SIMULATION FOR SAFETY ENGINEERING: A COMPARISON BETWEEN EXPERIMENTAL DATA AND FIRE MODELS

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ABSTRACT

A comparison analysis has been conducted between experimental data of a concrete structure and three different models developed with CFAST, by NIST. This work concentrates on the possibility of modeling simplified fire objects. Full-scale experiments are simulated by two-layers zone models. Through a reverse approach on heat release rate estimation, a comparison between different models is reported analyzing time to flash over, maximum temperature, shape of the time-temperature curve. The possible use of these models as an engineering design tool is carried out. Results show that different ventilations lead to an uncertain time-temperature response. The benefits that should come from decomposition of fire load into many fire objects is counterbalanced by reduced accuracy due to increased model complexity and interactions between fire plumes.

Keywords: fire modeling, CFAST, safety engineering, two-zone model.

1. INTRODUCTION

Fires are usually very complex to analyze. The complexity arises because of simultaneous presence of phenomenon which controls fire and smoke development, like combustion, turbulence, radiation, convection, etc. Reduced-scale experiments although provide useful information, yet they alone are not sufficient to reproduce full-scale features. A better understanding can be obtained by carrying out full-scale experiments, but they are expensive. Therefore, mathematical modeling can be used for reduce the needs of experiments. However, mathematical modeling should be validated by full- or reduced-scale experiments, wherever possible, in order to achieve a practical solution. A comparison between two-layers zone models and full-scale experiments is provided in this paper. Like all predictive models, the best predictions come with a clear understanding of the limitations of the model and care in the choice of data provided to the calculations. A number of models have been proposed (Olenick and Carpenter 2003) to assist fire safety scientists and engineers to predict fire growth and smoke movement, considered as essential components in fire risk analysis. These models can be grouped into three basic types: field models or CFD (Computational Fluid Dynamics), zone models and hybrid models (Yao et al., 1999). Compared to zone models, field models are relatively younger and usually require high setup, prohibitively high computational resources or unacceptably long computing time. They divide the space of interest into a large number of control volumes in space and steps in time, and then apply and solve a set of partial differential conservation equations over these volumes and steps to produce results with high temporal and spatial resolution. In contrast, zone models such as CFAST have a longer development history. They consider the regions of interest as a whole or divide the regions into only a few zones, assuming that the gas phase inside each zone is well stirred and uniform. Then, a set of ordinary differential or algebraic conservation equations are solved to obtain average variables for each zone (Zhang and Hadjisophocleous 2012).

The main interest of this research is to verify if the accuracy of model results obtained by simplified fire objects modeling and fast simulation time is suitable to use them in design phase. Zone models can give satisfactory although approximate results at a lower cost, while multi-layer zone models have been proposed (Suzuki et al. 2003, Xiaojun et al. 2005), the most frequently used zone models are still the single-layer and two-layer zone models. While single-layer zone models cannot be used in pre-flashover fires due to the assumption of homogeneous properties in the zone (Luo 1997). Two-layer zone models, such as CFAST (Jones et al. 2009), are often used. Two-layer zones concept was proposed in early 1960s (Cox 1995). However, two-layer zone approach emerged in the mid-1970s when fire development was intensively studied. Since then, many two-zone models have been proposed and reviewed; while they are different in features and details, they are similar in basic treatment, assumptions, and sub-models.

A building in which a fire occurs inside is considered for analyzing fires in growth phase and steady burning period. Our aim is to reproduce its geometry, developing a model within the software, analyzing the fire load, and studying the time-temperature response by comparing it with the experimental data obtained as a result of the full-scale destructive tests performed at BRE (Building Research Establishment) Cardington, Lennon and Moore (2003).

The 8 tests have been undertaken in a compartment with overall dimensions of 12 m x 12 m x height 3.4 m, they have investigated the influence of compartment linings, fire load type and through draft condition on the severity of fully developed, post-flashover fires. By this tests, fire development in the pre-flashover phase and smoke movement are investigated too. This experiment was chosen because the building is very similar not only in the geometry but also in the fire load, to many warehouses of small enterprises or big offices. In Italy, compartments over 100 m^2 and below 200 m^2 are very common. The fire load of 5760 kg wood equivalent (97920 MJ) is typical for small warehouses.

A common limitation of fire models is the estimation of heat release rate (HRR). The HRR is a critical parameter to characterize a fire, it can be estimated with different methods that are usually expensive and destructive. The most widespread techniques are based on mass balance if the heat of combustion of the fuel is known. If the burning material is unidentified, calorimetric principles can be used, relying on oxygen consumption or carbon oxides generation measurements. In the last tests provided in this study a reverse approach was chosen avoiding the need of HRR estimation.

2. THE MODEL

The Consolidated model of Fire growth And Smoke Transport (CFAST), developed by NIST, is a multi-room two-layer zone model, with the capability to model multiple fires and targets. This model divides a space into two layers: an upper, hot layer and a lower, cooler layer, considering obvious temperature gradients and hence buoyancy-induced stratification. It can be used to calculate, during a fire scenario, the evolving temperature and distribution of smoke and fire gases throughout a building. CFAST is a merging of ideas that come out from FAST and CCFM.VENTS projects.

CFAST, as many other two-layer zone models, considers heat and mass transfer from the lower layer to the upper one and even downward heat and mass transfer due to venting flows, nevertheless it ignore the mixing that pass through the interface between the two layers due to the temperature difference between the layers. According to Zhang and Hadjisophocleous (2012), both experimental data and results of numerical simulations of field models showed the existence of mixing at the interface, the lack of which is identified as an important limitation of two-layer zone models. The mixing maybe caused by natural convection as a result of the temperature difference between the two layers and the circulating flow resulted by the plume induced flow. Comparisons between experiments and modeling results (Remesh and Tan 2007, Peacock et al. 2008, Fu and Hadjisophocleous 2000) suggest that it may result in over-prediction of the upper layer temperatures and under-prediction of the lower layer temperatures. All the aspects that were considered in the development process of the model and in the software limitations are presented below.

2.1. Compartment geometry and thermal properties

The building used in the experiment has a regular shape which can be easily recreated in the model. Walls and floor are plain, only the ceiling is built with concrete slabs and its shape is more complex. CFAST is able to manage only plain surfaces for the ceiling, so it was modeled as a plain horizontal surface. Authors agree that is a minor limitation of the software and this should not considerably affect the results. The building is composed of only one compartment, so surface connections are not needed. Surface connections in are a system to consider gas species and energy flux between compartments.

The materials database available in CFAST is not very wide, therefore many materials were added inserting the specific characteristics of the products used in the experiment.

2.2. Flow vents

The building has only horizontal natural flow connections in the front and rear walls. In the model, openings are differently managed if we consider natural or forced ventilation. In this paper mechanical flow vents and vertical flow vents were not tested, because of in the experiment there was not fans, hatches, floor or ceiling holes.

Two cases were analyzed:

- front openings only, 2 openings, height 3.4 m, width 3.6 m
- front and back openings, 4 openings, height 1.7 m, width 3.6 m

In both cases, area remains 24.48 m^2, the opening factor changes because of different height. Even though predictions can be affected because two-layers zone models neglect radiation losses from room openings, which is not entirely insignificant at high temperatures, there are no other significant software limitations for modeling the building we are interested in.

2.3. Fires

Modeling fires is critical, every fire object is generated by a wide set of parameters, many of them are recognized to be very significant in literature. For the plume, McCaffrey model was used, however it was noticed no significant difference by the use of Heskestad in these models. CFAST has built in two types of fire modeling structure.

2.3.1. Fire modeling structures

The first one is to create a new database object with HRR data from a destructive test, it can be very accurate because it is possible to generate the HRR curve with high level of detail. Nevertheless destructive tests are expensive and their cost and complexity is usually too high for a predictive model. Moreover, the uncertainty of the model could be high even if the fire was modeled from a destructive test. The internal database for fires is very limited for using this type of fire modeling in many scenarios, also data from bibliography are not as much as they should be for this aim.

The second fire modeling method let us generate an HRR curve starting from 4 parameters. In real fires, the initial fire development is always accelerating, and a suitable way to describe this is to use the t-squared fire (i.e., HRR= $\alpha \cdot t^2$) (Karlsson and Quintiere 2000). The HRR curve is composed of two parabolic parts during growth and decay period and constant value in steady burning as shown in Fig. 1. This method is less accurate than the first but more easy to use as an engineering design tool. The parameters used to develop t-squared fires are:

- Time to 1 MW
- Maximum HRR
- Steady burning period
- Decay period

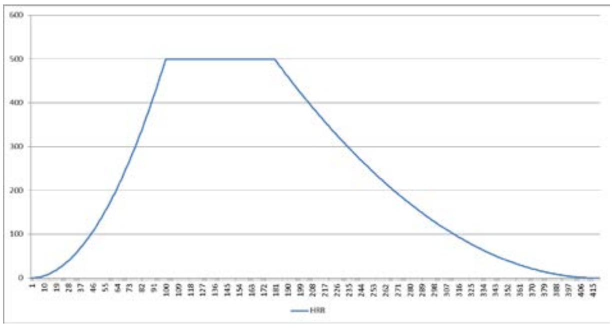

Figure 1: t-squared fire model

Both methods have many limitations in the software and because modeling fires is critical many alternatives have to be evaluated as to pass over software limits. This work concentrates only on the second method. Even if the experiment was conducted to ensure a rapid development of fire, it is possible to recreate this particular condition with CFAST.

2.3.2. Number of fire objects

In all the experiments 49 timber cribs burn in the compartment, but CFAST is limited to a maximum of 31 fire objects, so it is not possible to model every crib as a fire object. The simulation model must be simplified and this situation frequently happens when the building is big enough to contain a lot of furniture, accommodation and stored goods. In the model different fire objects were tested as to compare what solution is more suitable to simulate the experimental fire load. Modifying the number of fire objects, results consistently change.

In the first model only one fire object burns, so that its characteristics are equivalent to all 49 burning wood cribs. In the last model, 30 fire objects are distributed on the floor (with regular pattern) to maintain energy density per floor area equal to the experiments.

2.4. Detection / Suppression

The software provides tools for simulate smoke and fires detectors, sprinklers and suppression systems. None of these systems was used in the model because experiments were conducted without suppression systems.

3. METODOLOGY

A comparison between experimental and simulative results was conducted focusing on time-temperature response.

The accuracy of simulative results was analyzed in this paper. According to Lennon and Moore (2003) the fire growth and steady burning period was chosen as the limit for the comparison. Moreover two-layers zone model are a limiting factor in the prediction of the decay phase. Experimental results are provided every 60 seconds, so, for each step, relative error between experimental and simulative results was calculated. It would also be possible to generate a time-temperature curve by interpolation, using error analysis for continuous functions instead of discrete values, but this approach would create an intrinsic error due to interpolation itself.

For every test, the maximum temperature in the compartment (T_{max}), the time necessary to reach it and the steady burning period, were compared.

3.1. Test A

In test A, a model was created to simulate Cardington experiment 2. The purpose of this test is to evaluate if a fire load composed by only one fire modeled with the $\alpha \cdot t^2$ equation is suitable to fit experimental results. If the fire load is modeled with the generation of HRR in detail it would be possible to create a time-temperature response that fits almost perfectly the experimental one. By the use of the simplified t-squared method it is possible to create a series of fire objects with different values for all parameters (Time to 1 MW, Maximum HRR, Steady burning period) as to generate the most accurate time-temperature curve. Through a set of trials, a model that fits the experimental results with the highest accuracy is provided. The decay period is an useless parameter because we are not considering that phase in the comparison, so the number of trials is reduced.

By this approach, it is possible to minimize model error due to HRR response. According to Au, Wang and Lo (2007) it is found that the characteristic rate of heat release per unit area has the most critical effect on CFAST calculations. The parameters that minimize model error can be used as a baseline in next tests, therefore by this reverse approach there is no need to estimate HRR.

3.2. Test B

One of the more difficult aspects to analyze during the validation of a model is the capability to produce accurate results when the geometry changes. Cardington experiment 2 differs from 4 only for the shape of the building. In the experiment 2, there are only front openings, while in the experiment 4 the building has front and back openings. Openings area over compartment volume ratio remains unchanged.

Considering the fire load calculated by test A, it is possible to compare results of two models that differ only in geometry. Having reduced to the minimum the error on fire load, without need to estimate HRR, the model with the new geometry should fit experimental 4 curve.

3.3. Test C

Two-layers zone models are more accurate when the fire load is decomposed using as many fire objects as the real scenario. Nevertheless CFAST predicts fire development with higher accuracy when the fire object is in the centre of the compartment. The aim of this work is to assess this last statements and define how essential is the decomposition of fire load. A model was developed with a regular pattern of 30 identical fire objects. Using multiple fires let us spread over the compartment all the fire objects in order to recreate a pattern more similar to the experimental one. The energy density per floor area is the same as the previous tests and the experiment. The results of this test compared to Test A and experimental data show how much the prediction is influenced by the number of simplified fire objects.

4. RESULTS

4.1. Test A

A series of trials was conducted to evaluate the $\alpha \cdot t^2$ method for creating fire objects and the capability of CFAST to simulate accurately the experimental scenario. Each parameter involved in fire modeling was varied (with steps of 10 s or 0.5 MW) as to reduce the gap between model and experiment. The purpose is to check if simplified fire objects could be suitable to be used by designers. According to literature, the time to reach 1 MW in a fire with rapid development is 200 s. The estimated maximum HRR is 30 MW. A detailed description of fire load is provided in Lennon and Moore (2003).

The best combination of factors that minimize the error between model and experiment yields a time-temperature curve very similar for values and shape with experimental data, as shown in Fig 2.

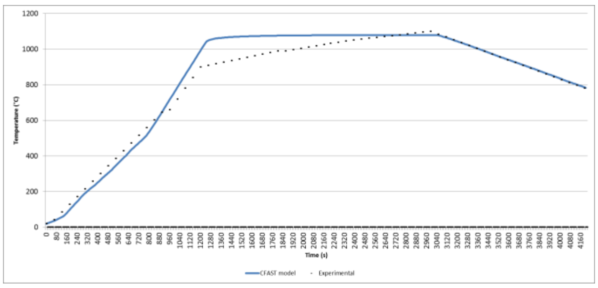

Figure 2: Upper Layer Temperature, Test A

Decay period starts 2990 s after ignition, until that time the error between model and experimental results is 8.68%. The maximum deviation between measurements is about 14%. This is the best result achievable with simplified modeling, is presented in bold in table 1. Only a small number of all other trials are presented in table 1.

Table 1: Fire Load Parameters

Time to 1 MW (s)	Maximum HRR (kW)	Steady Burning (s)	Decay Period (s)	Error %
260	**24000**	**1800**	**5000**	**8.68**
270	24000	1800	5000	8.91
250	24000	1800	5000	8.86
260	24500	1800	5000	8.98
260	23500	1800	5000	8.83
260	24000	1810	5000	8.72
260	24000	1790	5000	8.70

During steady burning the model over-predicts temperatures, as was to be expected considering limitations of two-zone models.

Table 2: Test A Results

Description	Experiment	Simulation	ε %
T_{max} (°C)	1100	1079	1.9
Time at T_{max} (s)	2990	3040	1.6
Steady Burning (s)	1740	1790	2.8

It is remarkable that also in the decay phase the model is very accurate, even if CFAST is not validated to analyze scenarios in this phase. Simulated and experimental curves almost coincide.

4.2. Test B

The aim of test B is to investigate the accuracy of the model when the geometry of the building change. The experiments 2 and 4 in Cardington differs only for the openings. Starting from the model used in Test A, front and back openings were modeled. If the modify does not affect much the result we should find a small error between new model and experiment 4 results. If the model would be able to perfectly manage the modifies in the geometry of the compartment, the error in this case would not be far to 8.68 %, as in Test A. The prediction of a slower fire development is appreciable, as shown in Fig. 3.

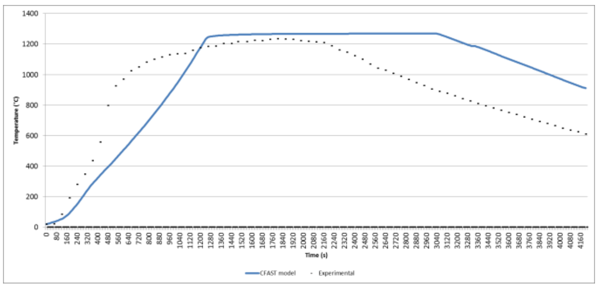

Figure 3: Upper Layer Temperature, Test B

Decay period starts 1800 s after ignition, until that time the error between model and experimental results is 29.12%. The maximum deviation between measurements is about 69%. The variation in the geometry is a critical factor in modeling with this software. However, the model correctly predicts the duration of the burning period and the maximum temperature. Nevertheless it is not able to capture the fire growth rate within the compartment.

If we consider that, during the design, a model is used only for prediction, the high error produced by a slight difference in the geometry is problematic. Even if the designer knows the behavior of the same fire in a different environment, the model is not accurate enough to rely on the forecast without analyzing more aspects in detail.

Table 3: Test B Results

Description	Experiment	Simulation	ε %
T_{max} (°C)	1235	1268	2.6
Time at T_{max} (s)	1800	2960	48.7
Steady Burning (s)	1540	1700	9.9

Comparing experimental results of both tests, a big difference in the quickness of fire development during the heating phase can be noticed. The 800 °C temperature is respectively reached in 1120 s and 480 s. The model is not able to correctly manage this change and it shows a very high sensibility to geometric modifies.

4.3. Test C

Test C investigates the simultaneous presence of 30 fire objects, spreading fire load all over the floor, evaluating if interactions of fire plumes are correctly managed in CFAST. The Cardington experiment 2 was simulated and results can also be compared to Test A.

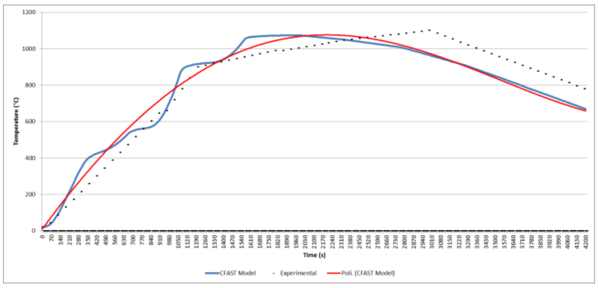

Figure 4: Upper Layer Temperature, Test C

Decay period starts 2990 s after ignition, until that time the minimum mean square error between model and experimental results is 11.2%. The maximum deviation between measurements is about 40%. The decomposition into many fire objects generate a time-temperature response with many peaks. It is difficult to recognize flash-over point and quantify steady burning period. However, the model correctly predicts T_{max}.

Table 3: Test C Results

Description	Experiment	Simulation	ε %
T_{max} (°C)	1100	1074	2.4
Time at T_{max} (s)	2990	1960	41.6
Steady Burning (s)	1740	uncertain	---

To assure that the error is not due to irregular shape of the evolving temperature curve, a polynomial approximation was calculated to reduce the number of peaks. The third grade polynomial is:

$$T= 2.03 \cdot 10^{-8} \cdot t^3 - 2.93 \cdot 10^{-4} \cdot t^2 + 10.11 \cdot t + 20$$

This curve, in red in Fig. 4, helps to recognize that in the growth phase the development rate is captured. The error between polynomial curve and experimental results is 10.7%. The accuracy of the model is lower than in the Test A, probably because of increased complexity. Because every crib has an intricate structure, fire growth on it can be quite complex and somewhat variable from one nominally identical sample to the next. In the model, fire objects are identical and according to Jain et al. (2008), fire objects located far from the centre of the compartment and especially those located near vents can lead to incorrect predictions.

5. CONCLUSIONS

A parametric study was performed to examine the effects of different fire characteristics. The use of CFAST in forecasting growth phase and steady burning of a fire is possible under a series of limitations. The need of HRR distribution obtained through a destructive test is a very limiting factor, it can be overcome with the simplified modeling of fire objects. The possibility to create an accurate model, compared to experimental data, was investigated by the use of t-squared fires. The results of using simplified fire objects are accurate and the evolving temperature profile is predictable when all fire load is collapsed in one fire object. In all performed tests T_{max} was predicted with a relative error lower than 2.6%.

During the heating phase, experimental data suggest that the quickness of the development is very influenced by openings. Even if the size of openings is constant, changing from front openings only to front and back highly decrease time to flash-over. The model shows a very high sensibility to geometric modifies and the error is increased of about 20%.

The time-temperature response is less accurate when the fire load is decomposed into many fire objects. During computation by CFAST, location of fire source in the compartment is a critical issue. The increased complexity of the model and the interactions between fire plumes do not lead to a more accurate prediction. The model behavior depends on a complex interaction of the combination of thermal and geometric characteristics of materials and fire objects and one fire object in which all the fire load is collapsed is better managed.

As an engineering design tool, CFAST is suitable to be used with t-squared fires, but a clear understanding of the limitations is necessary.

This study has also identified areas of future research. For example, different methods for generating simplified fire objects can be compared.

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