrete member. The paper demonstrates how gathered information allows updating the prior distributions about fire exposure and residual structural capacity.

1. INTRODUCTION

1.1. Post-fire assessment of concrete structures

Fire can cause extensive damage to concrete structures, including reduced structural capacity and stiffness, cracking, spalling, and residual deformations. However, concrete structures are typically able to withstand severe fires without collapsing, due to their thermal and mechanical properties and dimensions (Beitel and Iwankiw 2005). Nonetheless, fire damage may include altered mechanical properties, cracks, plastic strains, and thermally irreversible strains, all of which can significantly impact the structure's performance and residual life. To evaluate the residual structural capacity after a fire, a post-fire assessment must be performed, using a combination of non-destructive, destructive, and calculation-based techniques, and expert knowledge (Jovanović et al. 2023).

The fire phenomenon is highly complex and uncertain, which presents significant challenges for the post-fire assessment of concrete elements. The uncertainties are related to fire dynamics, such as fuel burned, burning rate, available oxygen, ventilation conditions, and fire spread, as well as to structural behaviour in fire, including heat transfer processes and material behaviour at high temperatures. Additionally, the fuel load is consumed during the fire, and thus cannot be directly measured after the fire. The mechanical properties of the materials cannot be directly measured without damaging the structure. As a result, the parameters must be assessed indirectly, through measurement of the fire's residual effects, such as residual deformations, damage patterns, discolouration, crack patterns, and material degradation (CIB W14 Report 1990).

In recent years, there has been a significant increase in research into the post-fire capacity of concrete structures, with experimental test programs, numerical studies and a combination of experimental and numerical approaches. Most of these studies have been deterministic, with a notable exception being the work of (Molkens et al. 2017), which applied a reliability-based methodology to assess the safety level of a fire-exposed concrete slab. However, this study only considered three fire exposure cases and probabilistic models of fire severity were in effect based on expert judgement, highlighting the need for a post-fire assessment method that considers the uncertainty of the influential variables and properly assesses the structure's capacity and safety level

1.2. Bayesian approach

Bayesian inverse techniques are a useful tool for evaluating influential variables and their uncertainty in fire safety problems. Previous studies have applied these techniques to determine the heat source magnitude from temperature data, using a zone model and measured gas temperature to find the fire size and origin in a multi-compartment structure, and inverting the fire's heat release rate based on room-scale temperature data.

However, these studies relied on data that is not available in real post-fire assessments. Therefore, in this paper, a Bayesian framework for the post-fire assessment of concrete structures is presented. The framework is based on the results of three different assessment techniques: visual inspection, reinforcement sample testing and colourimetry of sampled cores. The results of these three techniques are used to update prior assumptions on the experienced fire exposure and the initial material properties of structural members.

2. METHODOLOGY

In the following sections, first, the information obtained from these techniques is presented. Afterwards, the Bayesian framework is elaborated including the definition of the priors, errors and likelihood function. Finally, the application of posterior results to assess the structural member's residual capacity is described.

2.1. Visual inspection

One of the most commonly used techniques for post-fire assessment is the visual inspection. This technique consists of observing signs of fire, damage to the objects inside of the compartment and the residual condition of the structure. It is an essential step of the assessment and can provide valuable information on the position, intensity and extent of the fire that occurred. On the other hand, it does not provide a large amount of objectively quantifiable information. Through visual inspection, for instance, it can be inferred that a member was exposed to high heat flux, but not how large that heat flux was.

One of the rare quantitative indications which visual inspection can provide is the maximum temperature achieved during the fire. In most cases of fires in a built environment, multiple objects made of different materials are present in the compartment. Different materials melt or change their properties at different temperatures. As an example, aluminium melts at

600°C and brass at 900°C. Therefore, if during the visual inspection, it is observed that there are signs of melted aluminium, but the brass objects remained whole, it can be safely assumed that the maximum temperature achieved during the fire was in the range of 600°C to 900°C.

An indication of the maximum temperature in the compartment is not sufficient to characterize the fire exposure and the energy the structure receives during the fire. A common way of representing the fire is by using temperature time curves and one of the most often used is the Eurocode Parametric Fire Curve (EPFC) described in EN 1991-1-2 (CEN 2002). It defines the temperature-time curve as a function of the ventilation conditions (opening factor O), available combustabe material (fuel load q_f) and linings thermal properties (thermal inertia b). All three of these factors are highly influential with respect to fire exposure and hence the heat transfer and the residual condition of the structure. However, their determination during the assessment is difficult and prone to large uncertainties. For that reason, application of the Bayesian approach is recommended.

2.2. Reinforcement yield strength test

When exposed to elevated temperatures, reinforcement steel can experience a reduction of its mechanical strength properties. This reduction can be expressed using the strength reduction parameter $k_{y,res}$, whose behaviour as a function of the maximum temperature it experienced $\left(T_{\mathrm{max,reb}}\right)$ can be described using the following equation (Kodur and Agrawal 2016):

$$k_{res,y}\left(T_{\mathrm{max,reb}}\right) = \\ = \left\{ \begin{matrix} 1, & T_{max,reb} < 500°C \\ 1 - \frac{T_{max,reb} - 500}{1000}, & 1500°C > T_{max.reb} \geq 500°C \end{matrix} \right\} \tag{1}$$

The residual strength of the reinforcement not only contains the information on the fire exposure (as the reduction is a function of the temperature) but also highly influences the residual capacity of the structural member.

Therefore, removing a sample of the reinforcement and testing it for its residual yield strength can provide valuable information for the post-fire assessment.

It must be noted that reinforcement residual strength is not only a function of the reduction due to the temperature effects but also the yield strength it had before the fire. By also testing the strength of the undamaged reinforcement from the same member, additional valuable information on the temperature effect (and fire exposure that caused it) can be obtained.

2.3. Discolouration

Along with the decrease in strength, several other notable surface changes can be seen in the structural members, one of them being the colour change. The normal colour of concrete tends to change with increasing temperature to pink or red (300-600°C), whitish grey (600-900°C), and beige (900-1000°C). The pink-red discolouration comes from iron compounds in the fine or coarse aggregate, which oxidizes in this temperature range. The strength of this colour change depends on the type of aggregate, with siliceous aggregates showing a stronger change and calcareous and igneous aggregates showing a weaker change (Short et al. 2001). Detecting the first colour change is crucial as it usually signifies the beginning of a significant loss of concrete strength due to heating.

Therefore, by removing a concrete core from a fire-affected member and observing the colour change along its length, it is possible to obtain information on the position of the 300°C isotherm.

2.4. Bayesian updating

In order to combine the measurements from different techniques and their uncertainties, Bayesian updating is used. Through this updating process, the posterior distributions of the influencing parameters are obtained. The posteriors are proportional to the product of their prior distributions and the likelihood of the measured data. The considered influencing parameters in this study are the three factors affecting the fire exposure: opening factor O, fuel load q_f and thermal inertia b. Additionally, the ambient yield strength of the reinforcement f_y is included.

The prior distributions of these parameters are defined based on the literature data. The opening factor is obtained as $O = O_{max}(1-\xi)$, where O_{max} is a maximum possible value and ξ is a truncated lognormal distributed parameter with a mean and standard deviation of 0.2 (JCSS 2001a). The fuel load is described by a Gumbel distribution with a mean of 780 MJ/m^2 and a coefficient of variation (CoV) of 0.3 (CEN 2002). The thermal inertia follows a Normal distribution with the mean value for concrete equal to 1900 Jm^{-2}K^{-1}s$^{-1/2}$ and a CoV of 0.15 (Jovanović et al. 2020). The yield strength follows a Lognormal distribution with a mean equal to 560 MPa and a CoV of 0.054 (JCSS 2001b).

The likelihood expresses how likely observed data are for the unknown parameters, which requires a relation between the input parameters and the measued values. For the first technique, i.e. the maximum temperature estimation, expressing this relation is the most straightforward. Using the EPFC, the maximum temperature can be obtained as a function of O, q_f and b. The likelihood is defined as being equal to 1 when the maximum temperature is in the observed range and equal to 0 when it is not.

The EPFC is then used as a boundary condition for a 1-dimensional finite difference heat transfer calculation. Using the thermal and material properties from the (CEN 2004) a temperature profile is obtained. That temperature profile is then used to calculate the position of the 300°C isotherm and the temperature of the reinforcement needed to obtain the residual strength.

The likelihood for both the position of the 300°C isotherm and the reinforcement residual strength is obtained with the assumption of an unbiased normally distributed error with a standard deviation σ_{tech} . The likelihood is calculated using the following formula:

$$L_{tech} = (2\pi\sigma_{tech}^2)^{-\frac{1}{2}} \exp\left(-\frac{(y-M_{tech}(x))^2}{2\sigma_{tech}^2}\right) \tag{2}$$

where y is the measured value of one technique and $M(x)$ is the value obtained through the described modelling for a set of input values $x = (O, q_f, b, f_y)$. Eqn. $L_{tech} = (2\pi\sigma_{tech}^2)^{-\frac{1}{2}} \exp\left(-\frac{(y-M_{tech}(x))^2}{2\sigma_{tech}^2}\right)$ (2 is used for the likelihood of one measurement, in case of multiple measurements, the total likelihood is a product of the individual likelihoods.

There is a lack of literature information on the errors of both of these techniques. Taking into account the errors of the numerical models used in this study coupled with the measurement errors, by the author's judgment they are assumed to be $\sigma_{300°C} = 50\,mm$ and $\sigma_{f_y} = 40\,MPa$, for discolouration and reinforcement yield strength respectively.

The updating is conducted using the Markov Chain Monte Carlo (MCMC) method and the Metropolis-Hastings algorithm. Due to the high computational cost, the models used for discolouration and residual yield strength calculation in the function of the (O, q_f, b, f_y), are replaced with faster surrogate models.

In the following section, the methodology is applied to a theoretical case study where first the three techniques are applied individually and then together in order to assess their strengths and weaknesses.

3. APPLICATION

3.1. Case study overview

The fire in the case study is a flashover fire in a 4 m x 4 m x 2.5 m residential compartment with a 2 m x 1 m door and a 1 m x 1 m window, making the maximum opening factor during the fire $O_{max} = 0.05\,m^{1/2}$. The linings are made of concrete, with a 20 cm thick simply supported concrete slab on the ceiling. The slab contains $780\,mm^2/m$ S500 reinforcement at 25 mm distance from the surface.

The ”true” fire is defined as an EFPC with an opening factor $O = 0.04\,m^{1/2}$, a combustible fuel load $q_f = 1000\,\frac{MJ}{m^2}$ and linings with thermal inertia $b = 1600\,Jm^{-2}K^{-1}S^{-1/2}$. The ambient reinforcement yield strength is equal to $f_y = 620\ MPa$. The post-fire assessment is conducted from the perspective of an assessing engineer who is unaware of the “true” values listed above.

Using the listed “true” values, for each technique, measurement values are evaluated using the mentioned numerical models. The estimated maximum temperature in the compartment based on the visual inspection is 900-1000 °C. The 300°C isotherm depth is measured as 65 mm. Finally, the residual strength of the fire-damaged reinforcement was determined as being 590 MPa.

The updating is first conducted for each technique separately. Additionally, it is also conducted for a case where both damaged and undamaged reinforcement strength is tested. Figure 1Figure 4 present the results of the updating.

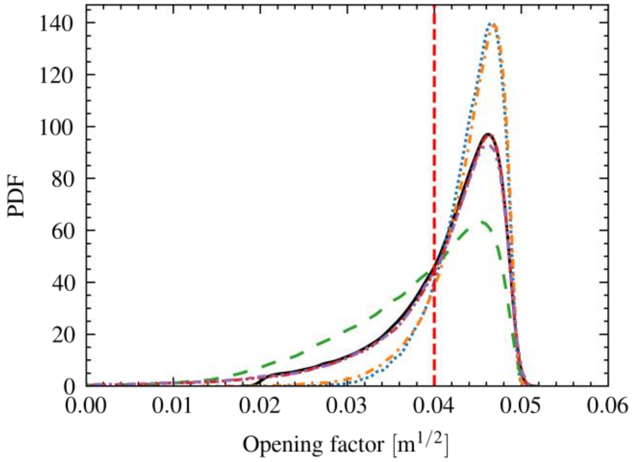

Figure 1. Updating results for the opening factor O using different assessment techniques – Prior (▬), All techniques (····), Maximum temperature (- · -), Discolouration (- - -), Damaged reinforcement yield strength (— · ·), Damaged and undamaged reinforcement yield strength (— · ·), True value (- -)

3.2. Maximum temperature estimation

The first situation considered in Figures 1-4 is based only on the maximum temperature in the compartment during the fire. As expected, the posterior distribution for the reinforcement yield strength is the same as the prior one as the maximum temperature in the compartment does not offer any information on it. The updating of the remaining three parameters is more substantial. In the cases of fuel load and thermal inertia, it is evident that the posteriors are located closer to the true values, but with limited reduction in the variance.

Contrary, for the opening factor, the posterior is not located closer to the true value, but to the most likely value of the prior. That suggests that the maximum temperature has higher sensitivity to parameters q_f and b than O. Based on the results, it can be concluded that the maximum temperature estimate provides valuable information on fire exposure.

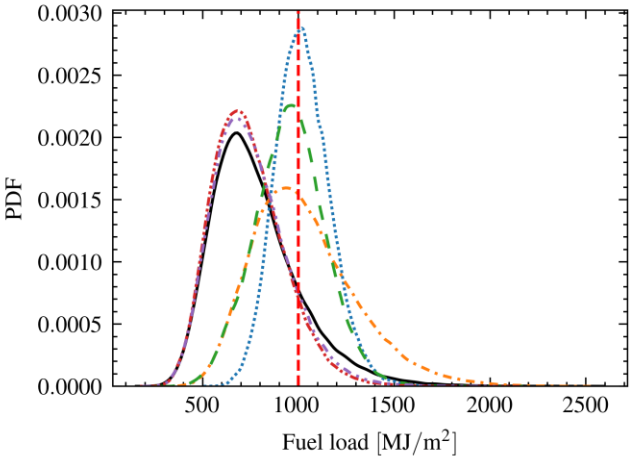

Figure 2. Updating results for the fuel load q_f using different assessment techniques– Prior (▬), All techniques (····), Maximum temperature (- · -), Discolouration (- - -), Damaged reinforcement yield strength (— · ·), Damaged and undamaged reinforcement yield strength (— · ·), True value (- -)

3.3. Discolouration

Similarly, the position of the 300°C isotherm provides information only on fire exposure. Firstly, as the posterior is almost identical to the prior, it can be concluded that it provides limited information on the thermal inertia. However, it provides more information on the opening factor and fuel load values.

3.4. Reinforcement yield strength test

The reinforcement yield strength test as expected, provides useful information on the yield strength before the fire. This is the case even if only the damaged rebar is tested or if it was coupled with the undamaged rebar test. The coupling of both tests provides more information on the yield strength.

For the fire exposure parameters, these tests yield only minimal information. This is due to the fact that the reduction caused by the fire is quite limited (only 5% in this case). In case of higher reduction, the updating from prior to posterior can be expected to be substantial. However, due to the thermal properties of concrete and common sizes of concrete cover, these situations are quite rare.

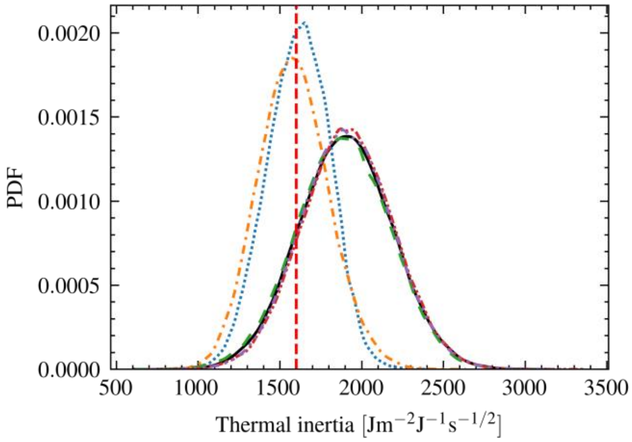

Figure 3. Updating results for the thermal inertia b using different assessment techniques - Prior (—), All techniques (⋯⋯), Maximum temperature (-·-), Discolouration (- - -), Damaged reinforcement yield strength (—··), Damaged and undamaged reinforcement yield strength (—·), True value (- - -)

3.5. All techniques

The combination of all techniques (designated by **'All'**) provides the most significant updating from prior to posterior. The maximum temperature estimation coupled with discolouration provides information on all three fire exposure parameters. It should be noted that the opening factor updating is similar to the updating as a result of the maximum temperature estimation.

The posterior for the reinforcement strength is closer to the "true" values when the maximum temperature and discolouration are also considered. It is because they bring added information about the fire exposure. This provides information regarding the difference between the damaged and undamaged strength and thus allows for an even better posterior assessment of the pre-fire strength.

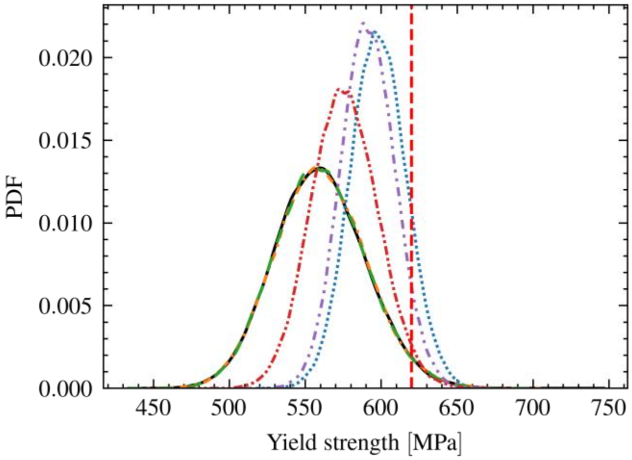

Figure 4. Updating results for the reinforcement ambient yield strength f_y using different assessment techniques - Prior (—), All techniques (⋯⋯), Maximum temperature (-·-), Discolouration (- - -), Damaged reinforcement yield strength (—··), Damaged and undamaged reinforcement yield strength ( ), True value (- - -)

3.6. Residual moment capacity

It has been demonstrated that these techniques can provide information on the influencing parameters (O, q_f, b, f_y). However, the common target of the post-fire assessment is to obtain updated information on the residual capacity and safety level of a structure and its members. For that reason, a calculation of the residual moment capacity of a concrete slab using updated information is performed.

As the 20 cm thick slab is exposed to the fire from the bottom side and therefore the compressed part remains cold, the following formula can be used for calculating the capacity (Chaudhary et al. 2021):

$$M_R = k_{y,res} \cdot f_y \cdot A_s \cdot \left(h - c - \frac{\emptyset}{2}\right) - \\ - \frac{\left(k_{y,res} \cdot f_y \cdot A_s\right)^2}{2 \cdot b \cdot f_c} \qquad (3)$$

where A_s is the reinforcement area, h is the slab height, c is the concrete cover, $\emptyset$ is the reinforcement bar diameter, f_c is the concrete compression strength and b is the slab width $(1\ m)$.

The product $k_{y,res} \cdot f_y$ is calculated based on the posterior distributions defining the fire severity. The rest of the parameters are stochastic and their distributions are given in Table 1.

The results are presented in Figure 5. Firstly, it is evident that using the maximum temperature estimation and discolouration the distribution for the residual capacity has a similar spread (standard deviation) as the prior, but lower mean value. This can be explained by the relatively low influence of the fire exposure on the residual strength of the reinforcement and the fact that it has no influence on the other parameters in Eq. $MR = k_{y,res} \cdot f_y \cdot A_s \cdot \left(h - c - \frac{\emptyset}{2}\right) -$

$$- \frac{\left(k_{y,res} \cdot f_y \cdot A_s\right)^2}{2 \cdot b \cdot f_c} \qquad (3).$$

The mean values are lower as in this case, the “true” fire exposure is more severe than the most probable one based on the priors.

As it is the most influential parameter for the residual capacity, in the cases where the reinforcement strength is taken into account, the variation is lower. When testing only the strength of the damaged reinforcement, the values are lower than when the undamaged one is also tested. This is because the updated ambient strength values are lower as can also be observed from Figure 4. When combined with the same distributions for the fire exposure parameters, this leads to a lower residual capacity.

Finally, when all the techniques are incorporated, the distribution is between the distributions obtained using the first two fire exposure oriented techniques and the distributions using the reinforcement strength oriented ones. This is because these results take into account, on one hand, more severe fire exposure and on the other hand higher yield strength of the “true” values in this case study than those obtained from the priors.

4. CONCLUSION

In order to accurately assess the reliability of a fire-exposed structure, uncertainties in each step of the post-fire assessment should be

Table 1. Stochastic parameteres used for the calculation of the residual capacity of a simply supported slab

Name	Unit	Distribution	Mean	Standard deviation
Total thickness - h	mm	Normal	200	5
Concrete compressive strength - f_c	MPa	Lognormal	42.9	6.4
Concrete cover - c	mm	$Beta\ [\mu \pm 3\sigma]$	25	5
Reinforcement area - $A_s(\emptyset = 10mm)$	mm^2/m	Normal	800	16

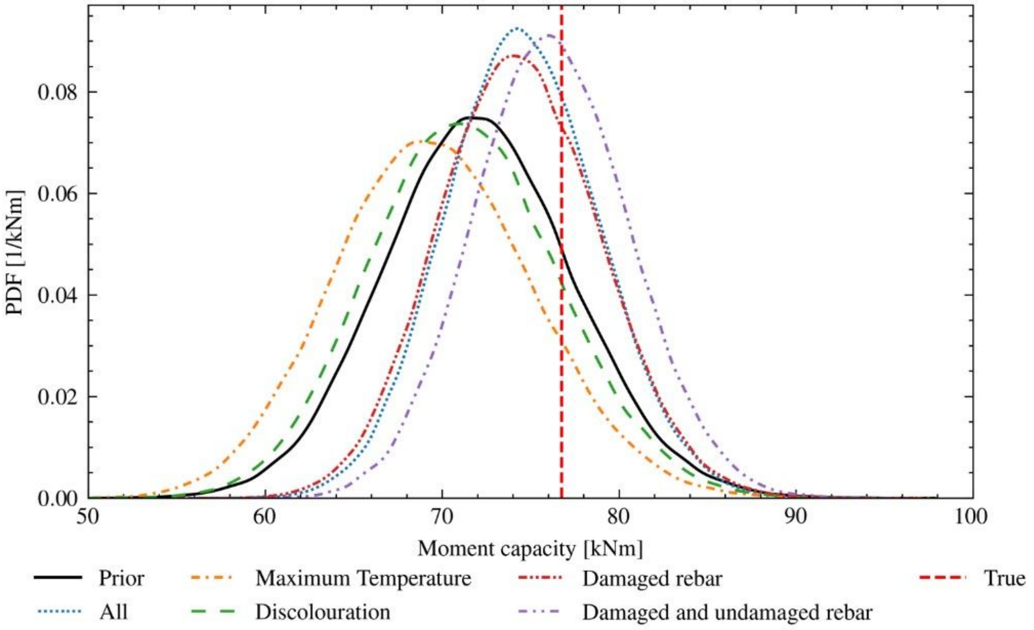

Figure 5. Residual capacity of a simply supported slab calculated using posterior distributions of different assessment techniques

incorporated. For that reason, a Bayesian framework for the post-fire assessment of concrete structures is presented.

This framework was demonstrated in a simple case study. The technique of maximum temperature estimation, concrete discolouration, reinforcement yield strength testing, and the combination of all techniques were used to evaluate the material and fire exposure parameters.

The results showed that the maximum temperature estimation provided useful information on the fire exposure, but only limited information on the opening factor. The discolouration technique provided better information on the fuel load and opening factor, but limited information on the thermal inertia. The reinforcement yield strength testing offered valuable information on the pre-fire yield strength, but limited information on the fire exposure parameters. The combination of all techniques provided the best results, providing information on all three fire exposure parameters and the difference between the damaged and undamaged reinforcement.

Finally, the residual moment capacity of a concrete slab was calculated using the updated information, demonstrating that these techniques can provide valuable information on the residual capacity and safety level of a structure and its members. The conclusion is that the combination of all techniques within a Bayesian framework provides the most comprehensive post-fire assessment, leading to more accurate and reliable results.

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