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A simple method for combining fire and structural models and its application to fire safety evaluation

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ABSTRACT

To consider the actual fire characteristics in the fire response analysis of building structures and to simplify the complex relationship between the fire analysis model and the structural finite element analysis model, a spatio-temporal model of the fire temperature and heat flux boundary for heat conduction analysis is developed. The proposed model adopts a two-way orthogonal polynomial approach for fitting the discrete data from the fire simulation and obtains continuous spatial polynomial equations. It is shown to be accurate for capturing the distributions of temperature and heat flux that are required for a heat conduction analysis and a thermal mechanical coupling analysis. Finally, the model is implemented through user-subroutines UTEMP and DFLUX in ABAQUS, and it is applied to a new archive in Beijing. The results show that this method may be used to combine fire simulation and structural analysis for the safety evaluation of structures under fire.

1. Introduction

To ensure the fire safety of buildings is an important aspect of building design. With performance-based design methods applied in most fire protection policies, understanding the actual fire characteristics is required for the overall performance analysis of a building structure [1]. A full-scale fire experiment method in the lab can be used to consider the characteristics of a real fire [2,3,4]. However, this kind of test is difficult and expensive, because it is time-consuming and difficult; therefore, the numerical simulation method is often adopted in fire research [5,6,7].

The numerical simulation analysis of buildings on fire generally consists of three parts: fire simulation, heat transfer analysis and thermo-mechanical structure analysis. Some advanced simulation software may be applied to each part respectively, such as FDS (Fire Dynamics Simulator), CFAST, and FLUENT for the fire simulation; and ABAQUS, MARC, and ANSYS for the thermo-mechanical analysis. Much research has been done in terms of the fire dynamics analysis and fire resistant analysis of structures under fire using various kinds of software. However, no software can cover all three of the factors noted above. For example, the NIST investigation (2005) [8] of the collapse of the world trade center towers in the US had to cobble together separate software packages (FDS and ANSYS), and a unique fire structure interface was developed for that investigation.

During integrated numerical simulation analysis, fire simulation is performed on the fire model to calculate the temperature and heat flux of the structure surfaces at each discrete time step, and then a heat transfer analysis may be conducted on the finite element model. However, there is no simple one-to-one correspondence between the fire model meshes and the finite element model meshes, and therefore fire simulation results cannot be used directly as the boundary conditions for thermal transfer analysis. Because of the lack of integrating systems that combine algorithms and data to cause individual characteristics, it is difficult to effectively use a set of disparate tools in a comprehensive fire response analysis. Gao (2006) [9] developed a physics mediation model to implement the connection between the fire simulation software FDS and the structure analysis software ANSYS, and Ren (2007) [10] applied this mediation model of a fire model and a finite element model to the fire response analysis of an Olympic stadium structure. This mediation model method can implement the connection between two different models, but this integration requires complex software development and modeling technology.

Because the fire simulation results consist of a significant amount of discrete data related to space and time, it is difficult to use them directly in the subsequent heat transfer analysis. Methods for simplified fire-simulation results and data reduction must be used to effectively simulate the refined boundary, and at the same time retain the efficiency of applying the boundary. However, a spatio-temporal analysis is an effective method of processing this type of data [11,12]. Nipesh [13] performed automatic spatio-temporal analysis of construction site

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equipment operations using GPS data, and various data analysis methods and rules for monitoring construction site equipment operations and activity were defined. Mu (2014) [14] developed a Spatial–Temporal Model to evaluate the impact of the large-scale deployment of plug-in electric vehicles (EVs) on urban distribution networks.

In order to simplify the relationship between a fire analysis model and a structural finite element analysis model, a spatio-temporal model of the fire temperature and heat flux boundary for heat conduction analysis is developed, and a simple method for combining fire and structural models is proposed in this paper. The spatio-temporal model maps the fire-generated temperature and thermal radiation fields onto the structural elements through continuous spatial polynomial equations, and it is implemented through user-sub-routines UTEMP and DFLUX in ABAQUS. In the following sections, the method and a case study are described and discussed in detail.

2. Spatio-temporal mode l of the fire temperature and heat flux boundary

2.1. Two dimensional components

A spatio-temporal model of the fire temperature and heat flux boundary can be regarded as a variable curved surface, and it can be described by continuous function equations. For two-dimensional components (shear wall and slab), the temperature distribution (or convective radiation) on the surface may be represented as a three-dimensional surface. Orthogonal polynomial regression equations are used to present the surface. The multi point-fitting criterion models are built with n-time polynomials and least square fitting criteria based on orthogonal functions. The specific process is as follows:

(1) Set the function value of n × m net points$(x_i,y_j)(i = 1,2,\cdots, n; j = 1,2, \cdots, m)$ in the rectangular area as Z_{ij}

(2) If y is fixed, the least square fitting polynomials of x are established:

$$G_j(x) = \sum_{k=1}^{p} \lambda_{kj}\Phi_k(x),\ j = 1,\ 2,\ \ldots, m \tag{1}$$

where $\Phi_k(x)(k = 1,2,\cdots,p)$ represents the polynomials orthogonal to each other and may be constructed by the Gram-Schmidt method:

$$\Phi_1(x) = 1,\ \begin{aligned} Q_{\max} &= 0.10\cdot m\cdot H_v\cdot A_V\cdot\sqrt{h_v} \\ &= 0.1\times 0.8\times 17.5\times 36.8\times\sqrt{1.2} \\ &= 56MW \end{aligned},\ Q = 10^6\times\left(\frac{t}{t_\alpha}\right)^2$$

Suppose $d_k = \sum_{i=1}^{n} \Phi_k{}^2(x_i),\ k = 1,\ 2,\ \ldots, p$ then:

$$\alpha_k = \sum_{i=1}^{n} x_i\Phi_k{}^2(x_i)/d_k,\ k = 1,\ 2,\ldots, p-1$$
$$\beta_k = d_k/d_{k-1},\ k = 1,\ 2,\ldots, p-1 \tag{2}$$

According to the principle of least squares, λ_{kj} becomes:

$$\frac{F_i}{V} = \frac{2\times 0.8 + 3\times 0.3 - 2\times 0.012}{2\times 0.3\times 0.014 + 0.012\times 0.772} = 140.2m^{-1} \tag{3}$$

(3) In the same way, the least squares fitting polynomial of y can be written as:

$$H_k(y) = \sum_{l=1}^{q} \mu_{kl}\Phi_l(y),\ k = 1,\ 2,\ \ldots, m \tag{4}$$

(4) The final fitting polynomial of the binary function becomes:

$$f(x,y) = \sum_{k=1}^{p}\sum_{l=1}^{q} \mu_{kl}\Phi_k(x)\Psi_l(y) \tag{5}$$

We may then convert it to the standard polynomial form, which can be written as:

$$f(x,y) = \sum_{i=1}^{p}\sum_{j=1}^{q} a_{ij}x_{i-1}y^{j-1} \tag{6}$$

In order to prevent computing an overflow in the actual calculation process, x_i and y_j may be superseded by: $x_i' = x_i - \bar{x}$, $i = 1,\ 2,\ \ldots, n$ and $y_j' = y_j - \bar{y}$, $j = 1,\ 2,\ \ldots, m$ respectively.

Where, $\bar{x} = \sum_{i=1}^{n} x_i/n$, $\bar{y} = \sum_{j=1}^{m} y_j/m$. As a result, the binary fitting polynomial becomes:

$$f(x,y) = \sum_{i=1}^{p}\sum_{j=1}^{q} a_{ij}(x-\bar{x})_{i-1}(y-\bar{y})^{j-1} \tag{7}$$

In addition, R^2 may be used as a parameter for evaluating the fitting accuracy, and R^2 is calculated as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}[z_{RS}(i) - z(i)]^2}{\sum_{i=1}^{N}[z(i) - \bar{z}]^2} \tag{8}$$

where $z_{RS}$is the fitted value, z is the measured value, and $\bar{z}$ represents the average of the measured value. The larger the R^2 value, the closer the fitting result is to the actual condition.

2.2. One-dimensional component

When considering only one direction, a one-dimensional component surface model may be obtained from the above formula (such as a beam-column space model of the surface boundary).

2.3. Spatio-temporal distribution model

Employing the above fitting method, the spatial temperature distribution surface may be obtained from the measured point that result from the fire simulation at each time step. When taking time into account, however, the distribution is irregular in the time dimension, due to the development and spread of the building fire. Therefore, in order to obtain the spatio-temporal distribution model of the temperature or the component surface radiation boundary, the linear interpolation method is applied here to the adjacent two sets of measured data points obtained from the fire simulation, and then the interpolation results are used as the measured values for the polynomial fitting. Thus, the space-time distribution of the overall space in the entire fire process may be obtained, and the subsequent heat transfer analysis may be performed.

3. Realization and verification of spatio-temporal model

3.1. Realization of the model

In this paper, FDS (Fire Dynamics Simulator) is used to simulate a compartment fire. The simulated model is subjected to a range of verification tests to assess the accuracy of the calculations [15]. This software is intended to provide a quantitative estimation of the certain likely consequences of a fire. The software ABAQUS is used to perform a thermal mechanical analysis. The proposed method of a spatio-temporal distribution model is used to combine the FDS simulation results and ABAQUS finite element model.

ABAQUS supports the subroutine development function, and user subroutines may be incorporated into an Abaqus analysis [16]. UTEMP may be used to define the node temperature of the finite element model. DFLUX may define the heat flux as a function of time and position and define the heat flux density at each analysis step. Based on these user subroutines, this paper compiles a spatio-temporal distribution model that uses the FORTRAN language.

For steel columns and beams, the temperature distribution of a section is assumed to be uniform, and the temperature distribution in