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A STUDY OF FIRE DURABILITY FOR A ROAD TUNNEL: COMPARING CFD AND SIMPLE ANALYTICAL MODELS

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Abstract. *The durability of various typical tunnel sections in the event of a prescribed 100 MW fire has been assessed. Cast-iron sections, pre-cast concrete sections and in-situ concrete cut and cover sections are all considered to be part of a 1 km long road tunnel. An analysis of the tunnel constructions and surrounding geology (based on a real tunnel) has led to the estimation of failure temperatures for the structural elements, internal cladding systems, jet fans and their fixings. A commercial computational fluid dynamics (CFD) code was used to simulate various fire scenarios and calculate the times to failure of tunnel elements. Simulations were carried out for fires in different locations for the three section types. In parallel to the CFD study, an analytical model was devised to predict gas temperatures in the tunnel. Both models used the same input variables and general assumptions and great attention was given to establish the highest possible accuracy for all input variables and general assumptions. Comparing the predicted gas phase temperatures shows that there is less than a 20% difference between the complex CFD and the simple analytical model; this is well within the bounds of uncertainty inherent in either model and to the input parameters. Using both sets of gas phase temperatures, a detailed heat transfer study was carried out to calculate the temperature evolution of each of the tunnel elements. The differences in gas temperatures between the two modelling methods did not alter the conclusions regarding the time to failure of any tunnel elements. It is found that fire durability can be better analyzed by separating the fire environment into two zones, a near field close to the flames, where accuracy is defined by the assumptions, and a far field where the precision of the results is linked to the modelling method. This approach allows establishing that, for this particular case, failure of structural elements can only occur in the near field. This study shows that the detail of the calculations needs to be consistent with the accuracy of the input parameters and assumptions. Although CFD models can give highly detailed results, the implied accuracy of the results is defined by the assumptions inherent in the model setup, thus, there is the potential of a very costly and refined computation that leads to results of comparable accuracy to simple, less costly, models.*

1 INTRODUCTION

In recent years, several accidents involving fires in tunnels, many including fatalities, have highlighted the importance of fire safety in this type of structure. Evacuation, suppression and ventilation strategies, as well as structural durability during and after a fire are crucial topics in making sound and robust designs.

Modelling tunnel fires is a difficult task. In addition to all the common difficulties in modelling fires, such as properly predicting combustion, the fluid dynamics of the fire and smoke and the fluid-solid interaction in terms of heat transfer to the solid and flame spread, one must add the complexity of the forced ventilation used in tunnels, the complex and uncertain nature of the vehicles and the unique form of confinement. Predicting the structural behaviour of tunnels in fires is also a complex process, where the thermal boundary conditions must be prescribed in order to perform the calculations, and the current knowledge on subjects like concrete spalling is insufficient, making the predictions inaccurate.

Several models have been developed to simulate fire conditions in tunnels, ranging from simple analytical expressions to complex and computationally intensive Computational Fluid Dynamics (CFD) codes. The analytical models have been used to calculate critical ventilation velocities, gas-phase velocities and back-layering length, but their validity has occasionally been contested [1, 2]. Zone models are more complex than the simple analytical expressions, addressing mass, momentum and heat transfer between the different zones, thus calculating values of temperatures, species concentrations, mass flow rates and velocities [1-3].

In the highest order of complexity lie the field models. Despite their complexity, these models appear to be the most commonly applied models for fire applications today. They employ computational techniques to solve simplified versions of the conservation equations, and are computationally intensive [4-11]. These models represent a powerful and effective tool for modelling smoke movement in complex geometries, but a high degree of accuracy using these methods is not necessarily guaranteed. The capabilities of current CFD models are limited by the current knowledge of fire phenomena, the uncertainty of input parameters and the potential use to be made of the output. CFD models are highly computationally intensive, having to repeatedly perform many calculations for each of hundreds of thousands of computational cells in the simulation domain. The calculation cycle has to be iterated many times until convergence is achieved. In order to speed up the process, the number and complexity of the equations to be solved is often reduced by introducing certain simplifications and assumptions, as knowledge of fire phenomena allows. Correct application of the computer model and proper interpretation of the simulation results require a thorough understanding of the assumptions, simplifications and limitations of the model.

The structural response of tunnels can also be predicted by simple expression or by more complicated and computationally intensive computer codes. In both extremes, the thermal boundary conditions have to be input in the models. This can be done by using a fire model as discussed above or by using a prescribed time-temperature curve [12-14]. In any case, the heat transfer into the solid must be calculated, in order to obtain an estimate of the evolution of the temperatures in the structure and thus the behaviour of the structure can be calculated. A common problem in tunnel fires, the phenomenon of concrete spalling is not yet fully understood, and no accurate methods of prediction of spalling have been devised to date [14].

Most of the issues described above have been extensively studied and numerous papers can be found in the literature. In contrast, there is no clear evaluation of the compatibility of models for the comprehensive assessment of fire safety in tunnels. As indicated above, the calculations can be divided in four different groups, the definition of the fire, the transport of mass and energy, the heat transfer to the structure and the structural modelling. In this study the issue of compatibility of tools is explored in detail.

1.1 Background

The present study is based on existing practices associated to the use of highly detailed CFD models to simulate fire conditions in a tunnel. Generally, various fire scenarios are defined on the basis of past experimental data and a Risk Assessment of the tunnel. Detailed engineering analysis is then used to identify failure temperatures of the various tunnel elements. Their durability is therefore established on the basis of critical temperatures, and the time to failure is determined through the heat transfer analysis as when the specific element reaches the failure temperature. The heat transfer analysis allows predicting times to failure of the tunnel elements, given the CFD results. A variety of tunnel elements have to be considered and include iron and concrete sections, steel cladding and plastic components.

This article presents three alternative methodologies for study of the fire durability of a hypothetical 1 km long tunnel. The three cases follow the above methodology and as an example, the methods will be tested with a 100 MW fire. The analyses were performed to calculate the heat input to the tunnel structure, cladding and jet fans. Two analyses used a commercial CFD package and the third used a simple analytical model. The results are compared and then used to estimate the behaviour of the tunnel structural elements, and ultimately calculating their failure times.

1.2 Description of the tunnel

The hypothetical tunnel considered here is based on several real road tunnels. The tunnel is built of three different types of circular sections: cut and cover reinforced concrete sections, cast-iron sections and composite precast concrete sections with steel face plates. The tunnel is considered to be 1000 m long, and descends about 20 m at its central sector. The inner radius is of 4.9 m throughout its entire length, while the thickness of the tunnel linings is variable and typical of the construction method. The tunnel includes inclines to establish the impact of such common geometrical characteristics.

The tunnel is ventilated by bi-directional jet fans and semi-transverse ventilation; the two extract points are positioned approximately halfway down the inclines (that is, at about one sixth and five sixths of the length of the tunnel).

The geology of the ground surrounding the tunnel is based on a real road tunnel in the UK. This tunnel is embedded in a terrain that contains layers of clay/peat, sand/gravel and chalk as the depth increases. In the cut and cover sections there is also a superficial layer of made ground. Typical properties were used for these materials. For each section of tunnel, the surrounding ground is assumed to be homogeneous; if the section being considered is located between two different layers of ground, the properties of the lower layer have been used in the analysis.

Figure 1: Schematic diagram of the hypothetical tunnel, depicting the worst case position for a fire (See Ch. 2.1)

2 GAS PHASE

In this study, the local temperature and velocity outputs have been used to compute the convective and radiative heat transfer to each of the tunnel elements. Three different methodologies were used, each with a different level of complexity. The different levels allow verification of individual assumptions and are as follows (in decreasing order of complexity):

1. Transient CFD analysis: Several 100 MW scenarios were run in a 3D geometry of the tunnel, including turbulence, buoyancy, convection and radiation. The transient velocity and temperature outputs have been incorporated into a heat transfer calculation to obtain transient temperature evolutions for each of the components considered. This analysis was conducted primarily for validation and only one 100 MW run (the worst case scenario) would have sufficed for this purpose. The computation time to solve one case is of the order of one week in a modern PC.
2. Steady state gas phase analysis: The gas phase attains steady-state temperatures much earlier than the solid phase. Thus, for the heat transfer calculations to the structural elements it can be assumed that the gas phase instantaneously achieved steady-state conditions. This allowed the analysis of many more scenarios without the computational cost of a transient gas phase analysis. These steady state calculations therefore give a conservative ‘worst case’ scenario. The computation time to solve one case is of the order of one day.
3. Steady state analytical formulation of the gas-phase temperatures: A simple control volume analysis was carried out. It was validated against the steady state and transient CFD calculations. The analytical model assumed an adiabatic tunnel wall which yielded slightly greater gas phase temperatures in the far field, and thus provided the most conservative estimates for failure of elements in that part of the tunnel. The computation time to solve one case with the analytical model is almost instantaneous.

For both CFD analyses, the 100 MW fire was prescribed as a source of constant heat and smoke production – no attempt was made to predict flame behaviour, combustion processes or fire dynamics, only heat and mass transfer along the tunnel. It is clear that this practice will generate significant inaccuracies in the vicinity of the fire, because the combustion process, and resulting temperature fields, are controlled by the fuel and tunnel characteristics. The definition of an arbitrary heat input does not take into account any of these variables.

It is important to note that developing the mesh that describes the tunnel is not a trivial task and, in this particular case, required several weeks of an engineer’s time.

In each simulation, the traffic flow is assumed to be unidirectional and all vehicles ahead of the fire location are assumed to have safely exited the tunnel, thus the downstream tunnel contains no obstructions. Various objects upstream of the fire location are included in each simulation to represent stopped vehicles in the tunnel; these are arranged in a reasonably typical configuration for road tunnels.

2.1 The Fire

The fire was prescribed as a ramp growing from ignition to a peak of 100 MW. A transient period of 30 minutes was prescribed for the fire based on past tunnel experiments. Beyond this initial transient, the fire remains constant at the peak heat release rate for 90 minutes. The growth was established as linear to simplify the analysis and because there is no justification for any more complex growth curve.

2.2 CFD analyses

For both the transient and steady state CFD analyses, the ventilation configuration in the tunnel was set such that all smoke and hot gases produced by the fire were directed downstream of the fire location. The 'worst case scenario' position for a fire in the considered tunnel is in the lower half of the downward incline. Here, the ventilation must push the smoke down part of the incline and along the length of the tunnel. The ventilation must overcome the natural buoyancy of the fire plume, resulting in the highest temperatures at the fire location.

The CFD analysis will not be described in great detail here. A commonly used commercial CFD code was used to predict the transient evolution of gas-phase temperature within the tunnel environment. The temperature profiles predicted by the CFD code are shown in Figure 2. A steady-state simulation of the same scenario was also modelled, and is also shown in Figure 2. As can be seen, the transient results at 30 minutes (and thereafter) are indistinguishable from the steady state results.

It is important to note that the extent of the transient period is intimately related to the growth curve established as input, thus has no real meaning for these calculations.

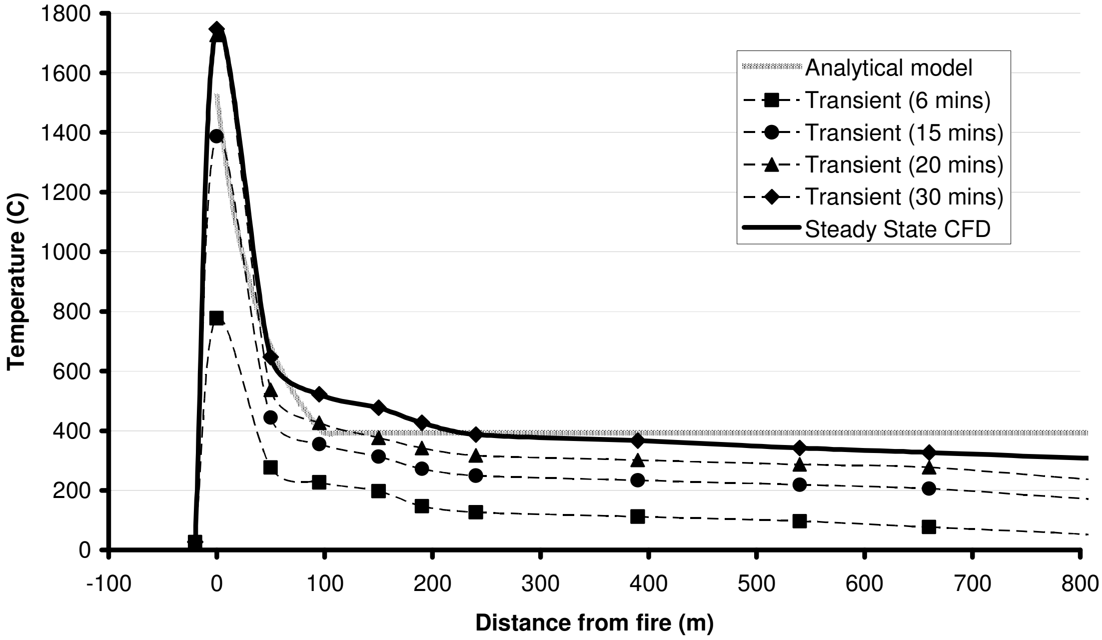

Figure 2: CFD and analytical calculations of the gas-phase temperature vs. distance for a 100 MW fire.

2.3 Analytical analysis

The analytical model used in this study assumes that the hot gases are ejected at the location of the fire and flow downstream. As they flow along the tunnel, they mix with fresh air and expand until the hot gases fill the whole section of the tunnel. This mixing phenomenon results in the cooling down of the gas and takes place in a length L_m, from the initial size r_0 to R (see Figure 3). Assuming no heat transfer to the tunnel (adiabatic walls), the gas temperature remains uniform downstream of the position L_m. Other heat transfer boundary conditions to the walls can be used if required, but the adiabatic condition represents the "worst case" situation.

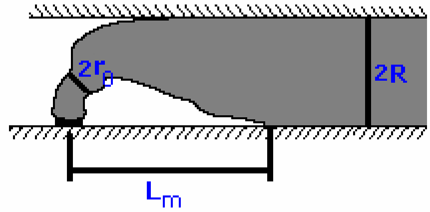

Figure 3: Flame and mixing lengths in the tunnel.

The governing equation for the temperature of the gas is expressed as:

$$\begin{aligned} \frac{\partial T_g}{\partial x} &= -\frac{2}{r}\left((T_g - T_0)\frac{R - r_0}{L_m} \right) && for \quad x < L_m \\ \frac{\partial T_g}{\partial x} &= 0 && for \quad x \geq L_m \end{aligned} \tag{1}$$

And the temperature of the gases at the fire point (the initial condition) is expressed as:

$$T_g(0,t) = T_{fire} = \frac{1}{c_{pg}\pi r_0^2}\frac{Q}{\dot{m}''} + T_0 \tag{2}$$

Also,

$$T_g(x = \infty, t) = T_0 \tag{3}$$

Different values of L_m could be used to account for the interaction of the fire gases with nearby tunnel elements (i.e. inclines, vehicles, vents, fans). However, a scale analysis of the mixing process at the plume [22] yields this mixing length to have a value of approximately 100 m for the geometry of the tunnel and a fire of 100 MW. The temperature profile predicted by the analytical model is also shown in Figure 2. The resulting gas temperatures are relatively insensitive to changes in this length (less than 1% change per additional m of L_m).

2.4 Comparison of results

Figure 2 shows the temperature distributions along the length of the tunnel for the worst case scenario (fire is located at x=0) using each of these models. The transient solution shows temperatures evolving for a period of approximately 30 minutes, beyond which the transient solution matches the steady state temperatures. Significant temperature differences can only be seen in the first 10 minutes of the test, a timescale defined by the fire growth curve and thus well within the uncertainties of the input parameter. It is clear that after 20 minutes the transient and steady state solutions are within 50°C along the entire length of the tunnel.

The fire environment along the tunnel can be classified into a near field and a far field. The near field is the part of the tunnel exposed directly to the flames of the fire. The far field is the section subjected to the influence of the hot gases (i.e. smoke layer), away from the flames. This division of the thermal field allows overcoming a well-known inaccuracy of fire model: the calculation of the flame temperature. For the accuracy levels required in the transient heating of structural elements, the temperature of a flame in a tunnel fire is more or less constant and of about 1500°C. This fundamental fact can be easily over or under estimated by CFD models that require many approximations and sub-models to simulate the region near the flame. Given this complexity, the choice of a prescribed fire is the norm. This approach will never give an accurate flame temperature. It is therefore a more consistent solution to prescribe an experimental flame temperature for this region. In contrast, CFD codes perform very well when calculating the temperature of the smoke layer as it travels along the tunnel and the energy gets dissipated.

Both transient and steady-state solutions show a high temperature region in the ‘near field’ of the fire (within 100 m) and a continuous decay, in the ‘far field’. This decay is entirely dependent on the assumed boundary conditions. Here, the wall boundary condition specified for the transient and steady-state CFD calculations is that of a thick (1.5 m) concrete envelope for the entire tunnel. The analytical solution shows almost identical trends but with no decay. The absence of decay is because in the analytical model no heat losses are allowed from the gas to the solid. This bounding condition is intended to provide a conservative calculation of the gas temperatures and the results are independent of the particular choice of a boundary condition for the wall. Other wall functions could easily be incorporated into the analytical model, if desired.

The gas-phase temperatures predicted by the CFD and analytical models are meaningless with regard to the fire durability of a structure without knowledge of the failure temperatures of the various tunnel elements and an understanding of the heat transfer between the gas phase and the solid.

3 SOLID PHASE

The high temperatures produced by a fire have a number of effects on structural elements. One of its most significant effects on most construction materials is to decrease its load capacity by means of reducing the yield stress. Another major effect is due to the thermal expansion of materials. This expansion generates an axial strain in the materials, which will induce further stresses when not allowed to expand freely. These stresses are generally compressive and depend on the material properties (modulus of elasticity) and the particular geometry of the element; however their magnitude increases as the temperature rises.

It is important to note that in reality, thermal expansion does not entirely translate into stresses, but a significant fraction of these stresses are relaxed via lateral deformation and displacement of the joints [20]. Deformations induced by thermal expansion require extremely complex calculations that, given the crudeness of the input parameters, clearly go beyond the scope of this article, therefore the analysis assumes the worst case condition, that is, that all thermal expansion is transformed into stresses, yielding conservative results.

Fire and high temperatures have other effects on concrete structures including cracking and spalling. These failures are not completely understood at the present time and no models are available which adequately describe these processes or predict their effects on the structural integrity of a tunnel. Consequently these processes have not been considered directly in the current study. However, the negative effects of cracking and spalling can be considered as being covered by the conservative nature of the calculations.

The following sections will briefly describe the methods used to estimate failure temperatures and failure times for the tunnel elements under assessment.

3.1 Failure temperatures

The following analyses have been based on the design guidelines given by Duddeck and Erdmann [15], and confirmed by the methodologies of Muir Wood [16], Morgan [17] and Gysel [18]. Details of the methods can be found in the reference papers and will not be reproduced here. When considering the variation of material properties with temperature, the values given in Eurocodes 2 and 3 have been used for most materials, except cast iron (not dealt with in the Eurocodes) where the values were taken from Smith et al [19].

In each step of the analysis, the least favourable sections and loads were considered to be present throughout the entire structure, thus the analysis should be understood as being conservative. For all calculations involving the primary tunnel linings, the surrounding ground has been assumed to have a full bond with the tunnel (that is, no tangential slip). This assumption does not predict stresses as high as those obtained when a tangential slip is considered, but it does give stresses significantly higher (circa 50%) than those predicted using Muir Wood's equations, where shear forces between the tunnel and the surrounding ground are neglected. In each case the results produced were compared to the Muir Wood model to ensure that they were coherent. In all calculations, it is assumed that there is no radial deformation due to thermal expansion, that is, the tunnel radius is assumed to be constant throughout. For each of the sections of the tunnel, the deepest point of that section was considered in the analysis.

The method used for the tunnel linings was the following:

1. Hoop forces and bending moments are calculated using Duddeck and Erdmann's equations.
2. Compressive stresses are calculated by dividing the hoop force by the tunnel lining's cross-sectional area.
3. Bending stresses are calculated by assuming that the tunnel lining is a curved beam subjected to a bending moment. This is a very rough estimate, but is considered a correct approach given the overall simplicity of the calculations.
4. Thermal stresses for a given temperature are calculated, assuming no relaxation.
5. All the calculated stresses are summed up and the total is checked against the admissible compression and tension stresses (i.e. the yield stress divided by a safety factor)
6. If the stress is smaller than the admissible stress, the whole procedure is repeated for a higher temperature.

For the tunnel claddings and jet fan fixings, the method was similar, except that the effect of thermal expansion was not considered. This is because the movement of these elements is not constrained, therefore any increase in temperature will cause the object to expand freely, not causing any stresses. The claddings are not load bearing, so the only load considered was their weight. For the jet fan fixings, the weight of the fans was taken as the only load. Only the most critical of the components of these fixings was analysed, such as the bolts in the case of the jet fan fixings.

The following failure temperatures were obtained for the tunnel elements.

Element	Failure Temperature
Cast iron lining	350-400°C
Pre-cast concrete lining	300-350°C
Reinforced concrete lining (cut and cover)	700-800°C
Steel cladding	500-600°C
Jet fan fixings	700°C
Jet fans	400-500°C

Table 1: Failure temperatures for the tunnel elements

4 HEAT TRANSFER & TIME TO FAILURE

As was stated previously, in this study it was found convenient to subdivide the tunnel into two distinct zones, the ‘near field’ and the ‘far field’. The near field is that part of the tunnel, in the vicinity of the fire, where radiation from the flames dominates the temperature profile.

It was also found helpful to separate the tunnel elements into thermally thick and thermally thin elements. Thermally thin elements are those where the material may be assumed to heat uniformly, that is, no significant thermal gradients within the element are likely. Most of the tunnel elements, except for the primary linings, were considered to be thermally thin.

The volume of the tunnel considered as the near field of the fire is dependent on the length and position of the flames from the fire, which is, in turn, dependent on the HRR.

The data from a series of fire tests carried out in an abandoned tunnel in Norway [21] was used to establish the flame lengths. Flame lengths of 40, 66, 84 & 95m were recorded for fires with heat release rates of 66, 119, 157 and 202 MW, respectively. Interpolating from these results suggests that a 100 MW fire would produce flames of around 62 m in length. For a conservative analysis, the near field of the fire was taken to be longer than these lengths. Here we assume that the near field of a 100 MW fire may extend to 100 m downstream of the fire. The near field may also be taken to extend a few tens of metres upstream of the fire location, due to the very high levels of radiative heat flux in the vicinity.

In the near field of any sizeable fire the gas phase temperatures will exceed 1000°C, even before the peak HRR is reached (see Figure 2, transient case). This is above the failure temperature of all thermally thin elements. Thus, the only justifiable assumption that can be made is that all thermally thin elements in the near field will fail early on in the fire. The time to failure of the thermally thin elements in the far field was determined in this study, but was found to be entirely dependent on the prescribed fire behaviour, namely the prescribed HRR growth rate. Given that the failure of thermally thin elements is based entirely on the assumptions of the model and not on the properties of the elements themselves, it was decided that it was unjustifiable to attempt to predict times to failure of such elements in a study of this sort.

Due to the sheer size of the elements which make up the primary linings of the tunnels, the rate of heating of these elements is several orders of magnitude slower than the rate of heating of the gases. Thus, a steady state gas phase temperature was used as input into a heat transfer model. From a comparison of the steady-state gas phase temperatures calculated using CFD with the steady-state gas phase temperatures predicted using the analytical model, it is clear that the gas temperatures are sufficient to bring about structural failure in near field. However, the heating time of the tunnel elements will be quite significant, due to the mass of material being heated, the thermal properties of the materials and the rate of the heat transfer processes.

The heat transfer process was studied following standard methods [23]. Convective heat transfer from the hot gas to the structural element is dependent on the properties of the element, the geometry of the element (a characteristic length scale needs to be defined for each element), the temperature of the flow and the magnitude of the flow. Here, the flow velocities were established using the steady-state CFD results, gas temperatures were taken from the various models, length scales were defined according to the actual dimensions of the elements (based on real tunnel elements) and the material properties were those used in the calculation of the failure temperatures.

An example of the results for a near field structural element (cast iron primary lining) is given in Figure 4. It is apparent that the uncertainty between methods in the calculation of the time to failure for thermally thick tunnel elements is of the order of ten metres in distance and half an hour in time. This is an acceptable amount of uncertainty given the methods used to estimate the failure temperatures of the elements.

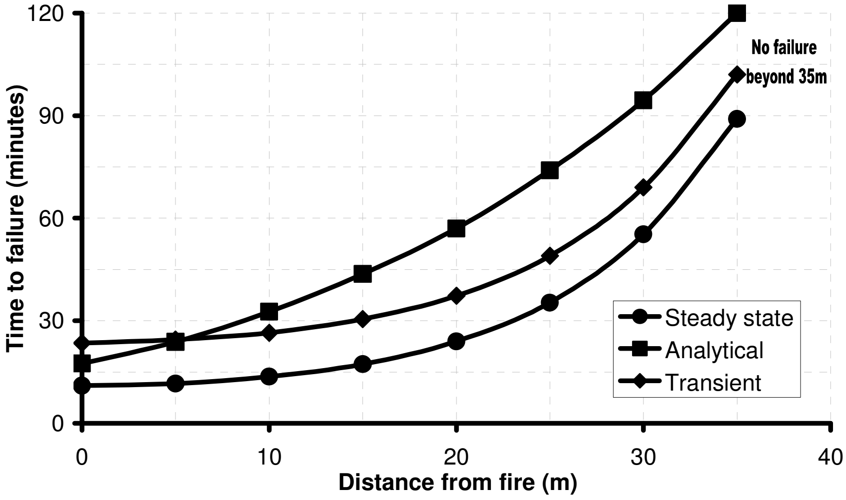

Figure 4: Predicted time to failure for the cast iron primary lining, based on temperature input from each of the three models.

Using the analytical model (which predicts lower temperatures in the near field) or the transient CFD model (which has lower temperatures in the early stages of the fire due to the lower prescribed HRR), the predicted times to failure are longer than using the steady-state CFD temperatures as input. However, given that the results using all three methods are of the same order of magnitude and exhibit the same general trends, it does not seem justifiable to choose the complexity of a CFD model over the simplicity of the analytical model for tasks such as this.

All three analyses (using transient CFD, steady state CFD and the analytical formulation) show that no thermally thick elements will fail in the far field of any of the scenarios considered.

5 DISCUSSION

The use of CFD in tunnel fire applications is prevalent and on the increase. These models have uses for which they are appropriate but are increasingly being applied to tasks where other tools would be better, faster and cheaper. In particular, one of the areas of weakness of many current CFD codes is the way in which heat transfer to the solid phase is calculated. There is little point in calculating the gas phase temperature with high accuracy only to use a very approximate method to predict heat transfer.

Here, a less detailed model than CFD has been used to predict gas phase temperatures and more time has been devoted to the calculation of heat transfer to the solid phase. This has resulted in considerably reduced calculation times and a more accurate prediction of the time-temperature behaviour of the solid elements.

In the vicinity of the fire, a discrepancy of approximately 200 °C can be observed between the analytical model and the CFD results. This difference is not a failure of the analytical model, but rather an indication of the unrealistically high temperatures generated by the CFD model. These unrealistic temperatures are associated to the absence of a combustion model and the subsequent need to prescribe the HRR. It is important to note that even with a sophisticated combustion model, the uncertainties on the input parameters will probably lead to equal levels of uncertainty and significantly enhanced computational cost.

The comparisons presented in Figure 2 show that the analytical solution can reproduce temperatures well within the error bars inherent in this study. They also demonstrate that any of the above methods will provide justifiable results when analysing the temperature of any of the components of interest.

All these methods are greatly dependent on the assumptions made, therefore great care should betaken when interpreting these types of results. One of the dangers of carrying out a transient CFD analysis of a problem such as this is that the user must prescribe a fire growth rate. In this study it was observed that the failure times of all thermally thin elements were entirely dependent on the assumed growth rate and not on the properties of the objects themselves. Furthermore, the uncertainties in the time to failure of thermally thick elements (tunnel linings, etc) are greater than the differences predicted between the transient and steady-state CFD methods. Thus, there is no justification for using a transient analysis.

Another assumption inherent in this type of study is the magnitude of the fire. This has not been analysed in detail here, but it should be noted that an analytical approach could enable to cover a wide range of HRR. The computational cost of a CFD analysis will make a parametric study of this nature unfeasible.

6 CONCLUSIONS

A simple methodology for the assessment of the durability of tunnel elements in case of a fire was developed and applied to a real tunnel. Three different methods to estimate the gas phase temperatures were carried out, each with a different degree of complexity. It has been shown that each method provided results within the error bounds expected in an engineering analysis like this one and thus can be used indistinctively. Given the uncertainties and objectives of the present fire durability study, there is no compelling reason to choose the detailed, yet highly time consuming CFD method over the simple analytical model.

The three methods presented are of comparable accuracy, but a transient CFD run takes over 150 hours of computer time, whereas the analytical results are virtually instantaneous. It has been stressed that more complicated models do not always provide better, more accurate results than simpler approaches; greater complexity does not always mean greater accuracy.

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