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SPALLING OF CONCRETE

Implications for Structural Performance in Fire

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INTRODUCTION

Spalling involves the breaking off of layers or pieces of concrete from the surface during thermal exposure. Spalling can broadly be classified into 3 different types: aggregate spalling, corner spalling (or sloughing off) and explosive spalling. Aggregate spalling and corner spalling are generally not considered to be critical for the performance of concrete structures in fire and are, therefore, not considered further here. Explosive spalling involves the ejection of pieces of concrete from the heated surface at high velocities. It typically occurs in the early stages of the fire when heating rates are high [1, 2]. Explosive spalling (hereafter referred to as spalling for brevity) poses the greater threat to structural stability; it is, therefore, the form of spalling focused upon in this paper.

Current research is predominantly concerned with establishing and modelling the precipitating mechanisms. Prediction of the stress state leading to spalling requires complex hygro-thermal-mechanical modelling; the reliability and accuracy of such models however is not yet sufficient to formulate design guidelines; hence, there is little guidance provided under BS 8110 part 2 [3] and the new Eurocode 2 [4] with regards to protection of concrete structures in the event of spalling. In this paper, a preliminary investigation on the effect of spalling on structural stability is performed through the finite element analyses of a reinforced concrete beam subjected to the Eurocode 1 [5] standard temperature – time curve. It is not the intention of this investigation to model explicitly the hygro-thermal-mechnical processes, rather to develop a framework for consequence modelling of spalling in a finite element analysis.

1 MECHANISMS OF SPALLING

Spalling of concrete can generally be categorised as pore pressure induced spalling, thermal stress induced spalling or a combination of the two. In general terms, pore pressure spalling occurs when migration of evaporated free water from the heated surface leads to increased pore pressure at some distance from the heated surface. Continued heating will result in the pore pressure reaching the tensile strength of the concrete, causing explosive local failure. No pore pressures have yet been measured which would exceed the tensile strength of concrete [6, 7]. Thermal stress induced spalling is thought to occur due to the steep thermal gradients which develop in concrete as it is heated. These gradients induce compressive stresses at the surface due to restrained thermal expansion and tensile stresses in the cooler interior. Surface compression may be augmented by applied loading or pre-stress. It is most likely that spalling results as a combination of the tensile stresses induced by thermal expansions and increased pore pressure. Much debate still surrounds the identification of the key mechanism (pore pressure or thermal stress). However, it is noted that the key mechanism may change depending upon the section size, material composition and moisture content [8].

2 SPALLING MODEL

2.1 Spalling Criteria

From the previous discussion of the governing mechanisms of spalling, it is evident that the stress state within the concrete will dictate whether spalling will occur. The stress state due to moisture migration and thermal stress will be influenced by several parameters; these parameters can be categorised as follows [1, 2]:

- Material Parameters: Initial moisture content, permeability, porosity, presence of cracks, aggregate type and size, amount of reinforcement.
- Geometric Parameters: Section shape and size.
- Environmental Parameters: Heating rate and profile, temperature level and thermal restraint.

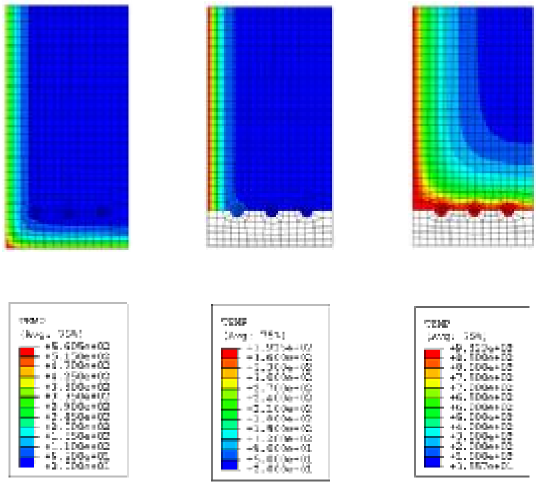
It is not the intention of this investigation to model explicitly the hygro-thermal-mechnical processes which determine this stress state leading to spalling. A comprehensive review of the substantial body of research which has sought to characterise the conditions under which spalling occurs has been undertaken to identify critical conditions or parameters for spalling which are applicable within a structural analysis. The fundamental assumption in this analysis is that spalling ***will*** occur, thus it is assumed that the material and geometric conditions which trigger spalling are satisfied.

Assuming that spalling will occur, it is then necessary to define ***when*** spalling will occur during fire exposure. The environmental parameters of heating rate and temperature level are useful indicators in a thermal analysis of when spalling may occur. From the literature it is found that heating rates in the range of 20–32^{o}C/min are significant for spalling [2]. Such high heating rates normally occur in the early stages of the fire which is consistent with the experimental observations. Several researchers have identified critical temperature ranges for the exposed surface at the onset of spalling. Aktaruzzaman and Sullivan [9] have cited exposed surface temperatures in the range of 375–425^{o}C for normal weight concretes.

2.2 Spalling Implementation

A 2-D heat transfer analysis of the member cross section is performed using ABAQUS finite element software [10]. The onset of spalling is triggered when the bottom surface temperature reaches the range of 375-425^{o}C. Spalling is modelled by removing all the elements making up the bottom concrete cover. The analysis is continued and the temperature distribution for the reduced cross section is calculated. Figure 1 presents typical temperature contour plots just prior to and just after spalling and one hour from the beginning of the analysis for the abrupt spalling analysis.

Removing all of the concrete cover instantaneously when the bottom surface reaches a certain temperature greatly simplifies the progressive nature of spalling. Slower and more progressive spalling can also be modelled by employing the same temperature criteria but only removing single layers of elements at time. The thickness of the layers removed will be a function of the element thickness used in the finite element analysis.



(a) Pre Spalling (b) Immediately post spalling (c) Final temp distribution

Fig. 1. Beam cross section temperature profile (^{o}C) for abrupt spalling.

4 CASE STUDIES

The performance of a simply supported RC beam exposed to the EC1 [5] standard temperature-time curve (Figure 2) and subject to spalling is investigated.

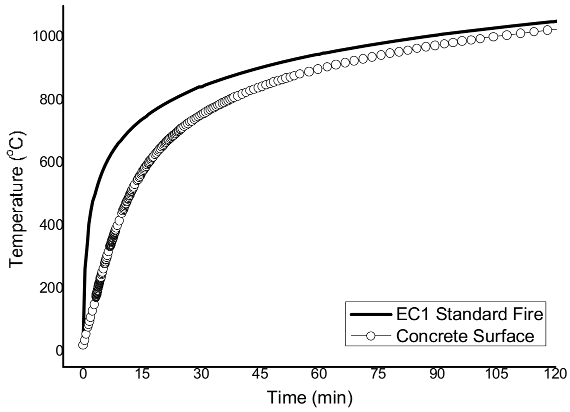


Fig. 2. Eurocode 1 standard temperature curve and concrete surface temperature.

The beam cross section is 600 mm deep by 300 mm. The concrete strength f_{cu} is assumed to be 30 MPa. The beam is reinforced with six 16 mm steel bars of yield strength, f_y = 500 MPa. The cover depth is assumed to be 45 mm. Temperature dependant material properties for both the concrete and reinforcing steel are taken from Eurocode 2

Advantage is taken of symmetry and half of the beam cross section is analysed for the case of no spalling, progressive spalling (8 mm layers) and abrupt spalling. The rapid evolution of concrete surface temperature in Figure 2 would indicate that varying the criterion temperature between 375°C- 425°C would have little effect on the final temperature distribution therefore the surface temperature criterion for the onset of spalling is taken as a single value of 400°C.

For each case the resulting evolution of temperature in the reinforcement is plotted in Figure 3 (a). The corresponding reduction in reinforcing steel yield strength is plotted according to the reduction factors provided in Eurocode 2 is plotted in Figure 3 (b).

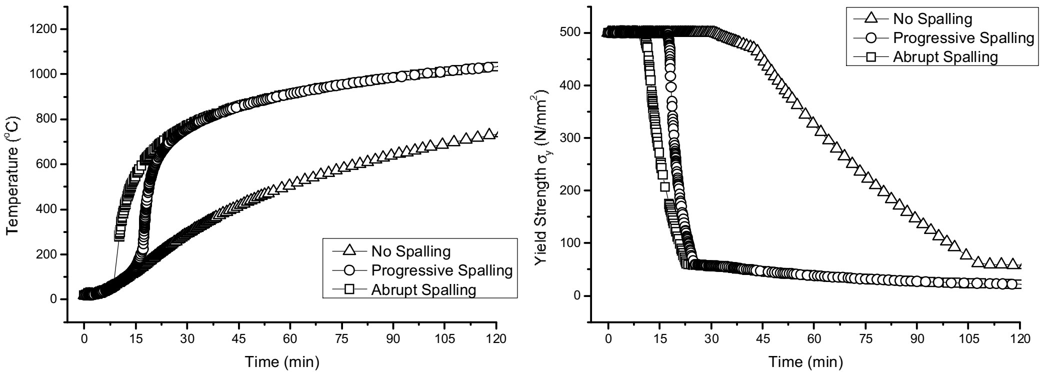


Fig. 3. (a) Temperature development and (b) reduction in yield stress in reinforcing steel on exposure to the standard fire.

For the case of no spalling the steel temperatures rise gradually, being insulated by the concrete cover. Removal of the concrete cover due to spalling instantly results in a sharp increase in steel temperatures and a corresponding reduction in steel strength.

4.1 Single span simply supported RC beam

For a simply supported beam a single point of failure will result in a stability failure. Thus, failure times can be calculated by comparing the load ratio, r_{load}, with the residual steel strengths. The load ratio, r_{load}, is defined as per Equation 1 below:

$$r_{load} = M^*_{fire} / R_{cold} \tag{1}$$

Where M^*_{fire} Applied bending moment in fire conditions

R_{cold} Ambient ultimate capacity

Table 1. Failure times for simply supported beam under standard heating.

r_{load}	No spalling (min)	Progressive spalling (min)	Abrupt Spalling (min)
0.4	78	21	17
0.45	73	20	16
0.5	71	20	16

The failure times for each scenario and a variety of load ratios representative of those expected in a real building [11] are presented in Table 1. It is apparent that spalling significantly reduces the failure time of the simply supported concrete beam when exposed to the standard fire. Note that the failure time predicted with spalling (even in progressive spalling) is well short of the time when the cooling phase typically starts in 'natural' or parametric fires (EC1 2002). Hence it can be argued that consideration of the cooling phase will not alter the prediction of failure time.

4.2 Two span simply supported RC beam

Continuous beams generally exhibit improved fire performance due to their ability to maintain stability through alternate load paths (moment redistribution). The fire affected moment capacity is calculated using the simplified method from EC2 [4] which assumes that concrete above 500°C is structurally insignificant and below 500°C the concrete is unaffected, the results can be seen in Table 2.

Table 2. Failure times for a two span RC beam under standard heating.

Spalling		Single steel layer (min)	Double steel layer (min)
Span 1	Span 2		
No	No	177	224
Yes	Yes	24	258
No	Yes	99	188

Figure 4 shows the bending moment distribution for the case of unsymmetrical spalling. Yielding at the mid span and near the support creates a failure mechanism in the spalling affected span.

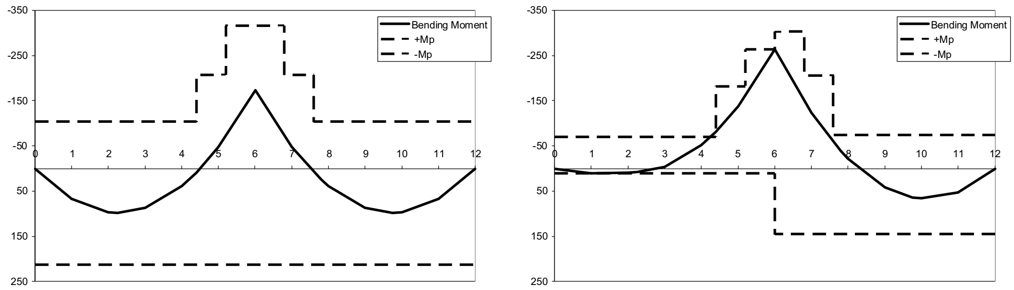


Fig. 4. (a) Ambient BMD (b) BMD at failure

The beam analysed has a 2 hour fire rating according to the requirements of EC2. For the normal design of a single layer of tensile steel failure times in the event of spalling are significant less than prescribed in design. The analysis was repeated using an equivalent quantity of steel but distributed in two layers thus increasing the insulation to 50% of the steel. This simple change significantly increases the performance of the beam.

In both analyses the standard temperature-time curve has been used to define the thermal exposure for the beam. This assumes a uniform thermal exposure along the length and across the width of the beam which, in conjunction with a thermal criterion for spalling predicts spalling affects the entire beam length. In reality this is not the case, because spalling may be localised to regions of high thermal exposure. The effects of localised spalling become more complicated in the case of a continuous multi-span beam or a slab.

6 CONCLUSIONS

Explosive spalling is a very complex phenomenon which poses a great threat to structural performance of some reinforced concrete structures in fire. There is a large body of research concerning the prediction of whether spalling will occur, but rather less research concerning the implications that spalling has for structural performance. Current design guidance for the consideration of spalling is limited thus spalling is largely ignored in the design process of concrete structures despite its potential consequences.

The results of the analysis of a simply supported beam indicate that spalling threatens stability of the structure by exposure of the reinforcement to high and rapidly rising temperatures. It is shown that under exposure to the standard fire, failure times are significantly reduced for both models of spalling (abrupt and progressive spalling).

Multi-span beams perform better due to their ability to utilise alternate load paths. However, in the presented example, extensive spalling still leads to premature failure. More sophisticated calculation methods considering the effects of end restraint are required to better establish performance in fire and spalling. In the future, the study will be extended to consider spalling implications in a finite element mechanical analysis using non-uniform heating definitions for multi-span beams and slabs.

7 SUMMARY AND ACKNOWLEDGMENT

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