BRE Centre *for* Fire Safety Engineering

EXPLOSIVE SPALLING OF CONCRETE: IMPLICATIONS FOR STRUCTURAL PERFORMANCE IN FIRE

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Explosive Spalling…

…is the most violent form of spalling, it typically occurs in the early stages of a fire and involves the ejection of pieces of concrete from the heated surface at high velocities. Parameters believed to influence the occurrence of spalling can be categorised as follows (Khoury 2000):

Material parameters	moisture content, concrete permeability, porosity and the presence of cracks, aggregate type, aggregate size and the amount of reinforcement
Geometric factors	section shape and size
Environmental factors	heating rate and profile, temperature level and thermal restraint

Structural implications

Concrete is inherently a highly insulating material. This characteristic has afforded concrete a good reputation for fire performance. Spalling has the potential to undermine this performance by exposing reinforcing steel to high and rapidly rising gas temperatures.

Spalling is however a terrifically complex phenomenon, prediction requires fully coupled hygro-thermal-mechanical (HTM) analysis. The efficiency and accuracy of such models is not yet sufficient to formulate design guidelines. Thus there is little guidance on spalling in the new EC2 or requirements to consider it when designing concrete structures for fire.

Figure 1 Explosive Spalling of ceiling slab (Bailey 2000)

Spalling Criteria

Will it or won't it?

It is not the intention of this study to model explicitly the hygro-thermal-mechanical processes which determine the concrete stress state.

"The fundamental assumption in this analysis is that spalling will occur"

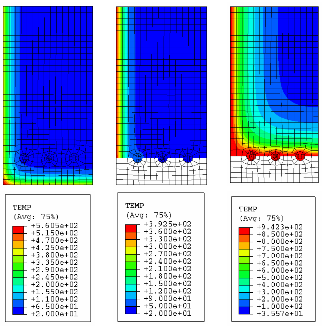
Thus it is assumed that the material and geometric conditions which are conducive to spalling are present.

When will it occur?

It is necessary to define when spalling will reasonably occur during fire exposure. Environmental factors such as heating rate and temperature level are useful indicators in a thermal analysis of when spalling will occur.

Several researchers have identified critical temperature ranges for the exposed surface at the onset of spalling. Aktaruzzaman and Sullivan (1970) have cited exposed surface temperatures in the range of 375-425oC for normal weight concretes.

Spalling Implementation



(a) 510 s *(b) 511 s* *(c) 3600 s*

Figure 2 Temperature profile (°C) through cross section at different times for abrupt spalling case

A 2-D heat transfer study of the member cross section is performed using ABAQUS finite element software (ABAQUS 2006). The onset of spalling is triggered when the exposed surface temperature reaches 400°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.

Case Studies

Single span simply supported RC beam

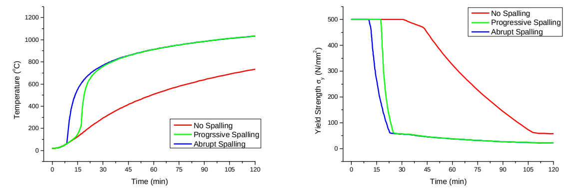


Figure 3 (a) ABAQUS predicted steel temperatures, (b) Steel residual strength during ISO fire exposure

For this member a single yield point will result in a stability failure, thus failure times are calculated based on the load ratio compared to the steel residual strength.

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	15

Table 1 Failure time of a single span RC beam when exposed to the EC1 standard temperature-time curve

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 (1996) which assumes that concrete above 500°C is structurally insignificant and below 500°C the concrete is unaffected.

Condition		Single Steel Layer	Double Steel Layer
Span 1	Span2	(min)	(min)
No spalling	No spalling	177	224
Spalling	Spalling	23.5	158
Spalling	No Spalling	99.2	188

Table 2 Failure time of two span RC beams when exposed to the EC1 standard temperature-time curve

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.

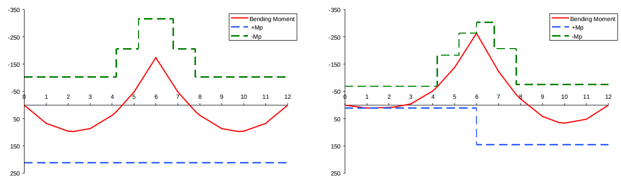


Figure 4 (a) Ambient BMD (b) BMD at failure

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 significantly less than that 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.

Conclusions

- The performance of RC beams as expected is severely undermined by the occurrence of spalling in both single and two span beams.
- In the occurrence of severe spalling (i.e. affecting one or two spans) continuity does not afford a significantly greater performance.
- Careful redistribution of reinforcing bars in the design process may mitigate against the effects of spalling on structural stability
- Further work in this study will include consideration of support conditions and more sophisticated material models

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