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Autor: Thomsen, Jens Vejlby / Karlsson, Max / Baden, Niels

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Probabilistic Fire Analysis. Limfjordstunnel. Denmark

Jens Vejlby Thomsen
Civil Engineer
Road Directorate
Copenhagen Denmark

Max Karlsson
Civil Engineer
RAMBØLL
Virum, Denmark

Niels Baden
Chemical Engineer
RAMBØLL
Virum, Denmark

Hanne E. Andersen
Civil Engineer
RAMBØLL
Virum, Denmark

Torben Arnbjerg-Nielsen
Civil Engineer
RAMBØLL
Virum, Denmark

Summary

Since its opening in 1969 the Limfjordstunnel has been continuously monitored, and during the latest years it has been inspected, reassessed and repaired. In relation to these activities a probabilistic fire analysis has been performed. Data on traffic and on transported goods in the tunnel has been collected, and a prognosis set up.
A spectrum of possible fire scenarios has been determined. The thermal impact on adjacent structural elements is calculated and their probabilities of occurrence are assessed. A simple structural reliability assessment has been performed leading to a design fire scenario that the Limfjordstunnel shall be able to resist. It is assessed whether the tunnel is able to resist the found design fire without fire insulation. As this is not the case, requirements to a fire insulation are set up.

1. Introduction

Considering road tunnels in various parts of the world, it is seen that some tunnels are fire insulated and others are not. The Limfjordstunnel has not been fire insulated from its opening. The present study which was initiated as a part of the planning of a larger repair of the tunnel gives a rational method for assessing the need for fire insulation. The presentation is based on a description of the analyses performed to assess the need for a fire insulation of the Limfjordstunnel in Denmark.

2. Limfjordstunnel

The Limfjordstunnel is located in Aalborg in the northern part of Jutland in Denmark. It is part of the north-south motorway in Jutland.

The Limfjordstunnel was opened in 1969 by the Danish Road Directorate. It is a 600 m long immersed tunnel. It comprises two tunnel tubes. The total width of each tunnel tube is 13.7 m, the internal width being 10.5 m. The total height of the tunnel structure is 8.25 m, the internal height being 5.4 m.

There are three traffic lanes in each tunnel tube, and 0.70 m wide emergency platforms in both sides of each tunnel tube. Emergency escape doors between the two tunnel tubes are placed for every 50 m.

3. Traffic

As part of the analyses, information on the traffic in the tunnel was collected, especially information on the transport of dangerous goods in the tunnel. The following sources were used:

- General statistics of Danish road traffic
- Traffic census in the Limfjordstunnel
- Statistical information on transportation of dangerous goods in Denmark
- Information from local companies

Based on this information a prognosis of the traffic in the Limfjordstunnel in the year 2010 was established.

The Limfjordstunnel is both used as a local connection between north and south of the city of Aalborg and as the south-north motorway in Jutland. It was concluded that the development of the traffic in the Limfjordstunnel has been very similar to the general development of road traffic in Denmark but less than the development of traffic on typical motorways in Jutland. In future, the traffic in the Limfjordstunnel is expected to increase due to the fact that it has been politically decided to try to move traffic from the nearby Limfjord bridge to the tunnel.

The amount of dangerous goods in the tunnel was found to be more or less the same as the average amount of dangerous goods transported on the Danish roads. In future it is expected that the amount of dangerous goods transported in the tunnel will increase - but the percentage of dangerous goods of the total traffic in the tunnel is expected to remain more or less constant.

Concerning the accident rate, it was concluded that the number of accidents per millions car-km is approximately 0.8 which is approximately 6 times the average for Danish motorways. This can be explained by

- A large traffic intensity especially during peak hours
- The approach systems just before and just after the tunnel

The approach systems before and after the tunnel lead to multiple shifts between the traffic lanes.

4. Frequencies and Consequences of Fire Scenarios

Based on the above mentioned information and analyses of various possible types of accidents, assessment of ignition probabilities, and assessments of fire escalation, the fires in the tunnel were categorised into 5 typical fire scenarios, for which the frequencies were calculated. All frequencies were calculated for a traffic prognosis for the year 2010. The main results are presented in Figure 4-1.

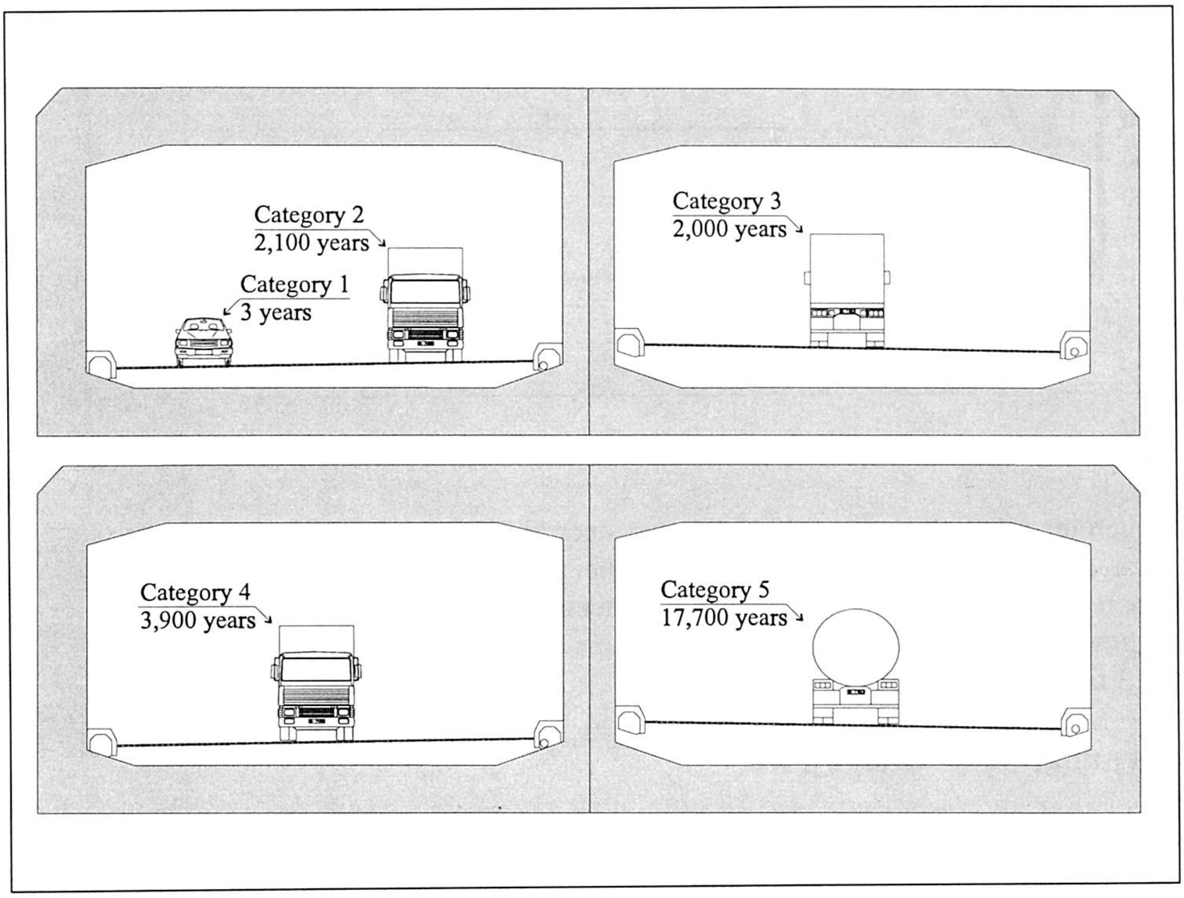

Figure 4-1 Return periods for the 5 main categories of fire scenarios.

The fire categories are described by the following typical fires:

- Category 1: Fire in a car.
- Category 2: Fire in a van with mail bags.
- Category 3: Fire in a van with plastic bottles.
- Category 4: Fire in a van with euro pallets (wood).
- Category 5: Fire in a tank lorry with oil products.

It is seen that a fire in an ordinary car is expected to occur once every 3 years in the Limfjordstunnel, whereas a large fire in a oil road tanker is expected to occur once every 17,700 year.

The consequences of the various fires have been assessed by fire calculations. As the main purpose of the study was to assess the need for fire insulation, the fire calculations have been focused on the calculations of the temperature development near the structural concrete of the Limfjordstunnel. Figure 4-2 shows the temperature development at the roof of the tunnel just above the fire.

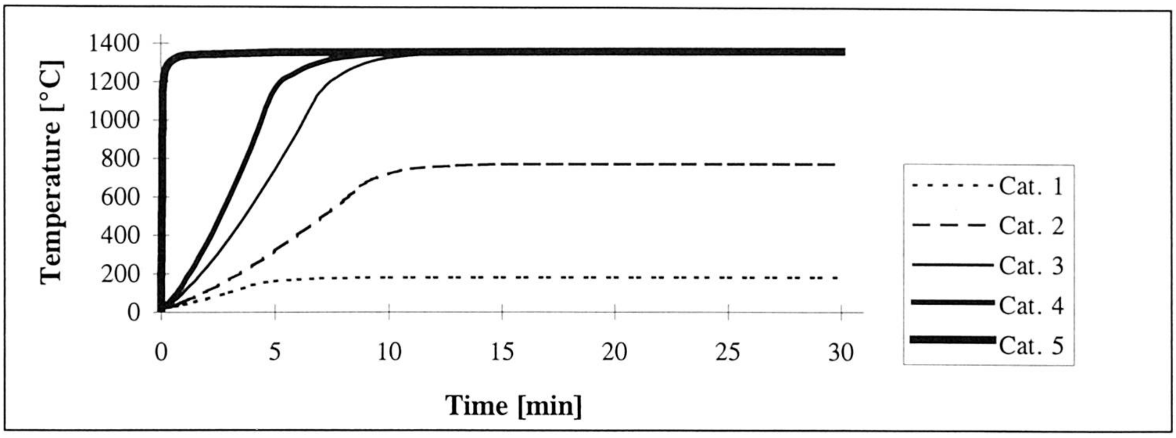

Figure 4-2 Temperatures at the roof just above the fire for the 5 main fire categories.

Even though the calculations are believed to be somewhat conservative it is seen that fires of categories 3, 4, and 5 will all lead to very high maximum temperatures. Furthermore, it is seen that the initial increase in temperature (the thermal chock) is increasing with increasing fire category, and that the initial increase in temperature in category 5 fires may be dramatic.

5. Determination of Design Fire

The purpose of the fire insulation is to protect the structures of the Limfjordstunnel in case of a fire. Consequently, it was decided to base the decision of fire insulation on an assessment of the structural reliability of the Limfjordstunnel. The basic structural reliability requirement for the Limfjordstunnel against fire loading shall be equivalent to high safety class in the Danish code of practice. This overall requirement may be assumed to be equivalent to an annual collapse probability of $1 \cdot 10^{-6}$, ref. /1/.

In an accident situation, as the considered tunnel fire, the structural reliability is the result of two factors:

1. The reliability that follows from a low probability of occurrence of the fire
2. The reliability that follows from the ability of the structure to withstand a certain fire with a certain probability.

Mathematically this may be formatted:

$$P_f = P_0 \bullet P_{f/fire}$$

where P_f is the probability of failure of the structure, P_0 is the probability of occurrence of fire, and $P_{f/fire}$ is the probability of failure of the structure given fire.
By use of this equation and rough structural reliability assessments it is concluded that the return period of the design fire shall be of the order of 20,000 to 100,000 years if the probability of collapse shall be less than $1 \cdot 10^{-6}$.

By use of the frequencies of the various fire scenarios, ref. Figure 4-1, it is concluded that the structures of Limfjordstunnel shall be able to withstand a medium category 5 fire if the structures shall be in high safety class.

6. Requirements to the Fire Insulation

In case of a fire in the tunnel two problems exist:

- Spalling of the concrete cover
- The load carrying capacity of the structure at high temperatures

As mentioned, a category 5 fire may lead to a very high initial temperature rise. The unprotected concrete is unable to withstand this temperature rise without serious spallings.

Whether these spallings are a problem in relation to the load carrying capacity of the structures depends on the structural behaviour of the element in question. The analyses of the structural elements are now ongoing.

The conclusion is that a fire insulation of the Limfjordstunnel is needed, and the extent of the fire insulation will be determined in the ongoing structural analyses. At least the roof of the tunnel is expected to be fire insulated.

Where fire insulation is necessary, the following requirements to this insulation are set up:

- The fire curve defined below shall be used
- The temperature in the contact layer between concrete and insulation must not exceed 380°C
- The temperature in the reinforcement must not exceed 250°C

For engineering reasons it has been decided to specify the requirement by means of a standard time-temperature curve. Especially the ISO 834 curve, the Hydrocarbon curve from the Eurocode ,/2/, and the Rijkswaterstaat (RWS) curve have been considered. These curves are shown in Figure 6-1.

By comparison between the standard curves in Figure 6-1 and the calculated fire curves in the Limfjordstunnel shown in Figure 4-2, is seen that even though the ISO curve may be suitable for lower categories of fires, it can not be recommended in the present case, as neither the initial temperature rise nor the maximum temperature are adequately modelled.

The HC curve seems to model very well the very high initial temperature rise that may occur in a category 5 fire. On the other hand the HC curve has a maximum temperature of 1100°C, whereas a maximum temperature of a category 5 fire in the Limfjordstunnel is expected to be 1350 degrees.

The RWS curve does not fully model the extremely initial high temperature rise but on the other hand the RWS curve has a maximum temperature of 1350 degrees.

Based on these considerations it was decided to use the RWS curve.

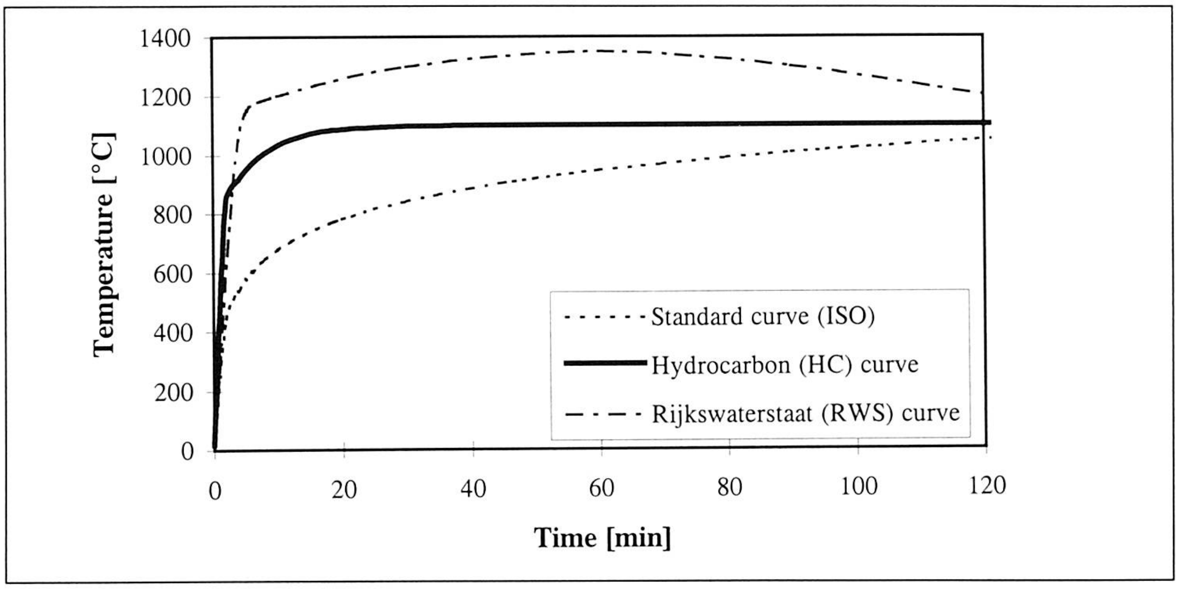

Figure 6-1 Standard Fire Curves

7. Concluding Remarks

In the probabilistic fire analysis of the Limfjordstunnel a rational method for assessing the need for fire insulation of a tunnel is demonstrated. The method can be used both in design of new tunnel structures and in the assessment of existing structures.

The effect of possible restrictions e.g. in the transport of dangerous goods, can be taken into consideration in the prognosis of the traffic population.

Finally, it shall be mentioned that the described method focuses on the structural reliability of the tunnel. However, this is only a part of the problems related to a tunnel fire. Especially assessment of user safety, including analyses of escape routes, have been performed. Concerning the Limfjordstunnel such assessments were performed primarily to assess the requirements to the ventilation system.

8. References

/1/ Nordic Committee for Building Structures (NKB): "Recommendation for Loading and Safety Regulations for Structural Design", No. 35 and 55, 1987.

/2/ Eurocode 1: "Basis of Design and Actions on structures, Part 2.7: Actions on structures Exposed to fire, ENV 1991-2-7 April 1993".