# A streamlined approach for tunnel structural fire durability design

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**ABSTRACT**

Tunnel structural fire safety design normally employs a performance-based approach, which considers the specific usage of the tunnel, and develop a project-specific design fire, i.e., the rate of temperature rises, and peak temperatures developed by fire plumes.

The structural fire durability is influenced by a series of parameters, including the application of the material and structural members, moisture content, structural member's shape, fire heat release rate, gas temperature and its increase rate, thermal radiant heat, gas-structure surface heat transfer coefficient, solid surface temperature and adiabatic temperature, etc.

The rate of the temperature rise in structural members plays a critical role in terms of structural fire durability. While considering the failure criterion, i.e., progressive collapse, as recommended in the NFPA 502, the calculated fire resistance ratings are based on a prescriptive time-temperature curve, or a specific temperature curve that is obtained with the performance-based approach.

This paper will propose a streamlined approach for the performance-based structural fire safety design solutions, and it will be applicable to various structural configurations, including slender structural members such as I-beams or Bulb Tee's with a convoluted surface profile.

Keywords: Structural fire safety, rate of temperature rise, tunnel structure, concrete fire durability, heat transfer coefficient, thermal radiation.

## 1 INTRODUCTION

Structural fire safety design is an important consideration for developing tunnel infrastructure solutions. Both prescriptive and performance-based approaches are acceptable to Authority Having Jurisdictions (AHJ) for a structural fire safety design. Since each tunnel is different, a performance-based approach is normally employed for the tunnel structural fire safety design.

Design criteria for tunnel structural fire safety design shall reference clauses 7.3.3 - 7.3.4 of the NFPA 502 (2020):

*7.3.3 During a 120-minute period of fire exposure or other time that is acceptable to the AHJ, (1) Regardless of the material the primary structural element is made of, irreversible damage and deformation leading to progressive structural collapse shall be prevented. (2) Tunnels with concrete structural elements shall be designed such that fire-induced spalling, which leads to progressive structural collapse, is prevented.*

*7.3.4 Structural fire protection material, where provided, shall satisfy the following performance criteria: (1) Tunnel structural elements shall be protected to achieve the following for concrete:*

- *a. The concrete is protected such that fire-induced spalling is prevented.*
- *b. The temperature of the concrete surface does not exceed 380°C (716°F).*
- *c. The temperature of the steel reinforcement within the concrete [assuming a minimum cover of 25 mm (1 in.)] does not exceed 250°C (482°F).*

If a design satisfies the above clauses of NFPA 502 (2020), then it will comply with the performance-based design criteria. Key considerations are "progressive structural collapse", maximum temperatures of 250°C for the steel reinforcement and 380°C for the concrete cover which is 25.4 mm on top of the steel reinforcement.

This paper will take a specific tunnel project as an example, to show how the streamline approach works. This considers specific fire safety provisions such as deluge system, vehicle stream that uses the tunnel, shape of the beams, as well as the design fire scenarios and its nominated design criteria acceptable to AHJ, to establish a performance-based solution.

## 2 CONCRETE STRUCTURE UNDER ELEVATED TEMPERATURE

Tunnel or bridge designers are increasing the required design life of tunnels by using high quality, dense concrete [1]. Due to their low permeability, these types of concretes are resistant to severe environmental exposure. On the other hand, during a fire these concretes can be at risk of spalling, resulting in a reduction of durability and service life of the structure.

Multiple factors influence the fire durability of concrete structure element. These factors can be classified into three categories [2]: (1) Material-related factors. (2) Structural or mechanical factors. (3) Heating characteristics. However, some of these factors would fit into more than one category.

Material related factors include moisture content, silica fume, permeability of concrete, cement content, compressive strength, quartzite aggregates, limestone filler, aggregate size, internal cracks, concrete age, lightweight aggregate, etc. Among these, the moisture content and silica fume play the most important role on the risk of spalling.

The structural or mechanical factors include applied load (compressive stress and restraint), cross section geometry (section size and shape), thermal expansion and tensile strength, etc.

The heating characteristics, which are the subject of this paper, are influenced by heating rate, temperature gradient, exposure on multiple surfaces and the absolute temperature that they are exposed to.

When the concrete temperature increases, its strength starts to decrease. As the temperature near the exposure surface increases, a temperature gradient along the depth of the concrete will develop, resulting in additional stresses caused by the expansion in local areas with higher temperature. On the other hands, when the temperature exceeds water evaporation point, the moisture contained in the concrete may vaporize and try to escape because of the increase in pore pressure, as shown in

Figure 2-1 for a column with one side exposed to a fire. Because of the concrete heat capacity, an increase in temperature will propagate into the depth of the concrete gradually. If the exposure temperature increases quickly, a higher temperature gradient may develop across the depth of the concrete, therefore resulting in higher thermal stresses.

With the heating rate increase, the concrete strength will decrease as shown in Figure 2-2. The figure also shows that the addition of silica fume content decreases its strength while it is being heated at the same rate when compared to the concrete without silica fume. The concrete may be at a risk of spalling when the combined effects of dead load, pore pressure, thermal stresses caused by the temperature gradient across local areas, and decrease in strength on the heated side, surpass the concrete strength.

Even though the rate of temperature increase plays a big role in concrete spalling, there is currently no consensually agreed criteria regarding the rate of temperature change at which spalling happens, considering various specifications of different concrete types and various application environments. Therefore, constant temperature criteria have been referenced in standards such as NFPA 502. Design provisions against explosive spalling are presented in Table 1.

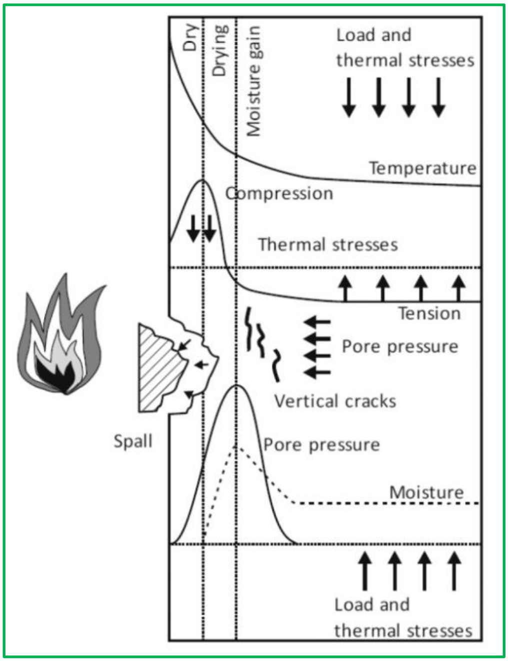


**Figure 2-1. Explosive spalling caused by combined thermal stresses and pore pressure by Khoury based on Zhukov [4]**

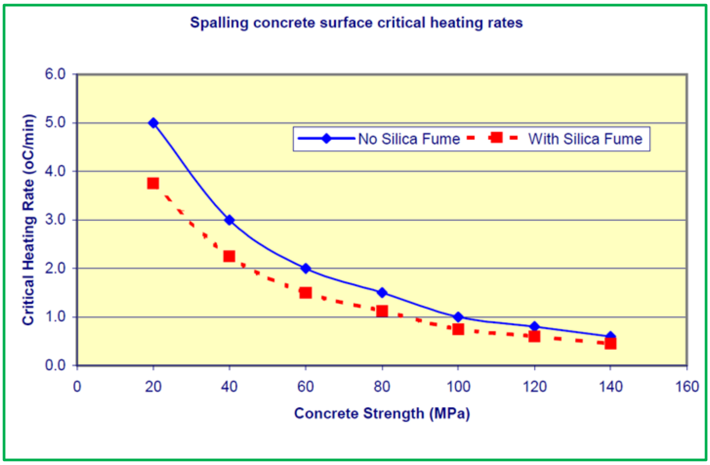


**Figure 2-2. Proposed concrete spalling criteria for critical concrete interface heating rate as function of concrete strength and silica fume content (source: Design Guide for FIRESHIELD 1350)**

**Table 1. Preventive measures response to factors causing spalling [3]**

| Factors influencing spalling | Basic measures | Specific measures |
|---|---|---|
| Concrete conditions<br>• High performance concrete<br>• Light-weight concrete<br>• Thermal properties<br>• Moisture contents<br>• Materials | • Thermal barrier<br>• Control of temperature rise in concrete surface layer<br>• Reduction of temperature gradient<br>• Relief & reduction of vapor pressure | • Use of fire resistive materials<br>• Coating of fire-proof paints<br>• Plastering of fire-proof mortars<br>• Covering of concrete by steel pipe, etc.<br>• Addition of synthetic fiber (Polypropylene fiber, etc.)<br>• Forced-drying of structural members<br>• Installation of moisture eliminatory tubes |
| Fire behavior & conditions<br>• High heating rate<br>• Fire exposure time | • Prevention of temperature rise | • Elimination of inflammable materials in building<br>• Make noncombustible of Materials<br>• Expansion of fire prevention facilities |
| Structural member conditions<br>• Section size & shape<br>• Concrete depth | • Fire safety design | |

## 3 PERFORMANCE-BASED SOLUTION

To confirm a design that satisfies the design criteria for structural fire safety, either CFD modelling or analytical approach can be employed. In this paper, a short tunnel below a land bridge in Washington State will be used as an example, and thermal physical parameters of concrete are summarized in Table 2 below:

**Table 2. Concrete Parameters**

| Parameter | Density ($kg/m^3$) | Heat Capacity (J/kg.K) | Heat conductivity (W/m.K) |
|---|---|---|---|
| Value | 2400 | 1600 | 1.0 |

The analysis is based on a design which includes a water-based fire suppression system for a heavy goods vehicle fire. Therefore, the flames and smoke from a fire will result in an increased surface temperature of the concrete walls, beams, and associated reinforcement of the structure facing the fire.

Structural analysis was utilized to determine the temperature which may cause the reduction of structural integrity or structural surface spalling to avoid progressive structural collapse. The impacts of spalling were analyzed based on the reinforcement bar (rebar) temperature to determine whether its performance had been compromised.

Per the 2020 edition of NFPA 502 Section 7.3.3 and 7.3.4, during the first 120 minutes after a fire starts, the temperature of the concrete surface does not exceed 380°C (716°F), and the temperature of the steel reinforcement within the concrete [assuming a minimum cover of 25 mm (1 in.)] does not exceed 250°C (482°F). This is sketched in Figure 3-1.

These criteria recommended in NFPA 502 section 7.3.4 assumed no spalling occurs, as the minimum concrete cover of 25 mm was assumed, and an absolute temperature value was specified instead of a rate of temperature change. When a concrete beam or column was exposed to a fire, the rate of temperature increases in the gas or concrete surface played the biggest role on the temperature gradient, as well as the thermal stress and pore pressure build up which may result in a risk of spalling. Therefore, additional layers may help mitigate spalling, such as a layer of normal concrete or the one with polypropylene fiber on top of the normal concrete.

Both fire protection with a water-based sprinkler system and the portal wind conditions are considered in the computational fluid dynamics modelling. A Heavy Goods Vehicle (HGV) fire is assumed detected at 96 seconds. Jet fans start operation against the wind at 111 seconds, and positive alarm sequence completion occurs at 276 seconds (positive alarm sequence provides an alarm delay of automatic detection devices for up to 180 seconds provided trained personnel acknowledges an automatic detection device alarm at the control panel within 15 seconds). Finally, sprinklers start to discharge water at 336 seconds, and the fire heat release rate will not be growing from 560 seconds because of the cooling effects and will remain constant[4] till the end of the CFD simulation as shown in Figure 3-2. This assumption is based on the tests as reported by Ingason, et al. It should be noted that any sprinklered intervened vehicles fire never recorded a gas temperature exceeding 800°C.

The CFD recorded time-dependent beam surface temperature at multiple locations near the ceiling beams above the fire. The highest temperature curve is chosen as the temperature which the beam was exposed to and will be used as the input for calculating the heat conduction into the beams to determine the thickness of the concrete.

Figure 3-3 shows the time-dependent gas temperature as well as the temperature inside the beam at various depths. If we examine the temperature at 120 minutes (7,200 seconds), surface temperature on the surface of the beam reaches 750 °C at 561 seconds, this coincides with the work by Andrew Coles[5]. With the one-dimensional heat conduction calculation, a temperature of 250 °C is reached but not exceed at 120 minutes at a 6 cm depth in the beam, and 380 °C was reached at 4 cm.

For the beam with the reinforcement bar is located 6 cm in the concrete, if the assumed concrete cover of 2.54 cm on top of the reinforcement bar just reached 380 °C but does not exceed it, the design would be able to satisfy the NFPA 502 design criteria per clause 7.3.4b.

Therefore, the performance-based solution for structural fire safety design would require a minimum of 6 cm concrete cover on top of the reinforcement bar, in lieu of 25 mm. This is not a special insulation board, but it is just an increased depth of the concrete cover (that serves as structural fire protection layer) therefore if measured from the surface of the concrete to the surface of the reinforcement steel, it will result in a total depth of 6 cm.

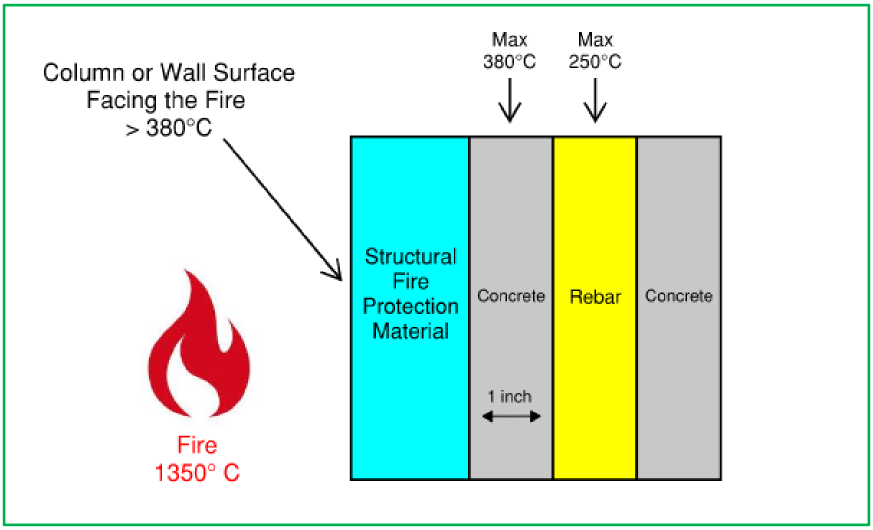


**Figure 3-1. Illustrated Interpretation of the solution**

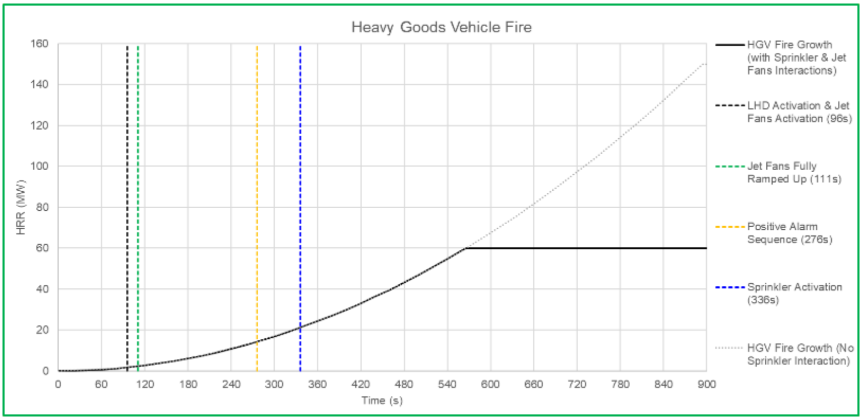


**Figure 3-2. Heat release rate for HGV fires with water-based fire suppression**

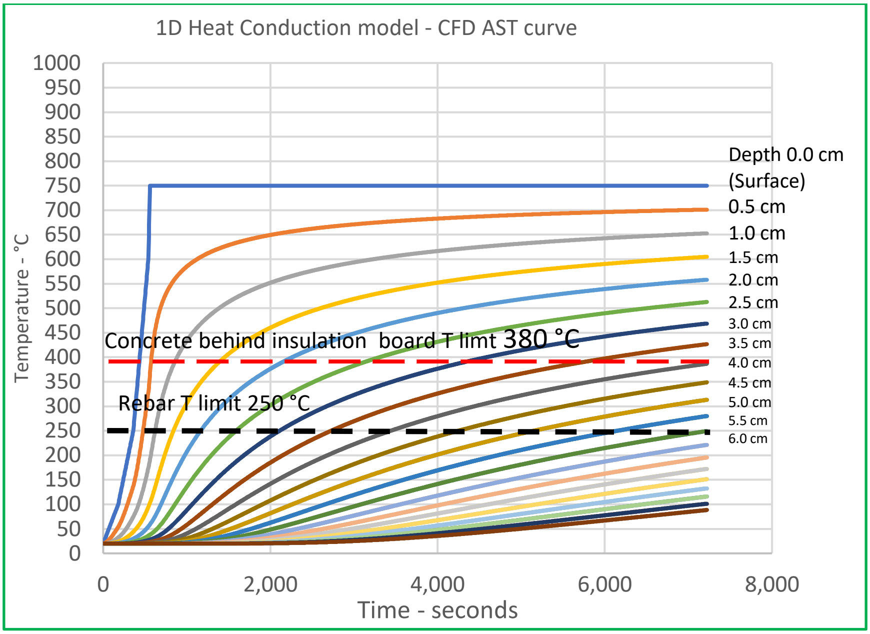


**Figure 3-3. Time-dependent time temperature curves considering water-based fire suppression and ventilation effects**

## 4 TIME-TEMPERATUE RWS CURVE

To compare the performance-based solution with that based on the RWS curve, heat conduction into the beams is also calculated considering the RWS curve. It should be specially pointed out that RWS curves refers to the gas temperature, which is approximately 1350°C at 60 minutes, as shown in Figure 4-1. Both thermal radiation and convective heat transfer exist between the hot gas and the structure being exposed to the fire,

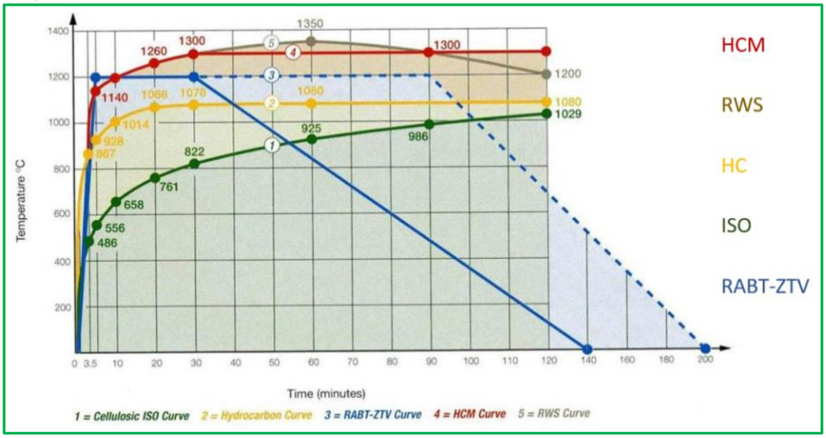


**Figure 4-1. RWS curves and other standard curves**

Since these standard curves doesn't consider fire suppression effects, the nominated temperature curves are normally higher than the case for the actual situation if a fire suppression system is in operation.

The surface temperature of a structural beam can be calculated based on combined convective and radiative heat transfer. To simplify the procedure, a combined heat transfer coefficient, h = hc + hr, has been applied in the calculation, where hc and hr are the convective and the radiative heat transfer coefficient, respectively.

If we estimate the convective heat transfer coefficient [8] hc= 22 W/m$^2$·K, the radiative heat transfer coefficient can be estimated between 5 ~ 635 W/m$^2$·K based on the following equation [7]:

$$hr = q_r / (T - T_\infty)$$

Figure 4-2 shows the time-temperature curves inside the concrete at various depth, it is found that to ensure the reinforcement bar no more than 250 °C, thickness of the concrete cover should be 7.5 cm. This is a significant increase in required thickness of the beams because the sprinkler cooling effects were not considered in the development of the RWS curve.

Figure 4-3 is a Figure showing the temperature profiles at different depth into the concrete at various times based on the extended RWS curve. The bottom scale (abscissa) is a depth in cm and time value in minutes with a scaling of 1/10). If we review the profile at 120 minutes, it can be found that the temperature of 250 °C has reached 7~8 cm deep into the concrete. This is consistent with the one-dimensional heat conduction solution with RWS curves in Figure 4-2, and it can be concluded that applying a prescriptive curve may result in over-design of a system.

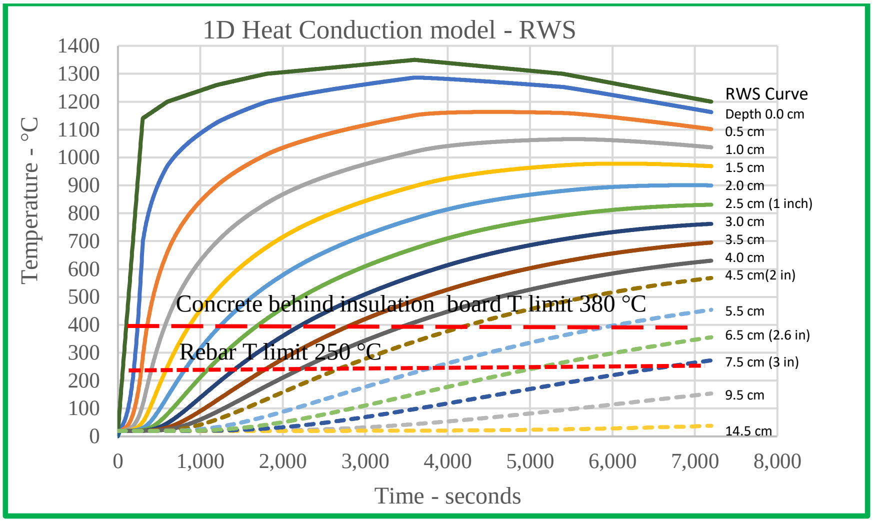


**Figure 4-2. Time-temperature curves inside the concrete**

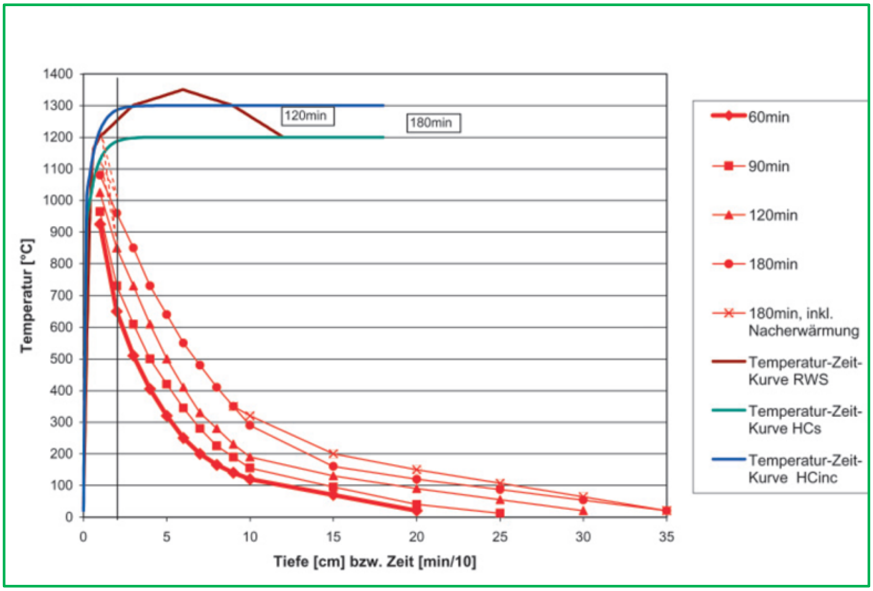

**Figure 4-3. Austrian Standards [RVS 09.01.45, September 2006]**

## 5 SUMMARY

Structural fire safety design solutions can be obtained through multiple ways, i.e., deemed-to-satisfy solution by complying with code prescriptive requirements, or performance-based solution with analysis based on project specific parameters.

For tunnel or bridge infrastructure projects, RWS or HC curves are conservative when compared to the performance-based solutions. The later can help avoiding over-design of a system as the project specific time-temperature has included the benefit of the specific provisions of the tunnel, such as suppression effects, vehicle types using the tunnel or bridge, and the benefit of various fire protection system can be considered.

This paper also illustrated that the heat transfer modes between the hot gas and the wall/ceiling surface not only include convective heat transfer of around 22 W/m.K, and thermal radiation heat transfer was determined to be an order of magnitude larger and should also be considered.

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