VII.4 Fire resistance of structures

VII.4.1 General

The fire resistance of a structure can be characterised by the time which elapses between the start of a fire and the time when the structure does not ensure its function any longer, due to unacceptable deformation or collapse.

In accordance with the general aims of fire and smoke control stated in section I (§ I.5), the objectives for fire resistance of tunnel structures are:

- to allow the evacuation of users,
- to make rescue and fire-fighting operations possible,
- to limit damage to tunnel structure and equipment, and to surrounding buildings.

The first two objectives relate to safety, the third one to the protection of property. A supplementary objective, strongly linked to the third one, is the following:

- to limit the time during which traffic will be disrupted due to the repairs after a fire.

The way these general objectives are translated into precise requirements concerning the accepted time before failure of tunnel structures depends on the consequences of a failure: the larger the consequences, the higher the requirements will be. As a consequence, these requirements will depend on:

- the type of tunnel (certain types of tunnels - as e.g. immersed tunnels, shallow urban tunnels or tunnels in soft or running ground - will be much more affected by a local collapse than other ones - as e.g. rock tunnels);

- the type of structure and its role for safety and protection of property (e.g. the slab separating the tunnel from a nearby building requires a stronger protection than an emergency exit to the open which cannot be used anyway when there are high temperatures at its entry in the tunnel);
- the type of traffic allowed in the tunnel (if only passenger cars, or also heavy goods vehicles, or also dangerous goods are allowed, the temperature-time curve to be used to check the fire resistance will be different - see section II - but also the duration of the fire will be longer and may require a longer time before failure).

The basic requirement is that a local collapse should not lead to generalised consequences in the tunnel. Specific applications of this principle are described in the following paragraphs, but two consequences apply in all cases:

- progressive collapse must be prevented, which means that the failure of a part must not transfer the stress to a nearby part in such a way that this part will fail and transfer the stress farther away, and so on;

a local collapse must not cut off a vital longitudinal system such as an electrical supply or communication cable, a duct necessary during a fire, etc. If it is not deemed necessary to protect the structure, then this vital longitudinal equipment must be located in such a place that it is protected in any case, for instance in an insulated trench under the pavement.

The next two paragraphs give information on fire resistance of various structures and spalling. Then recommendations are given on the fire resistance of the main and some other structures.

VII.4.2 Various tunnel structures

Various materials are used in tunnel structures and involve different precautions for fire protection.

In many rock tunnels, the lining is made of unreinforced concrete. In case of fire, it can suffer damage due to poor quality, inappropriate mix design, varying thickness, etc.

In a number of other cases, shotcrete support is left visible. It can be reinforced with steel mesh or various kinds of steel or polymer fibres. Further work is necessary to gain better knowledge in the fire behaviour of such materials.

Better known is reinforced concrete which is used in TBM driven tunnels, cut-and-covers, immersed structures, etc.

Due to the high intensity of the heat generated during a major fire, the reinforced concrete used in tunnel structures can lose its supporting function. The strength of the reinforced concrete largely depends on the temperature. This material quickly loses its strength at a temperature of 400°C. The high-grade steel in particular has a poor temperature characteristic.

The increase in temperature of the reinforcement is delayed by the concrete cover. In the past, it was common practice to have a rather thick (up to 5 cm) of concrete cover in combination with low-grade types of steel. At present, most often high-grade steel with a thinner cover of concrete is applied. Both facts, namely the thinner cover of concrete and the high-grade of the steel are a disadvantage in the event of a fire.

Prestressed reinforcement can be used for large spans. The prestressing ducts are fitted as low as possible in the structure, which means close to the surface which can be heated by a fire.

In all cases, an insulating fire-resistant protection can be applied to prevent early damage to the structure. It is then necessary to consider the fire resistance of the total construction (type and depth of reinforcement/prestressing, additional protection, etc.).

VII.4.3 Spalling

Differences in temperature and expansion inside the concrete and with the possible reinforcement can cause a spalling of the concrete. This may start already at a surface temperature of 200 °C. It causes a danger for the reinforcement which is more easily exposed to high temperatures. As stated in section I (§ I.5), due to the temperature and time needed to start spalling, it will generally not be a danger for evacuating people, but it may be dangerous for firemen.

A fire-resistant protection can be used to reduce the risk and the effects of spalling, although it never can be completely prevented due to the occurring high temperatures. If no protection is installed, this will automatically result in a higher risk of tunnel collapsing in the event of a fire.

The danger of spalling is increased by the fire-extinguishing activities. It may occur when the water used for fire-fighting cools down the structure too quickly. For more details on this subject please refer to paragraph VII.5.4 "Use of the fire extinguishing equipment".

VII.4.4 Fire resistance of the main structure according to the type of tunnel

Immersed tunnels versus land tunnels

A distinction must be made between immersed tunnels (under water) and land tunnels (under land).

In an immersed tunnel, a local collapse can cause the whole tunnel to be flooded with catastrophic consequences on people and construction. As such a tunnel is generally built of reinforced concrete, it will not be possible to repair it after a collapse, or if it is possible, it will take a lot of time and money. The additional economic loss of the lack of availability of the tunnel connection for a long period of time is very large. As a consequence, a complete protection is advisable during the total time of the worst fire. It is recommendable to install a fire-resistant insulation on those parts of the structure where the reinforcement is under strain of tension, the ceiling and a section at the top of the wall. The cost of such installation is around 50 euros/m^2.

In a land tunnel, a local collapse will generally have much smaller consequences on safety and property. It will often be repaired more easily and in a shorter time so that a more limited fire resistance can be sufficient.

However, a number of land tunnels can lead to consequences similar to an immersed tunnel should a local collapse occur. For example, the collapse of a tunnel in soft or running ground conditions with a high water table can be disastrous in terms of evacuation of people. Similarly shallow tunnels in urban situations, where their collapse can also affect and endanger overlying services and structures to a significant degree, also deserve high precautions.

Cut-and-covers versus excavated tunnels

A local collapse in a cut-and-cover may have very limited consequences on safety if the zone above the tunnel can be easily evacuated during a fire. It is generally possible to repair the structure within reasonable cost and time. This time is determined by the economic damage generated by the lack of the tunnel connection. If the connection is important, the repair period needs to be short, whereas in the case of less important connections, a longer repair period can be accepted. This will determine how much the structure needs to be protected against a fire.

In most excavated tunnels, a local collapse of the main structure will not have a major impact on safety, provided that vital longitudinal systems are located so that they are protected in any circumstances. However, a repair or replacement of parts of driven tunnels is often very difficult, due to the deep positions of these tunnels, but it is not impossible. It strongly depends on the soil conditions. Situations could arise in which, as a result of ground water penetration filling the tunnel, repair from the outside is essential. This leads to an extremely long repair time, and therefore high costs. The fire protection must be adapted to these stakes.

Rock tunnels

In rock tunnels, the risk of a total collapse is very low, but the fact that parts of the vault can fall down should be considered. This can constitute a danger to the people and equipment present in the tunnel, such as emergency service personnel and their equipment. However, nobody can normally survive near a place where the temperature is high enough to cause a collapse: the main risk is that important safety facilities such as supply or communication cables are cut off, which means that these should be protected.

What has been stated above about immersed tunnels does not apply to underwater tunnels built in rock, such as the undersea tunnels in Norway and Japan. Such structures behave as rock tunnels as described in this paragraph.

VII.4.5 Ventilation ducts

Attention must be given to the fire resistance of the ventilation system. The fans are discussed in Section V. This paragraph deals with the ducts which are necessary with semi-transverse and transverse ventilation systems.

In excavated tunnels, the ventilation ducts are frequently formed by a "false" ceiling in the tunnel tube. The top of the cross section is therefore used for the supply and/or extraction of the ventilation air. As this ceiling is exposed to high temperatures during a fire, there is a risk that the ceiling collapses and cuts off the supply and extraction of the air which is so vital during a fire situation. As a result of this, the risk of a large number of casualties may increase quickly.

Therefore it is necessary to examine the consequences of a local collapsing of a duct in case of fire. Whenever the consequences may be serious, such as the loss of control of the longitudinal airflow or the disruption of fresh air supply in a tunnel part where it is necessary, the duct should be protected for the time necessary for rescue and fire-fighting operations. In other cases, for instance when the only risk is to enlarge the smoke extraction opening to an exhaust duct by a local collapse, no special measure is necessary for safety (provided that there is no risk of progressive collapse). The duration of traffic disruption necessary for the repairs after a major fire may, however, justify a protection.

When the ventilation ducts are located under the road surface, the situation is better concerning the fire resistance, as the separation is not so much exposed to fire. However, there are also disadvantages attached to this design, such as traffic load, and the danger caused by flammable and/or explosive substances seeping into the ventilation ducts. If the fire spreads into the ventilation ducts, or an explosion occurs in this duct, the effects may be disastrous.

Safety considerations should be integrated in the design process at an early project phase, so that such risks are already taken into account in the preliminary design. By considering these fire and safety aspects while determining the tunnel type and systems in an early stage, a lot of time and money will not be spent in a later phase to change these principles in order to improve the tunnel safety.

VII.4.6 Escape routes

Escape routes are only used during the first phase of the fire for the escape of trapped people. It must be possible to use such routes for a period of at least 30 minutes. In cases where these routes are also used by the rescue and fire teams, the period may be longer. However, it is not necessary that these routes are protected against conditions which firemen cannot withstand at their entry in the tunnel.

Protection of escape routes means that the air in the route has to be free of smoke and other toxic products generated by the fire or accident. In addition, the temperature inside this area must not be too high. The structure must not be affected by the situation (major accident, fire, high temperatures) which may exist inside the tunnel itself.

VII.4.7 Suspending structures and other systems attached to the ceiling or walls

Use of plugs and anchors

All the fittings used for the fixing of equipment to the structures should be considered in relation to the fire situation. This means that use of the usual plastic plugs and similar devices should be prohibited. This material will either soften or melt at high temperatures, resulting in falling down of the equipment. This can even occur at places which are not directly exposed to the flames. Further research will have to demonstrate to what extent special plastic is suitable for fixing equipment inside the tunnel.

Also steel plugs and anchors should be checked for their behaviour during a fire situation. The tensile stress reduces at high temperatures. The calculation of these anchors should be based on the maximum temperatures at which the anchoring should be still properly working.

A distinction must be made between major equipment, which should remain in function during an emergency situation, and equipment whose functions may not be needed during or after a major disaster.

In all cases, as stated in section I (§ I.5), the minimum requirement is that heavy equipment should not fall down when evacuating users or rescue personnel are in the tunnel. This means that no heavy item must fall under exposure to temperatures of 400 - 450 °C during the time necessary to fight fire (in a tunnel, such temperatures can produce a radiation level of about 5 kW/m^2, which is the maximum tolerable value for firemen).

Use of aluminium

As aluminium loses its strength at a temperature of approximately 550°C, it is recommended to carefully consider the use of aluminium materials in a tunnel critically. Alternative materials are steel or stainless steel.