ADIABATIC SURFACE TEMPERATURE FOR CALCULATING HEAT TRANSFER TO FIRE EXPOSED STRUCTURES

Ulf Wickström
Swedish National Testing and Research Institute (SP), Boras, Sweden

Dat Duthinh and Kevin McGrattan
National Institute of Standards and Technology (NIST), Gaithersburg, Maryland, USA

INTRODUCTION

A basic and common understanding of heat transfer to solids is very important for the advancement of fire safety engineering in areas such as the prediction of the temperature and load bearing capacity of structural components as well as the burning behaviour of real materials. However, because researchers and test standard developers have different ways of expressing and measuring the various forms of convective and radiative heat flux, confusion often arises. This paper is intended to address this issue. The new concept of *adiabatic surface temperature* is introduced as a practical means to express the thermal exposure of a surface. The concept is particularly useful when calculating temperatures in fire exposed structures, as is shown in this paper. It can be used successfully when the exposure conditions are obtained either from a fire model or directly from measurements. In the latter case, the so called plate thermometer (PT), defined in the fire resistance standards ISO 834 or EN 1363-1, may be employed. This implies that the temperature of structural components tested according to these standards may be predicted using the plate thermometer measurements which are inherently designed to follow specified time-temperature curves.

Following the collapse of the World Trade Center in 2001, the issue of interfacing fire models with structural models became of primary importance in understanding the response of the buildings.[1] However, fire models and thermal/structural models operate with widely varying length and time scales, and different assumptions about respective boundary conditions. Fire models typically predict the heat flux to relatively simple solid surfaces; thermal/structural models typically assume a global gas temperature enveloping a fairly detailed model of a beam or column. This paper suggests a way of transferring to the thermal/structural model the relatively detailed description of the gas phase predicted by a fire model via a single quantity known as the *adiabatic surface temperature*.

BASIC THEORY

Heat is transferred from flames and hot gases to solid surfaces via radiation and convection, see e.g. ref.[2]. The two contributions make up the *net* total heat flux, $\dot{q}''_{\mathrm{tot}}$:

$$\dot{q}''_{\mathrm{tot}} = \dot{q}''_{\mathrm{rad}} + \dot{q}''_{\mathrm{con}} \qquad [1]$$

The radiation term in the above equation is the difference between the absorbed incident radiation and the radiation emitted from the surface. The heat transmitted through the surfaces is neglected, and no consideration is given to the influence of various wavelengths. Thus, as the absorptivity and emissivity are equal, the net heat received by the surface may be written as:

$$\dot{q}''_{\rm rad} = \varepsilon\left(\dot{q}''_{\rm inc} - \sigma T_s^4\right) \qquad [2]$$

where $\dot{q}''_{\rm inc}$ is the incident radiation, σ the Stefan Boltzmann constant, and T_s is the surface temperature. The emissivity, ε, is a material property of the surface. It can be measured, but, in most cases of structural materials being exposed to fire, it can be assumed equal to 0.8 except for shiny steel where it can be much lower. Because fires are characterized by non-homogeneous temperature distributions, the incident radiation heat flux should ideally include contributions from nearby flames, hot gases, and surfaces, in which case the incident radiation may be written as the sum of the contributions from all of the radiating sources:

$$\dot{q}''_{\rm inc} = \sum_i \varepsilon_i \, F_i \, \sigma T_i^4 \qquad [3]$$

Here ε_i is the emissivity of the i^{th} flame or surface and σ is the Stefan-Boltzmann constant. F_i and T_i are the corresponding view factor and temperature, respectively. To obtain the incident radiation using Eq. 3 is in general very complicated, but current generation fire models all have various algorithms for calculating it.

The convective heat flux depends on the difference between the surrounding gas temperature and the surface temperature. It is often assumed proportional to this difference and is then written:

$$\dot{q}''_{\rm con} = h(T_g - T_s) \qquad [4]$$

where h is the heat transfer coefficient and T_g the gas temperature adjacent to the exposed surface.

The Adiabatic Surface Temperature

From the discussion above, the total net heat flux to a surface can be expressed:

$$\dot{q}''_{\rm tot} = \varepsilon(\dot{q}''_{\rm inc} - \sigma T_s^4) + h(T_g - T_s) \qquad [5]$$

Consider the surface of a perfect insulator exposed to the same heating conditions as the real surface. Its temperature shall be referred to as the *adiabatic surface temperature (AST).* The total net heat flux to this ideal surface is by definition zero, thus:

$$\varepsilon(\dot{q}''_{\rm inc} - \sigma T_{AST}^4) + h(T_g - T_{AST}) = 0 \qquad [6]$$

The adiabatic surface temperature can be obtained as an output from a fire model as will be shown below. It can also be measured in real fire tests or experiments using a device such as the plate thermometer. In a sense, the adiabatic surface temperature is what would be measured by an ideal plate thermometer. Because the plate thermometer is used in fire resistance testing (ISO 834 and EN 1363-1) to control the furnace temperature, it harmonizes testing in various furnaces as well as it harmonizes testing and theory. That is, the quantity that is measured by the plate thermometer is precisely that which is needed in the calculation of the temperature of an exposed structural element. See ref. [3] and [4]. The error of such a calculation is relatively small, depending largely on the difference between the convective and radiative heat transfer parameters of the specimen and those of the plate thermometer.

Numerical Considerations

Numerically, the adiabatic surface temperature is a very useful quantity because it provides a natural interface between fire and structural models. A *fire model* in this context is any calculation method whose primary purpose is to predict the temperature and species concentrations of the fire-driven flow. Such a model computes the evolving temperature of the bounding surfaces out of necessity, but it does not necessarily include a detailed description of the solid objects. Even a computational fluid dynamics model may only approximate a bounding solid as an infinitely thick slab for the purpose of estimating its surface temperature. If one wants to use the results of the fire model to perform a more detailed heat transfer calculation within the solid, then some sort of interface is required to transfer information at the gas-solid interface. The most obvious quantity that comes to mind is the heat flux. However, there are two problems associated with heat flux. First, the net heat flux to a surface computed by the fire model is dependent on the corresponding surface temperature computed by the same fire model. Depending on the model, this might not be of the desired accuracy. Second, it is common in many popular solid phase heat transfer programs to input a prescribed heat flux based on boundary gas temperature and surface temperature (like in Eq.[9[9] below) rather than a prescribed heat flux. A solution to both of these problems associated with heat flux boundary conditions is to use the adiabatic surface temperature T_{AST} as intermediary between fire and structural models.

The interface is fairly simple. At every surface point at which the fire model (FM) computes an incident radiation heat flux, $\dot{q}''_{\rm inc,FM}$, and a corresponding gas temperature adjacent to the surface, $T_{g,\rm FM}$, it is trivial to solve the following implicit equation for T_{AST}, assuming that the emissivity and convective heat transfer coefficient are constant:

$$\varepsilon(\dot{q}''_{\rm inc,FM} - \sigma T^4_{AST}) + h(T_{g,\rm FM} - T_{AST}) = 0 \qquad [7]$$

Note that the fire model need not make any assumptions in computing the incident radiation heat flux. The above equation merely serves as the definition of the adiabatic surface temperature, but it does not imply that the fire model calculates the heat flux in any particular way. Most importantly, it does not imply that the fire model uses a fixed heat transfer coefficient, *h*. The values of T_{AST} are stored in a file according to a user-specified time interval and length increment appropriate for the application.

For the structural model (SM) the heat flux is computed based on the fire conditions computed by the fire model and the surface temperature computed by the structural model:

$$\dot{q}''_{\rm tot,SM} = \varepsilon(\dot{q}''_{\rm inc,FM} - \sigma T^4_{s,SM}) + h(T_{g,\rm FM} - T_{s,SM}) \qquad [8]$$

Now by subtracting Eq. [9] from Eq. [7] the total net heat flux to the surface can be computed as:

$$\dot{q}''_{\rm tot,SM} = \varepsilon\sigma(T^4_{\rm AST} - T^4_{s,\rm SM}) + h(T_{\rm AST} - T_{s,\rm SM}) \qquad [9]$$

Notice here that the adiabatic surface temperature is interpreted by the structural model as an effective *black body radiation* temperature for the purpose of computing the incident radiation and as the same *gas* temperature for the purpose of computing the convective heat flux. It may also be seen as a single fictitious temperature being used commonly for calculating both convective and radiative heat transfer.

An obvious question to ask at this point is why go through the trouble of translating the net heat flux of the fire model into a temperature and then translating it back to a net heat flux in the structural model? Why not simply transfer the heat flux from fire to structural model and apply the above correction to account for a possible surface temperature discrepancy between the two models? The answer is that one need only transfer one quantity, the adiabatic surface temperature, from fire model to structural model, rather than a heat flux, surface temperature, and convective heat transfer coefficient. A side benefit is that the structural model need not be reconfigured to accept a heat flux as its boundary condition. It need only be modified to accept a temporally *and spatially* varying "exposing" temperature for calculating the heat flux based on this temperature and the calculated surface temperature. Most models of this type already accept a temporally varying time versus "exposing" temperature curve. This is more than just a computational convenience. Large scale fire-structural analyses, like those done during the World Trade Center Investigation, involve huge datasets and complicated computer software. Any numerical technique that reduces the size of datasets and simplifies the running of computer models is ultimately going to reduce the potential for error and miscommunication of model results.

APPLICATION

To test the idea of using the adiabatic surface temperature as an interface between a fire and structural model, a series of compartment fire experiments performed at NIST was modelled using Version 5 of the CFD model Fire Dynamics Simulator (FDS)[5] and the commercial finite-element program ANSYS[6]. FDS computed the gas phase temperatures and heat fluxes to structural steel components, and produced as output a file of temporally and spatially varying values of the adiabatic surface temperature, which were then input into ANSYS following the procedure defined above. There is nothing within FDS or ANSYS that was deliberately set to facilitate the exchange of information. FDS simply used a 10 cm uniform mesh, and all solid obstructions were forced to conform to this mesh. ANSYS used a finite element mesh that conformed exactly to the shapes of the structural components. A simple interpolation scheme was worked out to translate uniformly spaced values of the adiabatic surface temperature calculated by FDS into boundary conditions appropriate for the solid phase heat transfer calculation performed by ANSYS.

Description of the Experiments

During the NIST Investigation of the World Trade Center collapse, a series of compartment fire experiments was conducted to assess the accuracy of the fire and structural models that were to be used as part of the overall analysis. The fire itself was relatively well characterized, and the heat release rate was measured and specified as a model input. The uncertainty in the measured heat release rate was reported to be 11 %. The compartment was heavily instrumented, in particular the structural steel components. A complete description of the experiments is found in Hamins *et al.*[7] A brief description is given here.

The geometry of the compartment was relatively simple. The overall enclosure was rectangular, as were the vents and most of the obstructions. Figure 1 shows the major geometric features of the compartment. Figure 2 shows the fire. The compartment walls and ceiling were made of 2.54 cm thick marinite boards. The manufacturer provided the thermal properties: density 737 kg/m^3, conductivity 0.12 W/m/K. The specific heat ranged from 1,172 J/kg/K at 93 °C to 1,423 J/kg/K at 425 °C.

Three types of steel components were selected for the experiments – simple bars, a hollow steel tubular column, and two bar joist trusses. The bars were nominally 3 m long and 25 mm in diameter. The column was 3.8 m tall, 0.26 m by 0.36 m in cross section, and 6 mm thick. The trusses were 4.6 m long and 0.8 m deep with 64 mm to 76 mm double angles for the top and bottom chords and 25 mm bar for the web members. The density of the steel was 7,860 kg/m^3; its specific heat ranged from 450 J/kg/K at 20 °C to 850 J/kg/K at 677 °C, and its conductivity ranged from 48 W/m/K at 20 °C to 30 W/m/K at 677 °C. For some of the experiments, the steel was insulated with sprayed fire resistive material. Its density was 208 kg/m^3; its specific heat ranged from 800 J/kg/K at 20 °C to 2000 J/kg/K at 677 °C, and its conductivity ranged from 0.05 W/m/K at 20 °C to 0.20 W/m/K at 677 °C.

The fires were fueled by one of two liquid fuels sprayed into a 1 m by 2 m steel pan. The first fuel was a blend of heptane isomers (C_7H_{16}). The second was a mixture (40 % and 60 % by volume) of toluene, C_7H_8, and heptanes, respectively. Six experiments were performed and the complete results can be found in Hamins *et al*[7].

Figure 1. Photograph of the test compartment, courtesy Anthony Hamins, NIST.

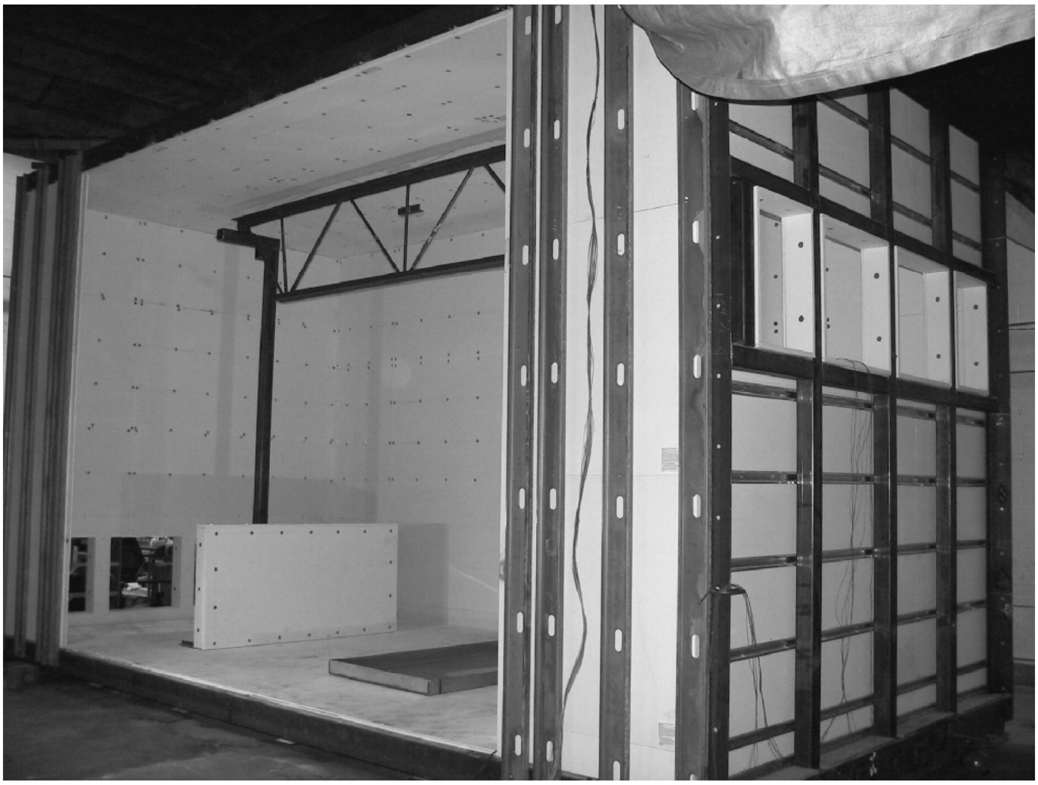
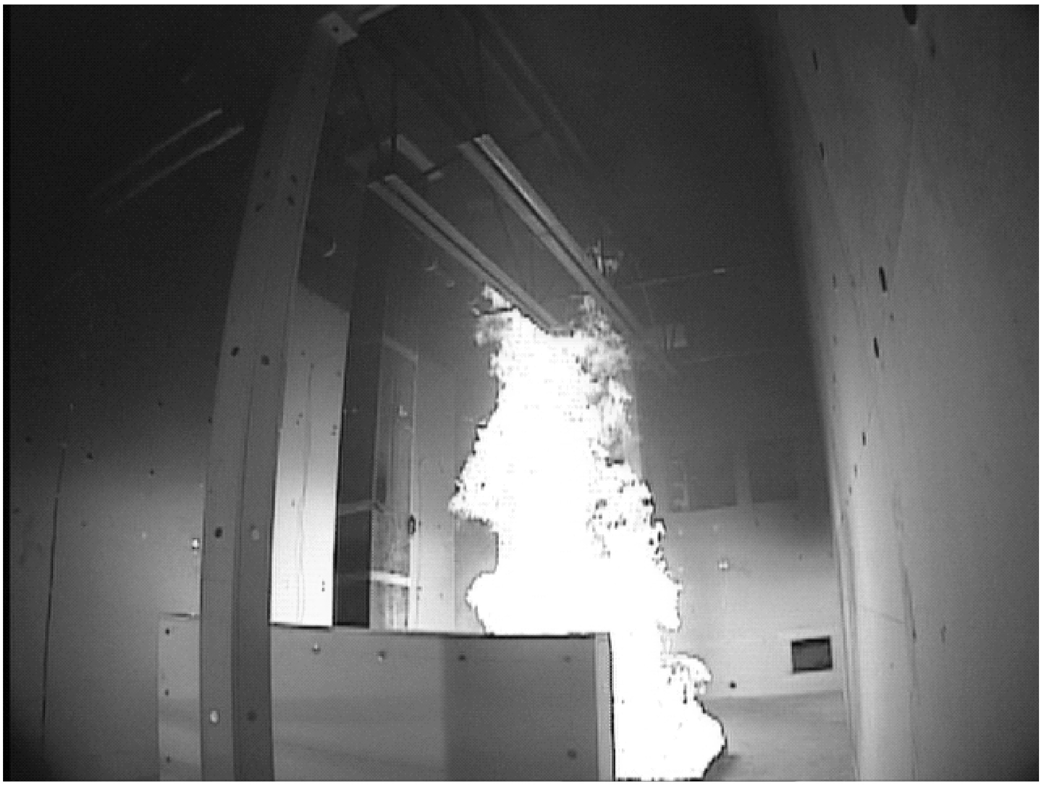


Figure 2. Photograph of a bare steel experiment.



Numerical Results

Of the six experiments conducted, three involved unprotected steel; three involved steel protected with various amounts of a sprayed fire resistive material, which shall be referred to here as *insulation*. The first test of the interface was for one of the bare steel experiments. The results for the box column are shown in Figure 3. Steel temperature measurements were made at heights of 0.7 m, 2.1 m, and 3.6 m from the floor, on all sides of the column. Shown in the figure are the east and west faces, which pointed at, and away from, the fire, respectively. The 2.4 MW heptane/toluene spray fire was roughly 0.5 m away from the column and lasted about 6 min. Note that the ANSYS calculations used FDS-generated adiabatic surface temperatures as input, on both the outside and inside of the box column. Thus, the extent to which the FDS and ANSYS results disagree indicates one of two possibilities – that the adiabatic surface temperature does not adequately convey the necessary information from FDS to ANSYS, or that the three dimensional ANSYS calculation is producing a different result than the one-dimensional solid phase heat conduction calculation that is performed by FDS. The fact that the only significant disagreement between FDS and ANSYS occurs at the back (west) side of the lower column suggests that the interfacing is adequate. It is expected that at the lower part of the column there is a significant different heating exposure level, leading to lateral heat conduction that is captured in the three-dimensional ANSYS calculation but not in the one-dimensional FDS calculation. In the upper layer, the heating of the column is more uniform, and a one-dimensional heat conduction calculation is adequate.

The point of this exercise is not to suggest where and when a fully three-dimensional heat conduction calculation is appropriate. That is left to the judgment of the analyst. Rather, the point is to show that the adiabatic surface temperature, the only quantity exchanged by FDS and ANSYS, is the appropriate means of information exchange between the two models.

A more challenging calculation is the prediction of the steel temperatures when insulation is applied. The thermal properties of steel are fairly easy to obtain and its thickness is not difficult to measure. Spray on insulation, however, is rarely applied uniformly, and its thermal properties are not as easily characterized. Nevertheless, for the purpose of validating the adiabatic surface temperature concept, it is only necessary that the fire model and the structural model use the same steel and insulation properties. The results of such a validation exercise are shown in Figure 4. In the fifth test of the series, a 3 MW heptane spray fire was fuelled for 50 min, and both the steel and insulation temperatures were measured. The 6 mm walls of the box column were coated with nominally 40 mm of insulation. Before considering the experimental measurements, it was necessary to compare temperature profiles computed by FDS using its one-dimensional heat conduction algorithm, and those of the three-dimensional ANSYS model. Even though the numerical method and gridding schemes are different, the temperature profiles are very close. Again, the only information provided to ANSYS was the adiabatic surface temperature computed by FDS on both the inner and outer walls of the column. Because the location of these profiles is the upper part of the column, the thermal exposure level was fairly uniform, and the heat transfer can be approximated as one-dimensional.

Figure 3. Predicted and measured steel temperatures for a box column

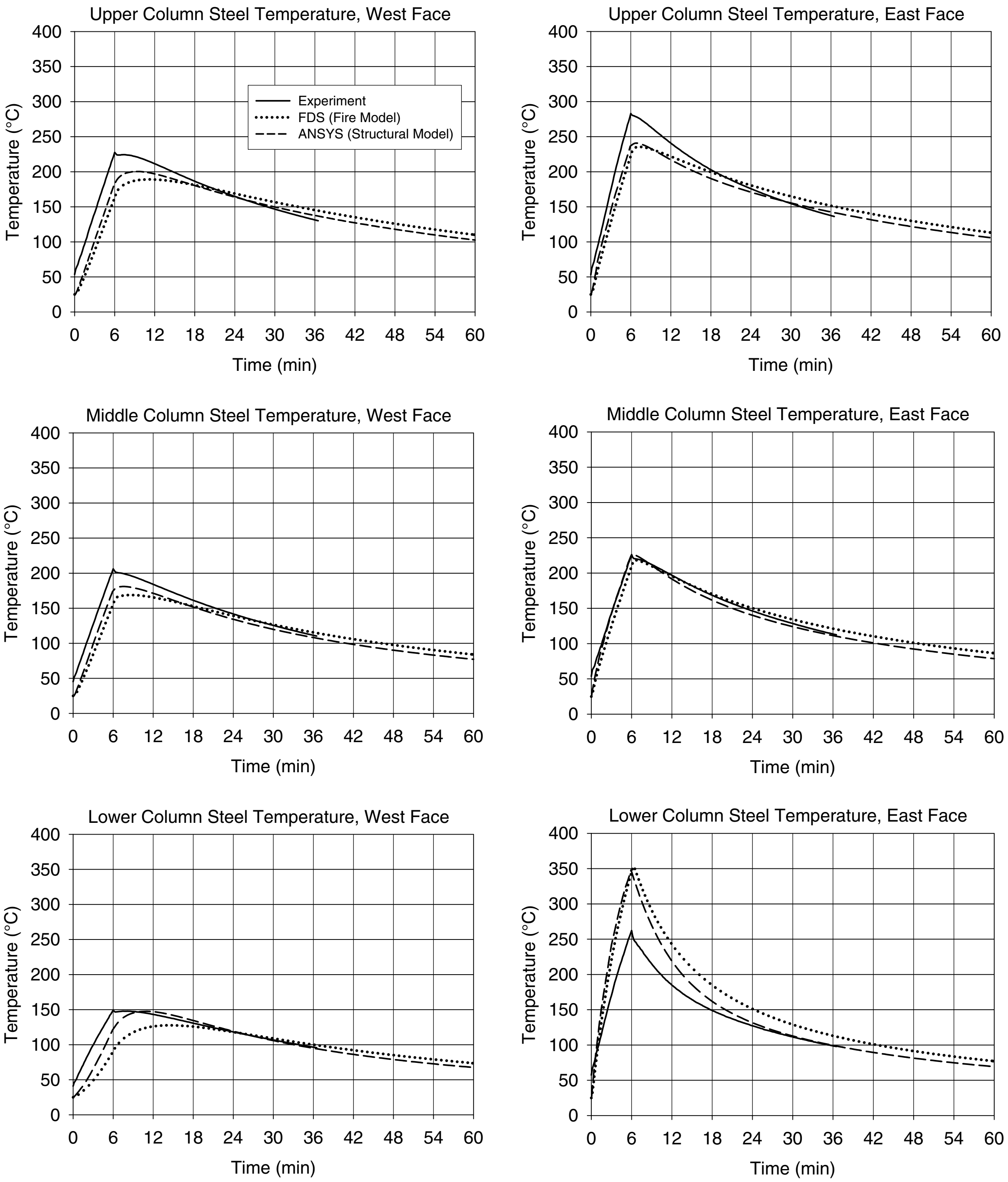


Figure 4. Computed temperature profiles of both FDS (1-D) and ANSYS (3-D) for an insulated box column. The position of the symbols denote the node locations of the 1-D FDS calculation.

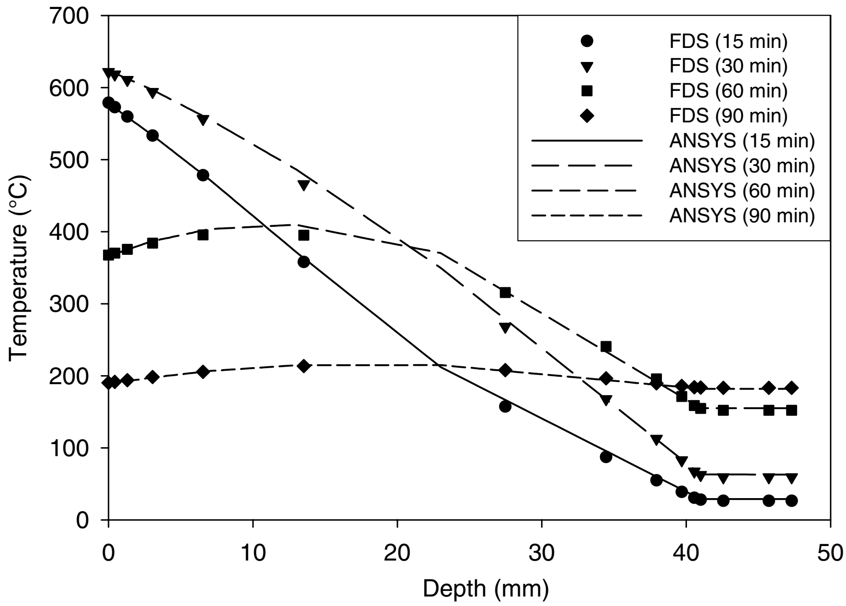
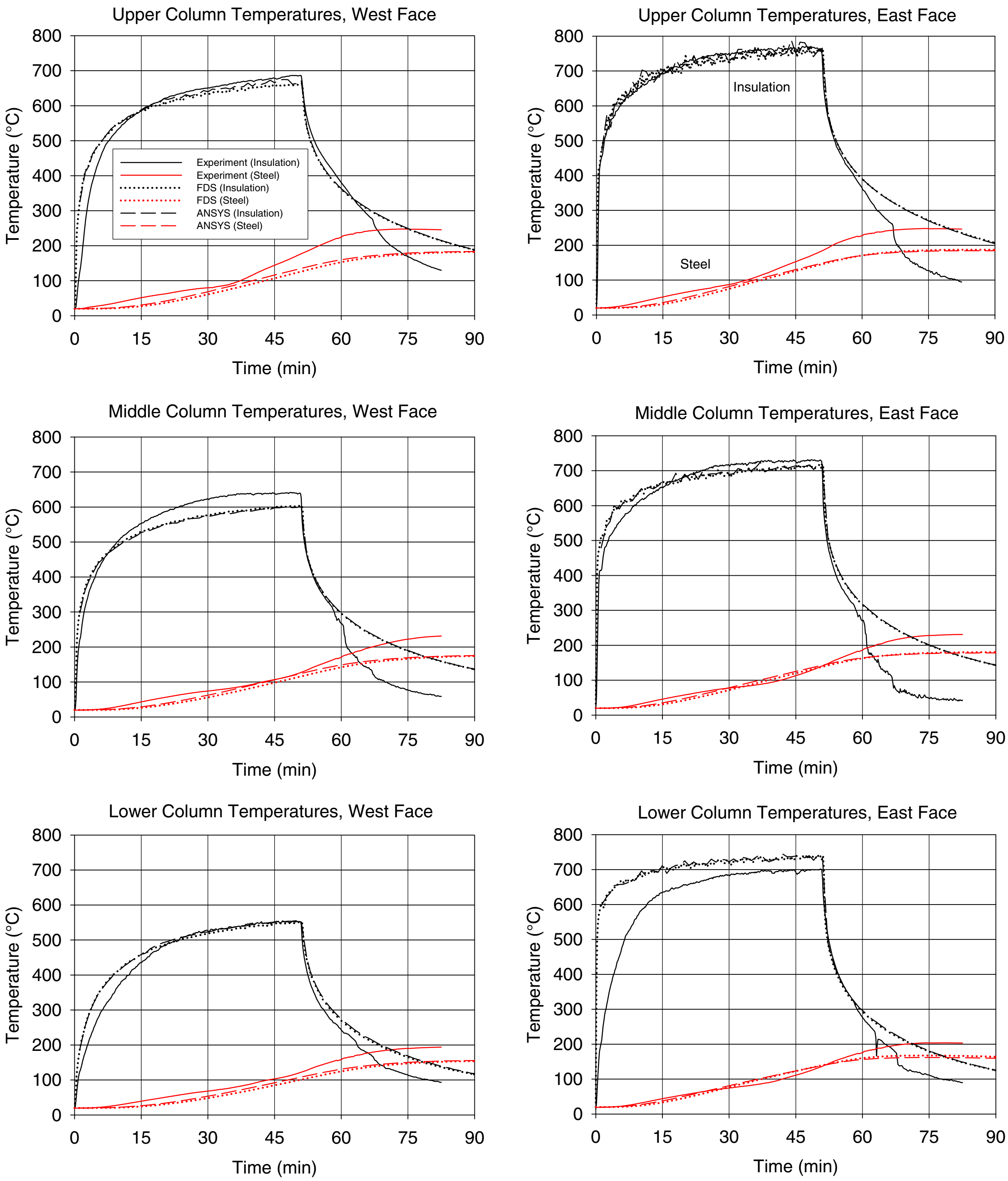


Figure 5 compares experimental measurements and numerical predictions of both steel and insulation surface temperatures for the same locations on the column as for the uninsulated steel case. The adiabatic surface temperatures transferred from FDS to ANSYS are very similar in magnitude to the insulation surface temperatures. At all locations, the predicted steel temperatures are lower than those measured, but that is mainly due to the fact that the specified insulation thickness was 38 mm, the mean was 41 mm, and the standard deviation (based on random spot checks) was 3 mm. FDS and ANSYS used the mean, rather than specified thickness; thus, the lower predicted steel temperatures may have resulted from the uncertainty in the insulation thickness. However, accuracy of the fire model is not really the issue here. Rather, it is the effectiveness of the fire-structure interface that is the issue, and it is clearly working very well judging from the nearly identical predictions of both FDS and ANSYS. Indeed, it is clear that the overall accuracy of the steel temperature predictions is almost entirely dependent on the fire model. The heat conduction calculation is not the source of error, nor is the interfacing if the adiabatic surface temperature is used as the intermediary.

The comparison of measured and predicted temperatures of the box column is an effective way to *verify* the use of the adiabatic surface temperature as an interface between models because the column was constructed of simple steel plates and the heat transfer was well characterized and easy to calculate. The term *verify* is emphasized because this is mainly a mathematical exercise – this is not a *validation* of either FDS or ANSYS, but rather a *verification* of an interface between them.

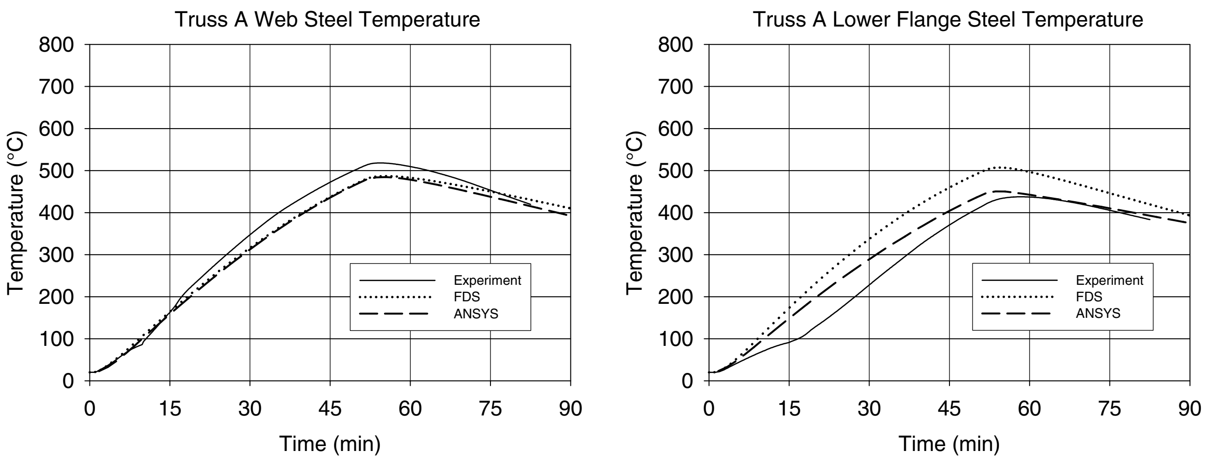
Figure 5. Predicted and measured insulation and steel temperatures for a box column.



In practice, typical structural components, like trusses, have more geometric complexity than a box column.

Figure 6 shows results for one of the two instrumented trusses in the same experiment (Test 5) that was discussed above. The truss was coated with a specified insulation thickness of 19 mm, but the mean thickness (used in the calculations) was 27 mm. The web of the truss consisted of circular steel bars, 25 mm in diameter. The close agreement between the models and the experiment for the web member is likely due to the fact that this component was uniformly heated and that lateral heat conduction was probably not important. For the lower angle bracket, however, it is suspected that lateral heat conduction was important, and that the three-dimensional ANSYS calculation is accounting for this while the one-dimensional FDS calculation is not.

Figure 6. Predicted and measured steel temperatures at two locations on a truss.



SUMMARY

In this paper the concept of an adiabatic surface temperature is introduced as a means of transferring data from fire models to thermal/structural models. As an example, compartment fire experiments conducted as part of the NIST investigation of the World Trade Center collapse demonstrate how the predicted heat fluxes from a fire model can be converted into an effective fire temperature that can be used as a boundary condition for a finite element thermal/structural model. Not only is the adiabatic surface temperature an easy quantity to compute, but it also allows the fire model and the thermal/structural model to operate without major modification. In effect, it expresses the heat flux in terms of an effective temperature, a quantity that is already well-understood as an input to thermal/structural models because of its equivalence to time-temperature curves that result from fire-resistance furnace testing. From a numerical point of view, the adiabatic surface temperature eliminates the surface temperature dependence of the net heat flux and reduces the amount of data that must be passed to the structural model.

REFERENCES

1 Gann, R. *et al.*, Reconstruction of the Fires in the World Trade Center Towers, *Federal Building and Fire Safety Investigation of the World Trade Center Disaster*, NIST NCSTAR 1-5, National

2 Wickström, U., *Fire and Materials 2004;* **28.**

3 Wickström, U., *Fire Technology*, **30**(2), 1994, pp. 195.

4 Wickström, U. and Hermodsson, T., *Fire Safety Journal*, **26**(4)(1996) 327-350

5 McGrattan, K.B., S. Hostikka, J.E. Floyd, H.R. Baum and R.G. Rehm, *Fire Dynamics Simulator (Version 5), Technical Reference Guide*, NIST SP 1018-5, National Institute of Standards and Technology, Gaithersburg, Maryland, July 2005

6 ANSYS Inc., 275 Technology Drive, Canonsburg, Pennsylvania (http://www.ansys.com)

7 Hamins, A. *et al.*, Experiments and Modeling of Structural Steel Elements Exposed to Fire, *Federal Building and Fire Safety Investigation of the World Trade Center Disaster*, NIST NCSTAR 1-5B, National Institute of Standards and Technology, Gaithersburg, Maryland, September 2005