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Recent progress in fire-structure analysis

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ABSTRACT: One recommendation of the National Construction Safety Team for the Federal Building and Fire Safety Investigation of the World Trade Center Disaster [1] is to enhance the capability of available computational software to predict the effects of fires in buildings, for use in the design of fire protection systems and the analysis of building response to fires. This paper presents two new interfaces in fire-thermal-structural analysis. The first interface uses adiabatic surface temperatures to provide an efficient way of transferring thermal results from a fire simulation to a thermal analysis. It assigns these temperatures to surface elements of structural members based on proximity and directionality. The second interface allows the transfer of temperature results from a thermal analysis modeled with solid elements to a structural analysis modeled with beams and shells. The interface also allows the reverse, namely the geometric updating of the thermal model with deflections and strains obtained from the structural analysis. This last step is particularly useful in intense fires of long duration, where significant deflections and strains could cause damage to insulation and displace the structure to a different thermal regime. The procedures can be used for a variety of fire simulation, thermal and structural analysis software.

Keywords: Adiabatic surface temperature; fire; insulation; plate thermometer; structural analysis; thermal analysis.

1 INTRODUCTION

Following the investigation of the collapse of the World Trade Center (WTC), the National Construction Safety Team (NCST) recommended, among other things, that efforts be made to enhance the capabilities of computational methods to study the effect of realistic fires on buildings, from ignition to the burn-out and cooling phases, or to collapse [1]. The recommendation was partially attributable to the difficulties experienced by the investigators in interfacing the fire, thermal, and structural models that were used to study various collapse hypotheses. This paper describes two recent advances in interface development; the first facilitates the exchange of information between a computational fluid dynamics fire model and a finite-element thermal model; the second transfers information both ways between the thermal model and a structural model. The goal of developing these tools, verified by experiments, is to assist the engineering community and the standards organizations in taking fire into account as a potential structural load.

2 ASTM E 119 STANDARD FIRE TEST

In the United States, the design of fire resistance in buildings has been traditionally achieved by prescriptive means. For this purpose individual structural members are subjected to standard time-temperature curves, e.g., ASTM E 119 [2], and coated with sufficient insulation as the case may be, to prevent them from reaching a certain temperature deemed detrimental to their performance. While this approach is simple and has worked well, as shown by the rarity of structural collapse due to fire of engineered structures designed according to current building and fire codes, it offers no guidance on the actual behavior and the margin of safety of a structure in fire. The main problem, of course, is that a prescriptive time-temperature curve does not reflect the actual temperature of various structural members exposed to a realistic fire that varies in time and space. To compound the difficulty, actual structures have many redundancies, and the increase in structural demand due to thermal expansion coupled with material softening due to heating may not necessarily lead to imminent collapse if alternate load paths still exist. These problems point to the need to treat fire as a realistic structural load.

3 FIRE-THERMAL INTERFACE

In a sense, the time-temperature curve such as ASTM E 119 is the fire model. The fire-structural interface is thus nothing more than the specification of the bounding gas temperature at all solid surfaces. However, in a performance-based design environment, it should be possible to model potential fire scenarios and pass spatially and temporally resolved temperatures to the structural model. This will involve much more information than just a single time-temperature curve, requiring some form of interface for data transfer. A proposed interface makes use of the adiabatic surface temperature (AST), an output of the fire model, to serve as the boundary condition for the thermal model. Adiabatic surface temperatures are the virtual equivalent of temperatures measured by plate thermometers placed in the vicinity of the surfaces of interest. This concept was first proposed by Wickstrom [3] as a means of better controlling the temperature of furnaces in fire tests. The plate thermometer is a thin metallic plate with insulated backing on the face opposite the surface of interest. It responds with negligible time lag to radiative and convective heat fluxes from the furnace, and thanks to its geometry, in the same proportion as what the surface of interest sees. Heat transfer to the plate thermometer is described by [4]:

$$\varepsilon_{pt}(\boldsymbol{q}_{inc} - \sigma \boldsymbol{T}_{pt}^4) + \boldsymbol{h}_{pt}(\boldsymbol{T}_g - \boldsymbol{T}_{pt}) = 0 \tag{1}$$

where q_{inc} = incident radiative heat flux, h = convective heat transfer coefficient, T = temperature, ε = emissivity (assumed equal to absorptivity), σ = Stefan-Boltzman constant, subscript g refers to gas and subscript pt refers to plate thermometer. The net heat transfer to a surface can be approximated as:

$$\boldsymbol{q} \approx \varepsilon_s \sigma (\boldsymbol{T}_{pt}^4 - \boldsymbol{T}_s^4) + \boldsymbol{h}_s(\boldsymbol{T}_{pt} - \boldsymbol{T}_s) \tag{2}$$

where subscript s refers to the surface. This is approximately equal to the more exact equation for heat transferred from a fire to the surface:

$$\boldsymbol{q} = \varepsilon_s \sigma (\boldsymbol{T}_f^4 - \boldsymbol{T}_s^4) + \boldsymbol{h}_s(\boldsymbol{T}_f - \boldsymbol{T}_s) \tag{3}$$

where subscript f refers to the fire. For this interface, the fire analyst calculates the time history of the AST, or what a perfect plate thermometer in the vicinity of the structural member would measure, at nodes defined by spatial coordinates and orientation. In doing so, he provides the thermal analyst the required input for heat transfer analysis in a convenient form [5], thus eliminating the need for a radiation analysis that accounts for the presence of all radiating structural members and fire at various locations in the compartment. With this interface, one needs to transfer only one quantity, the adiabatic surface temperature, from the fire model to the thermal model, rather than heat flux, surface temperature, and convective heat transfer coefficient. This is of great benefit in large scale fire-thermal-structural analyses, such as the WTC investigation, which involve huge datasets, in not only improving efficiency but also in reducing the risk of error.

The interface allows for two independent fire and thermal models, whose geometries may not coincide perfectly. This is a useful feature since the spatial resolution of fire models is typically less precise than that of thermal models. The only condition is that the AST nodes must not be contained within a solid material. For example, for a hollow tube, AST nodes that radiate to the outside surface of the tube must be outside, and AST nodes that radiate to the inside of the tube must be inside. Any AST nodes contained within the thickness of the tube walls are deemed to be erroneous and are not read. Since the idea is to simulate plate thermometers near the surface, the interface searches for the closest AST node in the half-space facing the surface element. When it finds one, it checks for orientation by ensuring that the dot product of the orientation vector associated with the AST node and the vector normal to the surface element is positive. If that is not the case, the interface expands its search to the next closest AST node. This directional check only becomes relevant when the discrepancy in geometry between the fire and the thermal models is rather large, e.g., when web members of a truss are modeled as vertical planes in the fire model, whereas they are faithfully modeled as inclined round bars in the thermal model. To resolve other possible ambiguities in assigning the correct AST nodes, e.g., in the case of two parallel adjacent trusses placed closely next to each other, the interface also allows the user to intervene and manually select a set of relevant AST nodes and/or shift the entire thermal model to better center it with the AST nodes.

4 COMPARISON WITH EXPERIMENTAL MEASUREMENTS

For verification, we used an experimental compartment fire performed at NIST [1]. Figs. 1 and 2 show the actual fire and the simulation model. Figs. 3 and 4 show the AST nodes used in the thermal analysis of the column and one of the trusses (A), and Figs. 5 and 6 compare measured temperatures versus those calculated with two different software codes. The calculations use the same insulation thickness and properties as in the experiments. Satisfactory agreement is achieved for the column, whose simple geometry allows close matching of AST nodes with their corresponding surfaces. As expected, for the web members of the truss, agreement between measurements and calculations is less close due to differences in model geometries mentioned previously.

Fig. 1 Fire experiment

5 THERMAL-STRUCTURAL INTERFACE

The second interface discussed in this paper is that between the thermal and the structural models. In the case of one of the software codes used in the WTC investigation, for example, the transfer of temperature results from a thermal model to a structural model, or the transfer of deflections and strains from a structural model to a thermal model (this latter step was not done in the investigation) can only be performed with compatible elements, e.g., solid to solid or shell to shell. These types of elements are prevalent in thermal analyses, and are often used in structural analysis as well, especially in smaller structures where a manageable number of solid or shell elements may suffice. For larger, more complex structures, such as the WTC towers, the use of beam elements to model the columns, floor and hat trusses is desirable to keep the structural model to a reasonable size. A procedure for efficient, general and automatic transfer of results between thermal and structural analyses is therefore needed. Temperature results would be transferred from the thermal to the structural analysis, so the effects of thermal expansion and evolution

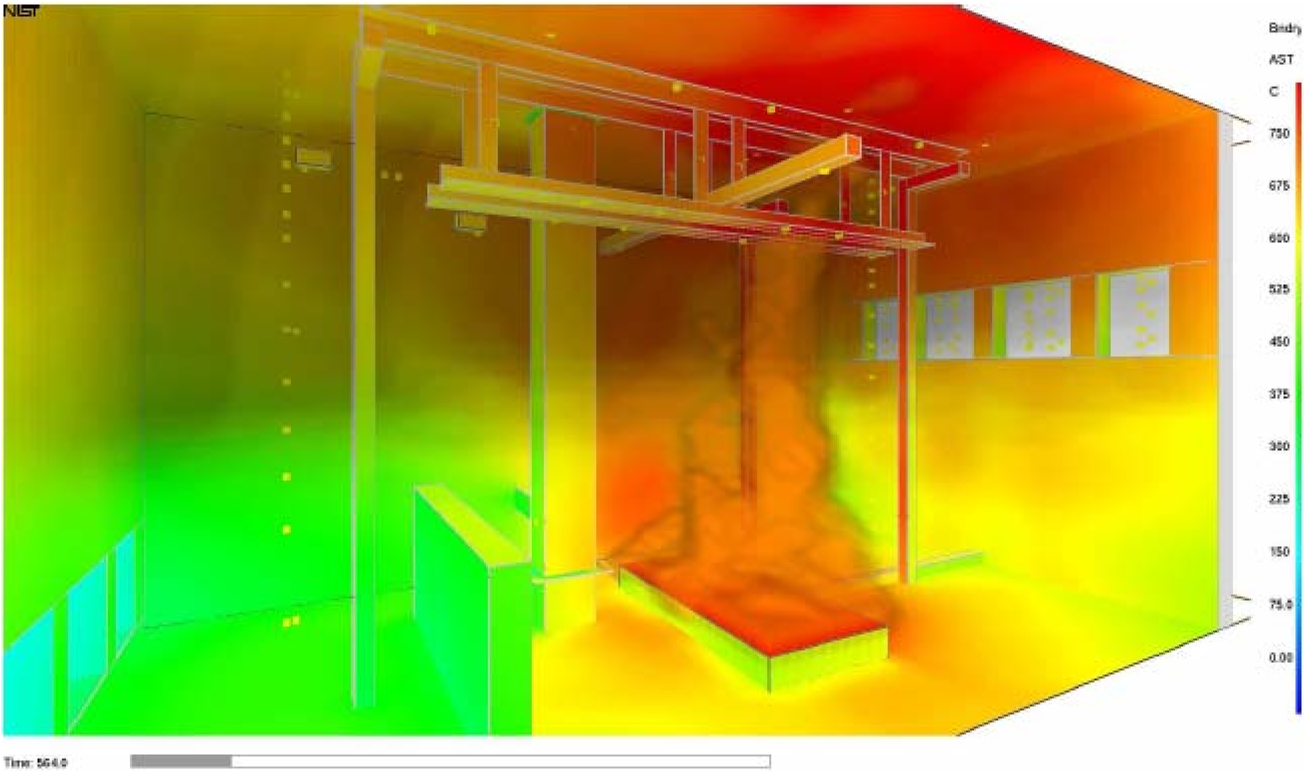

Fig. 2 Fire simulation straight

of material properties with temperature can be determined over time; conversely, structural deflections and strains would be transferred back to the thermal model. This last step is especially important in the case of intense fires of long duration, where significant structural deflections and strains may cause local damage to the insulation and move the structure to a different thermal regime. Furthermore, structural deflections may lead to changes in boundary conditions, such as new openings, that may affect the fire. This feedback would affect not just the thermal analysis, but the fire analysis as well. This last aspect is, however, beyond the scope of this paper. The interface requires that the thermal and structural models be geometrically compatible, within the tolerances specified by the finite-element program (default) or the user, and use compatible coordinate systems.

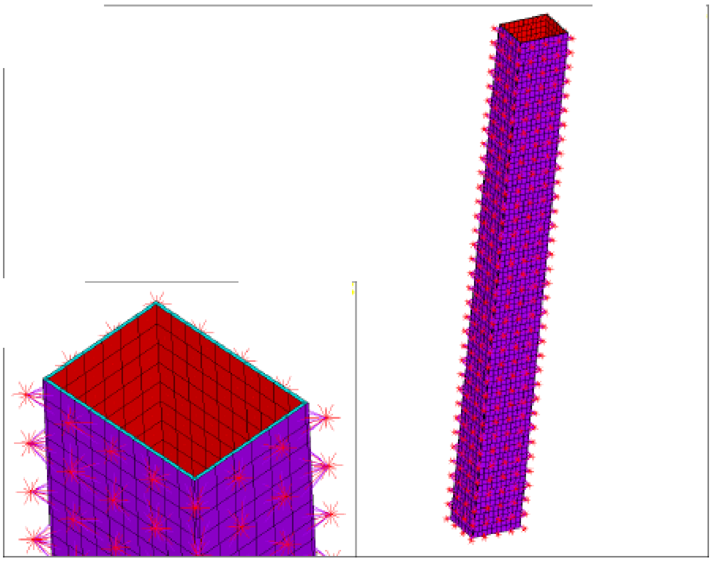

Fig. 3 AST nodes for inside and outside faces of column.

5.1 *Temperature data transfer*

In the thermal model, the temperature field is interpolated between corner nodes, linearly or quadratically depending on the finite elements. For shell elements in the structural model, temperature data are input in the same format as element body loads at the corners of the outside faces of the element and at the corners of the interfaces between layers, where, for the purpose of temperature data transfer, additional transfer nodes are created. The structural model nodes at the outside faces and the transfer nodes between layers are then mapped onto the thermal model, and temperatures at these locations interpolated from the temperatures at the nodes of the thermal model.

For beam elements in the structural model, at each end node of the beam, temperatures are also input in the same format as element body loads, in the form of a mean temperature and two temperature gradients in the element Y and Z directions (X is the longitudinal beam direction). The actual input at each beam end takes the form of three temperatures at $(x, 0, 0)$, $(x, 1, 0)$ and $(x, 0, 1)$, where x is either 0 or L (length of beam element). The location of the temperature data transfer nodes depends

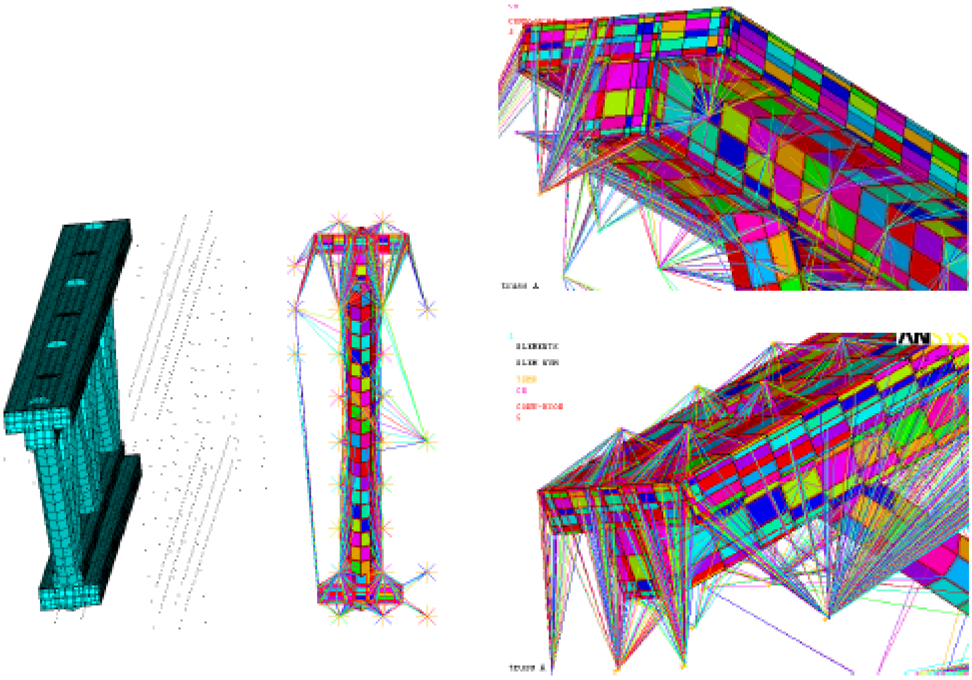

Fig. 4 AST nodes for truss

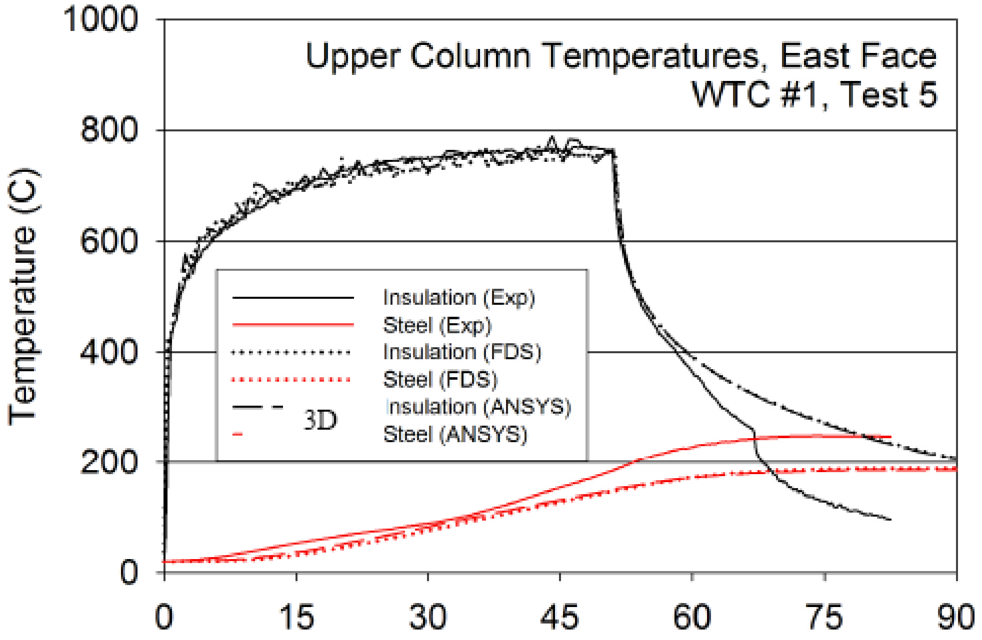

Fig. 5 Comparison of measured and calculated temperatures for column, upper location.

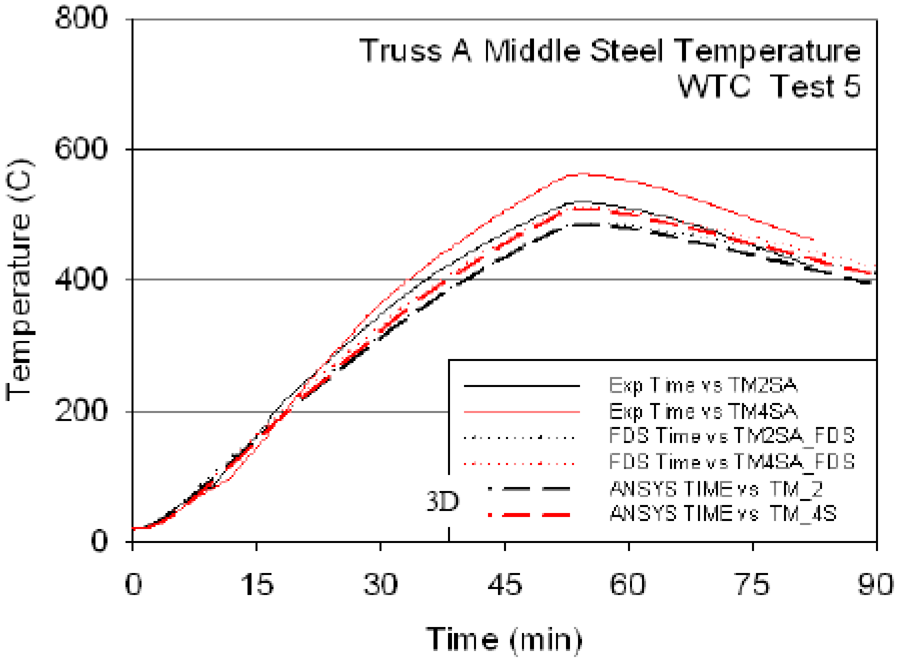

Fig. 6 Comparison of measured and calculated temperatures for truss A, middle steel

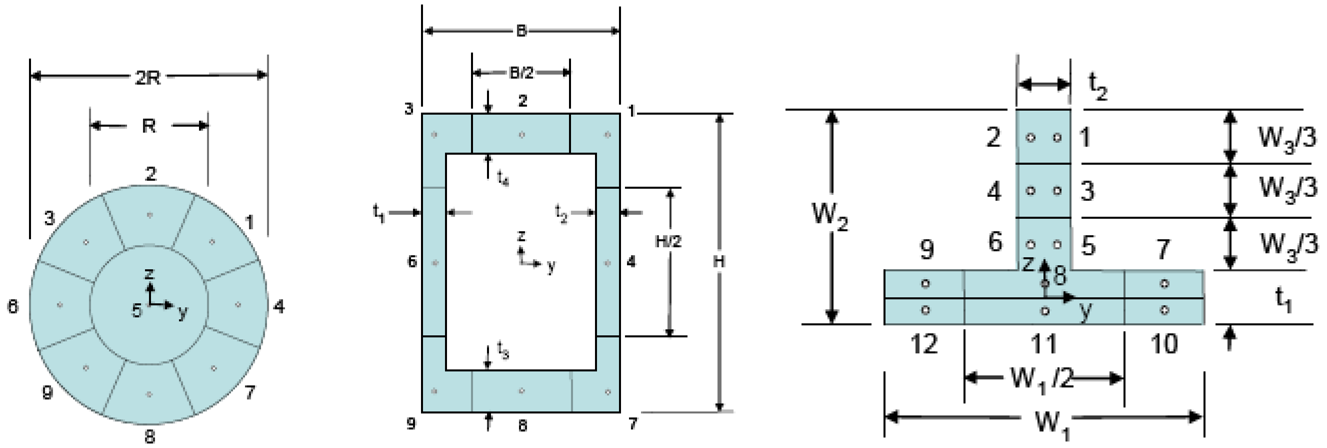

Fig. 7 Some common beam cross sections and their transfer points

on the cross section. A number of commonly used cross sections, either singly or doubly symmetric, are supported by the newly developed interface macros (Fig. 7). If later or different versions of the software transfer temperature results directly to beams at specific points, rather than through a mean and two gradients, the present interface would still work with minor adaptation.

5.2 *Deflection transfer*

Solid element nodes from the thermal model are first mapped onto the undeformed structural model. Displacements $\boldsymbol{u'}$ at the mapped nodes are calculated from structural displacements $\boldsymbol{u}$ and rotations $\boldsymbol{r}$ from the nearest beam or shell nodes by the kinematic vector equation (in bold), where $\boldsymbol{d}$ is the distance between the mapped node and the undeformed nearest structural node: $\boldsymbol{u'} = \boldsymbol{u} + \boldsymbol{r} \times \boldsymbol{d}$, where $\times$ denotes the vector cross-product.

5.3 *Strain transfer*

Since strain transfer is done solely for the purpose of determining insulation damage, it is not available at this stage for shells, which are typically used to model uninsulated slabs. For structural beams, strain results are available at both beam ends at the corner nodes of cross sectional cells created automatically by the structural software for various common sections. The strain ε_{xx} (x is the beam longitudinal axis) at various nodes on these section perimeters is mapped onto the thermal model and used to calculate by interpolation the strains at any nodes of the interface between steel and insulation. The interpolation is linear over three dimensions, and uses the thermal solid element shape functions. Currently, the user can input a failure criterion, such as the tensile strain at the interface between steel and insulation exceeding 5%. When the criterion is reached for a given finite element, the insulation is assumed to fail and its thermal properties degraded over its entire thickness. This criterion may be refined as experimental data become available.

5.4 *User-defined, multi-material beam cross section*

For the cases where the mechanical properties of the insulation are known to the level that they can be incorporated into the structural analysis, the thermal-structural interface makes available a cross section whose geometry and mesh can be defined by the user, who may assign different materials (e.g., steel or insulation) to various cells. Cross-section cells are used for thermal body load calculations by area averaging, and the user controls the accuracy by defining the number and distribution of cells. The user also defines the insulation fail-

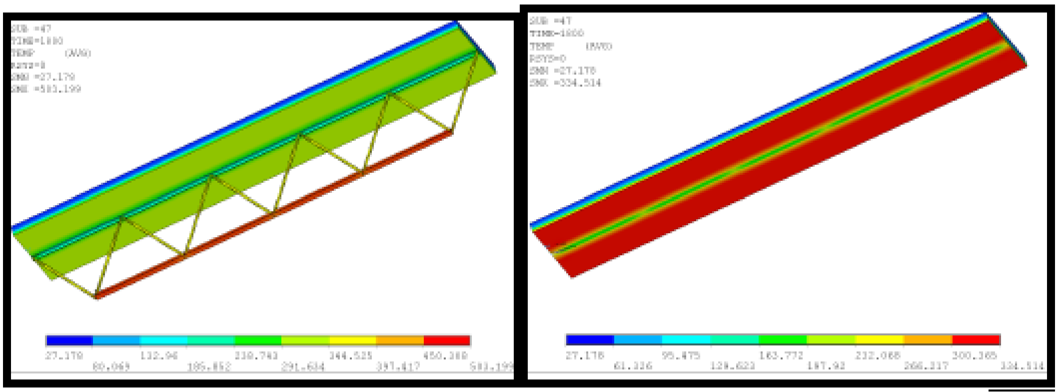

Fig. 8 Temperature results (°C) from thermal model, shown without insulation.

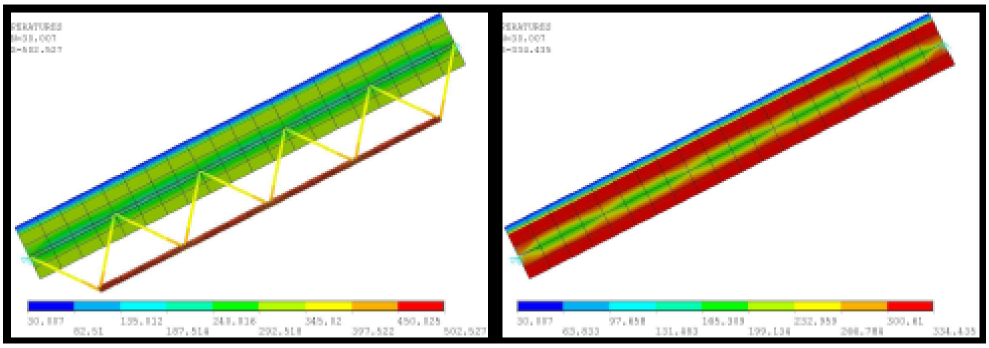

Fig. 9 Structural model – temperatures (°C) input as body loads.

ure criteria and intervenes to degrade the insulation elements that have failed. The geometry of the user-defined section is limited to a quadrilateral in the current version.

6 TEST CASE

As an example, a floor slab supported by an open web truss was tested. The truss is made of three different sections modeled with beam elements, and the floor slab is modeled with three-layered shell elements. The thermal model uses solid elements and, in addition, link elements to tie together the various members at the corners for thermal conduction. Insulation is present in the thermal model, but not in the structural model. A thermal flux of 10 kW/m2 was applied to the bottom surface of the insulated lower chord and concrete slab, except where it is in contact with the top chord, while a lower flux of 5 kW/m2 was applied to the other surfaces, except the top of the slab, where a convection boundary with a film coefficient of 25 W/(m2.°C) applied. The interface also allows other types of thermal input normally used in finite-element analysis.

Fig. 8 shows the temperature contours for steel and concrete at 1800 s from the thermal model. The temperature transfer macro was invoked after the thermal analysis was completed. Fig. 9 shows the temperature body loads as transferred by the macro for the full model and the slab. Differences in the temperature contours between the thermal and the structural models are due to the different mesh densities. In addition to the thermal body loads, the truss dead weight was activated together with symmetrical boundary condition along the long edges of the concrete slab and simple supports where the truss met the slab ends. Large deflection solution of the model resulted in deflections shown in Fig. 10. The deflection transfer macro was invoked, resulting in an updated thermal model. Fig. 11 shows the deflected thermal model, detection and removal of failed insulation based on strains εxx at 1800 s and insulation failure criterion εxx > 5 % at the interface with steel. The continuity of temperatures, deflections and strains appears satisfactory. Further verification of the software code against theoretical and experimental results is in progress and will be reported in a forthcoming publication.

7 CONCLUSION

This paper presents two user-friendly interfaces that complement existing fire-thermal-structural analysis software. The first interface uses adiabatic surface temperatures to provide an efficient way of transferring thermal results from a fire simulation to a thermal analysis. It assigns these temperatures to surface elements of structural members based on proximity and directionality. The second interface allows the transfer of temperature results from a thermal analysis modeled with solid elements to a structural analysis modeled with beams and shells. The interface also allows the reverse, namely the geometric updating of the thermal model with deflections and strains obtained from the structural analysis. This last step is particularly useful in intense fires of long duration, where significant deflections and strains could cause damage to insulation and displace the structure to a different thermal regime. The procedures can be used in a variety of fire simulation, thermal and structural analysis software.

8 REFERENCES

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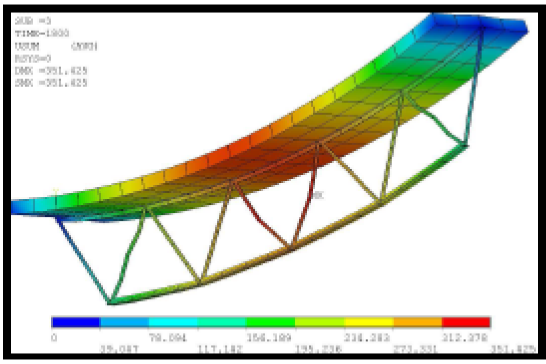

Fig. 10 Structural model – deflections (mm) under thermal loads and dead weight.

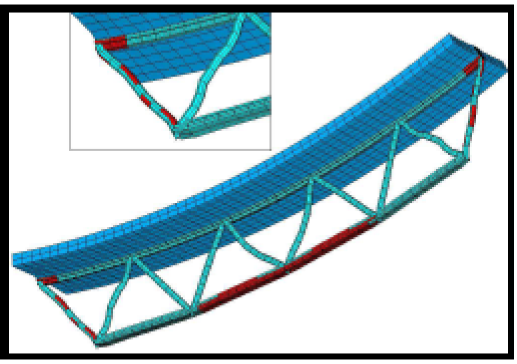

Fig. 11 Thermal model – updated geometry based on structural deflections and failed insulation (red).

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