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Øresund Tunnel - Control of Early Age Cracking

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Summary

The concrete segments for the Øresund Immersed Tunnel are poured in one continuous operation. This permits early age cracking to be controlled without the use of embedded cooling pipes. The feasibility of this was established at the project tender stage and was the principle around which the construction method was developed. The thermal analysis formed an integral part of both the tender and detailed design process and the work carried out by the two consultants involved is described in this paper. The project shows the benefits of dealing with early age cracking on the design table and not treating it as a problem to be overcome by implementation of measures on site. The construction method has been successful in eliminating early age cracking.

1. The Øresund Tunnel Casting Technique

The Øresund tunnel has a total length of 3.5km and comprises 20 immersed tunnel elements. Each element is formed by 8 segments. Watertightness of the structure is achieved by high quality concrete which is designed to be free of early age cracking. The 22m long, 8.5m high and 41.7m wide segments are each cast in a single concrete pour. Casting is carried out in a tightly controlled environment - factory conditions have been created in a purpose built casting facility. A highly complex formwork system, foundation and support jack system was developed to allow segments to be cast in the shed and then jacked forwards, making room for the next segment to be cast.

The construction method provides a watertight, durable structure without the use of embedded cooling pipes to control early age cracking. Similar construction methods have been used before for much smaller scale immersed tube service tunnels and outfalls. The Øresund Tunnel has extended the principle to a large, five bore tunnel cross section where 2700m^3 of concrete is placed continuously. The construction method was developed at the tender stage when the control of early age cracking was considered as an integral part of the design. Key constraints on the concrete properties and construction techniques were identified at this time. This early integration has lead to a high quality of construction and provides a lower risk construction method compared to the traditional cooling pipe solution.

2. Contract Requirements

The Contract specifications required the tunnel concrete to be free of early age cracks. The risk of cracking was limited to 70% of the available tensile strength of the concrete. Additionally, D_{int}, the difference between surface and core temperatures, was limited to 15°C and D_{ext}, the difference between new and old concrete, was limited to 15°C. The Contract assumed a traditional staged construction so the latter criteria was therefore not appropriate. A maximum temperature of 70°C was permitted in the base and 65°C in the walls and roof during the hydration period, in order to avoid expansion within the concrete matrix due to delayed ettringite formation (though this was later found not to be a problem for the type of cement used). Temperature and stress simulations were required, using a finite element method of analysis which took account of the liberation of heat of hydration, heat loss by convection and radiation, autogeneous shrinkage, the evolution of Young's modulus and ageing creep phenomenon of concrete loaded at early ages.

3. Design Method

3.1 Organisation

Thermal analysis was undertaken by specialist materials consultant Intron B.V. It was combined with the structural analysis performed by Symonds Travers Morgan to obtain a full understanding of the stress evolution at early ages. Whilst this type of approach is relatively uncommon it was necessary because of the unusual nature of the construction method. It required close co-operation between the main designer and the specialist materials consultant. Close liaison was also necessary with the production staff of the Contractor, Øresund Tunnel Contractors (ØTC), to accurately model the concrete behaviour and the conditions in the controlled factory environment.

3.2 Modelling Technique

The thermal analysis was performed with the module HEAT/2.5D of the finite element analysis software Femmasse. This type of software was necessary for modelling both the concrete temperatures and stresses and the changing support conditions of the tunnel segment at early ages. The analysis was time based, extending from the start of concrete placing through to the point when thermal equilibrium was reached. As well as time based events the analysis took full account of the time dependant properties of the concrete materials.

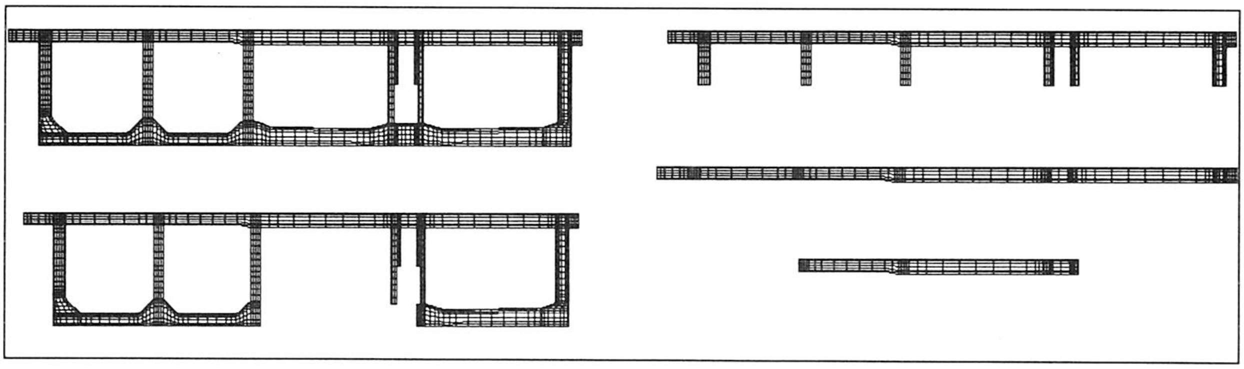


Figure 1. Finite element model for stress and temperature analysis, built up in stages corresponding to the casting sequence.

The FE model that was created for the analysis is shown in Figure 1. Because of the asymmetry the full cross section was modelled. The element geometry was selected to give accurate output in surface zones where the greatest stress gradient is present. Constant shear elements were used to minimise the amount of elements and thus save on computation time.

3.3 Input Parameters

There are many variable parameters which were input into the thermal analysis. To avoid analysing a large number of permutations of these parameters a benchmark condition was established and sensitivity analyses performed. The risk of cracking was computed for a variation in a single input parameter and compared back to the benchmark condition. The influence of each parameter on the risk of cracking was therefore evaluated in terms of whether it had a significant effect. Variations were considered for both winter and summer conditions for the following:

- Temperatures within the casting shed and inside the tunnel bores;
- Outdoor temperatures including daily fluctuations, thunder storms and wind velocities;
- Initial concrete temperatures at the time of placing;
- Total pour duration and casting sequence;
- External loading from formwork and second stage construction within the tunnel;
- Degree of retardation in the outer wall concrete;
- Early age shrinkage behaviour;
- Variations in cross section geometry e.g. ventilation fan niches in roof slabs.

Support conditions were modelled as rigid when the segment was supported by formwork and as soft springs when the weight was released onto the piston jacks. Cross-checks were made with the Lusas 3D finite element structural analysis model for a variety of load conditions to ensure the support conditions in the thermal analysis accurately represented the real behaviour. One of the sensitivity studies considered distortions arising from the piston jack supports of the segments. These were determined from the 3D structural model and were translated into the 2.5D thermal analysis model as imposed deformations at the supports.

The concrete mix used was an OPC mix. At the project tender stage a low w/c ratio blast furnace slag cement was thought to be necessary because of the beneficial slow heat development and high strain capability this would have at early ages. Pre-testing was carried out on two OPC and two BFSC mixes, in combination with two aggregate types. One aggregate enabled a lower elastic modulus to be achieved at early ages and test results for a mix with these aggregates and OPC were input into a thermal analysis and found to be satisfactory. The OPC mix also enabled higher early strengths to be achieved which allowed segments to be jacked earlier. This was crucial in enabling ØTC to meet the cycle time for segment production required by the construction programme. The main mix characteristics are summarised in Table 1.

Material/Characteristic	**Quantity/Property**
Aalborg Portland Cement	340 kg/m^3
Fly Ash	55 kg/m^3
Aggregate, Nordstone Granite	Maximum Size 25mm
W/C Ratio	0.39
Strength	40 MPa

Table 1. Summary of concrete mix characteristics.

4. Analysis Results

4.1 Segment Behaviour

The maximum temperatures computed were 48°C after 93 hours in the winter scenario and 65°C after 72 hours in the summer scenario. These peaks occurred locally in the thickest section in the roof slab above the service gallery. Because of the time required to complete the concrete pour (up to 48 hours) the peaks in temperature in the base, walls and roof occur several hours apart.

The delay in the temperature peaks in different parts of the structure causes distortions in the plane of the cross section. The roof slab expands relative to the base slab causing bending in the walls and the stresses caused by the bending combine with those due to thermal gradients across the sections. This aspect of the design was of particular concern because of the large width of the tunnel. However the single pour method is of significant benefit in minimising this problem as there is still some expansion occurring in the base when the roof is at its peak temperature. The effect of the heat development on structure distortions can be seen in Figure 2. This shows the bending effects generated in the outer walls at an exaggerated scale for the temperature distribution at 80 hours after pouring, when the top of wall temperatures are at a maximum.

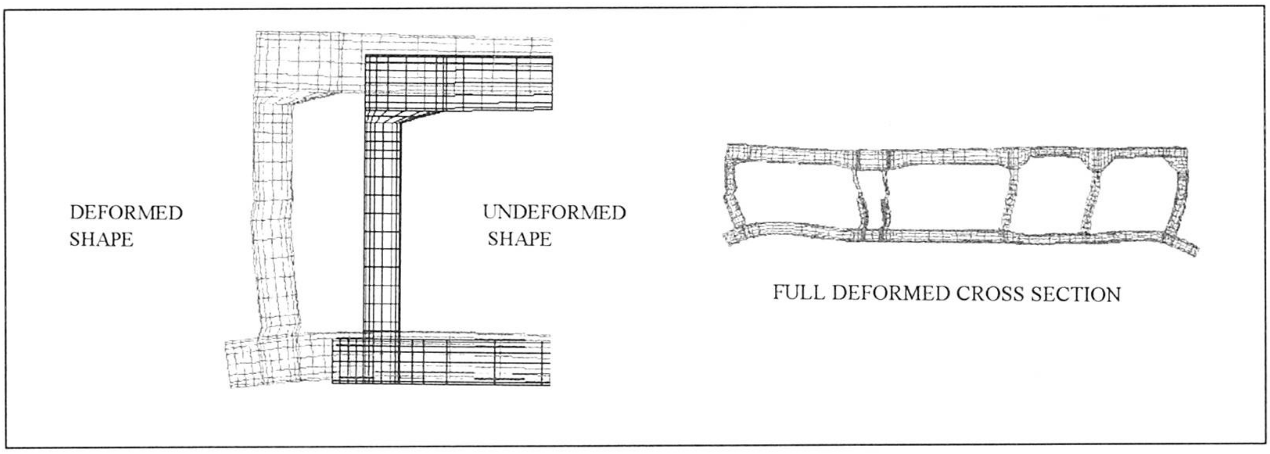
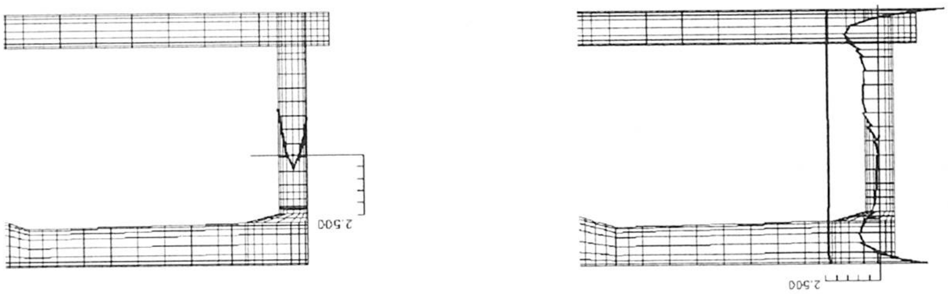


Figure 2. Distorted shape of tunnel cross-section due to temperature evolution.

In the longitudinal direction the length of the segment was not specifically modelled. Stresses were computed in the longitudinal direction assuming an infinitely long structure. Separate investigations were made for the actual segment length to determine the time permitted to complete the roof slab after finishing the outer walls. The delay in the temperature peaks in different parts of the structure also causes distortions in the longitudinal axis of the tunnel. The relative rate of expansion is important in this instance and a retarder was specified for the wall concrete to minimise the stresses caused by the roof slab expanding and pulling on the walls. The retarder caused the hydration process in the walls and roof to occur more simultaneously and also reduced the stiffness of the wall concrete at the point when the roof slab was expanding, so that stresses remained within the acceptable limits.

With traditional staged construction the tendency would be for the free ends of the segment to curl upwards longitudinally because of the shrinkage occurring in the last poured concrete. This phenomena is avoided with the continuous pour as the base slab, walls and roof slab all expand and shrink more closely together.

The full section casting minimises stresses arising from differential shrinkage between elements of the structure. No construction joints are present and the supporting jacks and shear key detailing allows the segments freedom to move relative to its adjacent segment. Stresses are therefore primarily the result of thermal gradients, the pour duration and the member thicknesses. The risk of cracking was found to be greatest in the top of the outer walls and at the section cores above the walls. Figure 3 shows a typical longitudinal stress distribution in outer wall of the motorway tube and the transverse stress distribution at the same point. Note that the tensile stress limit shown on the graphs corresponds to the P=0.70 limit imposed by the Contract.



(a) *(b)*

Figure 3. *a) Longitudinal stress profile in outer wall at the concrete core after 504 hours.*
b) Stress profile in plane of cross section in the outer wall after 504 hours.

When assessing the risk of cracking thermal stresses were considered in combination with stresses arising from static loads and the transfer of self weight from the formwork onto the piston jack supports. It was important to consider the superposition of these stresses as the thermal behaviour and formwork striking operations both cause bending stresses which combine with local thermal stresses. The combination of the stress profiles could result in through section cracking and present a risk to the watertightness and long term durability of the concrete. The combined effects were therefore checked to ensure the risk of cracking was not exceeded. This study was crucial in determining the earliest time when formwork could be stripped, when the weight of the segment could be transferred onto the piston jacks and when jacking operations could commence. Concrete strength criteria and specific points in the temperature evolution were specified as trigger points for each activity to commence on site.

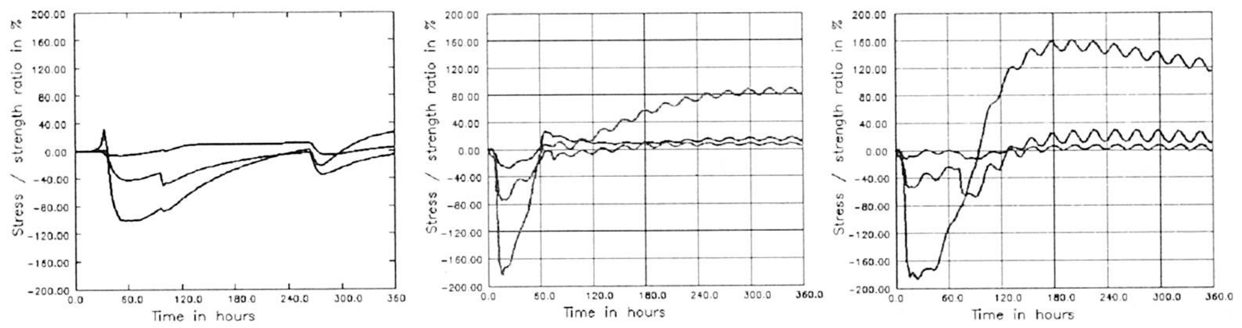
4.2 Benchmark and Sensitivity Analyses

The benchmark and sensitivity analyses showed that the risk of cracking was acceptable and that early thermal cracking would not occur if the following measures were taken during construction:

a) Retarding of the concrete in the outer walls by up to a maximum of 6 hours;
b) Insulation of the final segment was required if it was to be jacked out of the factory immediately after striking the shutters;
c) Insulation of thin sections was required, for example at ventilation fan niches in the roof slab;
d) Completion of the roof after the outer walls was required within a specific time period;
e) Temperatures in factory had to be kept up at 10°C throughout the winter period;
f) Temperatures within the bores had to be kept close to those outside of the segment;
g) Formwork stripping was limited by concrete strength and temperature peaks;
h) The maximum concrete temperature at placing was limited to 23°C.

5. Comparison to Traditional Construction Methods

To show the benefit of controlling the thermal stresses in the design phase it is useful to compare the risk of cracking for the full section casting with a 3 stage construction. This is done using the cut and cover approach structures of the tunnel. Figure 4 shows the risk of cracking in the outer wall for the 3 stage construction before and after cooling pipes are incorporated and compares this to the same point in the structure for the full section casting. Note that the 100% risk of cracking relates to the P=0.70 contract requirement. The risk of cracking is 160% in the uncooled 3 stage construction compared to 35% for the immersed tunnel segment. Cooling pipes reduce the risk of cracking in the approach structures to an acceptable level but the tunnel will have a greater margin of safety in the design. The economic benefits can be seen also as approximately 24 cooling pipes and the work associated with installing and operating a cooling system are saved for 160 tunnel segments. Construction risk is also reduced because variations in fresh concrete temperatures are accounted for in the design - for a cooling pipe solution a temperature variation could lead to cracking because the method is largely pre-determined and inflexible once set up.



(a) *(b)* *(c)*

Figure 4. a) Risk of cracking for full section casting 1.0m above base slab in outer wall.
b) Risk of cracking for 3 stage construction 1.0m above base slab in outer wall.
c) Risk of cracking for 3 stage construction with no cooling pipes.

6. Conclusions

The project demonstrates the benefits of viewing early age cracking not as a problem to be overcome after design (i.e. with cooling pipes), but as a problem that can be avoided by incorporating construction methods into the design. No early age cracking has been observed in the tunnel segments and temperature curves from the monitoring system used on site have been cross checked successfully with the design to show that the concrete is behaving as expected.

The use of cooling to control early age cracking will always be a viable method for many projects, particularly where the structures are simple and the technology is tried and tested. However the approach taken for the Øresund tunnel suits slightly more unusual projects and is particularly viable when a large number of repetitive concreting operations are required, such that the expenditure on the complex temporary works facilities remains economic.

The approach taken in the design is one which is most suited to design and build projects, but it should be recommended regardless of whether traditional or more creative methods are used to control early age cracking.