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Full-Scale Fire Tests as part of Risk Analyses

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Summary

The present paper presents the fire tests carried out in the wake of the fire which occurred in one of the TBMs during construction of the 8 km long railway tunnel under the Great Belt. Along with other investigations the tests formed basis for a general update of models describing the fire-performance of the tunnel lining. The paper describes the fire test design and the analysis of results in the context of Operational Risk Analysis updating.

1. Introduction

For tunnel structures the exposure to fire is a central issue. Fires may result in exposure of the structures to very high fire temperatures and recent in-situ experiences, from the Great Belt Project and from the Channel Tunnel, have shown that damage to concrete resulting from fire may turn out quite severe. Experience which accentuates the need and relevance of taking due account of risks of fires in the assessment of operational risks for tunnels. The implications of fires in hazardous goods may be disruption of tunnel operation and loss of revenue for several months and the structures may ultimately collapse possibly resulting in flooding of the tunnel.

For the bored tunnel under the Great Belt, which opened to traffic spring 1997, both durability and safety were emphasised early in the planning. The concrete was prescribed as a dense concrete containing fly-ash and microsilica, with a cylinder strength of 50 MPa. Extensive risk analyses have been made for managing safety and it was at an early stage decided to integrate the fire considerations in the Operational Risk Analysis, [3]. Design predictions on fire-performance of the tunnel lining, covering a.o. the spalling behaviour, was established based on international standards, literature and experts advice. Modifications of the structural design were made on the basis of these risk studies and an acceptable resistance towards fire in hazardous goods was thereby established.

The fire resistance was later to be reassessed in the update brought about by the fire that occurred in the TBM in 1994. A main part of the update, described in this paper, was the laboratory testing for reassessment of the prediction models on fire-performance. In these tests the spalling behaviour of the lining was the main matter of interest.

2. Failure Mechanism and Fire Design

The elevated temperatures prevailing during a fire will cause moisture in concrete to migrate away from the heated face. At a certain time the escaping moisture will be taken over by the advancing heat front and the restraining forces within the concrete, brought about by the evaporation of water, may cause spalling hereby exposing new concrete to fire temperatures. Thereafter the temperature in the remaining concrete will gradually increase accompanied by a decline of concrete strength and stiffness possibly in combination with continued spalling.

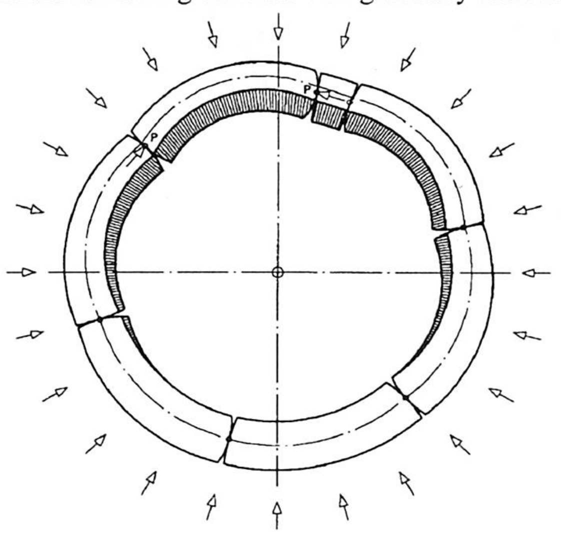

Fig. 1. Principle of damage to lining and deformation under hoop load

For a bored tunnel as the Eastern Railway Tunnel failure takes place when the remaining concrete section no longer can sustain the compressive hoop load. Critical loss of load bearing capacity may occur during the fire or in the cooling phase. In the latter event not because of spalling but as a result of continued loss of strength.

Fire design and the Operational Risk Analysis conducted at the design stage was based on theoretical modelling of fire-performance of the lining. The event of spalling was modelled in the analyses as foreseen to influence the fire-life of the structures. Based on international guidelines, literature reviews and experts advice it was assumed that the inner concrete cover, of size 40 mm, would spall away after 20 minutes of fire and that spalling would then cease. A transient heat equation was assumed for estimating concrete temperatures and thus the current load bearing capacity of the lining. Based on a study of fire scenarios a 1200°C hydrocarbon fire was selected for the analyses. It was, together with experts, assessed that the fire curve of RABT, which indicates a rapid increase in temperature and a constant temperature after 5 minutes, would provide the best representation of a hydrocarbon fire.

Based on the described assumptions and considering the tunnel specific behaviour, taking account of temperature-induced stresses and stress-relieving interaction with the ground as well as deformations in the lining, it was assessed that the lining would sustain the fire for 3-5 hours. With this estimate the risk of service disruption in excess of one month was well within the acceptance criterion, [1].

3. The Fire during Tunnel Construction

A fire in one of the tunnel boring machines took place 11 June 1994, and although the tunnel structure sustained the fire, the spalling damage was more severe than design predictions had suggested, [2].

Whether this could be due to the special conditions for a fire present during tunnel construction was not obvious at the time. Neither was it clear whether the experience would have implications on the operational risks for the tunnel and in the wake of the fire it was thus decided to update design prediction models on fire-performance of the tunnel lining; namely those that could significantly effect the fire-life of the structures.

The major part of the update was the performance and interpretation of full-scale fire tests of segmental lining under realistic loading conditions, but the updating also encompassed small scale laboratory tests carried out in order to confirm models for the concrete strength and elasticity during elevated temperatures, as well as reviews of relevant as-built documentation. Along with the updating, a literature study was conducted and international experts were consulted in order to be up to date with recent conceptions and results of research on the related subjects.

4. Fire Tests with Tunnel Segments at Full Scale

Test Conditions

The main purpose of the tests was to explore the spalling behaviour of the concrete segmental lining when subjected to a severe hydrocarbon fire.

The literature studies and consultations with experts confirmed that the concrete mix, the moisture content of concrete and the external mechanical pressure are important factors for the possibility, and possibly also for the severity of spalling. As to moist it is widely held that the more moist in the concrete the more vulnerable it will be towards elevated temperatures. Presence of compressive normal load may increase the risk of spalling but the magnitude of the load could also be a contributory factor for the risk and severity of spalling.

In the planning of the tests these aspects had to be considered plus the requirement that test conditions were to resemble those expected to prevail in the tunnel in its operation phase. As tunnel segments from the general production were still available these were obvious specimens for testing. The test programme set out comprised two full-scale tests, namely one with a segment at low pressure level (2 MPa) and another with a segment at realistic in-situ pressure level (5 MPa).

Overall, the moisture content of the segments subjected to testing equalled that of the segments already in-place in the tunnel; about 4% by weight. For the latter segments the moisture content is most likely to decline over the years why this test condition tend to be on the safe side compared with future in-service conditions.

The fire exposure was, as in the design calculations, set to an initial climb to 1200°C in 5 minutes, i.e. a fire curve resulting in high rates of heat flow and moisture movements most likely increasing the chance of spalling and accelerating its occurrence in combination with a quite rapid loss of concrete strength. The temperature was kept at 1200°C for 4 hours followed by 2 hours of cooling.

Test set-up and Measurements

The tests, specified and interpreted by the consultants of the Great Belt Link Ltd, COWI-MOTT JV, and undertaking by Swedish National Testing and Research Institute, took place with the segment placed on top of a horizontal furnace as shown in fig. 2. During the testing a purpose-designed loading arrangement provided the specified external load on the segment.

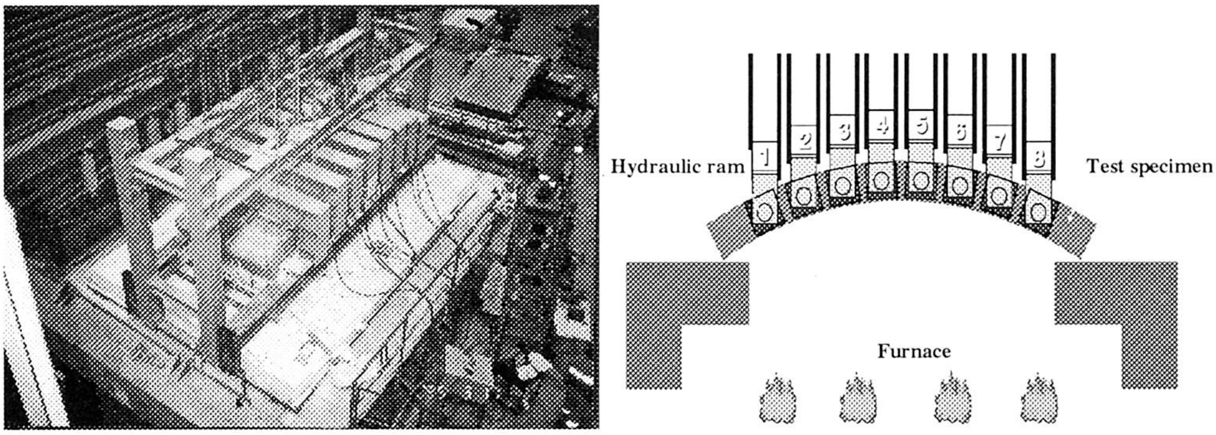

Fig. 2. Test Set-up for full scale fire tests.
External pressures corresponded to forces of 342 and 870 tons in the respective tests.

The destructive effects of the fire were visually observed through dedicated windows situated in the walls of the furnace. Temperatures inside the test specimen were recorded by thermocouples which further provided information on the current depth of spalling.

5. Test Results

Fig. 3. Concrete segment after fire test

Spalling Depths
After 4 hours of fire and 2 hours of cooling the segment was lifted off the furnace and appeared as can be seen in fig. 3. The size of damage that the concrete had encountered in the two tests differed only slightly and in both tests the remaining concrete appeared dome-shaped as was the case in the 1994 tunnel fire.

The contour plot in fig. 4 is produced based on a detailed mapping of the final damages. The virgin thickness of the segment was 400 mm.

The overall trend in the progression of spalling is illustrated in fig. 5. As can be seen the majority of spalling took place within the first 20 minutes of the fire, and the final spalling was more severe (90mm) than the design prediction model (40mm) had suggested. The spalling shown in fig. 5 is the spalling depth (cross sectionally averaged) in the worst affected cross section of the test specimen. As it was only possible to carry out a detailed mapping of damages upon completion of the tests the curve has been established on basis of visual observations made during testing and is thus rather approximative.

The fire resistance of the tunnel is determined by the weakest segment in the group of segments exposed to fire. Due to the random nature of spalling an increase in the number of exposed segments will, from a probabilistic point of view, increase the severity of spalling damage in the worst

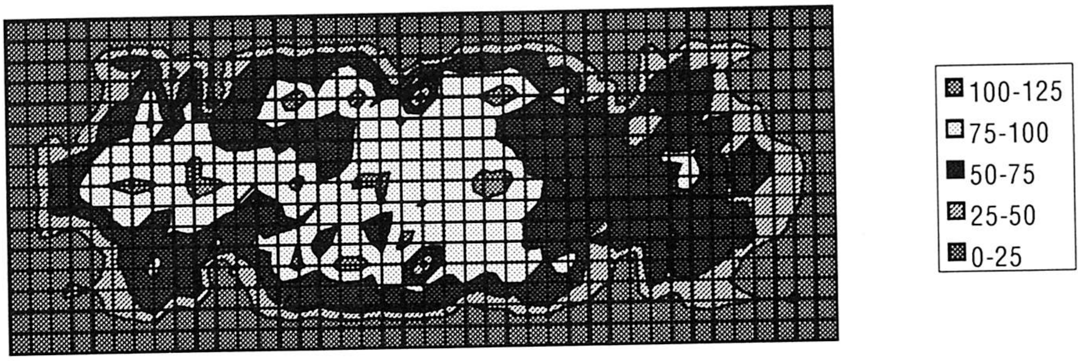

Fig. 4. Spalling depth in mm. Result from test with 5 MPa pressure is shown.

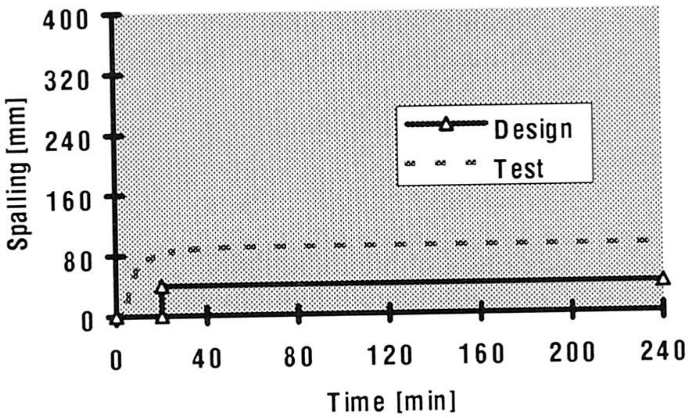

Fig. 5. Approximate rate of progression of spalling observed in tests along with design prediction.

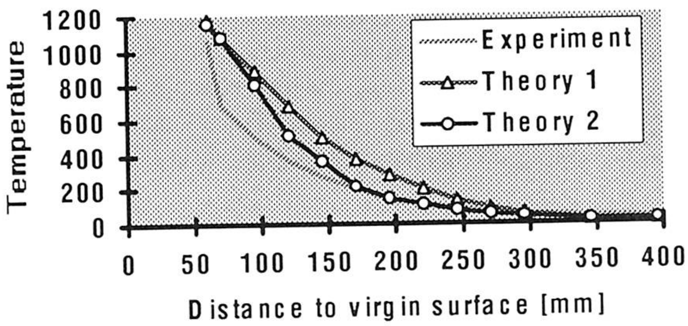

Fig. 6. Concrete temperatures in the remaining concrete.

affected segment. Conditioned that 30-300m of tunnel are exposed to fire then the best estimate for the worst affected segment is a spalling damage of 100-110 mm.

Segment Temperatures

The segment temperatures did not rise as rapidly as was predicted by the transient differential heat equation (fig. 6, Theory 1). As the temperature level determines the concrete strength the observation suggests that the decline of capacity of the remaining concrete will take place at a lower rate than originally predicted.

The lack of detailed information on the rate of progression of spalling (in time and space) introduces uncertainty when referring temperature registrations to depths below the exposed surface.

For the deeper thermocouples this uncertainty plays a minor role as regards the accuracy of the temperature profile, and the tests revealed that a more refined heat flow model (fig. 6, Theory 2) would be more accurate in estimating concrete temperatures than the design prediction model (Theory 1). The heat flow model in question takes account of the energy consumption of decomposing reactions in the concrete during heating, and was, due to its better performance for the particular concrete, applied in the subsequent update of fire resistance.

6. Update of Fire Resistance and Risk Analyses

The fire testing resulted in updating of prediction models for spalling (depth and time of occurrence) and for the heat flow in segments. Additionally, laboratory tests of smaller scale verified the design prediction model describing the concrete strength-temperature relation and a review of quality control documentation from the segment production documented that the cylinder strength of segment concrete was some 50% higher than the design value. In summary, a more refined calculation basis for determination of fire resistance for the particular structure was made available.

Inevitably, an element of uncertainty is associated with updating and for that reason the reassessment of fire resistance involved a sensitivity study in which implications of combinations of worst case and best estimate scenarios were investigated. The study embraced spalling scenarios ranging from 110mm (test result) over 150mm (the spalling recorded after the 1994-fire) to 180mm and fire temperatures of 1200°C as well as 1350°C. Based on the study it was concluded that the fire resistance is 4 hours or longer and as the design prediction was 3-5 hours the result had no implications on the existing operational risk account for the tunnel.

7. Conclusion

For the bored tunnel below the Great Belt the destructive effects of fire on the concrete lining were modelled and considered at the design stage. Subsequent fire testing with full-scale tunnel segments exposed to a RABT 1200°C fire curve provided a more refined model for the spalling behaviour of the particular structure. Additionally, the tests showed that a heat flow model taking account of energy consumption of decomposing reactions in the concrete performed better than the commonly used design prediction model. Testing was carried out with segments with a moisture content equal to that of segments in the tunnel, and under realistic loading conditions. The size of mechanical pressure acting on the test segments showed to have only marginal effect on the severity of spalling.

The subsequent update of fire resistance supported the robustness of the design prediction (3-5 hours), and with this estimate the risk of long-term service disruption is well within the acceptance criterion for the specific structure. For other concrete structures with other structural systems, e.g. immersed tunnels with large span roofs, spalling damages of sizes as those observed after only 10 minutes of fire testing could well result in structural collapse even quite early in a fire. For such structures fire insulation may prove to be very effective. In conclusion, the test results and in-situ experiences, from the fires in the Eastern Railway Tunnel and in the Channel Tunnel, accentuate the need for taking due account of the rather complex structural mechanisms at play during fires in the assessment of operational risks for tunnels.

8. Acknowledgement and References

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