

ACCEPTABLE RANGE FOR STRUCTURAL FIRE RESISTANCE IN PERFORMANCE BASED DESIGN

VAN COILE R.^{1,2}, CASPEELE, R.¹ and TAERWE, L.¹

¹*Department of Structural Engineering, Ghent University, Technologiepark-Zwijnaarde 904, 9052 Zwijnaarde, Belgium.*

E-mail: ruben.vancoile@ugent.be, robby.caspeele@ugent.be, luc.taerwe@ugent.be

²*Now at WSP | Parsons Brinckerhoff, 70 Chancery Lane, WC2A 1AF, London, UK.*

E-mail: ruben.vancoile@wspgroup.com

ABSTRACT

Structural fire safety engineering is increasingly moving away from prescriptive design rules to what is generally referred to as Performance Based Design (PBD) in which the structure or structural components are designed to satisfy performance requirements. By taking into account the specific characteristics of the structure, a PBD can allow for more directed investments in safety, resulting in structures which are both more economical and safer compared to designs according to traditional prescriptive rules. Although stakeholders mostly agree that the structure should have a good fire performance, determining the specific performance requirements can prove difficult, especially when the opinions of stakeholders with respect to key design parameters diverge. In this paper a decision support tool for investments in Life Safety is introduced and applied to determine an Acceptable Range for the structural fire resistance time for concrete slabs. The support tool takes into account the uncertainty related to amongst other the fire load density and the mechanical properties of the structural element, and can be used as a tool for aligning potentially diverging positions of different stakeholders.

Keywords: Decision making; Performance-Based Design; Cost-optimization; Safety level; Fire.

Introduction

Traditionally structural fire safety is based on prescriptive design rules which do not directly relate to the probability of a fully developed fire, or the available fire load. Therefore, in situations where

metadata, citation and similar papers at core.ac.uk

situations, a new design methodology known as ‘Performance-Based Design’ (PBD) has been gaining support. As a PBD takes into account the true characteristics of the structure – as for

example the probability of fire exposure, the fire load and the ventilation characteristics –a PBD results in a more efficient allocation of resources compared to a traditional design. Furthermore, PBD should result in more rigorous engineering and the development of innovative design solutions since satisfying design requirements no longer relates to the application of prescriptive rules, but is associated with the actual (calculated) performance of the structure.

In a PBD, the structure or structural components are designed to satisfy performance requirements. These performance requirements have to be determined beforehand taking into account the specific needs of both private stakeholders and the general public (SFPE, 2007). However, determining these performance requirements can prove difficult as psychological concepts like risk perception, availability effects and loss aversion can play an important role in the decision making processes (Kahneman, 2011), and the opinions of different stakeholders may diverge.

Nathwani et al. (1997) state that as a general goal, decisions on public expenditures and safety should be based on quantitative risk-based considerations, and day-to-day decisions about risk should be removed from the political arena. This would imply that the performance requirements for PBD should be fully fixed through quantitative risk calculations. In practice however, a full depoliticization is not desirable, as a purely technical risk-based determination of performance requirements would take away the stakeholders' experience of control over safety issues and would therefore negatively affect the perception of safety. Consequently, a practically feasible decision framework necessarily takes into account the risk preferences of the stakeholders, while making sure that the final decisions do not differ too much from the theoretical risk-based optimum.

In order to reconcile political risk preferences with reliability-based optimum solutions, a decision support tool has been developed in (Van Coile et al., 2015) which aims at narrowing the scope of political discussions and guiding decision makers towards optimum investments in safety by supplying the decision maker with an Acceptable Range for their final decision. The general concept of the proposed decision support tool is introduced in the next section, after which the tool is applied to determine the Acceptable Range for the structural fire resistance time t_R for a concrete slab. The paper ends with a short discussion of further ways in which the proposed methodology may support the decision making process for Performance-Based Design.

General concept of the decision support tool

Safety requirements are to a greater or lesser extent political in nature and are based upon an implicit or explicit target safety level or target reliability index β_t . Due to the inherent uncertainties, the practical implementation, the application of partial factors and variations in the application of safety requirements, the reliability index β_{STD} which is actually obtained when applying these requirements is uncertain. Consequently, β_{STD} is described by a probability density function (PDF) and is function of the target reliability index, i.e. $\beta_{STD} = f(\beta_t)$. On the other hand for every design problem an optimum reliability index can be determined through an optimization of investments in

safety, for example by considering the concepts of Lifetime Cost Optimization (LCO). Due to the uncertainties inherently associated with the input parameters of an LCO, this optimum reliability index β_{LCO} is uncertain as well and can be described by a PDF.

Although political preferences may justify a deviation of β_{STD} away from the optimum β_{LCO} , an unacceptable overinvestment in safety can be defined by Eq. (1) and an unacceptable underinvestment by Eq. (2), with θ_1 the maximum acceptable deviation factor for overinvestment ($0 \leq \theta_1 \leq 1$) and θ_2 the maximum acceptable deviation factor for underinvestment ($0 \leq \theta_2$).

$$\beta_{STD}(\beta_t) > \frac{\beta_{LCO}}{1 - \theta_1} \quad (1)$$

$$\beta_{STD}(\beta_t) < \frac{\beta_{LCO}}{1 + \theta_2} \quad (2)$$

The maximum acceptable deviation factor θ_1 for overinvestment and θ_2 for underinvestment are important parameters which directly indicate an over- or underinvestment at the level of the reliability index. Considering over- and underinvestment at the level of the reliability index has the advantage that it clarifies to the decision maker and to the public how much safety they accept at maximum to overinvest or underinvest for reasons of policy.

As both β_{LCO} and $\beta_{STD}(\beta_t)$ are described by a PDF, Eq. (1) and (2) can only be evaluated as probabilities, i.e. the probability P_1 of having an unacceptable overinvestment and the probability P_2 of having an unacceptable underinvestment. As both situations are undesirable, both probabilities P_1 and P_2 should be limited to limiting acceptable probabilities $P_{limit,1}$ and $P_{limit,2}$, resulting in Eq. (3) and (4) with $P[\cdot]$ the probability evaluator. Evaluating Eq. (3) and (4), and determining the value of β_t for which P_{limit} is reached, a bounded interval is defined with acceptable values for β_t . This interval will be denoted as the Acceptable Range. The calculation concept is illustrated in Figure 1.

$$P_1 = P \left[\beta_{STD}(\beta_t) > \frac{\beta_{LCO}}{1 - \theta_1} \right] \quad (3)$$

$$P_2 = P \left[\beta_{STD}(\beta_t) < \frac{\beta_{LCO}}{1 + \theta_2} \right] \quad (4)$$

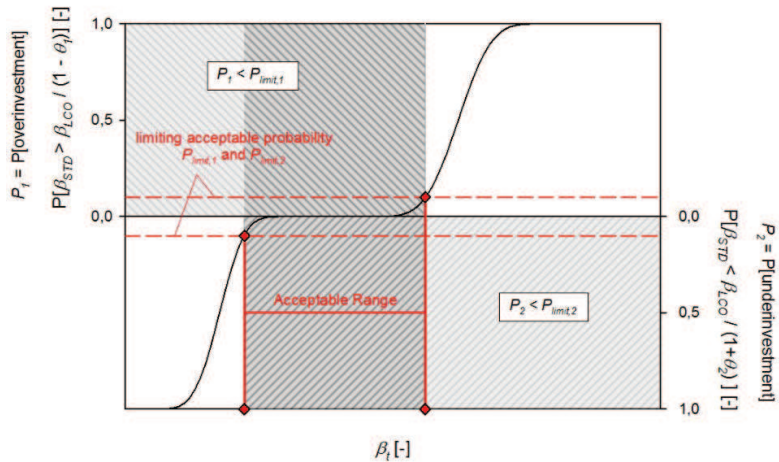


Fig. 1. Concept of P_1 (probability of exceeding overinvestment limit) and P_2 (probability of exceeding underinvestment limit), and visualization of the Acceptable Range for given limiting acceptable probabilities $P_{limit,1}$ and $P_{limit,2}$.

The Acceptable Range can be used to limit the discretionary competence of decision makers without taking away the possibility of deviating slightly from technical optimum safety levels for reasons of policy. Fixing the values of the maximum acceptable deviation factors θ_1 and θ_2 , and the limiting acceptable probabilities $P_{limit,1}$ and $P_{limit,2}$ could be left to the decision-makers during a process by which they voluntarily commit themselves to these limits.

Application to requirements of structural fire resistance for concrete slabs

When assessing the necessity of structural fire resistance in a PBD the different stakeholders may have very different motivations and opinions. Although “political” risk preferences should be taken into account the final design should not deviate too much from an optimum design solution. Else, the fundamental benefit of PBD of obtaining more efficient design solutions with increased safety at a reduced cost may be lost. Therefore, it is of special interest to determine what is the Acceptable Range for the structural fire resistance t_R (as defined by European legislation as the ISO 834 fire duration for which the Eurocode load bearing capacity criterion is maintained).

On the one hand, the safety level β_{STD} obtained in case of a specified fire resistance t_R is investigated. Since t_R relates to the ISO 834 standard fire, the actual reliability obtained in a more realistic natural or parametric fire is not well known. Furthermore, the severity of the natural fire is strongly dependent on the fire load density q and the opening factor O . Especially with respect to the fire load density very large uncertainties are associated, and thus q is modelled by a Gumbel distribution with a coefficient of variation equal to 0.3 (Albrecht & Hosser, 2010). Furthermore, an opening factor of 0.04 is considered as this value is seen as realistic for calculations related to modern buildings where windows usually do not break during fire.

Considering the EN 1991-1-2 parametric fire curve, and the methodology for reliability calculations presented in (Van Coile, 2015), the reliability index $\beta_{fi,tE}$ is evaluated for the set of one-way load bearing slab configurations of Table 1 (with \emptyset the reinforcement bar diameter) and for a load ratio χ (the ratio of the characteristic value of the imposed load to the sum of all characteristic loads) of 0.5. For each of these slab configurations the structural fire resistance time t_R is determined in accordance with the advanced calculation method of EN 1992-1-2. The obtained set of reliability indices for a given t_R is approximated by a Beta distribution. Results for a mean fire load density of 780 MJ/m² are visualized in Figure 2.

Table 1. Characteristics of the investigated slab configurations: property description, symbol and unit, stochastic distribution, mean value μ and coefficient of variation V .

Property description, symbol and unit	Distribution	μ	V
Concrete compressive strength at 20°C $f_{c,20}$ [MPa] ($f_{ck} = 25/30/35/40$ MPa)	Lognormal	$\frac{f_{ck}}{1 - 2V_{fc}}$	0.15
Reinforcement yield stress at 20°C $f_{y,20}$ [MPa] ($f_{yk} = 500$ MPa)	Lognormal	$\frac{f_{yk}}{1 - 2V_{fy}}$	0.05
Slab thickness h [mm]	Deterministic	150/200/ 250/300	-
Horizontal reinforcement axis distance s [mm]	Deterministic	100/150	-
Concrete cover c [mm]	Beta [$\mu - 3\sigma$; $\mu + 3\sigma$]	25/30/35/ 40/45	$\frac{5}{\mu_c}$
Reinforcement area A_s [mm ²]	Normal	$\frac{\pi \emptyset^2 b}{4 s}$	0.02

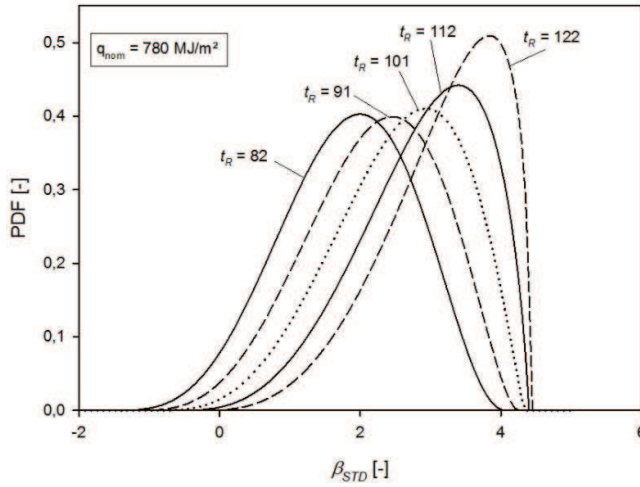


Fig. 2. Probability density functions (PDF) describing β_{STD} as a function of the target structural fire resistance time t_R for design according to the advanced calculation method of EN 1992-1-2

On the other hand, the optimum reliability index β_{LCO} for structural fire safety is evaluated using the Lifetime Cost Optimization concepts described (Van Coile et al., 2014). Increasing the concrete cover can be considered a cost-effective method for increasing the fire resistance. However, when fixing the values of all other design parameters (including the design value of the bending moment capacity $M_{Rd,20}$ in normal design situations) the reduction in lever arm associated with an increase in concrete cover is necessarily offset by an increase in reinforcement area. As this increase in reinforcement area comes at a cost, the cost-optimization methodology balances uncertain future gains in structural fire performance with increased initial construction costs. Consequently, the failure cost ratio ζ (total costs in case of structural failure relative to the initial construction cost) and the discount rate γ are important parameters, as well as the fire ignition frequency λ_{ig} and the probability p_{sup} of successful fire suppression.

The LCO is performed for the slab configuration of Table 1 with $f_{ck} = 30$ MPa and $h = 200$ mm (A_s and c are part of the optimization). Figure 3 gives the calculated optimum concrete cover c_{opt} as a function of the reinforcement bar cost ratio κ (cost of a single reinforcement bar relative to the total initial slab construction cost) for different deterministic fire load densities q_{DET} . The grey lines in Figure 3 indicate design solutions with the same safety level β_{min} in case of fire exposure.

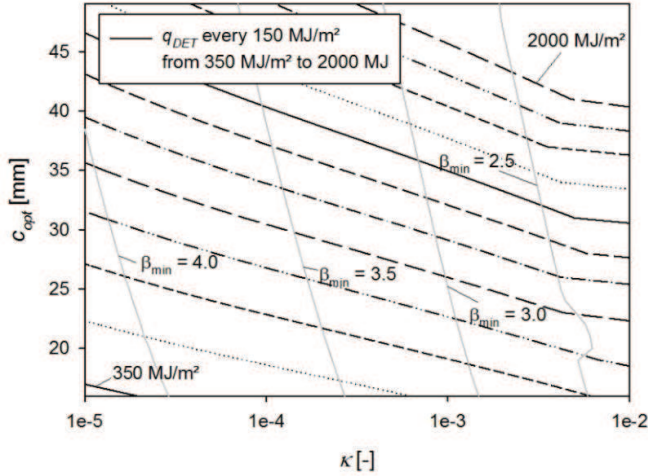


Fig. 3. Optimum concrete cover as a function of the reinforcement cost ratio κ and the deterministic fire load density q_{DET} , discount rate $\gamma = 0.02$, failure cost ratio $\zeta = 7$, $\lambda_{ig} = 2.5 \cdot 10^{-3}$, $p_{sup} = 0.9$.

Integrating the optimum reliability indices β_{min} over the Gumbel distribution for the uncertain fire load density q (for a given reinforcement cost ratio κ), gives κ -dependent distributions for β_{LCO} – for amongst others a given failure cost ratio ζ . Considering the cost parameters of Table 2 and dividing the corresponding deterministic value for κ by a lognormal model uncertainty K_M with mean 1 and coefficient of variation 0.1, an overall distribution for β_{LCO} is obtained. Results are visualized in Figure 4 for different failure cost ratio ζ ($\lambda_{ig} = 2.5 \cdot 10^{-3}$ / year and $q_{nom} = 780$ MJ/m²).

Table 2. Example cost properties for the considered slab configuration

Property	Dimension	Value
reinforcement cost	EUR / kg	0.75
reinforcement weight	kg / m ³	7850
concrete cost	EUR / m ³	100
labour cost	EUR / m ²	50
Overhead	%	10

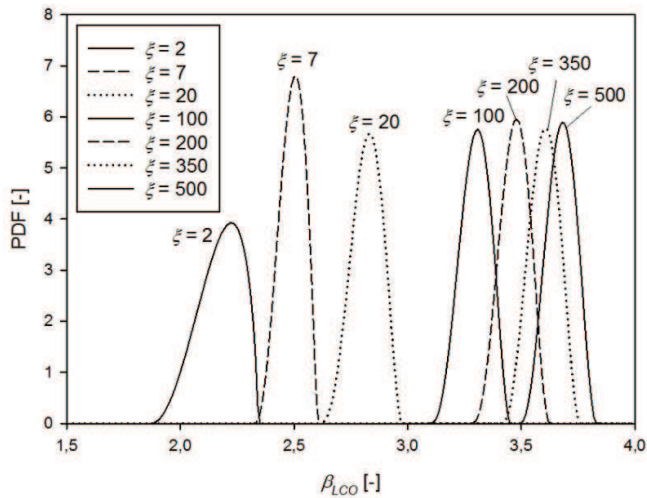


Fig. 4. Probability density functions (PDF) describing β_{LCO} for different failure cost ratios ζ ($\lambda_{ig} = 2.5 \cdot 10^{-3}$, $q_{nom} = 780 \text{ MJ/m}^2$)

Having determined distributions describing both β_{STD} and β_{LCO} , the decision support tool can be applied to determine the Acceptable Range. The obtained probabilities P_1 and P_2 are visualized in Figure 5, as well as the obtained Acceptable Range (for $\theta_1 = \theta_2 = 0.2$ and $P_{limit,1} = P_{limit,2} = 0.1$). For small failure cost ratio ζ no Acceptable Range is found as the uncertainty with respect to the fire load density dominates the utility of investments in structural fire safety, i.e. for any chosen t_R -value there always is an unacceptably probability that the chosen t_R constitutes either an unacceptable underinvestment or an unacceptable overinvestment. Only when ζ is large an Acceptable Range develops, indicating a range for t_R for which the criteria for avoiding unacceptable underinvestment and overinvestment are compatible. This obtained Acceptable Range can be compared with the applicable legal requirements. If these legal requirements indicate a fire resistance class below the Acceptable Range, the decision tool strongly recommends to opt for the additional investments in structural fire safety.

With respect to the unavailability of an Acceptable Range for low ζ (i.e. corresponding for example with regular residential buildings) multiple options exist to overcome this problem. For example, the uncertainty with respect to the fire load density can be reduced by appropriate fire strategy measures. Alternatively, one can accept the inability to avoid either underinvestment or overinvestment with a large confidence level and a choice can be made with respect to which criterion is more important. Then $P_{limit,1}$ and $P_{limit,2}$ can be chosen accordingly, for example accepting a probability of overinvestment of 0.5 or more, which in fact means that the design is governed by a large quantile of the fire load density, as is the case in many current design codes.

According to the authors, these difficulties do not downgrade the usefulness and value of the presented decision support tool as these choices related to over- and underinvestment are now clear to the decision makers.

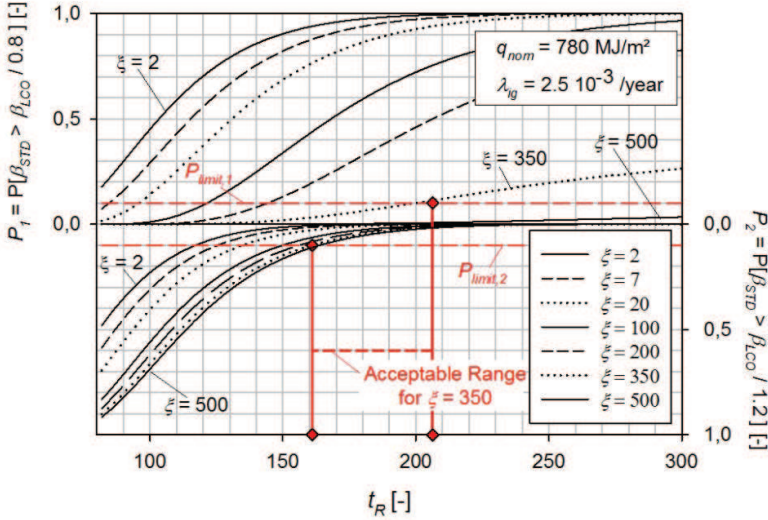


Fig. 5. P_1 and P_2 , and visualization of the Acceptable Range for given limiting acceptable probabilities $P_{limit,1}$ and $P_{limit,2}$, for β_{STD} as illustrated in Figure 2 and β_{LCO} as illustrated in Figure 4.

Note on possible application in case of diverging stakeholder opinions

In principle it is not necessary that different stakeholders agree up front on the limiting parameters. In case of disagreement parallel analyses with different sets of limiting parameters can be performed. If the corresponding Acceptable Ranges intersect, there is a range of design solutions which is acceptable for all stakeholders.

Similarly, it is not necessary that all stakeholders agree up front on the parameters for the design calculations and optimization. If different stakeholders insist on fundamentally different failure costs or fire load densities, parallel analyses can be performed. In case the respective Acceptable Ranges overlap, there exists a set of design solutions which is (implicitly) considered acceptable by all stakeholders.

Conclusions

A decision support tool for investments in Life Safety has been introduced and applied for determining an Acceptable Range for the structural fire resistance time for concrete slabs. The proposed tool balances political considerations with the necessity of obtaining societally acceptable levels of safety investment, while at the same time resulting in transparent decision parameters. For the specific application to structural fire resistance no Acceptable Range is found for small failure cost ratios as the uncertainty on the fire load density is too large for a single design to be acceptable according to the allowable limiting probabilities considered. However, for large failure cost ratios an Acceptable Range develops, indicating that e.g. for critical infrastructure the uncertainty with respect to the fire load density is of secondary importance compared to the potential losses in case of fire-induced structural failure. It is noted that the proposed tool can be used to find a design compromise even when different stakeholders fail to agree on the design parameters.

References

- Albrecht, C., Hosser, D. (2010). "Risk-informed framework for performance-based structural fire protection according to the eurocode fire parts". *Proceedings of the 12th Interflam Conference*. 05-07/07, Nottingham, 1031-1042.
- Kahneman, D. (2011). *Thinking fast and slow*. New York: Farrar, Straus and Giroux.
- Nathwani, J.S., Lind, N.C. & Pandey, M.D. (1997). *Affordable safety by choice: the life quality method*. Institute for Risk Research, University of Waterloo, Waterloo
- SFPE. (2007). *SFPE Engineering Guide to Performance-Based Fire Protection (second edition)*. Society of Fire Protection Engineers.
- Van Coile, R., Caspeepele, R. & Taerwe, L. (2014). "Cost-optimization of concrete slabs exposed to natural fires, taking into account post-fire behavior", *Proceedings of ASCE-ICVRAM-ISUMA 2014*, 13-16/07, Liverpool, UK
- Van Coile, R., Caspeepele, R., Taerwe, L. (2015). "Decision support tool in investments in life safety based on sampling theory", *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*. Online First.
- Van Coile, R. (2015). *Reliability-based decision making for concrete elements exposed to fire*. Doctoral dissertation, Ghent University, Ghent.