CFD 기반의 화재 시뮬레이션 기법 및 실제 화재 적용사례

Fire Simulation Technique based on CFD and Applications to Real Fire Cases


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1. Introduction

This article is about computational methods for fire simulation and applications to real cases. In general, existing commercial programs use two different numerical methods; Computational Fluid Dynamics (CFD) and the zone modeling method. According to rapid development of the computer power and memory, the CFD model becomes more useful in recent days. Among many commercial software using CFD modeling method, Fire Dynamics Simulator (FDS) is focused in this article, one of the decent fire simulation software developed by National Institute of Standards and Technology (NIST). The FDS is also known as open source code and convenient and easy to access the results. Later in this article, the FDS is applied to model full-scale fire tests performed in UK and a highway bridge collapsed by a fire due to truck accident in California, USA.

2. Fire simulation programs

Although the fundamental conservation equations governing fluid dynamics, heat transfer and combustion were first developed over a century ago, the practical mathematical models for fire simulation are relatively recent due to the natural complexity of the problem such as an enormous number of possible fire scenarios and a limitation of computing power and memory. CFD modeling method divides total volume into lots of sub-volumes and the law of mass, momentum, and energy conservation are performed to the sub-volumes. This modeling methodology is useful when dealing with complex geometries. Unlike CFD method, two-zone modeling method divides compartment into an upper (hot zone) and lower zone (cold zone) only. Mass and energy conservation equations are then solved for both zones for every time step. In this chapter, existing commercial software implemented with CFD modeling method are reviewed.

The Analysis of Smoke Movement in Enclosures (JASMINE) has been developed continuously at BRE over 20 years[3]. JASMINE contains a finite-volume CFD code and is able to model single and multiple compartment enclosures with arbitrary openings, obstructions, fire/heat sources and mechanical ventilation systems. Within the software, fire scenario can be modeled using the graphical user interface which allows the user to define the geometry and boundary conditions easily. The Simulation of Fires in Enclosures (SOFIE) was developed under the group of a consortium including a number of European fire research laboratories and initiated at Cranfield University[4]. SOFIE has a text only interface with no graphical pre- or post-processing but is able to export data in either Plot3D or Fieldview format. SOFIE uses a CFD computing method for fire modeling and can be used to determine smoke movement in buildings. The software can also predict complex fire phenomena such as fire growth and spread, toxic emissions and dispersion, fire-water spray interaction, which has not been accessed from the other software. In addition, Fire Risk Evaluation and Cost Assessment Model (FiRECAM) has been developed by the National Research Council (NRC) in collaboration with a number of partners since 1987[5]. The program can be used to assess the level of fire safety that is provided to occupants in an apartment or office building by a fire safety design. In addition, the model can assess the associated fire costs that include capital and maintenance costs of the fire protection systems and expected fire losses. The user can input the design information for the building through a graphical user interface with pull-down menus. FiRECAM uses statistical data to predict the probability of occurrence of fire scenarios and mathematical models to predict the time-dependent development and spread of a fire, the evacuation of the occupants and the response of the fire department. Finally, Fire Dynamics Simulator (FDS) was written by staff members of the Building and Fire Research Laboratory at the National Institutes of Standards and Technology (NIST), U.S.A[6]. The program calculates the temperature, density, pressure, velocity and chemical composition within each numerical grid cell at each discrete time step, based on Computational Fluid Dynamics (CFD) of fire-driven fluid flow. The computing within FDS can be carried out using either a Direct Numerical Simulation (DNS) method or Large Eddy Simulation (LES). The latter has relatively low Reynolds numbers and is not severely limited in grid size and time step as the DNS method. In addition to the classical conservation equations considered in FDS including mass species momentum and energy, thermodynamics-based state equation of a perfect gas is adopted along with chemical combustion reaction for a library of different fuel sources. The latter can be used in case where the fire heat release rate is unknown. FDS also has a post-processing program to visualize results, named “smokeview.”

3. Application of FDS for Cardington test simulation

In this section, application of FDS to simulate the Cardington fire tests performed in U.K. is presented. The Cardington fire test is performed on the 1st floor of eight-story building. The concrete block compartment which area is 135m^2 is subjected to fire and fire source consists of modern day furniture-like materials, such as computers, filing systems, wood, and plastic cribs. According to Newman et al.[7], the total material consumed in this severe fire is 46 kg/m^2, made of 69% wood, 20% plastic and 11% paper. The columns and the beam-to-column connections are fire protected but all beams and beam-to-beam connections are exposed to fire during the test. Figure 1 illustrates the refined FDS model of the compartment along with the structural elements. The FDS is conducted mainly in order to obtain time dependent temperatures on the surfaces of structural elements. The yellow floor area is the distributed fire source that can be specified directly as a heat release rate per unit area (kW/m^2). The solid darker lines indicate the enclosed fire area while the other solid lines indicate beam elements. The solid circles indicate locations where the vertical displacements are measured. Newman et al.[7] details the different materials (wood, plastic, paper) used in the test. Information is used in this study to estimate the FDS fire load curve as illustrated in Figure 2. The assumptions for this fire source is a growth rate of a=0.08 based on Karlsson and Quintiere[8]. The average heat density of consumed materials is taken as 33kJ/g assuming an upper limit of energy production based on the tables from Bwalya et al.[9] which provided itemized tables for heat combustion values of different materials with lower-medium-high range of heat generated in MJ/kg. This information is used in this study to create an average sum of the fire content consumed in the Cardington test. The maximum heat release rate is 1003 kW/m^2. Growth and decay phases are assumed where both are taken 2 minutes, while the steady-state phase lasts for 24 minutes. The FDS model is generated for the fire compartment and it

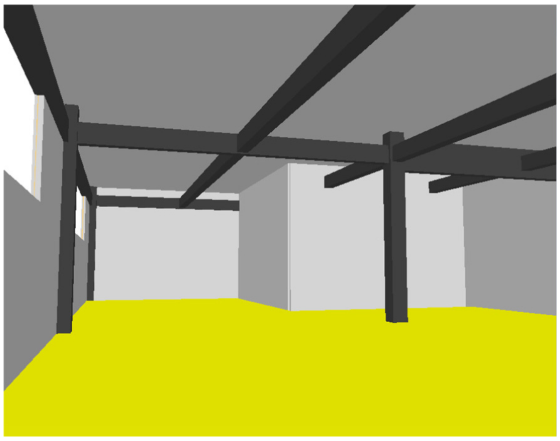


Fig. 1 The Cardington office fire demonstration test modeled by FDS

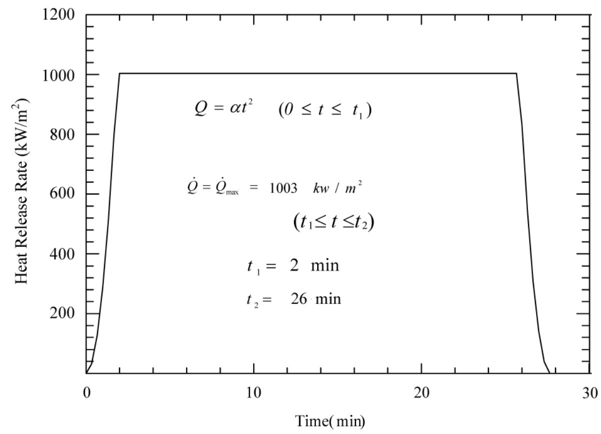


Fig. 2 A fire load curve used to simulate the source in the Cardington office fire test

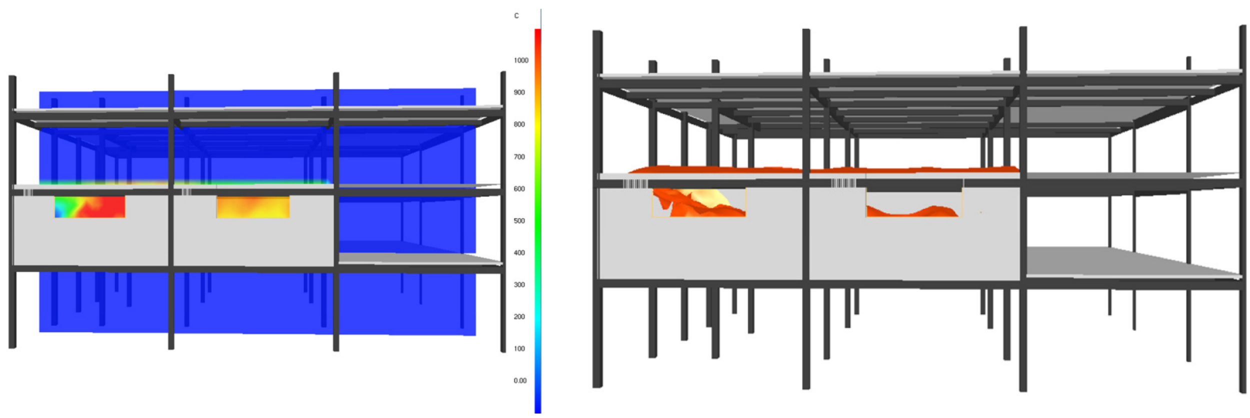


Fig. 3 Temperature slice picture (left) and HRRPUV (right) simulated using FDS

does not cover the entire building. Other larger FDS models including top and bottom floors have been examined but do not significantly alter the surface heat and temperatures within the fire compartment. The steel columns and beams are added in the FDS model in order to capture the temperature profiles on their surfaces by post-processing the interior surface temperatures. Figure 3 illustrates the FDS model and typical surface temperature results in the form of a contour on a slice plane (the blue plane in the left figure) and heat release rate per unit volume HRRPUV (right).

The measured temperatures on beams inside the office area are compared to those generated from the simulation. A range of temperatures measured during the test on different locations is also added as upper and lower values reported by Usmani et al.[10] as shown in Figure 4 since the exact location of the reported experimental measurements are not known to us. The dashed line is a curve generated directly from the FDS discrete temperature results and the solid line presents results from the temporal-spatial polynomial fourth-order approximation of the temperature for the entire range of fire simulation.[11,12] Figure 5

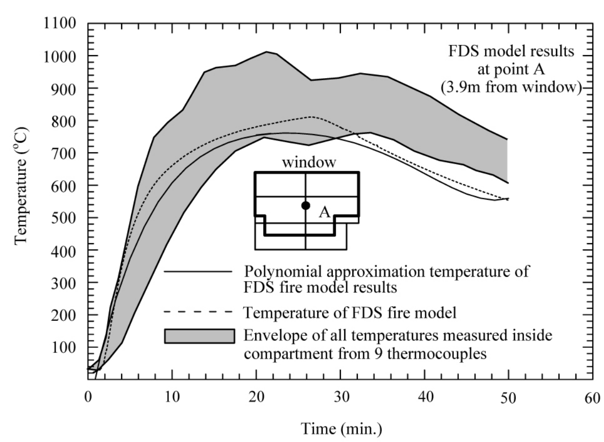


Fig. 4 Time-dependent temperatures at 'A' location predicted from FDS compared with experimental data

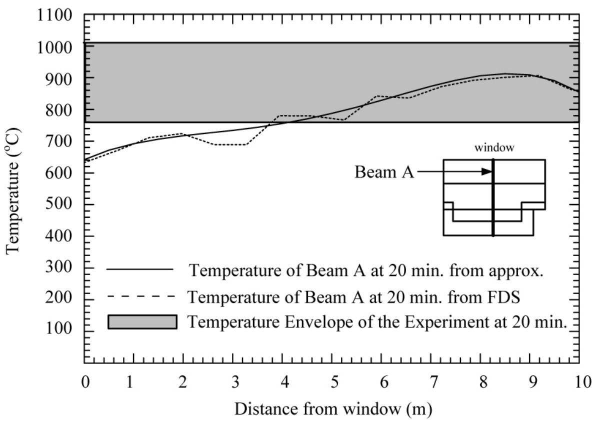
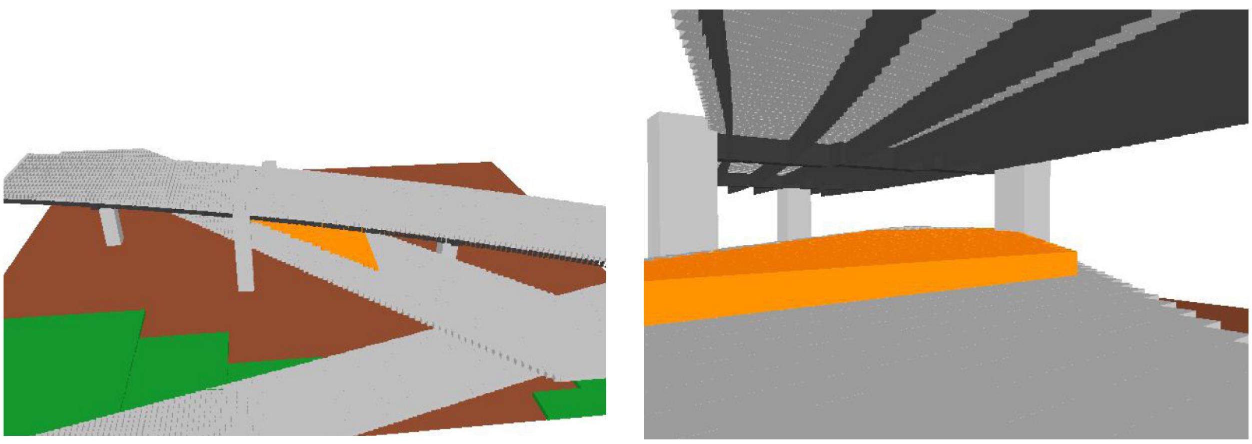


Fig. 5 Temperatures along with distances from window predicted from FDS compared with experimental data

shows similar results to Figure 4, however, the temperature is a function of the distance from the window along the center beam instead of time scale.

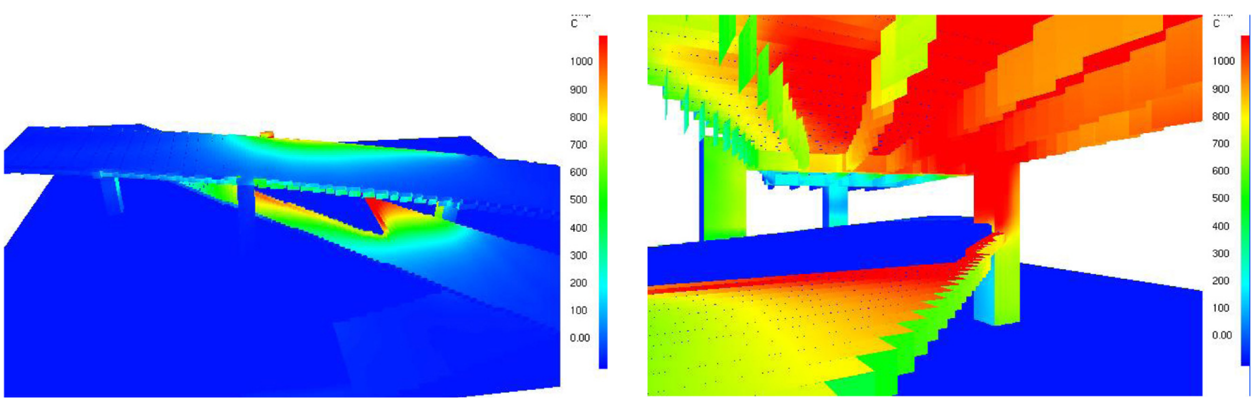
4. Application of FDS for fire simulation on the Oakland–San Francisco Bay Bridge

A FDS model for the collapsed I-580 bridge including I-80/880 bridge where the gasoline truck crashed is presented in this section. The FDS model is generated using FDS as shown in Figure 6 and gasoline spilled from the crashed truck is presented as orange object. The bridge geometry is approximated based on Google satellite maps[12,13] because the exact bridge dimensions are not available to us. It is assumed that 90% of the total spilled gasoline (8600 gallons) is left on the I-80/880 bridge deck and 10% of gasoline is on a ground based on the observation. Heat release rate per unit area for the fire source is assumed as 2500 kW/m^2 during the fire accident (21 minutes). Also, it is assumed that the fire is



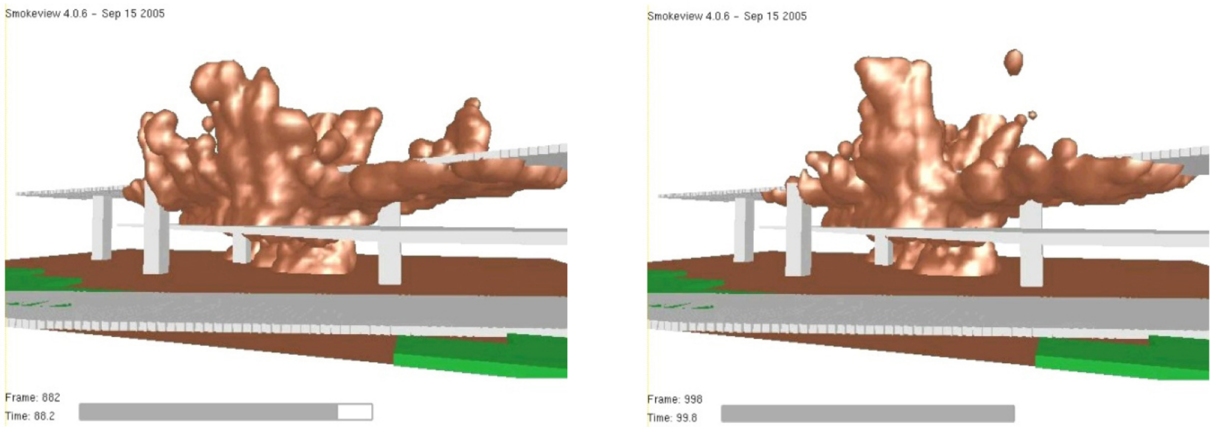
(a) Top view of the bridges (b) View under the I-580

Fig. 6 Oakland bridge model



(a) Top view of the bridges (b) view under the I-580

Fig. 7 Oakland bridge model with temperature contour predicted from FDS



(a) 15 min after accident (b) 21 min after accident

Fig. 8 Oakland bridge model with HRRPUV at different time frames predicted from FDS

ignited very quickly and then suddenly approached to steady-state phase. The concrete material is used for bridge decks and columns, and steel is for bridge girders. Based on weather cast, wind is considered as 2.6 m/s NW.[14] Figure 7 shows surface temperatures predicted from FDS and it is seen that temperatures of the bridge above the spilled gasoline are around 1000℃ after 21 minutes of fire accidents. From FDS, heat release rate per unit volume (HRRPUV) can be also assessed in a form of flames as presented in Figure 8.

5. Conclusions

Along with development of computing tools, CFD based fire modeling tools becomes very useful to simulate real fire scenarios. From these tools, it is possible to examine engineering and physical aspects of fire accident such as temperatures transferred to structural members and propagations of flames and smokes. Even if the current status of the fire simulating technique includes environmental effects from fire sources, wind or air flows, geometries and materials of the model, the more detailed simulating technique is still needed to include coupled effect of temperature-structure changes during the fire, which allows the more accurate results of fire simulation.

Reference

1. Jones, W. W., editor, CFAST Consolidated Model of Fire Growth and Smoke Transport (Version 6) Technical Reference Guide, NIST Special Publication 1026, National Institute of Standards and Technology (NIST), 2005.
2. Peacock, R. D., editor, CFAST Consolidated Model of Fire Growth and Smoke Transport (Version 6) User's Guide, NIST Special Publication 1041, National Institute of Standards and Technology (NIST), 2005.
3. Computer models for fire and smoke, Combustion Science and Engineering, Inc., http://www. firemodelsurvey.com/pdf/JASMINE_2001.pdf (Accessed July 3, 2008).
4. Rubini, P., SOFIE-Simulation of fires in enclosures, School of Engineering, Cranfield University, U.K, http://www.cranfield.ac.uk/ (Accessed July 3, 2008).
5. Fire Risk Evaluation and Cost Assessment Model (FiRECAM), National Research Council (NRC), http://irc.nrc-cnrc.gc.ca/fr/frhb/firecamnew_e.html(Accessed July 3, 2008).
6. McGrattan, K., Forney, G. P., Floyd, J. F., Hostikka, S., and Prasad, K., Fire Dynamics Simulator (Version 3) - User's Guide, NISTIR 6784, National Institute of Standards and Technology (NIST), 2002.
7. Newman, G. M., Robinson, J. T., and Bailey, C. G., Fire Safe design: A New Approach to Multi-Storey Steel-Framed Buildings. Steel Construction Institute, Ascot, UK, 2000
8. Karlsson, B. and Quintiere, J. G., Enclosure Fire Dynamics. CRC Press LLC, Boca Raton, FL, pp. 39-45, 2000.
9. Bwalya, A. C., Sultan, M. A., and Benichou, N., A Pilot

Survey of Fire Loads in Canadian Homes, National Research Council Canada, Ottawa, Canada, 2004.
10. Usmani, A. S., Ed., Report MD14: BS/TEST4 ABAQUS half-floor Model using elastic shell with rotational discontinuities, Corus RD&T, The School of Civil and Environmental Engineering, The University of Edinburgh, Edinburgh, UK, 2000.
11. Choi, J., Kim, H.S., and Haj-Ali, R.M. (2010), Integrated fire dynamics and thermomechanical modeling framework for steel-concrete composite structures, Steel and Composite Structures, An International Journal Vol. 10(2), 129-149.
12. Choi, J., Haj-Ali, R.M. and Kim, H.S., (2012), Integrated fire dynamic and thermomechanical modeling of a bridge under fire, Structural Engineering and Mechanics, An International Journal, Vol. 42(6), accepted.
13. Google maps, http://maps.google.com/ (Accessed July 10, 2008).
14. History for Oakland, CA on Sunday, April 29, 2007, The weather underground, Inc., http://www.wunderground.com/history/airport/KOAK/2007/4/29/DailyHistory.html (Accessed July 3, 2008).

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