FIRE IN STOREHOUSE 6 IN THE FREE PORT OF STOCKHOLM

Robert Jansson (1), Kai Ödeen (2)

(1) SP Technical Research Institute of Sweden, Fire Technology, Sweden
(2) KTH Royal Institute of Technology, Sweden

Abstract
Fire spalling of concrete has the potential to devastate a structure that has been exposed to fire. Our understanding of the fire spalling phenomenon has improved in recent years but there are still essential lessons to be learned from the study of historically significant fire events. This paper reviews the effect of a major fire in a building in the Free Port of Stockholm in 1966. The incident itself is some 45 years old but by the spalling issue is still the subject of “heated” debate.

During a fire in the upper cellar of a five storey storehouse in the Free Port of Stockholm on March 10, 1966, severe spalling occurred in the floor slab and columns on the floor of fire origin. Ödeen observed the fire on site and was involved in the damage assessment after the fire. The damage assessment included mapping of the damages, classification of five levels of spalling severity, mechanical tests on concrete and steel reinforcement samples taken at the fire scene as well as a calculation of the load bearing capacity of the structure after the fire. One conclusion from the assessment was that if the building had been loaded to the designed service load the floor might have collapsed. During the following refurbishing of the structure as much as 20 cm of the cross-section was removed and replaced with sprayed concrete.

Although the concrete structure was designed for a fire resistance of 4 hours, the structure was severely damaged after approximately 2 hour of fire exposure. The reason for the severe spalling was probably that the moisture content in the concrete was high as the building was in the later stages of construction. An important lesson from this case study is that although the spalling was severe the structure could be refurbished and did not need to be demolished. Further, this case study shows clearly that all types of concrete may be vulnerable to fire spalling especially at young age, even those that are not typically expected to spall.

1. INTRODUCTION

During the early hours of the morning of March 10, 1966, a fire started in the upper cellar level of storehouse number 6 in the Free Port of Stockholm [1]. An open gas flame, used for melt-sealing of an asphalt layer in a moisture barrier on all surfaces of the floor (i.e. walls, floor and ceiling), ignited the asphalt in such a way that it was not possible to extinguish the fire. The upper cellar, dimensions 48.5 m × 11.06 m, filled with cold storage rooms was in the later stages of construction at the time of the fire and large amounts of asphalt, cardboard, Wellit (an insulation material) and cork were present at the building site. The high fuel load led to a rapid fire development which inhibited efforts to extinguish the fire. Despite this a
large amount of water could be introduced into the structure resulting in significant cooling of
the floor covered with cork in the fire area. Once the fire had been extinguished this meant
that the floor was essentially undamaged. It has been assessed that the duration of the fire was
approximately two hours based on eyewitness accounts by Ödeen.

The building was comprised of five levels above ground and two cellar levels, see figure
1. The two cellar levels were constructed nominally below the surface of the water in the
adjacent port.

![Figure 1 Cross-section of the building [1]. The fire was restricted to the upper cellar (designated “ÖK” in the figure).](image)

The flat concrete slab floor over the upper cellar where the fire developed was 42–50 cm
thick with a fire rating of 4 hours, i.e. the construction was designed to withstand a fire for 4
hours when carrying its service load. The structure was designed with a large margin of
safety to support the building as a whole, e.g. columns had a diameter of 130 cm which can
be compared to 40 cm which would have been sufficient to obtain the same fire rating for a
roof construction.

The exact recipe for the concrete used in the structure is not available but we know that the
concrete was prescribed to be K350 (34 MPa) with a 28-day value of K400 (39MPa). The
bottom steel reinforcement in the slab had a diameter of 16 mm and 25 mm.

As this level of the building was planned to be used for cold storage, the concrete was to
be covered with an insulating membrane consisting of asphalt and 20-30 cm of Wellit, a type
of corrugated cardboard doped with tar. At the time of building this type of extremely
flammable insulation was common (until approximately 1970 when production was halted).
Parts of the construction had been covered and a significant amount of insulation material
was present in the cellar waiting to be mounted. Therefore, the equivalent fire load was
estimated to be 60 kg/m² wood per floor area.

2. **Mapping of Damage**

To obtain an overview of the damage, visual inspection of the structure was performed. A
small amount of cracks through the construction were established in the fire exposed slab but
many cracks were found at the upper surface of the cross-section when an extra 5 cm thick
layer of concrete used for smoothing the surface was taken away. Figure 2 shows a part of
the fire exposed structure after the fire. This figure clearly illustrated the fact that fire exposed
steel reinforcement was heated sufficiently to exhibit significant sagging.
As part of the investigation into the damage caused by the fire on the structure, a system was developed to define the degree of spalling severity based on visual assessment of the post-fire structure, see Table 1. This methodology, together with mechanical tests of core samples from fire spalled concrete and structural calculations, was used as a basis for assessing the potential for reconstruction of the building as an alternative to demolishing the structure. Similar but more detailed systems for visual classification of the level of damage to fire exposed concrete have been developed in recent years by the Concrete Society [2], [3] and fib [4].

Table 1 Degree of Spalling Severity.

<table>
<thead>
<tr>
<th>Levels of Spalling Severity</th>
<th>Description</th>
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<tbody>
<tr>
<td>1</td>
<td>Slight spalling of the surface, see figure 3a.</td>
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<tr>
<td>2</td>
<td>Bottom reinforcement partially visible see figure 3b.</td>
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<tr>
<td>3</td>
<td>Both layers of bottom reinforcement visible see figure 3c.</td>
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<tr>
<td>4</td>
<td>Bottom reinforcement totally uncovered, 8-10 cm of concrete spalled away see figure 3d.</td>
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<tr>
<td>5</td>
<td>Bottom reinforcement partly falling down see figure 3e.</td>
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Figure 3: Photos showing the different levels of severity of spalling [1] (a) first level, (b) second level, (c) third level, (d) fourth level, (e) fifth level.

In figure 4 a map of the fire damaged area can be seen. It can be seen that more or less severe spalling had occurred on major parts of the slab. The dimensions of the slab were 48.5 m × 11.06 m.

Figure 4 A map of severity of damage in the roof of the construction [1]. White area only soot on surface, horizontal lines spalling degree 1, dots spalling degree 2, vertical lines spalling degree 3, angled lines (almost gray) spalling degree 4 and squares spalling degree 5.
3. TESTING OF MECHANICAL PROPERTIES

To support an accurate residual structural assessment of the fire damaged area, mechanical tests on both concrete and reinforcement were performed. Concrete cores, diameter 10 cm, were removed from the concrete slab from areas representing all five degrees of spalling severity. Three centimeter thick sections were then cut from the cores to determine the tensile strength with the indirect Brazilian splitting strength method. This method was chosen as the tensile strength was deemed to be more sensitive to heating of this kind than the compressive strength. One section was cut as close as possible to the fire exposed area and the second section 5-10 cm from the fire exposed area and the third section in the cold “virgin” zone of the core. Large deviations in results were found but the average values for spalling severity level 4 and 5 at the three different depths were 3, 3.5 and 3.7 MPa, i.e. the difference in tensile strength in the cross-section was not significant. Further, cubes were cut to determine the compressive strength showing results between 36 and 41 MPa of compressive strength, i.e. no reduction in strength.

Measurements of the tensile strength of reinforcement with remaining deformations from the fire showed that the properties of the hot-roll carbon steel, Ks40, was not reduced after cooling down.

4. REFURBISHING

The first stage of refurbishing required sand-blasting and hewing of the concrete surface, to obtain a clean starting point for new application of material. After this, the visible reinforcement was brushed with steel brushes and water treatment of the concrete surface was performed for two days. Finally, additional complementary reinforcement was installed and the cross-section was restored with sprayed concrete using the dry mix procedure.

Based on the results of the tests on mechanical properties of the fire exposed concrete and steel reinforcement, a calculation of the load bearing capacity showed that after repair with sprayed concrete the construction could once again fulfill the original building specifications.

5. DISCUSSION AND CONCLUSIONS

The tests on tensile strength described above showed surprisingly low reduction of the splitting tensile strength. The reason for this might be attributed to the orientation of the fire load. The duration of the fire was estimated to two hours and the cork material at the floor was cooled down with water to such a degree that a large amount of the accessible fire load was not actually involved in the fire. Indeed, it was only the fire load attached to the ceiling itself that was active in the fire. As the products involved attached to the ceiling were designed as insulation, the bare surface of concrete was not really exposed to the fire for the whole period, i.e. until the insulation had been compromised. Therefore, the authors postulate that the spalling behavior was only during the very late period the overall fire exposure, leading to a short period of heat penetration into the newly spalled areas. This can explain the relatively low reduction of mechanical properties of the concrete in the cross-section.

A modern example of similar behavior in terms of very low reduction of the mechanical properties in the cross-section of a structure exposed to an intense fire was found during a fire under a road bridge in Sweden [5][6]. During this fire, concrete was exposed to a rapid fire leading to spalling but the heat penetration into the concrete cross-section was limited by the relatively short duration of the fire. The outcome of the residual assessment after that fire was that the construction was not damaged beyond repair.

This was not the case in an even more recent case study of a fire in a car park. After a one hour long fire in a car park also during the construction phase, the post fire assessment then led to demolition of all pre-stressed elements [7].

As the building was of young age the moisture content was probably high which gave a higher risk of spalling. Zhukov found that granite based concrete with a compressive strength
of 40 MPa spalled when the moisture content was over 3% [8]. When testing a similar concrete with the compressive strength 20 MPa the same limit of moisture content was 4%. When studying mechanical behavior of ultra high strength concrete with a compressive strength between 190 and 240 MPa Jumppanen found that small prisms, 40 × 40 × 160 mm3 spalled severely although the heating rate was low and the moisture content was between 2.3 and 3% [9]. In a study by Zheng et al on pre-stressed concrete slabs with a compressive strength between 22.8 and 56.9 MPa the conclusion was that the nominal stress along with the concrete strength had a major influence on spalling whereas the moisture content had minor effect [10]. The moisture content is although in most cases an important factor concerning prediction of the spalling behavior but the concrete mix, the cross-section and external loads are also important factors to also consider [11].

REFERENCES
[8] Zhukov V. V. “Reasons of Explosive Spalling of Concrete by Fire”, Beton I zhelezoobeton (Concrete and Reinforcement Concrete), No. 3, 1976