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CFD Studies Of Tunnel Fire Growth On Composite Lining Materials

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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 developed in FDS software in order to predict surface temperature and burning rate of the hot decomposing composite. It has been found that composite lining can be used a thermal protection barrier.

Keywords:- Charred material, concrete spalling, FDS code, Heat transfer in road tunnels, pyrolysis

I. INTRODUCTION

Numerous catastrophic tunnel fire events have occurred during the past decades, increasing the interest in structural fire safety of underground facilities. Detailed summaries of road and rail tunnel fire incidents can be found in the literature [1–4] 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 [1]. 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 [6]. The fire resistance of concrete can be improved by coating it with composite material. 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. In order to increase the market penetration and because of current stringent aviation and other legislation to increase safety, improvements in flame retardant coatings have been given significant priority. 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. 1). 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 [7].

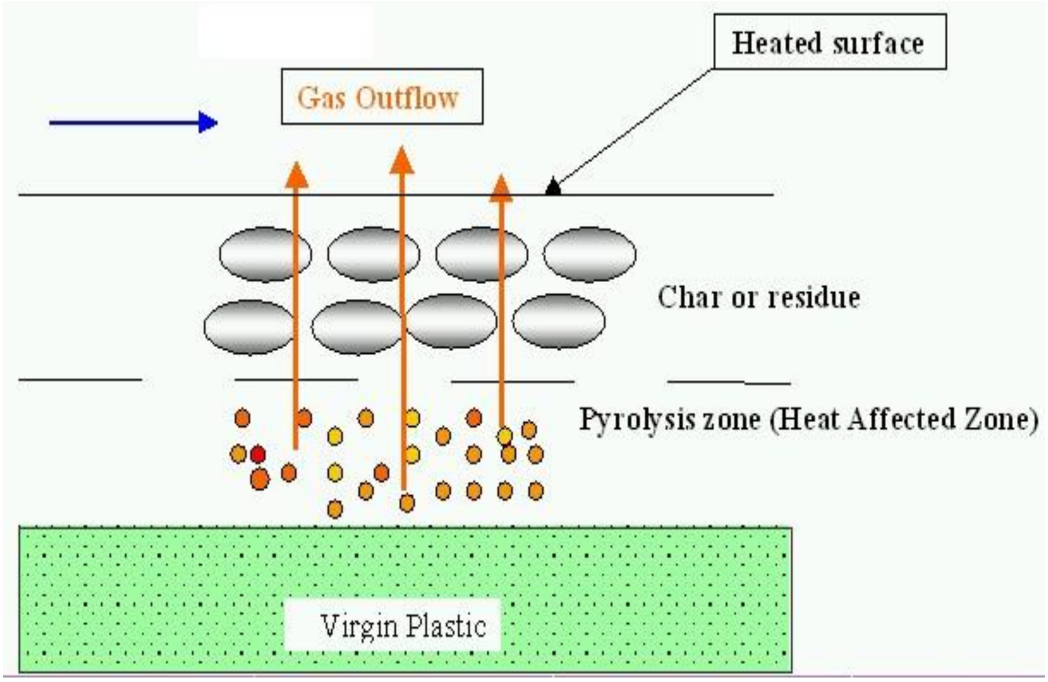

Fig. 1: **Composite degradation process**

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.

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. [8, 9]. 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 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. The latter is used in the case where the fire heat release rate is unknown. 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 2 [10].

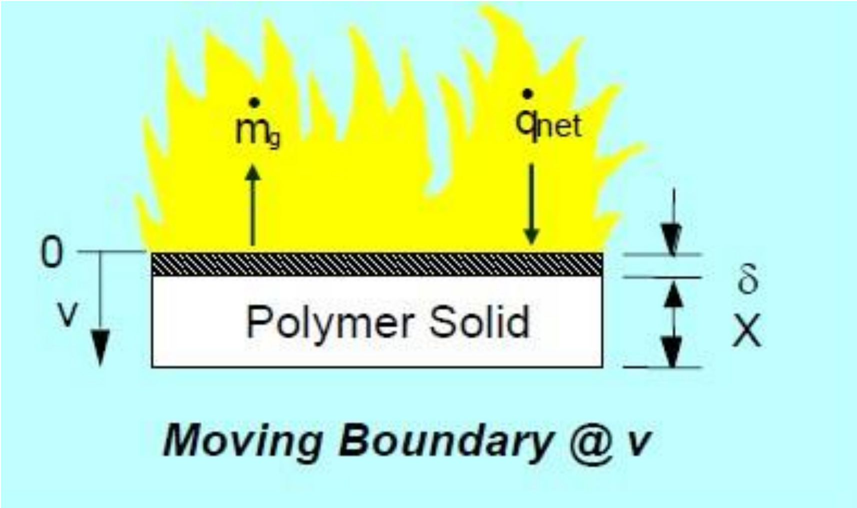

Fig 2: Burning process of polymer composite [10]

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) [9]

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

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:

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

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

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

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

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

ΔH_r Is the heat of reaction? The thermo physical properties (thermal conductivity, heat capacity and density) and the rate constants of the composite used in the calculation of FDS are shown in Table 1 [11].

Table 1: Thermo physical and thermochemical properties of coating composite

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	$kJ/kmol$
A_0	5.59E+13	$1/s$

III. DESCRIPTION OF CFD CALCULATIONS

The dimensions of the tunnel were 20 m long, 7.4 m wide and 5 m high. The configuration of the tunnel is shown in figure 3. 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 the tunnel openings are sealed.

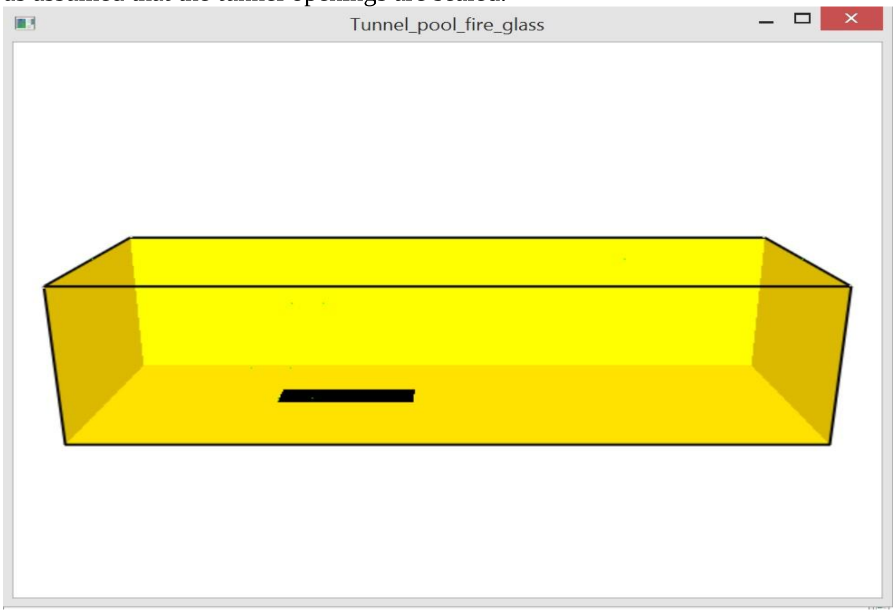

Fig. 3: Configuration of fire tunnel.

IV. RESULTS

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=156 s is shown in figure 4.

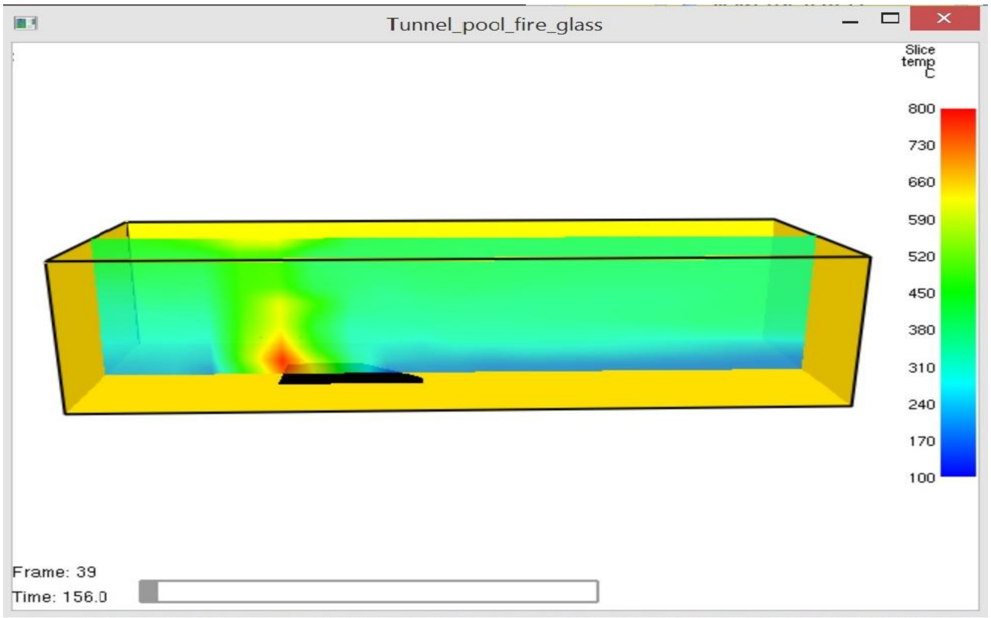

Fig. 4: Temperature field in the tunnel at t=156 sec

It can be seen from figure 4 that the ceiling temperature at time =156 sec approaches to 600ºC. The calculated oxygen mole fraction is shown in figure 5.

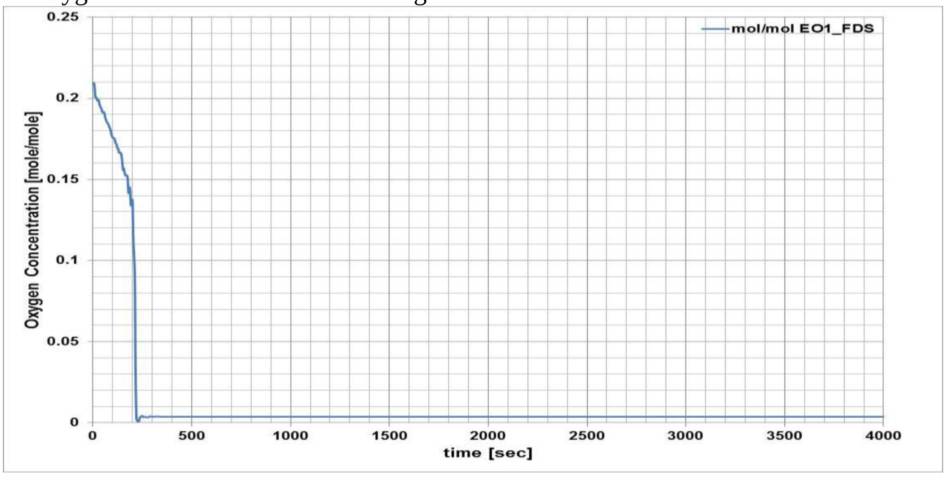

Fig. 5: Calculated oxygen mole fraction

Figure 5 shows that the combustion reaction causes the oxygen concentration to decrease. In Figure 6, a comparison of the surface temperature without the coating and wall surface temperature (with the coating) are presented.

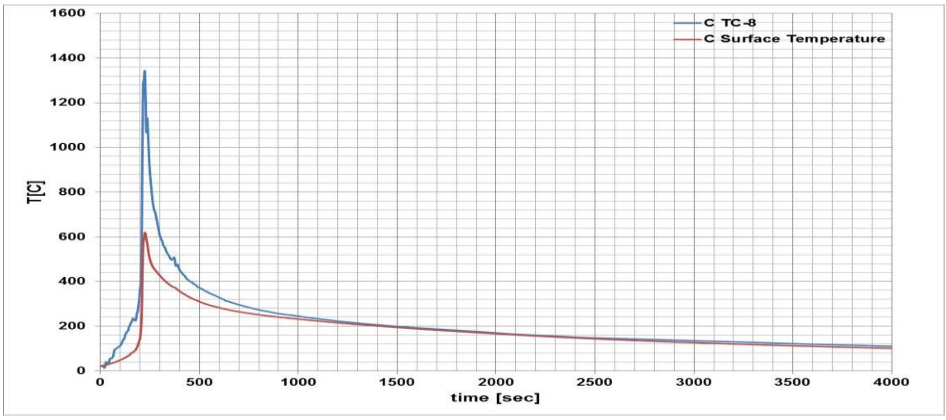

Fig. 6: Calculated thermocouple and wall surface temperatures

Figure 6 shows that the temperature of the composite lining is smaller than the surface temperature (without the coating). This phenomenon occurs because the composite act as thermal barrier. There are two effects that decrease the two temperatures:

a) The heat penetrates to 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.
The surface temperature of composite decays more rapidly.

V. CONCLUSION

This paper presents thermal model for predicting the temperature of polymer laminates 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 temperature for the composite. It has been found that composite lining can be used a thermal protection barrier.

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