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Coupled fire dynamics and thermal response of complex building structures

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Abstract

Simulation of the effects of severe fires on the structural integrity of buildings requires a close coupling between the gas phase energy release and transport phenomena, and the stress analysis in the load-bearing materials. The connection between the two is established primarily through the interaction of the radiative heat transfer between the solid and gas phases with the conduction of heat through the structural elements. This process is made difficult in large, geometrically complex buildings by the wide disparity in length and time scales that must be accounted for in the simulations. A procedure for overcoming these difficulties used in the analysis of the collapse of the World Trade Center towers is presented. The large scale temperature and other thermophysical properties in the gas phase are predicted using the NIST Fire Dynamics Simulator. Heat transfer to subgrid scale structural elements is calculated using a simple radiative transport model that assumes the compartment is locally divided into a hot, soot laden upper layer and a cool relatively clear lower layer. The properties of the two layers are extracted from temporal averages of the results obtained from the Fire Dynamics Simulator. Explicit formulae for the heat flux are obtained as a function of temperature, hot layer depth, soot concentration, and orientation of each structural element. These formulae are used to generate realistic thermal boundary conditions for a coupled transient three-dimensional finite element code. This code is used to generate solutions for the heating of complex structural assemblies.

Keywords: Fire dynamics; Heat transfer; Radiation; Structures

1. Introduction

There has been a resurgence of interest in response of building structures to fires over the past several years [1–5]. This interest was greatly enhanced by the attack on, and subsequent collapse of, the World Trade Center (WTC) towers [6]. The coupling between fire dynamics and structural analysis in building fires is largely due to radiative heat transfer from combustion products to structural elements. A common assumption used in the thermal analysis of structures is that the radiant heat flux q incident upon the surface of the element is related to the local gas temperature T by the formula $q = \sigma T^4$. Here, σ is the Stefan–Boltzmann constant (5.67×10^{-8} W/m^2 K^4). Thus, given a spatially uniform enclosure temperature and a "time–temperature curve" the thermal environment of the enclosure is specified, and attention can be confined to the calculation of the temperature and stress distribution in the structural elements.

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However, this is tantamount to assuming that the radiation field is in local equilibrium with the gas, an unlikely scenario in most fires. In general, the radiation field must be determined from solutions of the radiative transport equation, which relates the incident flux to the spatial distribution of temperature and combustion products (most particularly the distribution of soot particulate) as well as the enclosure geometry. Such calculations are typically performed as part of a CFD based simulation of the fire dynamics. However, the ability to couple such codes as the NIST Fire Dynamics Simulator (FDS) [7] directly to a suitable structural analysis code does not yet exist. The enormous differences in spatial and temporal length scales, differences in numerical techniques, and the complexity of the computer codes make the development of an efficient coupled analysis of fire–structure interactions a daunting task. CFD codes like FDS assume that the radiative transport to a surface and the thermal response of that structural element can be calculated as if the surface is locally one dimensional. However, important elements of the WTC structure (e.g., trusses and perimeter columns) are inherently three dimensional. Moreover, many of the critical segments of these structures lie below the resolution limits of any CFD calculation that attempts to simulate the fire dynamics over the entire floor or multiple floors of the WTC towers. Finally, the computed temperature distribution in the structure must be in a format accessible to the code used to perform structural analysis.

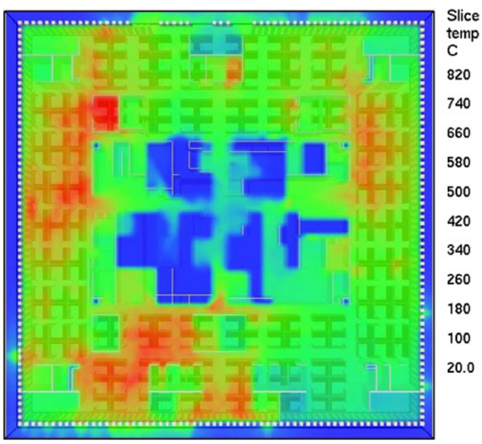

Fig. 1. Computed upper layer temperatures as predicted from an FDS simulation for World Trade Center Tower 1, Floor 96. The temperature contours (in degree celsius) are shown at 1000 s after the impact of the airplane.

An interim approach to the calculation of the coupled heat transfer problem is presented here. It employs a technique borrowed from the simplest compartment fire models, the "zone models," which assume that the compartment is divided into a hot, soot laden upper layer and a cool relatively clear lower layer [8]. The temperature in each layer is taken to vary slowly in the horizontal directions, but rapidly in the vertical. The layer temperatures and radiative properties are taken from suitably chosen temporal and spatial averages of output generated by FDS (Fig. 1). Note that the floor is about 63 m on a side and 4 m high. The time averages are chosen to be compatible with the time scales associated with thermal diffusion through the smallest structural members of interest. The spatial averages replace

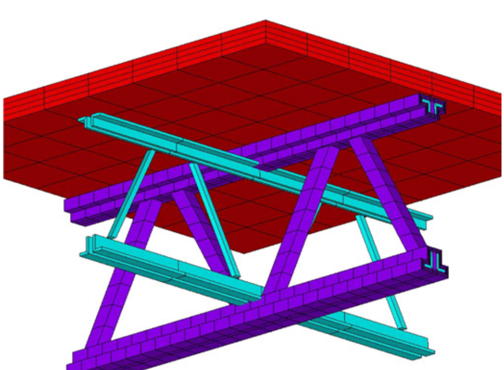

Fig. 4. Finite element model of the main steel truss covered with spray on insulation (violet) and the transverse truss that is assumed to be uninsulated. The steel angle can be seen in the cross-section (cyan color) of the main truss and the transverse truss. Also shown is the concrete deck (red) that is supported by the steel truss. The truss measures 73.7 cm in height and is 203 cm long. This pattern is replicated to cover the entire floor of the WTC Tower.

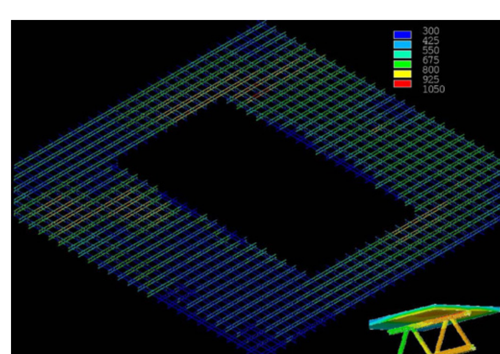

Fig. 5. Computed temperature contours (in degrees Kelvin) on the surface of the steel truss of the World Trade Center Towers. The temperature contours are shown at 1000 s after the impact of the airplane. The floor deck that is supported by the truss grillage is not shown in the main figure but is included in the figure inset.

the detailed vertical temperature and absorption coefficient profiles with an effective local "zone model" profile.

For this simplified geometry, the radiative transport equation can be solved exactly and explicit formulae for the heat flux obtained as functions of the temperatures, hot layer depth, soot concentration, and orientation of the structural element. The basic analysis is quite well known in the heat transfer community [9]. These formulae can be used directly as input into finite element computer codes widely used for time-dependent three-dimensional structural analysis. The output of such codes yields the temperature distribution required for computing the thermal strains/stresses induced in the structural assembly when exposed to a fire. The higher temperature induced in the solid can also degrade the strength of the material (yield strength) and affect the elastic–plastic stress–strain relationship. Thus, an approximate methodology capable of dealing with the heat transfer to realistic models of a building structure can be developed.

The objective of the present paper was to demonstrate how this approach can be applied to study the heating of a complex building structural geometry that is an idealization of an entire floor of one of the World Trade Center towers. The general solutions to the radiative transport equation and explicit results for radiative heat flux to vertical and horizontal planar surfaces are summarized in the next section. A brief discussion of the application of these results to the thermal analysis of structures follows. The method is applied to the analysis of a complex insulated steel truss system in an enclosure with participating concrete floor and ceiling. The role of insulation damage is illustrated for isolated columns. These analyses, when combined, provide a methodology to couple a realistic representation of time evolving fires to a detailed thermal analysis of the WTC structure.

2. Radiative transport modeling

Two major simplifications are introduced so that results that can be applied to the thermal analysis of structures are obtained. First, we employ the concept of a *grey gas*, whose properties are independent of frequency. If the spectral absorption coefficient κ_ν is replaced by some average value κ to be defined later, then the radiative transport equation can be expressed in terms of the integrated intensity $I(\vec{r},\vec{\Omega})$:

$$\vec{\Omega}\cdot\nabla I=\kappa\left(\frac{\sigma T^4}{\pi}-I\right), \quad (1)$$

$$I(\vec{r},\vec{\Omega})=\int_0^\infty I_\nu\,\mathrm{d}\nu. \quad (2)$$

The utility of this approximation depends strongly on the properties of the absorbing medium. For the problems of interest here, soot particulate is the dominant absorber and emitter of thermal radiation. The typical soot size distribution and temperature range are such that the spectral dependence of the soot varies slowly compared with that of the Planck distribution. The result is that the soot absorption coefficient can be approximated as follows:

$$\kappa=(\mathrm{const})f_\mathrm{v}T\ (\mathrm{cm}^{-1}). \quad (3)$$

Here, f_v is the soot volume fraction. Formulae of this type, with some variation in the numerical coefficient, are widely used in the combustion and fire research literature [10]. The quantity $(\kappa)^{-1}$ based on representative values for the enclosure in question is the *optical depth* of the soot laden gas.

The second simplification is that the enclosure geometry induces a vertically stratified distribution of temperature and combustion products. Specifically, it is assumed that the vertical dimensions of each part of the enclosure that can be considered as a separate entity are much smaller than either of the horizontal dimensions. As a fire develops in such an enclosure, the hot layer that forms has spatial variations in the above properties that vary much more rapidly in the vertical than in the horizontal directions (Fig. 2). If d denotes the depth of a hot layer of roughly uniform thermal properties, and L denotes any of the horizontal directions, then the analysis of the radiation field as a vertically stratified layer is internally consistent if $\kappa L \gg 1$. Physically, this means that the thermal radiation from remote points of the hot layer cannot penetrate to affect the local radiation fields. In a typical commercial building environment with ceiling heights of a few meters, we are interested in situations in which $\kappa d \approx 1$. If $\kappa d \gg 1$, then the radiation is in equilibrium with the matter at the local temperature T and the local heat flux is σT^4. If $\kappa d \ll 1$, then the gas is locally transparent to thermal radiation.

The quantity of most interest in the analysis to follow is the heat flux incident on a material surface. Let $\vec{n}$ denote the unit normal pointing outward from an element of surface. Then the radiation heat flux to that surface q_n is determined by the formula:

$$q_n=-\int_{\vec{\Omega}\cdot\vec{n}\leqslant 0} I(\vec{\Omega},\vec{r})\vec{\Omega}\cdot\vec{n}\,\mathrm{d}\vec{\Omega}. \quad (4)$$

Clearly, the orientation of the surface as well as the radiation field in the gas plays a role in the analysis. We will be particularly concerned with both vertically oriented (columns) and horizontally oriented (floors, ceilings, and trusses) surfaces.

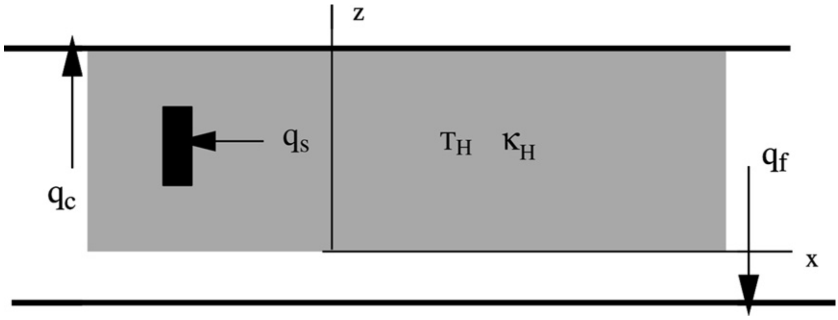

Fig. 2. Schematic of two-layer model of fire environment showing hot layer at temperature T_H and absorption coefficient κ_H. The heat flux to the ceiling is q_c, the flux to the floor is q_f, and the flux to a vertical target surface is q_s.

3. Plane layer analysis

Now consider the analysis of a plane heated layer of depth d. We define a Cartesian coordinate system $\vec{r} = x\vec{i} + y\vec{j} + z\vec{k}$ such that (x, y) are the horizontal coordinates and z is the vertical coordinate with $z = 0$ at the bottom of the hot layer. If the hot layer extends down to the floor, then the origin is at the floor. However, we always have $0 \leqslant z \leqslant d$ no matter how deep the layer is (Fig. 2). The absorption coefficient $\kappa = \kappa(z)$; similarly, the temperature $T = T(z)$. The unit vector $\vec{\Omega}$ can be represented in terms of a spherical polar coordinate system oriented so that the polar angle θ is measured from the positive z axis:

$$\vec{\Omega} = \sin\theta\cos\phi\vec{i} + \sin\theta\sin\phi\vec{j} + \cos\theta\vec{k}. \tag{5}$$

In this system of coordinates, the integrated intensity I depends only on z and $\cos\theta$. The radiative transport equation becomes:

$$\cos\theta\frac{\partial I}{\partial z} = \kappa(z)\left(\frac{\sigma T^4(z)}{\pi} - I\right). \tag{6}$$

Considered as a function of z, Eq. (6) is in fact two equations. For values of $\cos\theta \geqslant 0$ the radiation emerges from the bottom of the hot layer. We denote the intensity of this radiation as I^+. For values of $\cos\theta \leqslant 0$ the radiation emerges from the ceiling. Let this radiant intensity be I^-. Boundary conditions for I^+ and I^- are obtained by assuming that radiation entering the hot layer from below is in equilibrium with a "cool" floor at "ambient" temperature T_a, while radiation emitted by the "hot" ceiling is in equilibrium with the ceiling temperature T_c.

The result of these assumptions is that Eq. (6) must be solved subjectrd to the following boundary conditions:

$$I^+(z = 0) = \frac{\sigma T_a^4}{\pi}, \quad I^-(z = d) = \frac{\sigma T_c^4}{\pi}. \tag{7}$$

The solutions can now be readily obtained in terms of local optical depths $\tau^+(z)$ and $\tau^-(z)$ defined as follows:

$$\tau^+(z) = \int_0^z \kappa(z)\,\mathrm{d}z, \quad \tau^-(z) = \int_z^d \kappa(z)\,\mathrm{d}z. \tag{8}$$

We are now in a position to evaluate the heat flux to a target surface. If the enclosure is completely unobstructed, then only the heat flux to the floor and ceiling need be considered, and no further assumptions are necessary. These results are well known and will emerge as part of the analysis to follow. However, to calculate the heat flux to structural elements it is necessary to assume that each surface is unobstructed by others for the purpose of calculating the incident flux. This is a reasonable assumption if the cross-sectional area of each element is small compared with the unobstructed area in each plane normal to the axis of each of the elements. For example, the projected floor area of a room containing several columns must be much larger than the cross-sectional area of all the columns. Similarly, a vertical plane crossing the enclosure should have an area much larger than that of all the trusses that penetrate the plane.

First consider horizontal surfaces. There are two possibilities: a ceiling-like or downward facing surface corresponding to $\vec{n} = -\vec{k}$, and a floor-like or upward facing surface corresponding to $\vec{n} = \vec{k}$. The lower surface of a truss would be an example of a downward facing surface, while the upper surface would be an upward facing surface. Let $q_c(z)$ be the heat flux to a downward facing surface located at a height z and $q_f(z)$ be the corresponding flux to an upward facing surface. If we further assume that the upper layer temperature T takes on the constant value $T = T_H$ and that the absorption coefficient $\kappa = \kappa_H$ is also constant, the following explicit results are obtained:

$$\tau^+ = \kappa_H z, \quad \tau^- = \kappa_H(d - z), \tag{9}$$

$$q_c(z) = 2\sigma T_a^4 E_3(\tau^+) + \sigma T_H^4(1 - 2E_3(\tau^+)), \tag{10}$$

$$q_f(z) = 2\sigma T_c^4 E_3(\tau^-) + \sigma T_H^4(1 - 2E_3(\tau^-)). \tag{11}$$

Here, $E_n(z)$ is the exponential integral as defined in [11].

The flux to a downward facing surface starts out from very low values because at the bottom of the hot layer the surface only "sees" radiation from the "cold" lower surface. As the downward facing surface is moved upward through the hot layer, the surface sees more and more of the hot layer radiation, and eventually reaches a value corresponding to equilibrium radiation from an infinitely thick layer. The flux to an upward facing surface typically starts from a somewhat higher value near the ceiling, since the ceiling temperature is usually much hotter than the floor temperature. As the upward facing surface moves down through the hot layer, it also sees more and more radiation from the layer, and ultimately the flux again reaches a value corresponding to radiative equilibrium in the layer. In both cases, however, a substantial fraction of the layer is far from radiative equilibrium with much lower fluxes to the surfaces.

The heat flux to a vertical surface is not usually calculated within the context of the plane layer problem. While the analysis is not difficult, it does not seem to be readily available. We consider this case next. Let the direction of the outward pointing normal to the surface be $\vec{n} = -\vec{i}$. Since the radiant intensity is independent of the azimuthal angle ϕ, any horizontal direction could be chosen, and this choice is convenient for the analysis. Under these circumstances, $\vec{\Omega} \cdot \vec{n} = -\sin\theta\cos\phi$. Thus, we need to evaluate Eq. (4) over the domain $0 \leqslant \theta \leqslant \pi$, $-\pi/2 \leqslant \phi \leqslant \pi/2$. Denoting the heat flux to the vertical surface by $q_s(z)$, we have:

$$q_s(z) = 2\left(\int_0^{\pi/2} I^+ \sin^2\theta \, d\theta + \int_{\pi/2}^{\pi} I^- \sin^2\theta \, d\theta\right). \tag{12}$$

Equation (12) shows that the solution is a sum of two terms involving I^+ and I^-, respectively. Denote the respective contributions of these terms as q_s^+ and q_s^-, respectively. Then:

$$q_s(z) = q_s^+(z) + q_s^-(z). \tag{13}$$

Again, letting the upper layer temperature and absorption coefficient be constant, the necessary integrations can be carried out to yield:

$$q_s^+(z) = \frac{2}{\pi}\sigma T_a^4 f(\tau^+) + \frac{2}{\pi}\sigma T_H^4 g(\tau^+), \tag{14}$$

$$q_s^-(z) = \frac{2}{\pi}\sigma T_c^4 f(\tau^-) + \frac{2}{\pi}\sigma T_H^4 g(\tau^-), \tag{15}$$

$$f(z) = Ki_1(z) - Ki_3(z), \tag{16}$$

$$g(z) = \frac{\pi}{4} - Ki_1(z) + Ki_3(z). \tag{17}$$

Here, $Ki_r(z)$ is the rth iterated integral of the modified Bessel function $K_0(z)$ [12].

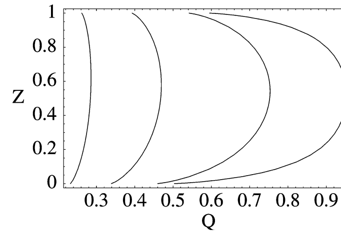

Fig. 3. Dimensionless heat fluxes $Q = q_s(z)/\sigma T_H^4$ showing profiles as functions of dimensionless height $Z = z/d$. The flux profiles correspond to values of dimensionless optical depth $\kappa_H d$ (starting from the left) of 0.1, 0.3, 1.0, and 3.0. The floor and ceiling temperature ratios are $T_a/T_H = 1/3$, $T_c/T_H = 2/3$. Note that in no case is the radiative equilibrium flux achieved.

These results are illustrated in Fig. 3, which shows profiles of radiative flux to a vertical surface as a function of the dimensionless optical depth $\kappa_H d$. The floor and ceiling temperature ratios are, respectively, $T_a/T_H = 1/3$ and $T_c/T_H = 2/3$. The most important observation is the extreme sensitivity of the results to the optical depth of the hot layer. In the present example, the flux corresponding to radiative equilibrium is not reached anywhere for any of the profiles. The maximum value of the flux is reached near the center of the hot layer, since both the upward and downward moving radiation have had some chance to be absorbed and re-emitted at the higher temperatures. However, unless the layer is either much thicker or sootier than is the case for the present example, the equilibrium flux cannot be achieved.

4. Results and discussion

The critical structural elements in the floors of the World Trade Center Towers consisted of 10.16 cm of light weight concrete on a 3.81 cm thick non-composite steel deck. The floor deck was supported by a series of composite floor trusses that spanned between the central core and exterior wall [13]. A small section of the floor truss is shown in Fig. 4. The top chord and the bottom chord of the truss consist of L-shaped steel angles (cyan color) with a flange width of 5.1 cm. The top and bottom truss chords are held together by steel rods (2.54 cm diameter)-which form an M-shaped pattern. The main truss is covered with a fibrous insulating material (violet color), while the transverse truss is assumed to be uninsulated (Fig. 4). At typical floors, a total of 59 perimeter columns were present along each of the flat faces of the building. These columns are built up by welding four plates together to form an approximately 35 cm square section, spaced at 1 m intervals [13]. The FDS simulations used to generate Fig. 1 were performed on a 50 cm × 50 cm × 40 cm grid. It should be noted that neither the truss nor the perimeter columns are resolved in the FDS simulations.

To analyze the effect of the fires on the structural elements and to subsequently predict failure, the steel/concrete has to be loaded with temperature data obtained from the thermal analysis. Spatial and temporal variation in temperature will result in thermally induced stresses/strains and reduced load bearing capacity that could lead to failure of the structure. A finite element model was constructed to compute the temperature distribution and to understand the thermal response of floor decks supported by steel trusses. A flexible method for creating truss sections with varying levels of insulation thickness and material properties was developed using the ANSYS version 7.1 parametric design language. Use of the finite element code for thermal analysis ensures that the resulting temperature distributions are in a format compatible with any subsequent stress analysis. To easily mesh the rod geometry and to avoid modeling the weld contact between the rod and the chords, the cross-section of the rod is modified to a square cross-section instead of the round cross-section, without changing the cross-sectional area. The high thermal conductivity of steel allows this simplification to be made with negligible loss in accuracy. The insulation thickness is assumed to be 1.9 cm and is uniform over the entire truss. The truss section shown in Fig. 4 was replicated to cover the entire floor area as shown in Fig. 5. The floor deck that is supported by the truss grillage is not shown in Fig. 5, but is included in the figure inset, for clarity. A total of approximately 467,000 nodes and 657,000 elements were used to mesh the complete truss section shown in Fig. 5. Calculations have also been performed by doubling the number of elements in the insulation to check for accuracy and consistency. In addition, the analysis as described above was used to accurately predict the temperature distribution in a full scale truss column assembly heated by a heptane pool fire. These results [14] provide a validation for the entire coupled FDS, interface, and ANSYS analysis.

The plane layer analysis described earlier is used to compute the radiative fluxes incident on the exposed surfaces. Spatially and temporally varying profiles for upper layer temperature, absorption coefficient, hot layer depth, and the ambient temperature are obtained from a fire dynamics simulation. The exponential integrals and the rth iterated integral of the modified Bessel function $K_0(z)$ are computed from SLATEC numerical analysis libraries and are read in by ANSYS in tabular format. The use of macros

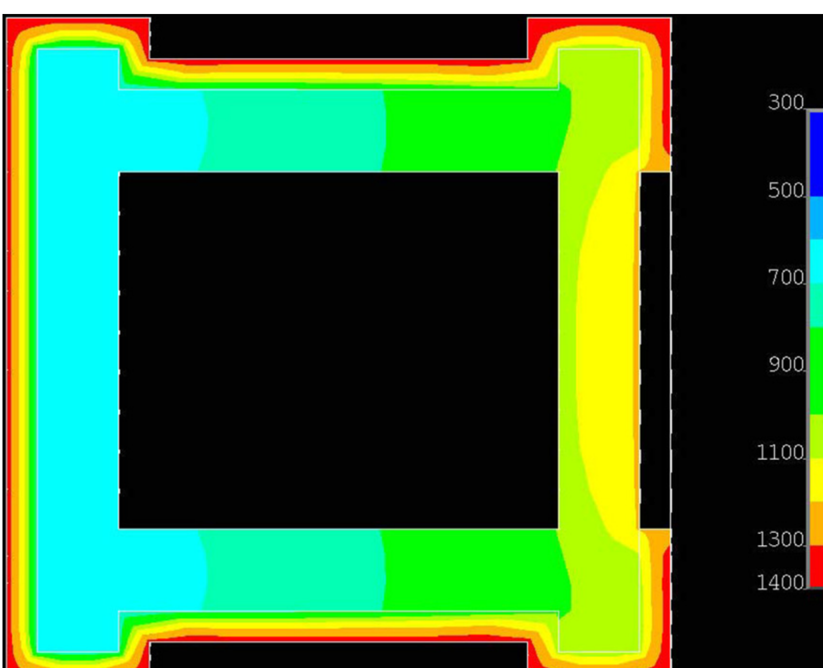

Fig. 6. Computed temperature contours (in degrees Kelvin) through the cross-section of a typical core column in the World Trade Center Towers. White lines show the boundary of the box column and the insulation wrapped around the column. The fibrous insulating material is assumed to be damaged on right face of the column and is intact on the remaining faces. The gas temperature is assumed to be 1400 K in this simulation.

allow us to efficiently pick a set of external faces (for example, all the downward facing surfaces) and apply the computed radiative flux ($q_c(z)$). The computed flux is a function of the location and orientation of the external face, and utilizes the temperature and absorption coefficient information computed from a fire dynamics simulation. The initial temperature of the entire truss assembly is set to 27 °C. Re-radiation and convective heat transfer are modeled through the use of surface effect elements. A surface emissivity value $\epsilon = 0.9$ is assumed. Most of the re-radiation comes from the concrete floor slabs that are also accounted for in the calculation. Temperature dependent material properties for thermal conductivity, heat capacity, and density were included in the finite element analysis. The initial time step is chosen to be 1 s. However, the finite element method can adapt the time step to maintain a desired level of accuracy and an optimal level of convergence. Simulations have been performed to predict the thermal response of a single floor of the World Trade Center for a 1 h period. The total CPU cost for the entire simulation using a 3.0 GHz Intel Pentium single processor machine is approximately 6 h, which is fast enough to allow for a variety of possible fire scenarios to be investigated.

As the truss assembly is subjected to radiative fluxes, its temperature starts to increase very rapidly. The incident radiative flux to a surface varies from zero to a high value of approximately 50 kW/m^2 setting up complex temperature gradients in three dimensions. Moreover, these spatial distributions change with time as the fire moves about the enclosure (Fig. 1). Figure 5 shows the steel temperature contours superimposed on the truss at 1000 s after the imposition of external radiation. The maximum temperature is on the surface of the insulation that is exposed to the radiation, while the steel truss stays at a lower temperature. The resulting time temperature curve at any location on the steel truss is highly variable and bears no relation to the ASTM E 119 curve. This methodology has been used to assess the effects of uneven applications and either missing or damaged spray on fire-proofing. The concrete slab acts as a large heat sink. The temperature profile through the floor slab exhibits an advancing thermal wave moving from the heated side. This front persists for the duration of the simulation.

The columns on a typical floor (affected by fires) of the World Trade Center Towers can be divided into core columns and perimeter columns. Numerical simulations were performed to understand the thermal response of these columns with varying levels of insulation thickness. Random number generators are used to simulate the variability in the thickness of the insulation. Figure 6 shows temperature contours through the cross-section of a typical core column. White lines mark the boundary of the box steel column and the insulation that is wrapped around the column. It was assumed that insulation on the right face of the column was damaged, but the insulation was intact on the remaining faces. This results in very high temperatures in the steel on the right side and low temperatures on the left side resulting in very steep temperature gradients through the cross-section. Such temperature gradients can induce large stresses and horizontal deflections of the columns.

5. Conclusions

The coupling between fire dynamics and structural analysis due to radiative heat transfer from the hot combustion products to the structural elements is studied. A simple radiative transport model is developed that permits the prediction of radiative flux incident on the surface as a function of the orientation of the structural element, temperature, hot layer depth, and soot concentration. The model is used to study radiative heat transfer to a realistic model of a typical WTC floor truss system and column. Finite element techniques are then used to solve for the three dimensional, time-dependent temperature field in the floor system and core column. This approximate method is thus a simple and powerful approach for studying the thermal/structural response of realistic building geometries to fire loads calculated using CFD based fire modeling techniques.

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Comment

James G. Quintiere, University of Maryland, USA. Your last figure showed the load carrying capacity of the core columns in the North Tower under three heating-damage scenarios, and the most severe one indicates an approach to failure at near the actual collapse time of 102 min. Since you did not consider the truss under three equal scenarios it is incumbent on you to do so, and plot these on the same graph. If you do, it will show that the most severe damage scenario is inconsistent, and it will indicate failure occurs due to the truss—with minimal damage.

Your computational analysis is very elegant, but I wonder, have you computed the thermal resistances of the convection-radiative gas phase with the resistance of conduction for the steel insulation? This might reveal some further possible simplifications in your computational interface.

Do you iterate your structural heat loss back into the CFD fire computation? If not, why?

Reply. The figure in question illustrated an application of this methodology by calculating an upper bound to the load carrying capacity of the structure at the 96th floor level in response to a hypothetical one-floor fire. The results illustrate the sensitivity of this capacity to initial aircraft impact damage and fireproofing damage under fire and gravity loading. The analysis is based on a global static force balance between the weight of the building above the 96th floor and the maximum carrying capacity of all the columns. The columns alone bear the vertical force generated by the weight of the building. The product of the temperature dependent yield strength and cross-sectional area of all of the columns for an elastic-plastic stress strain curve determine the maximum carrying capacity. Since this represents an upper bound there is no way to determine the actual loads on any of the structural elements (including trusses) without performing a detailed stress analysis.

Yes, the principle heat feed back to the gas phase is from the concrete and this effect is accounted for within FDS. The fact that the steel columns and trusses are too small to be resolved in the FDS simulation means that there feedback to the gas phase is correspondingly small. The principle non-structural feedback is the fire-induced window breaking. This is too difficult to calculate directly. Instead, the visual observations taken from videotapes of the burning towers are used to ensure the accuracy of the simulations.