CFD Studies of Tunnel Fire on Glass/Vinyl-Ester and Epoxy Resin Coatings

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 Abstract: *Recent fire disasters in European road tunnels have shown that fires in a tunnel represent high risks. The users and the rescue services are endangered by heat and smoke while the tunnel is often damaged considerably. In the event of fire the temperature in tunnel rises extremely rapidly within a short amount of time. Large scale fire tests that maximum of 1200ºC or even above could occur. The result is an increased risk of concrete spalling of the tunnel lining. Depending on depth and quantity of these spalling, the structure could be damaged seriously. A fire proof concrete is one relatively new and promising measure to avoid spalling of the tunnel lining during fire. The fire resistance of concrete can be improved by coating it with composite material. In this work CFD calculations have been carried out in order to study the tunnel fire growth on composite wall lining materials by using Fire Dynamic Simulation software (FDS). It has been applied in order to solve the turbulent flow, diffusion, combustion and energy equations. The temperature of the solid boundary was determined by numerical solution of the heat conduction equation. A new pyrolysis model has been applied in FDS software in order to predict surface temperature and burning rate Glass/Vinyl Ester and Epoxy resin. It has been found that the erosion of Epoxy resin is greater than Glass/Vinyl Ester.*
Keywords: Glass/Vinyl Ester, Epoxy resin, concrete spalling, FDS code, Pyrolysis

I.   Introduction

Numerous catastrophic tunnel fire events have occurred during the past decades (see figure 1), increasing the interest in structural fire safety of underground facilities [1].
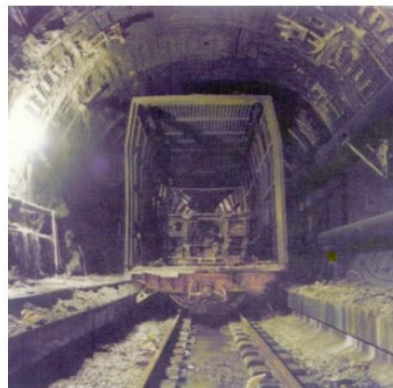

Fig 1: The aftermath of the Channel Tunnel fire (18.11.96) [1]

Detailed summaries of road and rail tunnel fire incidents can be found in the literature [2–5] clearly highlighting the importance of factoring fire risk in the design of tunnels. Although fires in road tunnels are more frequent, the number of fatalities during fires in railway systems generally seems to be far greater [2]. However, apart from fatalities, injuries and property loss, a prolonged disruption of operations may occur, mainly due to considerable structural damage of the lining. The special feature that distinguishes tunnel fires from the ordinary ones (e.g., those that occur in buildings) is the sharp rise of the ceiling gas temperature, often in excess of 1000°C, within few minutes. This phenomenon affects the structural integrity of the tunnel lining [5]. Different possible structural measures to protect the concrete tunnel lining in order to reduce or avoid damages in cases of fire exist. A fire-proof concrete is one of relatively new and promising measure to avoid explosive concrete spalling of the tunnel lining during a fire [7]. The fire resistance of concrete can be improved by coating it with Glass/Vinyl Ester or by using Epoxy intumescent coating.

Composite materials have become very competitive engineering materials in recent years and have successfully replaced conventional metallic and other polymeric materials in many important sectors of industry. Epoxy resin matrix based composites because of their favorable mechanical, physic-chemical properties and high strength to light weight ratios are used in load-bearing structures such as aircraft, military vehicles, ships, building and offshore structures. The heat impinging on the surface causes degradation of the

resin leading to its ignition. Further penetration of the heat below the first glass layer causes degradation of the underlying resin. The degradation products migrate to the burning zone through the glass and any char retained in the glass reinforcement. This process goes on until all layers of the resins are burnt. However, if the char formation can be enhanced which can then act as a thermal barrier, it can slow down this migration resulting in stopping or slowing down burning. As the composite is heated, the original virgin material (or rather one or more *components* of the original composite virgin material) pyrolyzes and yields a pyrolysis gas, which percolates away from the pyrolysis zone, and a porous residue, which for most materials *of* interest is a carbonaceous char, possibly reinforced with refractory fibers or cloth (see figure 2). Superimposed on this basic problem may be a number of even more complex events. The pyrolysis gases percolating through the char may undergo further chemical reactions among themselves, and may react with the char, either eroding it or depositing additional residue upon it ("coking"). The char itself may collapse or fragment from mechanical or thermal stresses, and the refractory reinforcements may melt or suffer mechanical damage. Finally, various constituents of the residue structure may react chemically with each other, changing the nature of the char, and various mechanical forces may remove material from the surface [8].
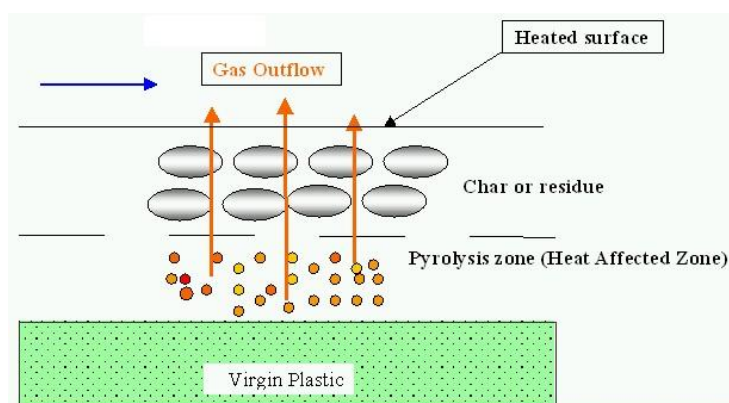

Fig. 2: **Composite degradation process**

Despite these complexities, it is found that the "simple physics" described by: Virgin plastic → char + gas. This reaction underlines a wide range of problems of technical interest, and for a great many materials, such as carbon phenolic, graphite phenolic, and wood, constitute all the events of interest. Such events as coking, mechanical erosion, melting, and subsurface reactions (other than pyrolysis) are less common and generally characterize specific problems. Therefore in any effort to compute the in-depth response of pyrolyzing materials is to characterize the heat conduction and the primary pyrolysis reaction, which have useful generality.

Epoxy intumescent coatings are materials characterized by a swelling behavior when exposed to high temperatures, due to the generation of gaseous compounds during thermal decomposition of the organic matrix [9, 10 and 11]. The swelling phenomenon contributes in retarding the heat transmission to the protected surface. Thus, these materials may be used as a passive fire protector (PFP), delaying the temperature rise of metal surfaces exposed to fire and preventing the damage of metal structures.

II.   Theoretical Model

2.1 CFD Model
The fire dynamics simulator (FDS) has been developed at the Building and Fire Research Laboratory (BFRL) at the National Institutes of Standards and Technology (NIST), e.g. McGrattan et al. [12, 13]. The program calculates the temperature, density, pressure, velocity, and chemical composition within each numerical grid cell at each discrete time step. It computes the temperature, heat flux, and mass loss rate of the enclosed solid surfaces. The latter is used in the case where the fire heat release rate is unknown. The following is a brief description of the major components of the model.

Hydrodynamic Model FDS code is formulated based on Computational Fluid Dynamics (CFD) of fire-driven fluid flow. The FDS numerical solution can be carried out using either a Direct Numerical Simulation (DNS) method or Large Eddy Simulation (LES). The latter is relatively low Reynolds numbers and is not severely limited in grid size and time step as the DNS method. In addition to the classical conservation equations considered in FDS, including mass species momentum and energy, thermodynamics based state equation of a perfect gas is adopted along with chemical combustion reaction for a library of different fuel sources.

Combustion Model For most applications, FDS uses a mixture fraction combustion model. The mixture fraction is a conserved scalar quantity that is defined as the fraction of gas at a given point in the flow field that originated as fuel. The model assumes that combustion is mixing controlled, and that the reaction of fuel and oxygen is infinitely fast. The mass fractions of all of the major reactants and products can be derived from the mixture fraction by means of "state relations," empirical expressions arrived at by a combination of simplified analysis and measurement [14].

Radiation Transport Radiative heat transfer is included in the model via the solution of the radiation transport equation for a non-scattering gray gas. In a limited number of cases, a wide band model can be used in place of the gray gas model. The radiation equation is solved using a technique similar to a finite volume method for convective transport, thus the name given to it is the Finite Volume Method (FVM) [14].

FDS also has a visual post-processing image simulation program named "smoke-view".

2.2 Solid wall model

In this study, the solid wall surface is divided into many elements, according to the CFD grid generation. In a fire, the combustible thermal protection material and the walls exposed to the flame and hot gas are heated up through convection and radiation heat transfer. After certain time, the composite material will start to decompose and burn, as shown schematically in figure 3 [15].
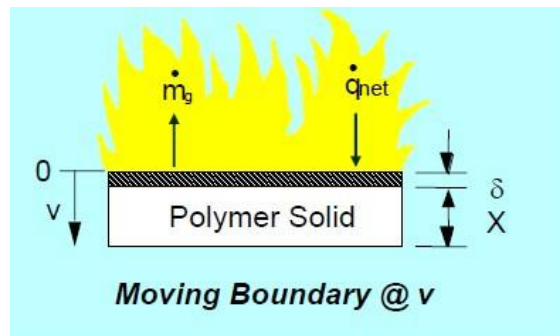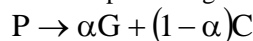

Fig 3: Burning process of polymer composite [14]

In this work, we have assumed that the composite degraded to a gas plus char. The reaction scheme is shown:

$$P \rightarrow \alpha G + (1-\alpha)C$$

During the pyrolysis reaction, mass of the polymer is consumed and produces a fraction, α, of gas and the remaining char. The first order reaction rate for the composite is:

$$\frac{dr_p}{dt} = -k_0 r_p$$

Where r_p is the thickness of the polymer in [m], t is the time in [sec] and k_0 is the rate constant for pyrolysis reaction in [1/sec].The rate constant in for the pyrolysis reaction, k_0, is a function of temperature and is better described by the Arrhenius relationship:

$$k_0 = A_0 \cdot \exp\left[-\frac{E_{A0}}{R \cdot T}\right]$$

Where A_0 is the pre-exponential factor of pyrolysis reaction [1/sec]. E_{A0} is the activation energy of pyrolysis reaction [kJ/kmole], R is gas constant [J/mole/K] and T is the temperature in [K]. The pre-exponential factor and activation energy can be found by thermogravimetric analysis. A 1D heat conduction equation for the composite temperature $T_s(x,t)$ is applied in the direction x pointing into solid (the point x=0 represents the surface) [10]

$$\rho_s c_{p,s} \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_s \frac{\partial T_s}{\partial t}\right) + \dot{q}_s$$

The source term, $\dot{q}_s$, consists of chemical reactions, radiative absorption and convective heat transfer.

$$\dot{q}_s = \dot{q}_{s,c} + \dot{q}_c$$

The convective heat flux is calculated by using the following equation:

$$\dot{q}_c = h\left(T_g - T_w\right)$$

In Large Eddy Simulation (LES) calculation, the convective heat flux to the surface is obtained from combination of natural and forced convection correlations:

$$h = \max \begin{bmatrix} C\left|T_g - T_w\right|^{\frac{1}{3}} \\ \dfrac{\lambda_g}{L} 0.037\,\mathrm{Re}^{\frac{4}{5}}\,\mathrm{Pr}^{\frac{1}{3}} \end{bmatrix} \mathrm{w/m^2/K}$$

Where C is the coefficient for natural convection (1.52 for horizontal surface and 1.31 for vertical surface), L is characteristic length related to the size of the physical obstruction, λ_g is the thermal conductivity, and the Reynolds Re and Prandtl Pr numbers are based on the gas flowing past the obstruction. The chemical source term of the heat conduction equation consists of the heat of the reaction

$$\dot{q}_{s,c} = -\rho_s k_0 \Delta H_r$$

Where ΔH_r is the heat of reaction. The thermo-physical properties (thermal conductivity, heat capacity and density) and the rate constants of the Glass/Vinyl ester used in the calculation of FDS are shown in Table 1 [16].

Table 1: Thermo physical and thermochemical properties of Glass/Vinyl Ester coating composite [16]

Parameter	Value	Unit
ρ_s	1,140	kg/m^3
$c_{p,s}$	760	J/kg K
λ_s	0.43	$w/(m \cdot K)$
E_{A0}	2.13E+05	J/mol
A_0	5.59E+13	1/s

The thermo physical properties (thermal conductivity, heat capacity and density) and the rate constants of the Epoxy resin used in the calculation of FDS are shown in Table 1 [17].

Table 1: Thermo physical and thermochemical properties of Epoxy resin coating [17]

Parameter	Value	Unit
ρ_s	1,200	kg/m^3
$c_{p,s}$	1,800	J/kg K
λ_s	0.20	$w/(m \cdot K)$
E_{A0}	1.34E+05	J/mol
A_0	3.0E+10	1/s

III.   Description Of CFD Calculations

The dimensions of the tunnel were 20 m long, 7.4 m wide and 5 m high. It was assumed that the heptane fuel was burned. 12 thermocouples have been placed inside the tunnel. An oxygen concentration detector has been placed at the left corner of the tunnel. In this paper, it was assumed that there isn't ventilation in the tunnel.

IV.   Results

This section divided into two parts. In section 4.1 the model results of Epoxy resin is shown. In section 4.2 the model results of Glass/Vinyl Ester is shown.

4.1 Epoxy Resin

The CFD simulation result will be presented in this section. One advantage of CFD simulation is that it can provide much detailed information on the fire, including the local and transient gas velocity, gas temperature, species concentration, solid wall temperature, composite burning rate, radiation heat transfer, convection heat transfer and heat release rate (HRR). The temperature field at t=9 s is shown in figure 5.
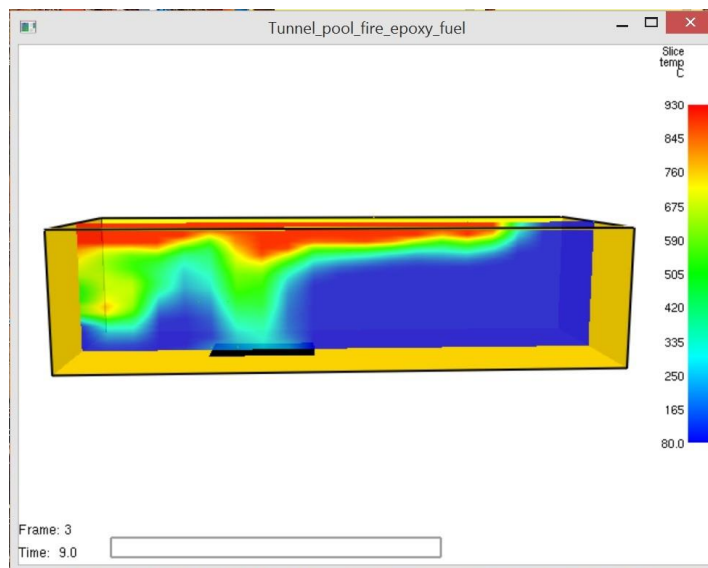

Fig. 5: Temperature field in the tunnel at t=9 sec

It can be seen from figure 4 that the ceiling temperature at time =9 sec approaches to 930ºC. The spatial concentration of the soot inside the tunnel is shown in figure 6.
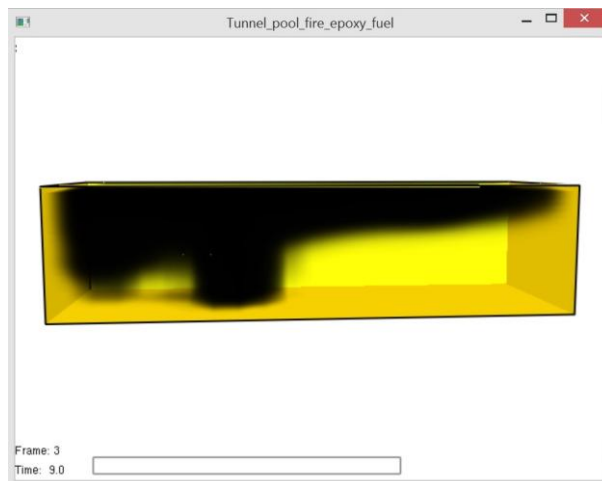

Fig. 6: Soot concentration field in the tunnel at t=9 sec

It can be seen from fig. 6 the effect of "back layering". Back layering (also known as "back-flow") is the name given to the phenomenon when smoke from a fire is observed to move against the direction of the airflow in the tunnel [18]. The calculated oxygen mole fraction is shown in figure 7.
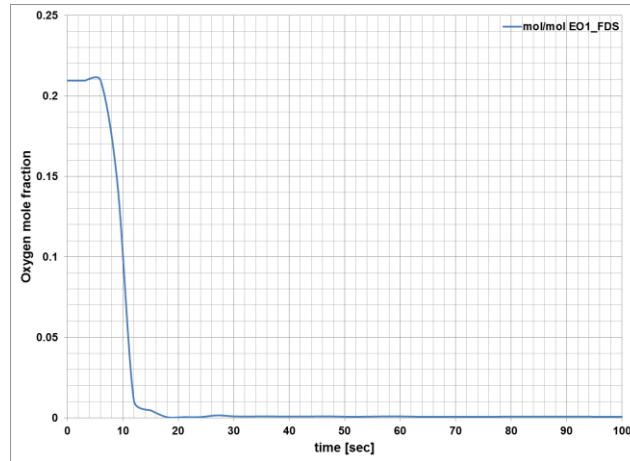
Fig. 7: Calculated oxygen mole fraction

Figure 7 shows that the combustion reaction causes the oxygen concentration to decrease. In Figure 8, a comparison of the surface temperature without the coating and wall surface temperature (with the coating) are presented.
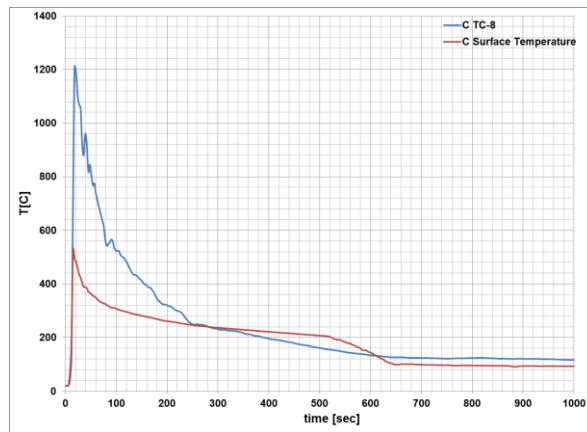

Fig. 8: Calculated thermocouple and wall surface temperatures

Figure 8 shows that the surface temperature of the Epoxy resin (679ºC) is smaller than the wall temperature (without the coating). This temperature is reaches to 1180ºC. This phenomenon occurs because the Epoxy resin acts as thermal barrier. These two temperatures decays with time. There are two effects that decrease the surface temperature:
a)   The heat gradually penetrates int the inner layers of composite
b)   The oxygen inside the tunnel is consumed, thus prevents the combustion reaction to proceed. As a consequence of that, there isn't supply of heat flux to the tunnel walls.
Figure 9 shows the predicted thickness of the Epoxy resin coating as a function of time.
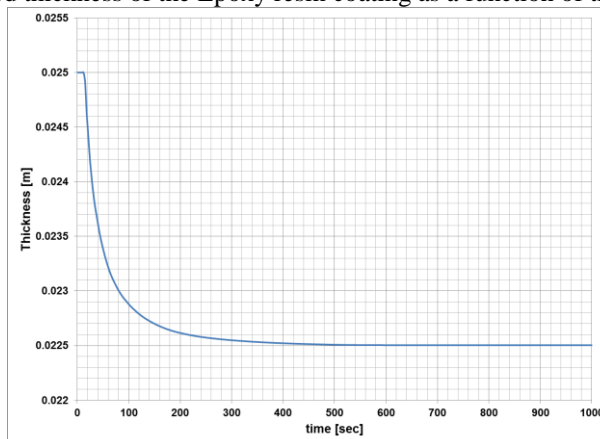

Fig. 9: Predicted thickness of the Epoxy coating as a function of time

From Figure 8 it can be seen that the erosion of the composite is 2.5 mm. The ablation process is completed after the oxygen consumed.

4.2 Glass/Vinyl Ester

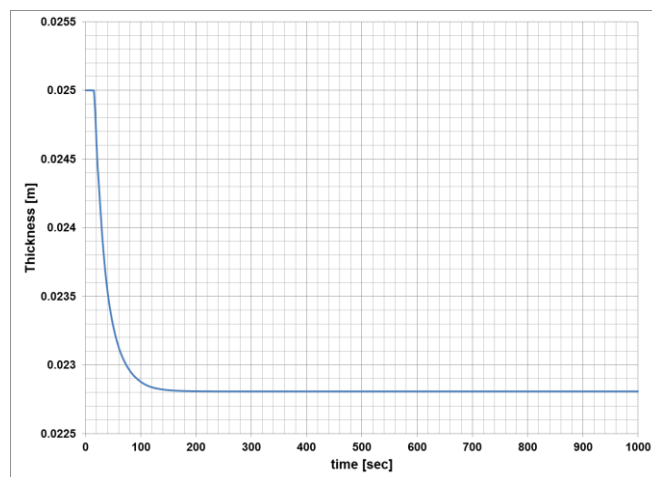Figure 10 shows the predicted thickness of the composite coating as a function of time.

Fig. 10: Predicted thickness of the Glass/Vinyl Ester as a function of time

From Figure 10 it can be seen that the erosion of the composite is 2.2 mm. Thus the erosion of Epoxy resin is greater than Glass/Vinyl Ester. It is because:
1) The glass contains compounds such as Silica, Magnesium Oxide and Alumina which are durable at high temperature
2) The glass is dense than the epoxy.

V.   Conclusion

This paper presents thermal model for predicting the temperature of Epoxy resin and Glass/Vinyl Ester exposed to one-sided radiant heating by fire. The models predict the temperature rise and through-thickness temperature profile in a hot decomposing laminate exposed to fire. The models assume that one side of a laminate beam is heated by convective and radiative heat flux. The proposed approach is divided into two simulation parts. The first part is the fire simulation where the FDS model is utilized. The FDS model generates a solution of several state variables, such as pressure, temperature, heat, velocity vector. In the second part, the conduction equation was solved in order to compute the surface instantaneous temperatures for the Glass/Vinyl Ester and Epoxy resin coatings. It has been found that these linings can be applied as a thermal protection barrier. It has been found that the erosion of Epoxy resin is greater than Glass/Vinyl Ester. It is because:

•   The glass contains compounds such as Silica, Magnesium Oxide and Alumina which are durable at high temperature
•   The glass is dense than the epoxy.

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