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State-of-the-art review of the reliability evaluation of concrete beams exposed to fire

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Abstract

Purpose – This paper aims to investigate the state of the art for the reliability evaluation of reinforced concrete beams in a fire situation. Special emphasis is placed on addressing which parameters were considered probabilistically or deterministically, the prescribed probabilistic models for the assumed stochastic variables, the treatment of the heat transfer mechanism, the quantification of the structural fire performance and the assumed target reliability levels.

Design/methodology/approach – Research papers were identified through a search on the Web of Science, Google Scholar and detailed searches within the journals *Journal of Structural Fire Engineering*, *Fire Technology* and *Fire Safety Journal*, supplemented with references known by the authors.

Findings – Considering the state-of-the-art review, gaps in the literature are identified related to (1) the probabilistic evaluation of shear capacity for standard fires and parametric fires, and bending capacity for parametric fires, (2) the absence of reference fragility curves for immediate design application/code calibration and (3) the specification of target safety levels for reliability-based design.

Originality/value – The lack of research papers gathering studies on the reliability of reinforced concrete beams in fire situation makes it difficult to further develop research in the area. The value of this work lies precisely in the collection of the basic information, making it possible to identify gaps to be addressed in future research and the suggestion of a research framework.

Keywords Reinforced concrete, Reliability, Fire, Uncertainties, Beams

Paper type Research Paper

1. Introduction

Structural stability and integrity during fire are crucial for the overall safety of a building. The basic principle is that in a fire situation a building should not collapse, injuring occupants or firefighters. The structure should allow sufficient time for the occupants to evacuate the building and/or be rescued, and should, preferably, survive a complete burnout (Bailey and Khoury, 2011).

In general, reinforced concrete (RC) structures perform well in fire situations (Bailey and Khoury, 2011). This occurs because concrete is a non-combustible material and has a relatively low thermal conductivity, which results in a slow heat transfer inside the concrete. The slow heat transfer implies that the interior of the concrete cross section remains relatively cool also for longer fire durations, and that the reinforcing steel is not rapidly affected by temperature. This delay in the thermal response also explains why concrete structures may exhibit delayed (cooling phase) failure, as demonstrated by Gernay (2019).

During the high temperature exposure, concrete experiences a series of physical and chemical changes, such as water evaporation, disintegration of hydration products

The authors would like to show their gratitude to Marcus Achenbach, for referring them to the 1995 and 2008 reports by Hosser *et al.*

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and aggregates, coarsening of microstructure and increase of porosity (Ma *et al.*, 2015). These changes are considered to be responsible for the deterioration of mechanical properties of concrete at high temperature.

Designing structures in fire is one of the most difficult tasks faced by engineers (Fitzgerald, 1996), mainly due to the complex and unpredictable nature of both (1) the behaviour of fire itself and (2) the response of structural elements when exposed to fire. In addition, the complexity of the models demanded can end up generating a high degree of uncertainty (Achenbach *et al.*, 2019).

Structural fire performance, thus, has to account for the uncertainties with respect to, for example, the fire exposure, the mechanical properties, the thermal response and loading conditions. Comprehensively taking into account the uncertainties in the performance evaluation allows to ensure safety, not through trial and error, but through explicit reliability-based design (Van Coile *et al.*, 2019).

In this aspect, modern design specifications are aimed to achieve an acceptable level of performance by defining minimum design requirements that ensure safety of occupants during specific design events. Design conformance to prescriptive criteria on materials, configuration, detailing, strength and stiffness are implicitly taken as evidence that desired performance will be achieved (Szoke, 2015). For traditional prescriptive fire safety recommendations, the underlying target safety levels are not clear to the designer, nor is the associated balancing of risk and investment costs, which raises the need for performance-based design (PBD) (Hopkin *et al.*, 2020).

PBD is founded on the premise that structural systems must meet specific performance objectives. Specific performance expectations are set for the completed design, and processes are prescribed in minimal terms (Szoke, 2015). PBD, therefore, reverses the design process by defining the end goal as the starting point. The next step is to identify optimal solutions to multiple, and, sometimes, competing objectives. The design is completed by demonstrating complying performance through analysis, simulation, testing or a combination of thereof (Szoke, 2015).

A PBD procedure, in its turn, must be based on reliability-based design principles, which have evolved over the past decades. In these terms, a simplification for this approach is usually the application of the limit states, or safety factors.

For this, initially, a statistical characterization of the stochastic variables involved in the problem is necessary. A target level of safety should also be defined based on the class of structure and materials involved. Finally, an initial attempt for the partial factors can be proposed and the evaluation of its appropriateness made by reliability analysis methods (first-order reliability method (FORM), Monte Carlo, etc.) (Nowak and Szerszen, 2003). Then, main objective is to minimize the error between the computed reliability and target reliability index. A minimization problem is then established (Faber and Sørensen, 2002).

Based on this premise, it can be seen that the performance of the structural elements designed using traditional prescriptive approaches may not be adequate: sometimes it may be overinvesting drastically and, in other cases, investing too little. Crucially, the uncertainty in the performance of structures when exposed to real fires implies that a structure will have a probability of failure when subject to a (severe) fire. Only when accounting for this uncertainty can the costs and benefits of fire safety investments be evaluated rationally. This also implies that design methodologies should take into account an understanding of reliability.

That way, it remains evident that RC structures under fire should have their reliability investigated. Amongst the RC elements, beams are the central theme of this paper, that aims to investigate the state of the art for reliability evaluations of RC beams exposed to fire, with the intention to determine whether any gaps in knowledge should preferably be addressed in future research. Similar studies with respect to other load bearing RC elements such as columns and slabs are recommended, but they are outside the scope of this paper.

2. State-of-the-art review

A state-of-the-art review of the reliability evaluation of RC beams exposed to fire is presented below. Papers were identified through a search on the Web of Science, Google Scholar and detailed searches within the journals *Journal of Structural Fire Engineering*, *Fire Technology* and *Fire Safety Journal*, supplemented with references known by the authors. References listed in identified papers were investigated, as well as references to the identified papers. Only a very limited number of papers related to the topic were identified. Some papers, specific to beams, which at first sight appear relevant to the proposal were not included in this review, as their content was found to be beyond the scope of this research. These papers deal with, for example, the use of carbon fibre reinforced polymer (CFRP) sheets in beams, and the estimation of residual load-carrying capacity and reliability after fire (Li and Tang, 2005; Tang, 2006; Bai *et al.*, 2007, 2009; Cai and Feng, 2019). The same goes for pre-stressed concrete beams (Eamon and Jensen, 2012).

An important note for all papers is that (1) they are based on single span beams and (2) they consider that the beam is exposed to fire on three sides (top side not exposed).

A timeline of studies about the topic is shown in Figure 1, highlighting the main advances over time. In this literature review, three apparently distinct lines of research was verified, which do not refer to each other. This suggests that these research lines have so far been developed independently and that there is an opportunity to synthesize them.

2.1 Ellingwood and Shaver (1977)

The first identified study on the reliability of RC beams exposed to fire was developed by Ellingwood and Shaver in 1977. In this study, methods for analytically predicting the

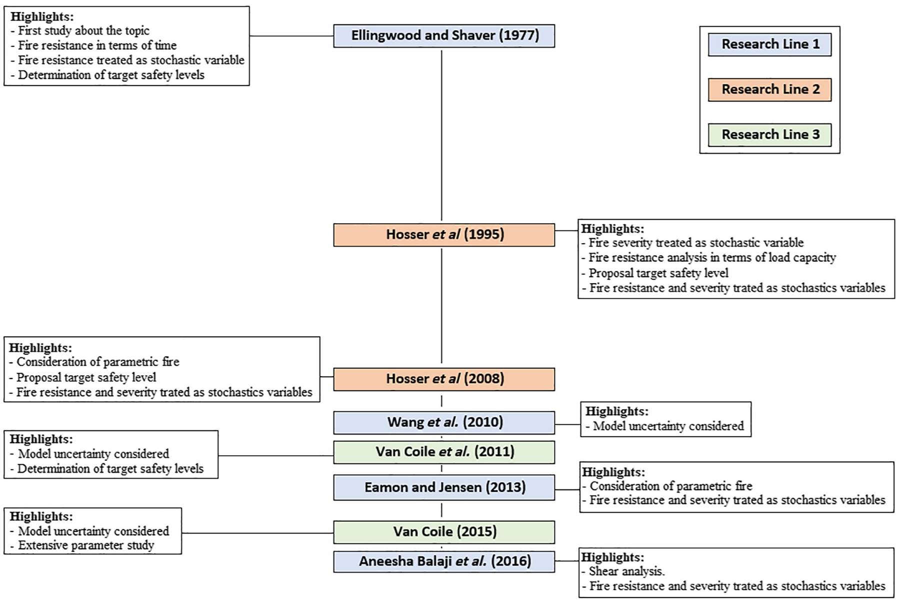

Figure 1.
Timeline of the papers

behaviour of RC beams subjected to fire are presented. The parameters that are important for predicting beam behaviour are identified through a sensitivity study, considering the reliability of a T-beam. The loads were assumed deterministic, and the resistance was given by the Weibull distribution. The application of reliability analysis techniques for developing fire-resistant design procedures is also examined in that paper.

2.2 Hosser et al. *(1995)*

This study presents an application in order to evaluate the reliability of RC beams under standard fire exposure, using FORM as the probabilistic approach, considering the Eurocode equations. Target reliabilities are proposed, based on normal design reliability targets (considering the natural fire safety concept, whereby the target reliability for normal design is divided by the fire frequency, i.e. without considering the specific costs and benefits of fire protection). The study concludes that the uncertainty in the reinforcement temperature is dominant for the reliability evaluation.

2.3 Hosser et al. *(2008)*

Based on the study developed in 1995, this research also presents an application in order to evaluate the reliability of RC beams under both standard and natural fires. In this more recent paper, the authors use Monte Carlo simulation in combination with an in-house non-linear code for structural fire analysis. Again, target reliabilities are proposed, based on the same premises as the previous study (i.e. a simple frequency scaling of the normal design target reliabilities). The study highlights that uncertainty in the fire characteristics dominates the overall reliability.

2.4 Wang et al. *(2010)*

In this study, a simple time-variant analytical model of the resistance of RC beams under fire has been studied. The reliability index of different specifications of concrete beams at different time has been analysed, considering standard fire exposure.

The influence of key parameters on the evolution of the reliability index with time has been presented, and the results have shown that increasing the reinforcement ratio and concrete cover thickness is an effective measure to improve the fire resistance of RC beams. Wang *et al.* (2010) considered random dead and live loads, but treated the beam resistance as deterministic.

2.5 Van Coile et al. *(2011)*

Van Coile *et al.* (2011) present a simple computational tool, which provides insight into the time and temperature dependent reliability of concrete beams during fire. The uncertainty of basic variables is taken into account through Monte Carlo simulation, resulting in a quantification of the uncertainty regarding the bending moment capacity during fire and the corresponding evolution of the safety level.

The results of these probabilistic simulations are compared with the design values specified in the Eurocodes, providing insight into the reliability level achieved by the current design documents. A specific finding was that the fire resistance of a beam can be increased by altering the beam configuration (e.g. increasing the nominal concrete cover), or by decreasing the uncertainty on the concrete cover, for example, through improved quality control (Van Coile *et al.*, 2011).

2.6 Eamon and Jensen (2013)

By Eamon and Jensen (2013), a procedure for conducting a reliability analysis of RC beams subjected to a fire is presented. This involved identifying relevant load combinations, specifying critical load and resistance random variables, and establishing a high-temperature performance model for beam capacity. Based on the procedure, an initial reliability analysis is conducted using currently available data based on a previous study by Jensen *et al.* (2010). Significant load random variables are taken as dead load, sustained live load and fire temperature. Resistance was taken in terms of moment capacity, with random variables taken as steel yield strength, concrete compressive strength, positioning of reinforcement, beam width and thermal diffusivity (Eamon and Jensen, 2013). A semi-empirical model is used to estimate the beam moment capacity as a function of fire exposure time, considering standard and parametric fire exposures. This model is calibrated to experimental data available in the literature. The effect of various beam parameters was considered, including concrete cover, beam width, aggregate type, concrete compressive strength, dead-to-live load ratio, reinforcement ratio, support conditions, mean fire temperature and other parameters. Using the suggested procedure, the reliability was evaluated from zero to four h of fire exposure using Monte Carlo simulation. It was found that reliability decreased non-linearly as a function of time, while the most significant parameters were concrete cover, span/depth ratio when axial restraints are present, mean fire temperature and support conditions (Eamon and Jensen, 2013).

2.7 Van Coile (2015)

This doctoral dissertation contains an extensive parameter study on the reliability of concrete beams, considering standard ISO 834 heating. Improved probabilistic models are used relative to Van Coile *et al.* (2011), and the underlying cross-sectional capacity evaluation is done through an improved non-linear fiber model which uses the constitutive laws of EN 1992-1-2:2004 as a basis. Again, the mean value and standard deviation of the concrete cover are found to have a very large impact on the reliability, while the effect of the cross-section variation is rather small. Also the effect of taking into account uncertainty on the strength reduction factors is found to be small, but the applied model was based on a limited amount of tests. Recent investigations by Qureshi *et al.* (2020) have shown that the actual variability at elevated temperatures is much higher than adopted in the studies developed by Van Coile (2015).

2.8 Aneesha Balaji et al. *(2016)*

Aneesha Balaji *et al.* study a methodology for computing the probability of structural failure of RC beams subjected to fire. The significant load variables considered are dead load, sustained live load and fire temperature. Resistance is expressed in terms of moment capacity and shear capacity with random variables taken as yield strength of steel, concrete class (or grade of concrete), beam width and depth. The flexural capacity is determined based on the design equations recommended in Indian standards and the simplified method named "500 °C isotherm method", detailed in Eurocode for simplified fire design for standard fire exposure. The shear capacity is evaluated in a simplified way through analytic equations of the Indian code IS 456:2000. A transient thermal analysis is conducted using finite element software ANSYS.

Reliability is evaluated from the initial state to 4 h of fire exposure based on the first order reliability method (FORM). A procedure is coded in MATLAB for finding the reliability index and the procedure is validated with the available literature. The effect of various parameters such as effective cover, yield strength of steel, grade of concrete, distribution of reinforcement bars and aggregate type on reliability indices are studied. Effective cover of concrete and yield strength of steel are found to have a significant effect on reliability of beams (Aneesha Balaji *et al.*, 2016).

3. References analysis

Analysing the mentioned references, significant differences are found with respect to (1) the failure mode considered, (2) fire specification and (3) reliability calculation (i.e. the consideration of stochastic variables). This is explored in the following and summarized in Table 1.

A probabilistic evaluation of RC beams in fire situation demands basically (1) a deterministic model of the phenomenon and (2) statistics of stochastic variables and their distributions. A brief overview on both aspects is presented in the following for the identified references, presenting the variables that were considered as deterministic or probabilistic in each study.

For the establishment of the deterministic analysis model, three points are fundamental: (1) how the fire resistance will be considered (in terms of time, temperature or strength), (2) if the limit states of bending and/or shear were analysed and (3) how the heat transfer inside the concrete was developed (e.g. finite element (FE) software). This aspect is explored in Tables 2 and 3.

For the establishment of the probabilistic model, two points are crucial: (1) which and how many variables were treated as probabilistic or deterministic and (2) if the used statistics (mean and variance) are up to date with the current state of the art.

3.1 Failure mode

When considering system reliability, it is important to recognize that failure of a single component may or may not mean failure of the larger structure. Systems can be classified as series or parallel systems. Series systems are characterized by the fact that the failure of one element leads to the immediate failure of the entire system, while, in the parallel system, the system has redundancy and all parallel elements must fail before the system fails. Note that this failure can still go fast, as load redistribution following the failure of one or more elements may result in an overloading of the remaining elements. However, most structures do not fit the idealized classification as series or parallel, as they are a combination of series and parallel sub-systems. Therefore, it is necessary to identify the elements that are critical for system

Table 1.
Summary of how failure mode, fire and reliability are handled in references

	Failure mode		Fire		Reliability		
	Bending analysis	Shear analysis	Standard fire	Parametric fire	Fire resistance*	Fire severity*	Target safety levels
Ellingwood and Shaver (1977)	X		X		P	D	X
Hosser *et al.* (1995)	X		X		P	P	X
Hosser *et al.* (2008)	X		X	X	P	P	X
Wang *et al.* (2010)	X		X		D	P	
Van Coile *et al.* (2011)	X		X		P	D	X
Eamon and Jensen (2013)	X		X	X	P	P	
Van Coile (2015)	X		X		P	D	
Aneesha Balaji *et al.* (2016)	X	X	X		P	P	

Note(s): *P – Probabilistic/D – Deterministic

	Ellingwood and Shaver (1977)	Hosser *et al.* (1995)	Hosser *et al.* (2008)	Wang *et al.* (2010)
Fire resistance analysis	In terms of time ($t_{fi,d} > t_{fi,\mathrm{req}}$)	In terms of load capacity ($R_{fi,t} > E_{fi,t}$)	In terms of load capacity ($R_{fi,t} > E_{fi,t}$)	In terms of load capacity ($R_{fi,t} > E_{fi,t}$)
Heat transfer	Experimental tests	Average concrete temperatures (background could not be verified as part of the current review)	Temperature distribution in the cross section was calculated by the program FIRES-T Natural fire in accordance with a model proposed in Zehfuss and Hosser (2007)	Temperature distribution in the cross section was defined according to temperature profiles studied by the authors in another research
Mechanical response	Experimental tests	Calculations based in Eurocode equations	Calculated by an in-house non-linear code	The profile of the beam has been divided into an elastic zone and a plastic zone based on the section temperature studied by the authors in another research

Table 2.
Type of fire resistance analysis, heat transfer mechanism and mechanical response of the RC beam

	Van Coile *et al.* (2011)	Eamon and Jensen (2013)	Van Coile (2015)	Aneesha Balaji *et al.* (2016)
Fire resistance analysis	In terms of load capacity ($R_{fi,t} > E_{fi,t}$)	In terms of load capacity ($R_{fi,t} > E_{fi,t}$)	In terms of load capacity ($R_{fi,t} > E_{fi,t}$)	In terms of load capacity ($R_{fi,t} > E_{fi,t}$)
Heat transfer	Temperature distribution in the cross section was calculated by the finite element software DIANA	For standard fire exposure, Wickstrom (1985) equates to determine the reduced cross section. For parametric exposures, the temperature distribution in the cross section was calculated by the finite element programme SAFIR	Temperature distribution evaluated through an in-house finite difference code	Temperature distribution in the cross section was calculated by the finite element program ANSYS
Mechanical response	Calculated by an in-house fibre model	The 500 °C isotherm method to determine the reduced cross section	Calculated by an in-house fibre model	500 °C isotherm method to determine the reduced cross section

Table 3.
Type of fire resistance analysis, heat transfer mechanism and mechanical response of the RC beam

stability. This issue has not been explored in the listed references, and the failure probabilities thus refer to element failure probabilities.

For the case of single element RC beams, failure modes related to ultimate limit states are classified into two major types: (1) flexural failure and (2) shear failure. Amongst the works identified herein, the shear limit state is evaluated in only one of them, with the others being limited to the analysis of the bending limit state.

3.2 Fire severity

The fire severity is a measure of the destructive potential of a fire. For a given severity, a structural component with relatively less fire resistance will lose its load bearing capacity before a component with relatively greater fire resistance.

Fire severity is usually defined in terms of a standard fire exposure time period. In this aspect, internationally known curves have emerged that aim to enable this standardization. An example is the ISO 834 fire (ISO 834:2019), the "standard curve" or "standard fire", which does not depend on the dimensions, purpose of the compartment or the thermal characteristics of the materials (Costa *et al.*, 2004). It is worth mentioning that any extrapolation of conclusions about a standard fire to a real fire must be carefully analysed, as the behaviour of the standard curve is not faithful to the curve of a real fire (Costa and Silva, 2003).

To solve this issue, parameterized fires have been proposed. The great advantage of these curves is that they allow taking into account the compartment geometry, fire load density and ventilation characteristics, while at the same time maintaining the simplicity of a straightforward analytical formula (Van Coile, 2015).

That way, in terms of fire severity, the analysis may be performed using the (1) standard fire (ISO-834) and (2) parametric fires curves. It is clear that the standard fire curve does not adequately represent the fire in a room, as it does not take into account extremely consequential factors, such as ventilation and the fire load present in it (Harmathy, 1970; Law, 1973). However, despite these limitations, the use of standard fire curves is the form of analysis most found in the analysed references. Parametric fire exposure is taken into account in only two of the studies (Hosser *et al.*, 2008; Eamon and Jensen, 2013). Both studies demonstrate the great impact of this consideration on the reliability of RC beams exposed to fire.

3.3 Fire resistance

Being a term that is often attributed to the behaviour of structural components in a fire situation, fire resistance is a measure of the ability of a structural component to withstand a fire. More specifically, the fire resistance of a component, or set of components, is the ability to withstand exposure to fire without loss of bearing capacity. It is often quantified as the expected time for the elements to meet certain criteria when exposed to a standard fire resistance test.

In most international standards (EN 1992-1-2:2004 and ACI 216R – 89: Guide for Determining the Fire Endurance of Concrete Elements), these criteria are (1) stability – resistance to structural collapse; (2) integrity – resistance to heat transfer; and (3) isolation – resistance to excessive temperature on the unexposed (internal) face. Nonetheless, considering that this study is restricted to the structural performance of RC beams, the relevant criterion is stability.

The properties of the materials vary according to the temperature of the gases to which they are submitted by the action of fire and, therefore, it is essential to know the temperatures in these structural elements. The thermal action on concrete and steel is translated by the reduction of mechanical properties, which, under high temperatures, experience a decrease in strength and Young's modulus.

In the literature, especially the Eurocode (2002), adequate fire resistance can be demonstrated in three ways: (1) In terms of time ($t_{fi,d} > t_{fi,\mathrm{req}}$), (2) in terms of load capacity ($R_{fi,d,t} > E_{fi,d,t}$) and (3) in terms of temperature ($\theta_d < \theta_{cr,d}$). Only the first work on the theme, developed by Ellingwood and Shaver (1977), performs its analysis in terms of time; the other studies focus on the evaluation of the load capacity.

3.4 Structural assessment

Regarding the structural assessment, the following methods to account for the strength loss due to fire were identified in the papers: (1) 500 °C Isotherm Method: Concrete with temperature below 500 °C retains full strength, and the rest is disregarded and (2) finite element methods (FEM).

In the cross sections of the beams, simplified calculation methods may be used to determine the ultimate resistant capacity of an RC element in a fire situation. These methods are applicable to structures subject to standard fires (Eurocode 1992–1–2, 2002). Simplified calculation methods are generally performed reducing the cross-section, based on (1) temperature profiles (based on the Eurocode appendix and/or previous research) and (2) reduced cross section (Isotherm 500° and Zone Method). Some authors state that the zone method is more accurate for small cross sections than the 500 °C isotherm method (Robert *et al.*, 2012) and that it could be promising for natural fires (Hertz, 1985), but this method was not used in any of the selected papers referenced in this study.

However, despite the possibility of applying simplified methods, in the identified papers, mainly FEM was used for the structural assessment. More specifically the software DIANA, SAFIR and ANSYS have been used to this purpose, as well as in-house codes. Eamon and Jensen (2013) mention that the 500° isotherm method shows results with little deviation from the FEM when the standard fire is applied, which is not the case for parametric fires.

3.5 Model uncertainty

The formulation of the structural design based on reliability implies the recognition that the physical variables considered in engineering problems are subject to variability.

According to Guedes Soares (1997), because the same structural problem can be evaluated according to different engineering theories, an additional source of uncertainty must be incorporated into the reliability formulation. Therefore, the model error concerns to the uncertainty in the representation of the physical behaviour of a structure (Melchers and Beck, 2018).

In the case of the references under analysis, only Wang *et al.* (2010), Van Coile *et al.* (2011) and Van Coile (2015) mention the inclusion in their calculations of a parameter related to the uncertainty in the model. By Wang *et al.* (2010), a factor to compute the uncertainties is applied in the used resistance model; however, the value is not mentioned. By Van Coile *et al.* (2011) a lognormal factor with mean of 1,2 and standard deviation of 0,15 is used to compute the uncertainties in the model is used, based on the Joint Committee on Structural Safety (JCSS) probabilistic model code, used for room temperature conditions. Taking into account that the performance in fire is expected to be less conservative than for normal design situations (e.g. because of the loss of reserve strength beyond the reinforcement yield plateau), a less optimistic model uncertainty was adopted in Van Coile (2015). For the resistance effect a lognormal distribution with mean of 1,1 and coefficient of variation of 0,1 was used. The model uncertainty for the load effect was taken in accordance with the JCSS (see Jovanović *et al.*, 2020 for an overview of the total load model).

4. Discussion

4.1 Failure mode

Aneesha Balaji *et al.* (2016) point out the importance of reinforcement yield strength for the shear limit state, and highlight the importance of considering the possibility of shear failure.

In this study it is observed that the reliability with respect to shear is less than that of flexure in the initial stages of fire (from time 0 to 2.5 h of fire exposure) and after that the condition reverses. This implies that at the initial stages of fire, for the beam considered in that study, limit state of shear is more critical and after about 2.5 h limit state of flexure becomes more relevant.

Nevertheless, the shear capacity model used by Aneesha Balaji *et al.* is a simplified one, being an adaptation of an Indian standard model for usual design conditions. Some authors state that little information is available about this failure mode in fire (e.g. Eamon and Jensen, 2013). Shear capacity evaluation of concrete beams during fire is a topic of ongoing research (Gernay *et al.*, 2021).

4.2 Fire severity and resistance

To interpret the reliability analysis, it is important to evaluate how fire resistance and severity are treated, whether they are treated in a deterministic or in a probabilistic way. On one hand, it is clear that over the years, studies tend to consider both parameters (fire resistance and severity) in a probabilistic way, bringing a more realistic assessment. About this, only the research developed by Hosser *et al.* (1995, 2008), Eamon and Jensen (2013) and Aneesha Balaji *et al.* (2016) treated both of them in a probabilistic way. It is important to mention that the study conducted by Aneesha Balaji *et al.* is closely related to the one conducted by Eamon and Jensen, with regard to the methodologies and statistical values of the variables involved.

4.3 Stochastic variables and uncertainties in the models

With respect to the probabilistic description of the stochastic variables, a great variability in the types of (1) distribution, (2) mean values and (3) correlation coefficients is noticeable. An example is the values related to the correlation coefficient of concrete strength used by Aneesha Balaji *et al.* (2016) and Van Coile *et al.* (2011), with 41% of difference. This highlights that the probabilistic models for RC concrete beams exposed to fire are not fully consolidated in the literature and require further investigation.

Likewise, uncertainties in the model are not treated in all studies, as mentioned before. As clearly seen from the previous sections, ultimate conditions for RC beams, i.e. ultimate stress and ultimate strain, cannot be predicted with certainty. The uncertainties associated with such predictions, or model errors, may be much more significant than those associated with inherent variability (Ang and Tang, 1990). In this sense, it is noticed the inexistence in the literature of a database of experiments in RC beams on fire that could subsidize the calculation of the uncertainties in the models used by the different authors. This fact probably justifies the absence of the use of this factor in the papers, or the use of the same ones used at room temperature.

Also, the uncertainty in the thermal properties is not fully considered. Material strengths at high temperatures exhibit a large variability, and there are no consolidated probabilistic models in the literature to quantify it. Recently, studies related to probabilistic models for temperature-dependent strength of steel and concrete are available (Qureshi *et al.*, 2020) and can serve as a reference for future studies.

For the case of loads (dead and live) in fire situation, some recent studies point out a consolidated probabilistic load model, where the recommended distribution, mean and covariance (COV) are listed in Table 4 (Jovanović *et al.*, 2020). Based on historical data, the study of Jovanović *et al.* indicates that relative differences of the probability of failure in the order of 10% can be observed in function of the load models used (Jovanović *et al.*, 2020), proposing the parameters presented in Table 4 for dead and live loads in case of fire.

Regarding the determination of target safety levels, only three of the authors address this issue for RC beams (Hosser *et al.*, 1995, 2008; Ellingwood and Shaver, 1977; Van Coile *et al.*, 2011) and the determination of reference fragility curves and a lifetime cost optimization analysis dedicated to RC beams was not found within the available literature about the theme.

4.4 Gaps identified

Three main gaps have been identified: (1) probabilistic evaluation of bending and shear capacity for standard fires and parametric fires; (2) failure probability evaluation (development of reference fragility curves for immediate design application/code calibration); and (3) evaluation of target safety levels for reliability-based design (e.g. through lifetime cost optimization).

It is worth highlighting that all the presented studies can be considered as case study applications. This means that there was no analysis of a large spectrum of cases, allowing a generalization of reliability indices. None of them presented reference fragility curves, which can be used directly in follow up studies or design and assessment in an RC beams fire analysis. Most papers are limited to assessing the influence of the parameters of (1) concrete, (2) steel, (3) beam, (4) fire and (5) loads on the reliability of the RC beam.

The availability of reference fragility curves for structural elements is important to enable a simple analysis of the RC beam, used for immediate design application. In this case, a target failure probability (or in other words, a target reliability index) is necessary to apply fragility curves in design. Obtaining such target reliability indices can be considered part of the code calibration process. In accordance with Rackwitz (2000) and Vrouwenvelder (2002), lifetime cost optimization allows to evaluate optimum reliability levels, which can then function as a generalized target for reliability based design applications. Studies dedicated to steel structures (Hopkin *et al.*, 2020) and RC slabs (Van Coile *et al.*, 2014) are available. No published studies, which focussed on RC beams, in particular, are available, making this an important topic for future research.

About the mentioned lifetime cost optimization analysis, it has turned out to be a very important and essential tool for PBD. It is basically related to the analysis of costs over the lifetime of the structure, seeking to facilitate and improve the decision making of the designer and enabling the calibration of codes. The possession of the target reliability index enables, for example, the use of fragility curves directly or the development of partial safety factors. These two important points of study (fragility curves and lifetime cost optimization) were not addressed in previous research on concrete beams exposed to fire and end up becoming important points of future research.

5. Conclusions

In this paper, the gaps in literature with respect to the reliability evaluation of RC beams exposed to fire have been determined through a literature review.

It was noticed in this study the lack of a consolidated model for the strength of the beam in fire, given the low investigations in the scope of the reliability of RC structures in a fire situation.

Load	Distribution	Mean	COV
Dead loads	Normal	Equal to the nominal permanent load	0.10 (for a first assessment, if not evaluated on a project basis)
Live loads	Gamma	0.2 times the nominal live load	0.60 for large load areas (> 200 m^2) and 0.95 for smaller load areas (< 100 m^2)

Source(s): Jovanović *et al.* (2020)

Table 4. Probabilistic characteristics of the live and dead load

Basically, there is little literature about the theme, making it difficult to run advanced calculation models, the reason why several of the authors end up using in-house or simplified calculation models. The advantage of using this last one was the ease in carrying out the modelling of the resistance behaviour of the beam in fire, as well as its accuracy, despite the simplicity.

Based on the studies in the area and in the great variability found, the conclusion that can be drawn is that deterministic or "single value" analysis in this kind of design can give very misleading results if the variability of properties and the full range of possible scenarios are not taken into account.

This is especially true for the fire case, for the very reason that fire behaviour, and its effect on material properties, generates huge scatter in the data. In these circumstances, the application of the reliability assessment would highlight any deficiencies or gaps in the project and would provide a good basis for re-examination of it, in order to satisfy the expected performance requirement.

Almost all existing studies considered the standard fire exposure, thereby, neglecting uncertainty in the fire exposure. In this point, studies into the reliability of concrete beams considering parametric fire exposure will add to the topic a more realistic view of the reliability in the built environment.

Besides that, the reliability study of RC beams under fire subjected to pure bending was investigated by all the presented research, but with respect to shear capacity, only one study could be obtained as part of this review, still being a simplified study. Research studies focussing on the shear performance are thus necessary to obtain a complete picture of the reliability in case of fire. Along the same lines, studies are based on single span beams. The case of continuous beams is little known and explored in literature.

Furthermore, the available studies focussed on specific case studies, and no fragility curves could be obtained which are applicable to a wide range of design cases. The absence of such published fragility curves is considered an obstacle for the application of reliability-based considerations in structural fire design.

Once this probabilistic assessment is made, target safety levels can be established, in order to be a reference for code calibration and design application, i.e. to allow a reliability-based design. Lifetime cost optimization can be applied in this regard to determine optimum safety levels.

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