Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 78 (1998)

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DOI: https://doi.org/10.5169/seals-59049

Risk analysis as a tool to determine design load due to explosion in a tunnel.

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Elisabeth Ahlenius, born 1953, received her Master of Science degree from Technical University of Gdansk in 1977 and from Royal Institute of Technology in Stockholm in 1983. During the last two years worked with the risk analysis of the construction and operation phases of tunnel systems for road and rail traffic and pipe lines.

Summary

This paper presents a method for estimation of the design load due to explosion in a tunnel. The method is based on risk analysis together with cost-benefit comparison and was applied in particular for the load bearing structure in Ringen in Stockholm. Risk is defined as a measure of the probability and the severity of an explosion and is expressed in terms of cost. The analysis takes into account risk connected with the accidents or adverse events during the normal operation stage of this tunnel. The stages of the analysis were: to determine causes of an explosion, estimate probabilities, consequences and calculate the risk. Two alternatives of the tunnel were studied: one structure with normal and one with increased resistance. For each alternative, the yearly cost of risk was determined and the savings in risk were compared with the cost for increase of the resistance.

1. Scope

Ringen is the name of a system with 3 links for road traffic planned to be built around the city of Stockholm. The whole system will consist of the roads and the tunnel sections. The tunnels will be constructed as rock tunnels with concrete sections with the length of about 300 m at each end. One link will contain a submerged section. The total length of tunnels in Ringen including the ramp tunnels will be about 30 km. The traffic flow is estimated to 50000 vehicles per day in average.

When designing a road or railway tunnel, the question about load due to explosion has to be dealt with. Explosion is an accidental situation and one of the design situations for the tunnel structure.

According to the special regulations established for Ringen [6], the value of this load is treated by assuming a static pressure of 70 kPa.

According to the Swedish Regulations "Tunnel 95" [1] the value of the load caused by explosion is given as a static load with a value which depends on the distance between the place of the explosion and the end of the tunnel. The value of the pressure above atmospheric pressure (which is 100 kPa) is assumed to vary between 150 kPa at the end of the tunnel and the max. value of 500 kPa at the distance of 2 km from the end of the tunnel.

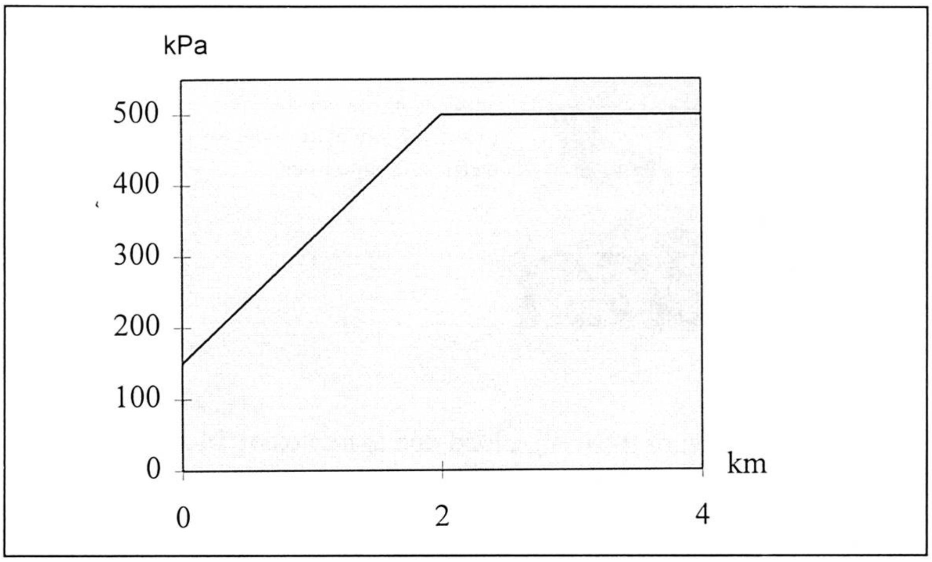

Fig. 1 The pressure above atmospheric pressure (100 kPa), [*1*]

As an alternative, "Tunnel 95" gives also the opportunity to use risk analysis to identify other kinds of the accidental loads or other values of these loads.

The Local Authority decided to use this option.

2. Risk analysis

Risk analysis is an estimation and a valuation of risks. In this analysis, risk was expressed in terms of cost, as:

$R = P \times C$

where

P = annual probability of the damage to the construction,

C = cost of the damage to the construction.

The object for this work was the estimation of risks connected with the normal use of the tunnels. The whole system of tunnels was treated as one unit with given length and traffic flow. The given traffic flow corresponds to a situation expected in the year 2005.

The risk analysis was performed in the following stages:

- identification of causes,
- estimation of probabilities of causes,
- quantification of consequences,
- calculation of risks.

Fault trees were used to calculate the probability of the explosive events.

The identification of causes, the estimation of probabilities of causes and probabilities of damage required experience in a large range of technical disciplines as: explosives, transport, concrete structures and rock engineering, hence the analysis involved experts in all these domains.

3. Causes

The scope for the analysis was that an explosion can occur during operation of the road tunnel, which means that an explosion is caused by dangerous goods transported in the tunnel.

Dangerous goods is a general name for a wide range of substances. According to the classification used in ADR (European Agreement Concerning the International Carriage of Dangerous Goods by Road) [2], ten classes of goods have been defined.

Some of the classes contain substances which can explode with different magnitudes. Only certain kinds of explosives (classified as class 1) and oxidising substances (which are class 5) can explode with such a magnitude that it will cause damage to a concrete or rock structure.

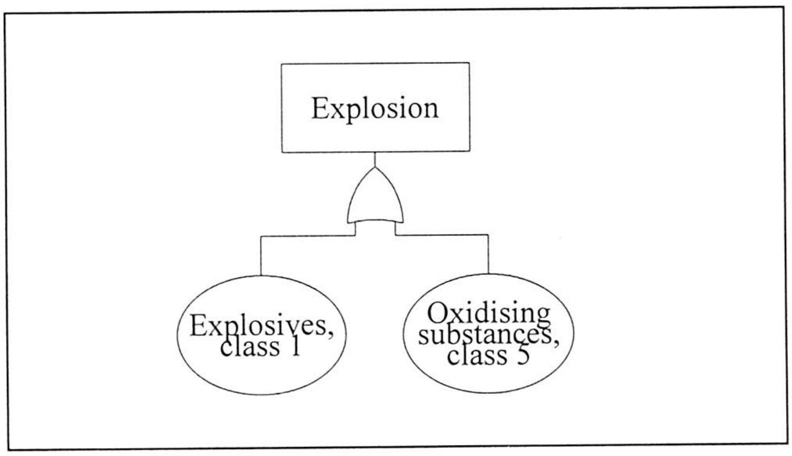

Fig. 2 Causes for an explosion

Other kinds of dangerous goods, such as bottled gases, can explode and cause danger for people but the pressure will not cause damage to the load bearing structure of the tunnel.

4. Probabilities

4.1 General

Assessment of the risks is based on frequency estimates for the occurrence of different categories and load sizes of dangerous goods.

The probability of the damage was based on the following:

1. The estimation of the total transport and the transport of goods.

2. The assumption about the probability of occurrence of goods which can explode in transport, based on the available reports concerning the road traffic in general [4], [5] and especially on the studies performed for Ringen. The assumption about the distribution among different kinds of dangerous goods was that dangerous goods participate in transport in the same proportion as they are produced. Both explosives and oxidising substances were assumed to be 1% of dangerous goods.

3. The assumption about the probability of occurrence of different load sizes.

Transported goods were divided into 4 load groups. The following assumption about the probability distribution of load sizes was used:

Load group	Load size	Probability of occurrence in transport
Load group 1	< 30 kg	20%
Load group 2	30 - 300 kg	20%
Load group 3	300 - 1000 kg	30%
Load group 4	1000 - 15000 kg	30%

Table 1. Probability of occurrence of different load sizes in transport.

4. The estimation of the probability of initiation, based mainly on the Health and Safety Commission´s report [4] about hazard aspects of transport of dangerous substances, which contains statistics about road accidents and events reported in Great Britain over 40 years.

The probability of initiation of goods which can explode was calculated separately for explosives (class 1) and for oxidising substances (class 5) and for all load groups (group 1- 4) as shown in Fig. 6.

4.2 Detonation of explosives

All explosives are thermodynamically unstable. They remain inert until they receive sufficient energy to initiate. In principle, detonation of explosives can be caused by impact, fire or unsafe explosives which means that badly packed, manufactured or out of specification material may explode during normal transport.

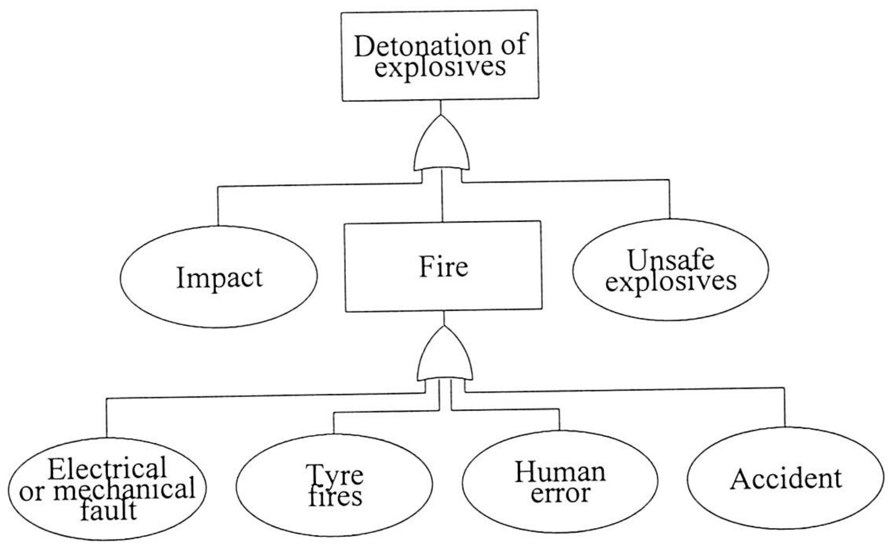

Fig. 3 Detonation of explosives

Estimation of probability of detonation was done separately for each group of explosives. The assumption was that only small quantities of explosives (load group 1) can be transported without any restrictions and larger quantities (load group 2, 3 and 4) have to be transported with escort, which reduces probability of explosion caused by road accidents and fire. The probability of road accidents involving one vehicle only was assumed to be reduced by 50% and collisions totally eliminated if the transport will be escorted. Probability of explosion caused by fire in a vehicle loaded with explosives was reduced by 90% for transport with escort.

The explosion caused by impact was assumed to occur in 2% of collision type of road accidents on basis of statistics about reported accidents and results from laboratory tests.

Fire can be caused by:

- ignition by electrical or mechanical fault in the cabin or engine
- tyre fires,

- human error,
- collisions.

Tyre fires are the dominant cause and correspond to about 80% of cases that a fire arises.

The frequency of unintentional initiation of unsafe explosives was estimated as one to one thousand million of vehicle km.

4.3 Explosion of oxidising substances

Oxidising substances are not dangerous by themselves. They can explode if they escape and come into contact with flammable substances, and there is an ignition source. The pressure will be of the same magnitude as for explosives.

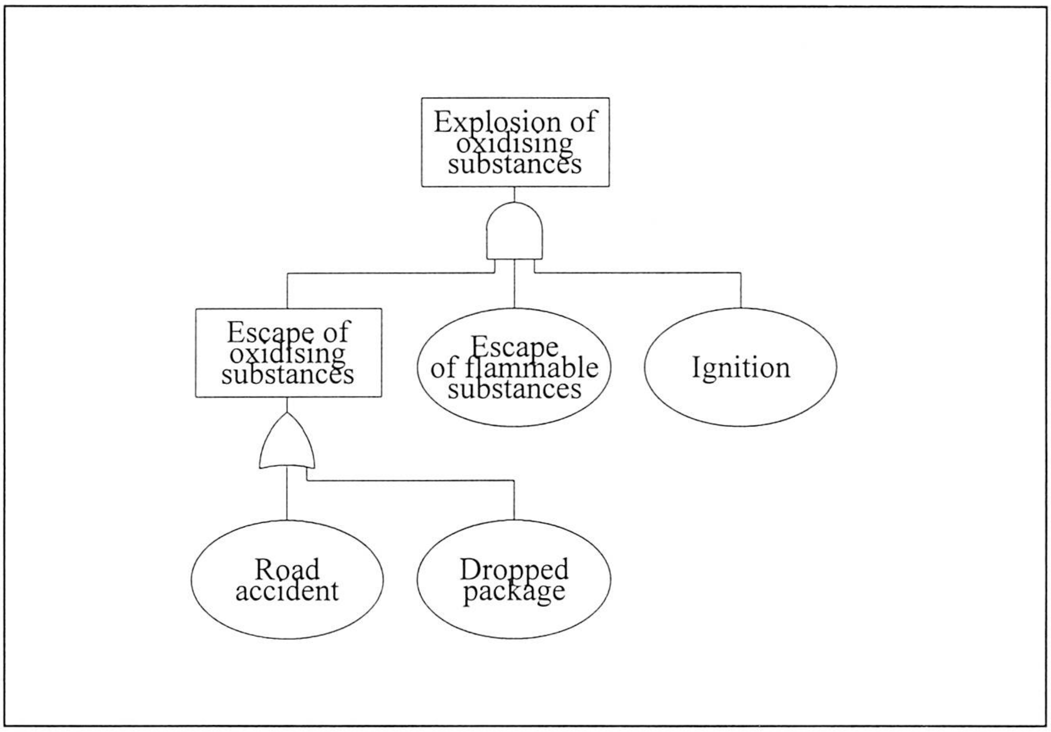

Fig. 4 Explosion of oxidising substances

The limitation is that escape of both oxidising substances and flammable substances has to occur at the same place and the same time. This analysis was based on the assumption that both these events have to occur within the distance of 1 meter and in less than 5 minutes.

Escape of oxidising substances can be caused by a road accident with oxidising substances involved or because a package is dropped from a vehicle during normal transport. The assumption was that 90 road accidents and 100 incidences of traffic such as a blow-out of tyres or a dropped package can be expected in Ringen annually.

The escape of oxidising substances was assumed to occur in 70% of road accidents and events of dropped packages. The escape of flammable substances happens in 10% of road accidents.

The probability of ignition in a tunnel was assumed to be 25%.

4.4 Summary

The result of the calculations is presented in the following table.

Goods	Probability of explosive events
Explosives, class 1	3 events per 100 000 years
Oxidising substances, class 5	5 events per 100 000 years

Table 2. Probability of explosive events

5. Consequences

An explosion in a tunnel would cause a pressure with a magnitude varying with the distance from the place of the explosion.

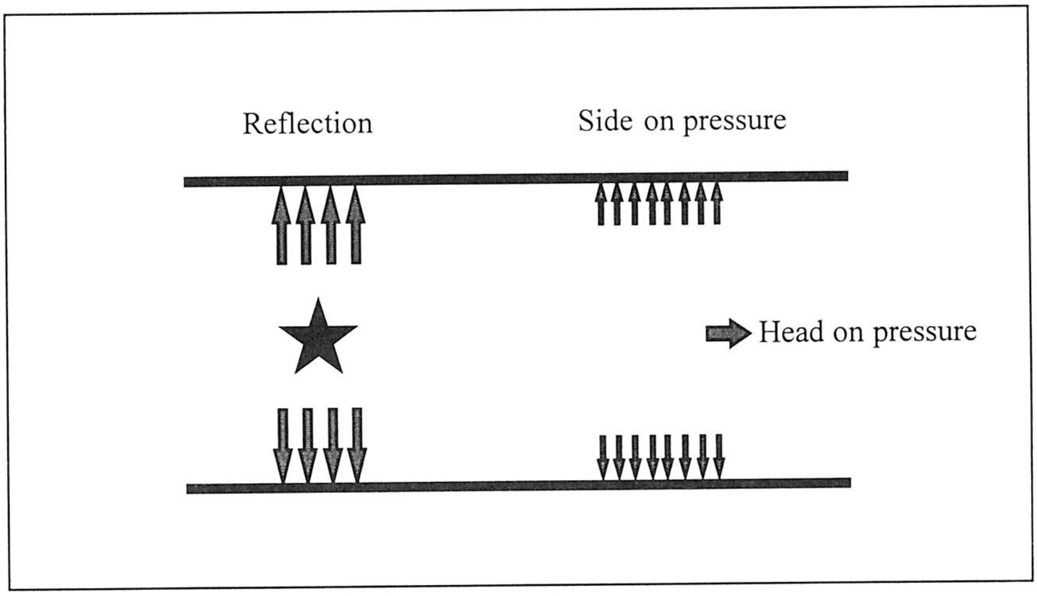

Fig. 5 The pressure after the explosion in a tunnel

Pressure near the place of the explosion is named reflection.

Pressure at a greater distance from the place of the explosion is named:

- head on pressure which acts in the direction of the tunnel axis,

- side on pressure which affects all sides of the tunnel.

The values of the pressure above atmospheric pressure after the explosion of an explosive charge of 30 and 300 kg TNT are presented in the following table:

Explosive charge [kg]		Distance [m]	Pressure [kPa]
30	Reflection	2	21 000
	Reflection	4	3 000
	Head on	30	100
	Side on	30	70
300	Reflection	2	120 000
	Reflection	4	34 000
	Head on	30	600
	Side on	30	300

Table 3 The pressure after the explosion in a tunnel

Assumptions for the calculation were: cross-section of the tunnel is 75 m^2, explosion occurs 1 m above the floorlevel and the explosive substance is TNT.

The conclusions were that:

1. Reflection depends on the distance between the explosive charge and the wall. Reflection caused by the explosion of 300 kg of TNT at a distance of 4 m from the wall is of the same magnitude as that caused by the explosion of 30 kg of TNT at a distance of 2 m from the wall.

2. The pressure decreases rapidly with the increased distance from the place of the explosion. Reflection affects the surface which is limited by the angle of 40 degrees to the line perpendicular to the wall.

Consequences expressed in terms of cost contain costs for the repairs of the damage to the structure and the equipment and costs for the interruption of traffic.

The consequence of an explosion have been studied for two different alternatives of the tunnel structures.

Alternative 1 - "normal resistance" - the concrete and rock structure was designed for explosion of 30 kg of TNT.

Alternative 2 - increased resistance - the concrete and rock structure was designed for an explosion of 300 kg of TNT. The increased resistance of the concrete structure was obtained by increased amount of reinforcement. Increased thickness of roofs and walls would reduce the flexibility of the structure and make the response to dynamic loads worse. Increased resistance of the rock structure was obtained by increased amount of the rock bolts. These measures have to be applied to all the surfaces of roofs and walls in the whole length of the tunnel.

Alternative 2 gives two effects:

1) The range of damage and cost of repairs will be decreased.

2) The construction cost will be increased.

Quantification of the consequences to the tunnel structures was based on the experience of the response of similar concrete or rock structures to the pressure caused by an explosion.

Three different ranges of consequences was defined and expressed in terms of cost.

Name	Range of damage	Interruption of traffic
Consequence 1	None or slightly damage to one tunnel tube.	24 hours
Consequence 2	Medium damage to one tunnel tube.	1 - 20 weeks
Consequence 3	Large damage to both tunnel tubes.	1 year

Table 4. Quantification of the consequences

The calculation of the consequences for different alternatives of the structure was based on the valuation of the costs for the repairs of the damage to the structure and costs for the interruption of traffic. The costs connected with repairing equipment was assumed to be the same for both alternatives of the structure.

Alternative 1, with normal resistance:

- loads of group 1 (0-30 kg) will cause the consequence 1,
- loads of group 2 and 3 (30-300 kg and 300-1000 kg) will cause the consequence 2,
- loads of group 4 (1000-15 000 kg) will cause the consequence 3.

Alternative 2, with increased resistance:

- loads of group 1 and 2 will cause the consequence 1,
- loads of group 3 will cause the consequence 2,
- loads of group 4 will cause the consequence 3.

6. Risk

The yearly risk could then be estimated as a yearly probability of an explosion in a tunnel times the cost of consequence for this explosion for all groups of loads and both classes of goods. The same calculation was done for both design alternatives of the tunnel structure.

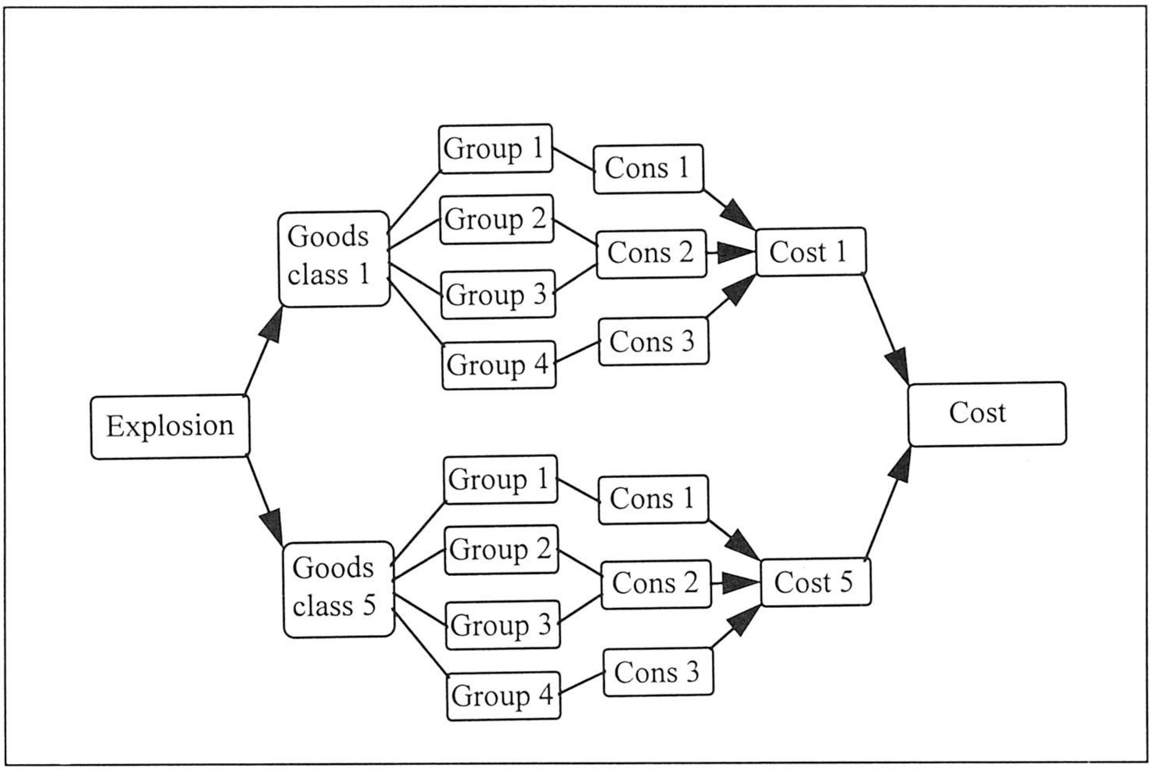

Fig. 6 Calculation of risk for Alternative 1.

Finally, the yearly savings in risk were calculated as the difference between the yearly cost of risk for Alternatives 1 and 2 and compared with yearly costs for increase of the resistance of the tunnel structure. The pay-back time for the tunnel was assumed to be 30 years.

The result of this comparison was that yearly cost for increase of the resistance was 10 thousand times higher than the savings in risk.

The conclusion was that it is not economically worthwhile to increase the resistance of the tunnel structure above the value determined for the explosion of 30 kg of TNT.

7. Design load

An explosion causes an impulse which can be expressed as the force times the duration of the impulse or, which is equivalent, as the mass times velocity. Calculations based on the static load often give the incorrect picture of the forces caused by an explosion. To design the tunnels for the impulse load and not for the static load is more equivalent to the structure´s real behaviour. The mass has much a bigger influence on the value of the bending moment and internal forces when the calculations take into account the dynamic response of the structure.

A simplified method has been developed to calculate the bending moments and the deformations of the concrete tunnels exposed to the impulse load caused by an explosion, and determined by the risk analysis.

The basis for the calculation was a equalisation between, on the one hand, the energy of the explosion, and on the other, the internal work in the structure and the work necessary for lifting the mass of the earth which loads the structure.

The assumptions for the calculation were:

- the duration of the impulse is short in comparison with the natural frequency of the structure.
- pressure is expressed as the density of the impulse or force times the time of the duration of the impulse per m^2, [kPa][s],
- plastic deformations are allowed.

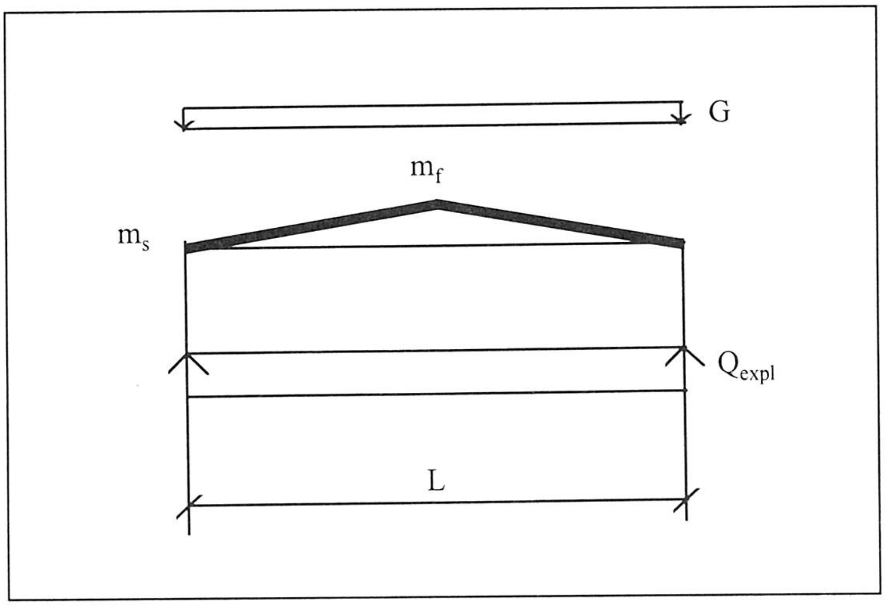

Fig. 7 The plastic deformation caused by an explosion

The deformation was limited to 1/100 of the span of the structure. A distinction was made between the dynamic response of a roof and a wall, depending on the benefit of the mass of the earth. The dissipation of the energy caused by friction in the earth was estimated.

The design load for the tunnel structure was defined as the impulse load with the same duration, density of impact and pressure, with the triangular distribution as the load caused by an explosion of 50 kg of TNT. The increased value of the explosive charge was chosen with consideration to uncertainties about the distance between the place of the explosion and the tunnel structure.

Finally, the Swedish National Road Administration has accepted the suggested method for the calculation.

8. References

[1] TUNNEL 95

[2] ADR, ADR-S, Inrikes transport av farligt gods på väg och i terräng, Statens Räddningsverks författningssamling SRVFS 1994:5.

[3] Brockhoff H, Extraction and classification of accident data on road transport of dangerous goods.

[4] Health & Safety Commission, Major hazard aspects of transport of dangerous substances

[5] Nilsson G, Vägtransporter med farligt gods - Farligt gods i vägtrafikolyckor, VTI rapport nr 387:3, 1994

[6] Ringengemensam Byggnadsteknisk Beskrivning (RiBB)