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Simulating the fire-thermal-structural behavior in a localized fire test on a bare steel beam

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ABSTRACT

The engineering design practice may include fire protection design of steel structures in large volumes. Prescriptive methods in fire codes are based on the concept of fire compartmentation and might be inapplicable to large volumes. As an alternative, fire engineering performance based methods are developed, which may need sophisticated numerical models to adequately simulate the responses of structures in the design fire scenarios. This paper discusses an integrated fire-structural simulation model for performance based design. Sub-models were clearly described. The fire-structure simulation model was successfully applied to model the fire-thermal-structural behaviors in two localized fire tests on a real-scale steel beam recently conducted at the National Fire Research Laboratory (NFRL) of the National Institute of Standards and Technology (NIST). The model might be used in performance based structural fire safety design.

1. Introduction

A large amount of effort was devoted to research on structural fire engineering in the past few decades and most of this work has assumed a post-flashover fire, which affects the entire building, or a fire compartment of the building, because it is generally believed that a post-flashover fire poses the largest risk to structural safety. Although the fire protection scheme might be rationalized with a structural fire engineering approach under such circumstances, fire mitigation strategies are still required. When the structure is subjected to low fire risk, typically unlikely to go to flashover, with fire risk analysis and subsequent structural fire engineering design, a large amount of fire protection costs may be saved. Typical project examples include suspension bridges subjected to a lorry fire, large atriums with limited fuel load, etc. Models are developed for specific occasions. For example, the Steel Construction Institute (SCI) report [1] and the Eurocode 1 [2] include a calculation method for members outside a building facade and subjected to window fire. However, these empirical models only apply to a pre-defined, simplified fire situation, while, in reality, the space geometry, the structural form, and the fire location may all vary. It is very important that advanced tools be developed to simulate the combustion behavior in various environments and to evaluate the consequence of the fire on adjacent structural members.

Fig. 1 shows an example of an airport terminal in Beijing, China. The giant roof covers an area of approximately 76,000 m^2 and creates a huge indoor open space for the terminal. The roof is supported mainly by eight C-shaped columns with a span of over 100 m between the columns. The roof adopted a special grid system, which gradually mixed with the columns seamlessly. Fig. 1b shows the overall structural geometry of the roof and a localized view of a C-shaped column. Because of its huge size, the column is unlikely to be completely engulfed by a big fire. In the worst condition with a fire source right adjacent to the column, a few steel members will be directly impinged by fire while the majority of steel members will be near the fire. To appropriately evaluate the response of the structure in fire and then to design the fire protection scheme, it is essential to evaluate the influence of a possible fire to the column (e.g. nonlinear temperature distribution of the steel members), and, therefore, to have sophisticated fire-structure simulation models.

Fire-induced temperature rise has two effects on a structural component: it weakens mechanical properties and it causes thermal expansion. Restrained thermal expansion generates mechanical stress and the difference in thermal expansions causes thermal bowing [3]. Additionally, fire-induced asymmetrical temperature distribution may

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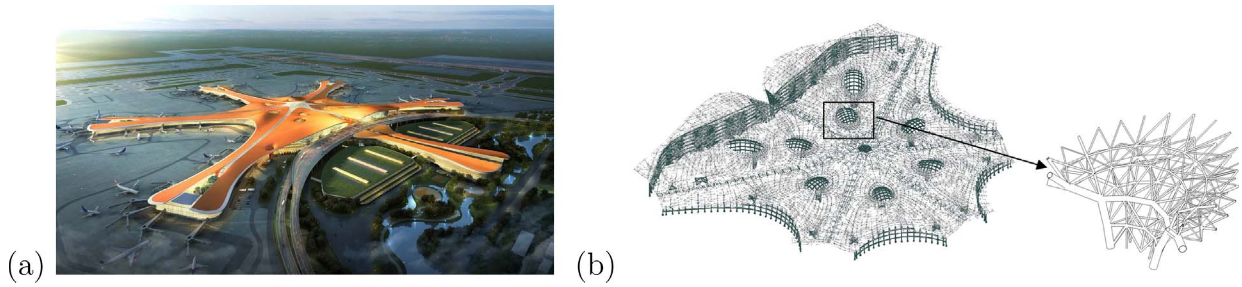

Fig. 1. Beijing new airport terminal. (a) Bird view; (b) structural form of the airport roof and a typical C-shaped column.

lead to a *P* - delta effect (or secondary moment) in compressive components [4]. The temperature degradation effect on structural materials has been well investigated and is considered in the current fire codes. Although many studies have shown that (restrained) thermal expansion can have a significant effect on load-bearing capacity of structural members, the effect of (restrained) thermal expansion is not considered in most fire codes. Experimental studies on the effects of fire-induced temperature gradients are limited. Available theoretical studies [4–7] show that ignoring fire-induced temperature gradient may be unconservative in evaluating the fire safety of steel structures in large enclosure (e.g. the steel column shown in Fig. 1).

2. Background

Most of the structural fire tests reported in literature are conducted in an enclosed furnace, some are conducted in real compartments (e.g. the Cardington full-scale fire tests [8]), and a small number are conducted in an open condition or a localized fire condition [9–11]. Furthermore, these tests seldom measure the heat release rate of the fire, which is the most important parameter in fire hazard assessment [12]. Recently, the National Institute of Standards and Technology added a unique facility named the National Fire Research Laboratory (NFRL), which allows for researchers to conduct tests on real-scale structural members and systems subjected to realistic fires [13]. This facility is equipped with an exhaust hood for fires up to 20 MW, a strong-floor, a strong-wall, and a structural loading apparatus to apply gravity loads on multi-story buildings. As part of commissioning the structural-fire test capabilities at the NFRL, a series of tests were conducted on loaded structural steel beams exposed to a localized fire [14]. Table 1 gives the matrix of the NFRL tests. In this paper, test 6, 7 and 8 were considered.

In absence of test guidelines, an engineering approach was proposed by the authors to conduct pre-test simulations to design a testing fire for the NFRL experiments [15]. The approach adopts a simple analytical model to approximately calculate the critical value of heat release rate required to reach a target temperature in the test specimen and uses a sophisticated numerical model to verify/refine the calculation. The

Table 1
Test matrix according to Ref. [14].

Test no.	BCs[a]	Fire load	Structural load
1, 2	Simply supported	Natural gas fire (increased in 10 kW increments up to 500 kW)	Not applied
3, 4, 5	Simply supported	Natural gas fire (fixed at 400 kW)	Not applied
6	Simply supported	Not applied	Increased to failure
7	Simply supported	Fire1, steady-state heating	Force1
8	Simply supported	Fire2, transient heating	Force2
9	Shear connection	Fire2, transient heating	Force2

[a] Boundary conditions at the end of the beam.

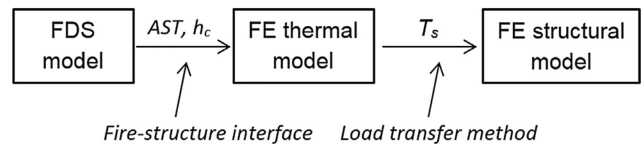

Fig. 2. Illustration of the FDS-FEM simulation methodology.

analytical model is developed by the first author in his previous work [16], which assumes the fire plume volume as a cylinder and uses the theory of heat radiation in participating medium to calculate the radiative heat fluxes to the horizontal surface (bottom surface of the beam specimen). The sophisticated numerical model is an integrated fire-structure model. As shown in Fig. 2, the numerical model first uses the Fire Dynamics Simulator (FDS, introduced later in Section 3.1) [17] to simulate the realistic fire behavior and to predict the thermal boundary conditions of adiabatic surface temperatures (AST, introduced later in Section 3.2) and convective heat transfer coefficient (h_c) at the exposed surfaces of the structures considered; then, a fire-structure interface scheme or tool is used to transfer the data of thermal boundary conditions from the FDS model to a finite element (FE) thermal model and conduct a heat transfer analysis using the FE thermal model to get the temperature data (T_s) of the structures considered; and, finally, a load transfer method is used to map the steel temperature data (T_s) from the FE thermal model to a FE structural model and conduct a mechanical analysis to get the structural responses (deformations, stresses, strains, etc.). In [15], the proposed approach adequately predicted the critical value of heat release rate for the NFRL thermal tests (Tests 1 and 2 in Table 1), which demonstrates the capability of the approach for predicting the thermal boundary conditions in localized fires. In this paper, the sophisticated numerical model is used to simulate the NFRL structure fire tests (Tests 7 and 8 in Table 1), which intends to investigate the capacity of the model for predicting the temperature field and mechanical behavior of structures in realistic fires.

3. Methodology

3.1. The FDS code

Fire Dynamics Simulator (FDS) is a large-eddy simulation (LES) based CFD (computational fluid dynamics) code [17]. For the simulations performed in this study, FDS version 6.2.0 was used. LES is a technique used to model the dissipative processes (viscosity, thermal conductivity, material diffusivity) that occur at length scales smaller than those that are explicitly resolved on the numerical grid. In FDS, the combustion is based on the mixing-limited, infinitely fast reaction of lumped species, which are reacting scalars that represent mixtures of species. Thermal radiation is computed by solving the radiation transport equation for gray gas using the Finite Volume Method (FVM) on the same grid as the flow solver. FVM is based on a discretization of the integral forms of the conservation equations. It divides the problem domain into a set of discrete control volumes (CVs) and node points are used within these CVs for interpolating appropriate field variables. The