MATEC Web of Conferences **6**, 05004 (2013)
DOI: 10.1051/matecconf/20130605004

Prediction of the spatial occurrence of fire induced spalling in concrete slabs using random fields

R. Van Coile, P. Criel, R. Caspeele and L. Taerwe

Ghent University, Department of Structural Engineering, Magnel Laboratory for Concrete Research, Ghent, Belgium

Abstract. As the loss of concrete cover can significantly influence the reliability of concrete elements during fire, spalling should be taken into account when performing reliability calculations. However, the occurrence and spatial variation of spalling are highly uncertain. A first step towards a probabilistic analysis of spalling is made by combining existing deterministic models with a stochastic representation of the concrete tensile strength and by using random fields to model the tensile strength spatial variation.

1. INTRODUCTION

During a fire, some types of concrete are known to be susceptible to a sudden detachment of the outer layer if a specific combination of influencing factors occurs. This phenomenon is generally known as explosive spalling. However, for a given reinforced concrete slab configuration, the occurrence of spalling is highly uncertain. It is unclear which percentage of slabs can be expected to suffer from spalling and what may be the spatial extent of the loss of concrete cover. While deterministic calculation tools have been proposed to calculate the occurrence of spalling, these models have not yet been linked to existing probabilistic frameworks (to the best of the authors knowledge). However, this would allow to assess the probability of occurrence and predict spatial variations. The simplified approach proposed in this paper can be considered as a first step towards a probabilistic assessment of fire-induced spalling.

2. NECESSITY OF A PROBABILISTIC ASSESSMENT OF SPALLING

Since performance based design codes and regulations are being implemented by an increasing number of countries, as e.g. the United Kingdom [1] and New Zealand [2], the safety level of structural elements during fire should be assessed to allow for comparing design alternatives. Using a cross-section calculation tool, Van Coile et al. [3] quantified the influence of the concrete cover on the structural reliability $\beta_{fi,t}$ during exposure to the ISO 834 standard fire (Fig. 1). The differences between the curves can be related to the accelerated heating of the reinforcement in case of a smaller concrete cover. When assuming that the concrete cover is spalling immediately at the beginning of the fire, which is a conservative assumption, the reliability is strongly reduced for very short fire durations (Fig. 1).

Clearly, spalling can have a significant impact on the reliability and should be taken into account in a performance-based design. However, assuming the immediate occurrence of spalling is overly conservative. Therefore, the probability and time of occurrence should be assessed, as well as the spatial variation.

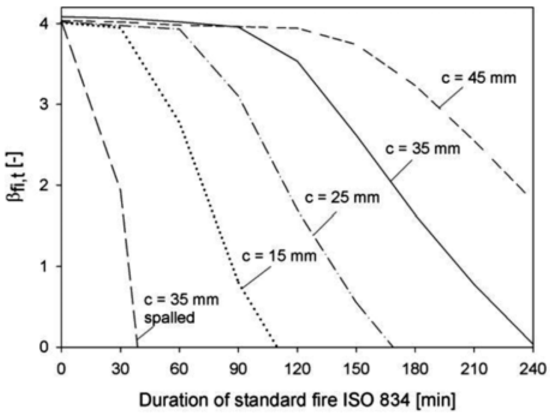

Figure 1. Reliability $\beta_{\mathrm{fi,t}}$ as a function of the ISO 834 duration, for different values of the concrete cover c.

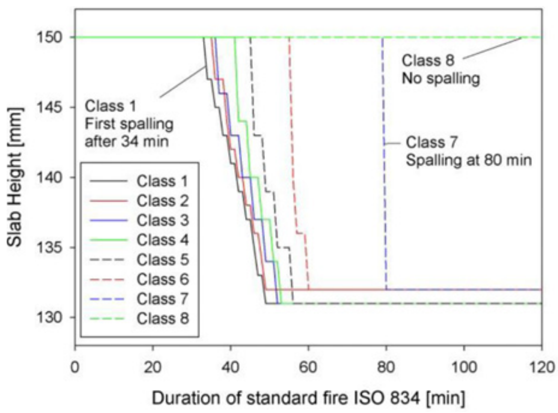

Figure 2. Spalling behavior for different classes of $f_{\mathrm{ct},20^\circ\mathrm{C}}$ as a function of the fire exposure time.

3. DETERMINISTIC MODEL PROPOSED IN LITERATURE

Spalling is thought to be caused by the combined effect of the buildup of pore pressure during heating due to water evaporation [4] and tensile stresses caused by the temperature-gradient across the concrete cross-section [5]. Hertz performed a comprehensive literature study of different available theories that explain the spalling phenomenon and concluded that the formation of vapour inside the concrete is the most important factor [6].

Bazant and Thonguthai developed a hydrothermal model which calculates the pore pressure and temperature in heated concrete walls taking into account the water released into the pores by dehydration at elevated temperatures [7]. Dwaikat and Kodur proposed a similar model for predicting fire-induced spalling in concrete structures by assuming that spalling occurs when the effective pore pressure in the concrete exceeds the temperature dependent tensile strength of the concrete [8]:

$$n P_v \geq f_{\mathrm{ct},\theta} = k_{\mathrm{fct},\theta} f_{\mathrm{ct},20^\circ C} \tag{1}$$

with n the concrete porosity, P_v the pore pressure, $k_{\mathrm{fct},\theta}$ the temperature dependent reduction factor for the concrete tensile strength, and $f_{\mathrm{ct},20^\circ\mathrm{C}}$ the 20 °C concrete tensile strength.

Table 1. Characteristics of the investigated slab configuration.

Symbol	Name	Dimension	Nominal value
h	total slab thickness	mm	150
l	span of the slab	m	6
b	width of the slab	m	6
$f_{c,20^\circ C}$	$20\,^\circ$C concrete compressive strength $f_{ck}(20\,^\circ C) = 60$ MPa	MPa	82.7
c	concrete cover	mm	20
$k_{fc,\theta}$	concrete compressive strength reduction factor at temperature θ	-	temperature dependent [8]
ρ_c	cement content per m^3 of concrete	kg/m^3	415
RH	initial relative humidity inside the concrete pores	-	0.9
m_{l0}	mass of water for saturation of the concrete at $20\,^\circ$C unit volume of concrete	kg/m^3	75
k	initial intrinsic concrete permeability at $20\,^\circ$C	m^2	10–18

Table 2. Subdivision of realization for $f_{ct,20^\circ C}$ in 8 classes.

Class [MPa]	Class number [-]	Class representative value [MPa]	Number of realizations	Percentage of realizations [%]
]0; 2.2]	Class 1	2.1	2	0.02
]2.2; 2.4]	Class 2	2.3	8	0.08
]2.4; 2.6]	Class 3	2.5	18	0.18
]2.6; 2.8]	Class 4	2.7	28	0.28
]2.8; 3]	Class 5	2.9	49	0.49
]3; 3.2]	Class 6	3.1	75	0.75
]3.2; 3.4]	Class 7	3.3	91	0.91
]3.4; ∞[	Class 8	-	9729	97.29
Total	-	-	10 000	100

The simplified model proposed by Dwaikat and Kodur can be used to predict the time of occurrence of spalling. Results are given in Fig. 2 for the slab configuration of Table 1, for different $20\,^\circ$C concrete tensile strength values $f_{ct,20^\circ C}$. It is assumed that spalling is limited to the depth of the concrete cover due to the restraining effect of the reinforcement.

Clearly, the $20\,^\circ$C concrete tensile strength $f_{ct,20^\circ C}$ has a very large influence on the spalling behavior predicted by the model. If the stochastic representation of the tensile strength (see next section) is linked to the results of Fig.2, a first assessment of the probability of spalling can be made.

4. ASSESSING THE PROBABILITY OF SPALLING

According to JCSS [9], the $20\,^\circ$C concrete tensile strength $f_{ct,20^\circ C}$ is related to the $20\,^\circ$C compressive strength $f_{c,20^\circ C}$:

$$f_{ct,20^\circ C} = 0.3\left(f_{c,20^\circ C}\right)^{2/3}\eta_{fct} \tag{2}$$

with η_{fct} a stochastic multiplication factor with mean 1 and coefficient of variation 0.3. The compressive strength itself is modeled by a lognormal distribution with mean $f_{ck} + 2\sigma$ and coefficient of variation 0.15 [10].

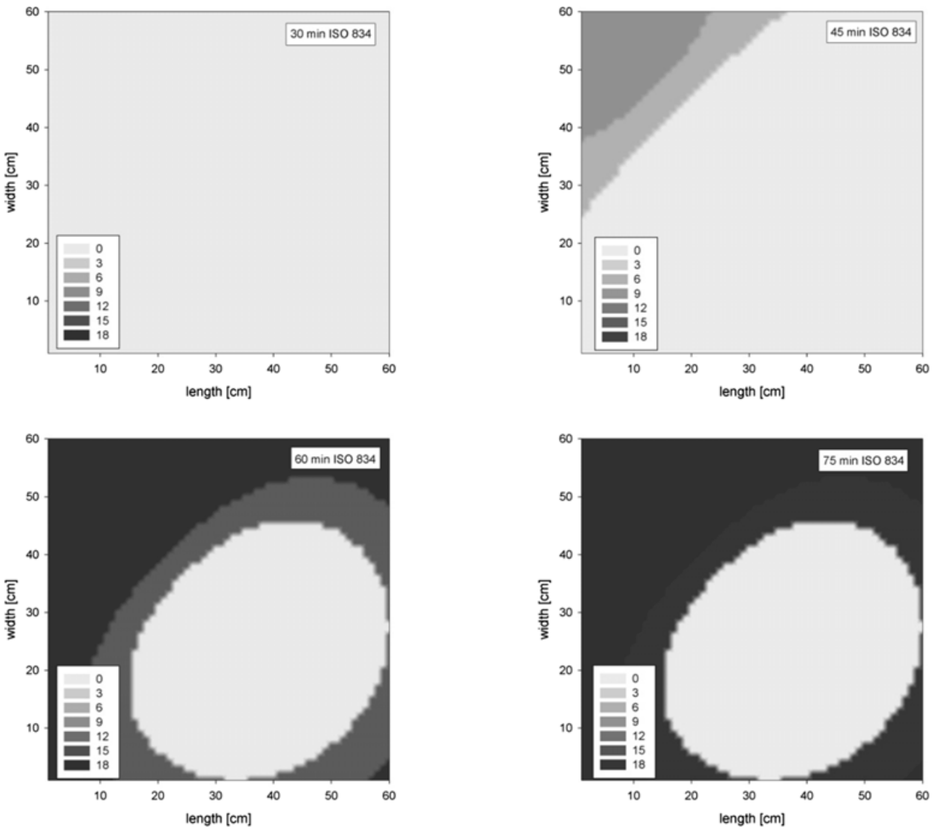

Figure 3. Example 1 of the spatial occurrence of spalling for a concrete slab with mean $f_{ct,20^\circ C}$ of class 6 (3.1 MPa) for different ISO 834 durations – first realization of the random field.

Using 10 000 Monte Carlo simulations, and subdividing $f_{ct,20^\circ C}$ in 8 classes in accordance with Fig. 2, the probability of the different curves of Fig. 2 is assessed (Table 2).

Based on these considerations, a probability of spalling of 2.7% is determined. As the calculations are based on many simplifying assumptions, this result should be considered with caution. However, it may be useful to compare the probability predicted by the model for different design alternatives. Furthermore, the results of Table 2 can be used for reliability calculations.

However, when using the results of Table 2 as input for the cross-sectional reliability tool developed by Van Coile et al. [3], spalling is assumed to occur across the entire exposed surface and the bending capacity of the slab will be underestimated. A first step towards a more realistic consideration of the spatial occurrence of spalling can be made by applying random fields to model the spatial variability of the concrete tensile strength.

5. ASSESSING THE SPATIAL OCCURRENCE OF SPALLING USING RANDOM FIELDS

In concrete slabs, mechanical properties may deviate considerably across the length and width of the element. This spatial variation of mechanical properties can be modeled through random fields. In this paper a random field with an exponential decay of the covariance function is assumed:

$$COV\,(A,B) = \sigma^2 \exp\left(-\frac{\tau\,(A,B)}{b}\right) \tag{3}$$

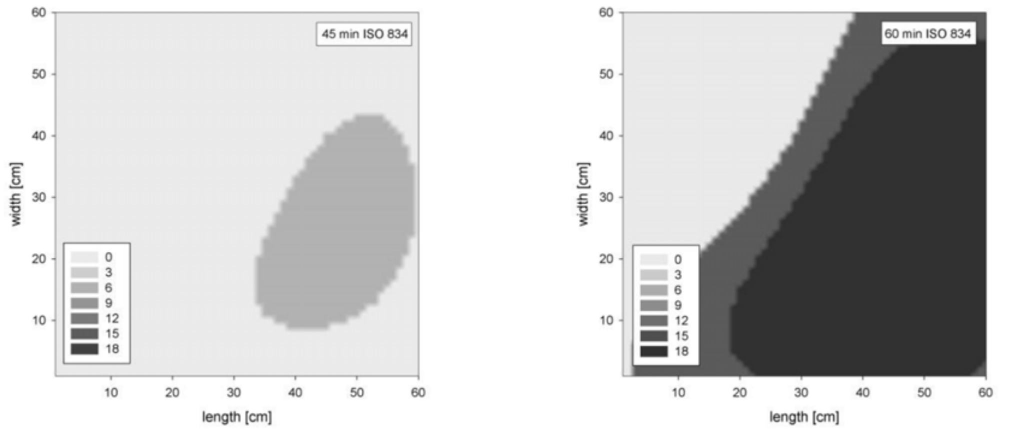

Figure 4. Example 2 of the spatial occurrence of spalling for a concrete slab with mean $f_{ct,20\,^\circ C}$ of class 6 (3.1 MPa) for different ISO 834 durations – second realization of the random field.

with A and B two points on the slab, COV(A,B) the covariation between these points, τ(A,B) the distance between the points and b the correlation length.

In order to avoid unrealistic small fluctuations of the random field, the five first eigenvalues of the correlation matrix are used to define the actual random field.

For every simulated slab the mean concrete tensile strength is determined according to the classification of Table 2. Subsequently, a Gaussian random field of $f_{ct,20\,^\circ C}$ is generated assuming a coefficient of variation 0.1, a correlation length of 2 m, and using a discretization of the slab width and length in square elements with size 10 cm^2 .

The following graphs Fig. 3 and Fig. 4 have been generated for class 6, i.e. for a mean 20 °C concrete tensile strength of 3.1 MPa. If this mean value is assumed to be representative for the entire slab, spalling is assumed to occur across the entire slab surface after approximately 56 minutes, up to a depth of 18 mm (Fig. 2). However, if the spatial variation of the tensile strength is taken into account, some areas exhibit spalling earlier, while other areas exhibit no spalling at all. Clearly, this will significantly affect the calculated structural behavior.

Clearly, taking into account the spatial variation of spalling will have a large influence on the subsequent calculations of strength and deflection during fire exposure. Furthermore, it is very interesting to note that every random field realization will result in a different spatial distribution of spalling, e.g. Fig. 3 and Fig. 4. Consequently, a large number of simulations would be necessary in order to determine the expected area which spalls.

While the proposed method needs to be elaborated further before it can be applied for actual performance-based design, the use of random fields seems promising. If the stochastic variation of crucial parameters as the concrete tensile strength are taken into account, a better estimation can be made of the reliability of concrete elements subject to spalling, and different design alternatives can be compared.

6. CONCLUSION

- Combining existing deterministic models for spalling with a stochastic representation of the input variables, a first estimation can be made of the probability of spalling and the spalled surface area.
- As an example, the spalling model proposed by Dwaikat and Kodur (2009) is combined with a stochastic representation of the 20 °C concrete tensile strength and the probability of spalling is estimated. However, this method assumes the tensile strength to be uniform for the entire slab.

- Subsequently, random fields are used to model the spatial variation of the tensile strength. This allows to visualize random realizations of the spatial occurrence of spalling. The use of random fields appears to be promising.

References

[1] Morgan H.P., Moves towards performance-based standards in the UK and in the European committee for standardization, *International Journal on Engineering Performance-Based Fire Codes*, 1, 98–103, 1999.

[2] Wade C., Beever P., Fleischmann C., Lester J., Lloydd D., Moule A., Saunders N. and Thorby P., Developing fire performance criteria for New Zealand's performance based building codes, Fire Safety Engineering International Seminar, Paris, 26/04-27/04, 2007.

[3] Van Coile R., Annerel E., Caspeele R. and Taerwe L., Assessment of the safety level of concrete slabs during fire, 10th IAFSS Symposium, Washington, 19/06-24/06, 2011.

[4] Kodur V.K.R. and Phan L., Critical factors governing the fire performance of high strength concrete systems, *Fire Safety Journal*, 42, 482–488, 2007.

[5] Ulm F-J., Acker P. and Lévy M., The Chunnel Fire II: Analysis of Concrete Damage, *Journal of Engineering Mechanics*, 121, 283–289, 1999.

[6] Hertz K.D., Limits of spalling of fire-exposed concrete, *Fire Safety Journal*, 38, 103–116, 2003.

[7] Bazant Z.P. and Thonguthai W., Pore pressure in heated concrete walls: theoretical prediction, *Magazine of Concrete Research*, 31, 67–76, 1979.

[8] Dwaikat M.B. and Kodur V.K.R., Hydrothermal model for predicting fire-induced spalling in concrete structural systems, *Fire Safety Journal*, 44, 425–434, 2009.

[9] JCSS, Probabilistic Model Code, The Joint Committee on Structural Safety, available online at www.jcss.byg.dtu.dk

[10] Holický M. and Sýkora M., Stochastic models in analysis of structural reliability, International Symposium on Stochastic Models in Reliability Engineering, Life Sciences and Operation Management, Beer Sheva, 08/02-11/02, 2010.