FIRE DESIGN OF STRUCTURES WITH THE AID OF COMPUTATIONAL FLUID DYNAMICS

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1. SUMMARY

In Eurocode 1 part 2[1] nominal temperature fire curves and simplified models are given for the calculation of the fire loads and actions, but either they do not represent the real fire conditions arising in a fire event, leading to unnecessary over-designing, or have a limited field of application and cannot be used for new contemporary architectural designs or large industrial facilities. An alternative approach is the use of Computational Fluid Dynamics (CFD) with special codes specifically developed for the study of heat transport from fires, such as the Fire Dynamics Simulator of NIST. The models can be used as the base for developing performance based design in addition to the structural models used subsequently. This method, when used properly within its field of application, can help the engineer, through the simulation of fire scenarios, to study fire spread, smoke and toxic gas production and distribution, spatial and temporal temperature development in the compartment and in the vicinity of the structural members and calculate heat fluxes at the points of interest, gaining all the necessary data for the structural analysis. Some sample results of a CFD fire analysis in an industrial building are presented.

2. INTRODUCTION

The advances in structural modelling and structural analysis in the last decades have allowed engineers and architects to pursue bolder and unconventional building designs both in architectural style and structural formation. Buildings have become higher and span lengths are pushed to their limits allowing larger indoor spaces to accommodate the needs of their occupants. New materials and construction techniques replace the old, larger and heavier steel and concrete sections with lightweight frames and truss systems, which have better aesthetics and most importantly are more economical. However, the combination of lighter element sections and larger compartments has made buildings more “sensitive” in case of fire events.

Fire is a hazard that can cause damage in multiple forms. In its most catastrophic aspect it can lead to total building collapse [2]. Still, even if the structural collapse is avoided, a fire event resulting in human casualties of the occupants due to ineffective evacuation or the fire fighting crew on duty is equally a design failure. In the current economy, even simple property loss due to a fire would not be considered by many as an engineering success. Thus, Fire Safety Engineering has become a necessity and a major aspect in building design that tries to address and solve the aforementioned issues.

Fire Safety Engineering can be described as the application of science and engineering principles to protect people, property, and their environments from the harmful and destructive effects of fire and smoke. In Eurocode 1 part 2 “the essential requirements for the limitation of fire risks demand that:

- the load bearing resistance of the construction can be assumed for a specified period of time,
- the generation and spread of fire and smoke within the works are limited,
- the spread of fire to neighbouring construction works is limited,
- the occupants can leave the works or can be rescued by other means,
- the safety of rescue teams is taken into consideration.

In order to be able to follow all phenomena concerned with fire, the engineer needs data both of the early stages of a fire (fire spread rate, smoke production) and of the later stages (temperature distributions in the building). This data can be acquired either by a prescriptive or a performance based design approach. Codes offer guidelines to be implemented in fire design regarding fire data and safety measures in order to provide an acceptable level of safety. The given information is based on past experience dating back to almost a century, and essentially, is a set of restrictions offered as solutions to fire engineering problems. These include prescribed values of thermal actions and parametric temperature – time curves that can be applied to compartments of limited size and dimensions (compartments < 500 m^2 with heights < 4 m and without roof openings). In simple buildings the application of the codes is sufficient and it provides quick and straightforward solutions. In more complex designs, however, the codes not only fail to deliver cost effective solutions, but also impose many architectural restrictions (i.e. compartmentalization). Performance based design is the only solution in such cases.

3. COMPUTER FIRE MODELS FOR PERFORMANCE-BASED DESIGN

Performance-based design against fire, as defined by the Society of Fire Protection Engineers (SFPE), is an engineering approach to fire protection design based on (a) established fire safety goals and objectives; (b) deterministic and probabilistic analysis of fire scenarios; and

(c) quantitative assessment of design alternatives against the fire safety goals and objectives, using accepted engineering tools, methodologies and performance criteria. The engineering tools in this case require advanced mathematical techniques and computations that constitute the various computer fire models.

Computer fire models have been used to study fire since the 1970s and their advancement is analogous to the advancements in computer technology. The equations that describe the motion of fluids and their interaction with solid bodies have been introduced since the 1840s (Navier–Stokes), but due to the fact that they were closely coupled they were very difficult to be solved. Some explicit solutions were given only for very low Reynolds numbers and for very simple geometries. The potential for solution of turbulent flows was invoked with the appearance of computers powerful enough to allow computations, at least nominally, to be extended to considerably higher Reynolds numbers. Since then, with the advance both in computer capabilities and numerical methods, computer models are applied in every discipline that involves flow movement, including fire modelling. Computer fire models can be divided in two main categories: one/two-zone models (Fig.1a) and Computational Fluid Dynamics (CFD) models (Fig. 1b).

One/two – zone models divide the compartment in different control volumes, or zones. The most common zone models split a compartment into two zones, an upper hot zone and a lower cold zone. The basic assumption is that the combustion products will accumulate in a layer beneath the ceiling, with a horizontal surface. In the upper layer the characteristics of the gas are assumed to be uniform and the exchanges of mass, energy and chemical substance are calculated between these different zones. In a fire compartment with uniformly distributed fire load, a two zone model may develop into a single zone fire. The temperature should be calculated considering:

- the resolution of mass conservation and energy conservation equations;
- the exchange of mass between the internal gas, the external gas (through openings) and the fire (pyrolysis rate);
- the exchange of energy between the fire, internal gas, walls and openings.

Examples of two zone models are the codes CFAST and OZone.

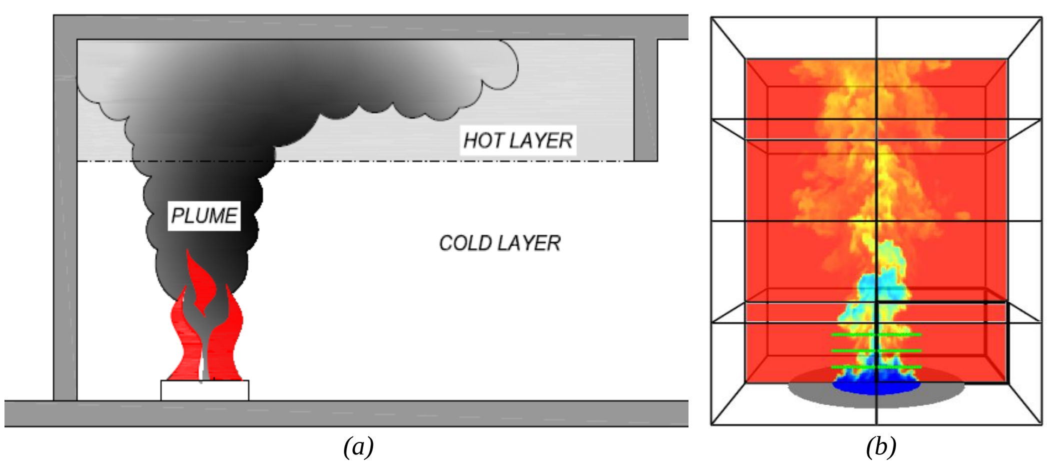


Fig. 1 a) Concept of a two-zone model b) CFD model [3]

Computational Fluid Dynamics models are the cutting edge of fire models. CFD models solve numerically the partial differential equations giving in all points of the compartment the thermodynamic and aerodynamic variables. These models analyse systems involving fluid flow, heat transfer and associated phenomena by solving the fundamental equations of the fluid flow. These equations represent the mathematical statements of the conservation laws of physics:

- the mass of a fluid is conserved;
- the rate of change of momentum equals the sum of the forces on a fluid particle (Newton's second law);
- the rate of change of energy is equal to the sum of the rate of heat increase and the rate of work done on a fluid particle (first law of thermodynamics).

A key aspect in CFD models is the handling of turbulence. The main techniques used are a) the Reynolds-averaged form of the Navier – Stokes equations (RANS) which is a time-averaged approximation of the conservation equations of fluid dynamics; b) The Large Eddy Simulation (LES) which is based on the observation that the small turbulent structures are more universal in character than the large eddies, therefore, there is no need to compute the momentum and energy transfer of these small turbulent structures, but only the momentum and energy transfer of the large eddies; c) Direct Numerical Simulation (DNS) where the solution is obtained by solving directly the Navier-Stokes equations without any turbulence model, which by definition requires finer meshes and very high computational recourses. Examples of CFD models are the codes FDS, Fluent, JASMINE.

4. USE OF COMPUTATIONAL FLUID DYNAMICS MODELS

The main advantage of CFD models over zone models is that they can provide values of the thermodynamic and aerodynamic variables in all points of the rectilinear grid used to solve the equations of fluid flow in a compartment of any shape. This makes them the best candidates for fire analysis in buildings of contemporary design, with large compartments, halls, indoor atria and non rectilinear geometries. The second advantage is that they can be used to study fire development, smoke movement and temperature-time distributions in the whole model. The strategic steps of a fire scenario analysis using the CFD code Fire Dynamic Simulator (FDS) [4], a CFD code for the simulation of thermally driven flows with an emphasis on smoke and heat transport from fires, is given below.

1) Description of the compartment geometry. A detailed 3D model with all the geometric data of the building/compartment is created including all the divisions, openings and ventilation and fire suppression systems to be analysed in the simulation (Fig. 2).

2) Selection of the appropriate mesh and time discretization. The mesh or multiple meshes are chosen with respect to the detail of the required solution and the computational resources. Multiple meshes can be used for parallel processing. A grid convergence study is necessary because the solution highly depends on the numerical grid and time discretization.

3) Structural material properties and boundary conditions. Boundary conditions are applied to solid surfaces. Materials are defined by their thermal conductivity, specific heat, density, thickness, and burning behaviour. External environment conditions of ambient temperature, pressure and humidity can be applied on the outer boundaries.

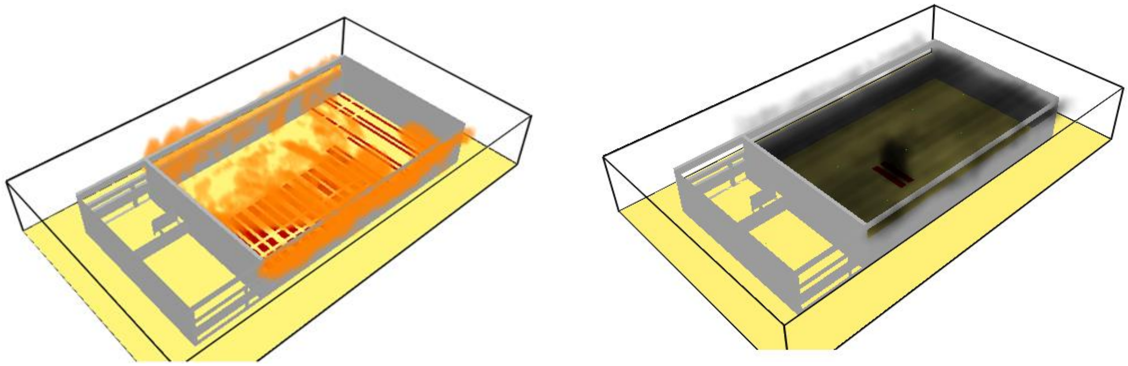
4) Simulation of fire. This is the most important parameter of the fire analysis. In FDS there are two ways to model the fire. The first is to directly specify the Heat Release Rate Per Unit Area (HRRPUA), which could be either constant or changing with time. This is a fairly straightforward method that allows almost full control of the fire parameters. The second is to allow FDS to predict the energy released from the fire by specifying the thermo-physical properties of the materials that act as fuels. This method is considerably more complex as it tries to simulate both the pyrolysis process with its produced gases and after that the actual combustion. For a more accurate solution of the pyrolysis equations a very fine grid is needed, which would be inappropriate for most civil engineer cases. In both methods the input data needs to be carefully chosen in order to avoid the Garbage In – Garbage Out phenomenon.

5) Results data acquisition. In FDS it is necessary to prescribe from the beginning of the simulation what kind of data needs to be recorded as it is done in a physical experiment. Some of the parameters that can be recorded are:

- Temperature time histories in specific positions near the steel frames
- Temperature time histories of element surfaces
- Temperature distributions with time at planes in the interior and exterior of the building (temperature plane slices)
- Velocity fields at planes in the interior and exterior of the building
- Pressure fields at planes in the interior and exterior of the building
- Total Heat Release Rate of the analysis
- Smoke production and concentration

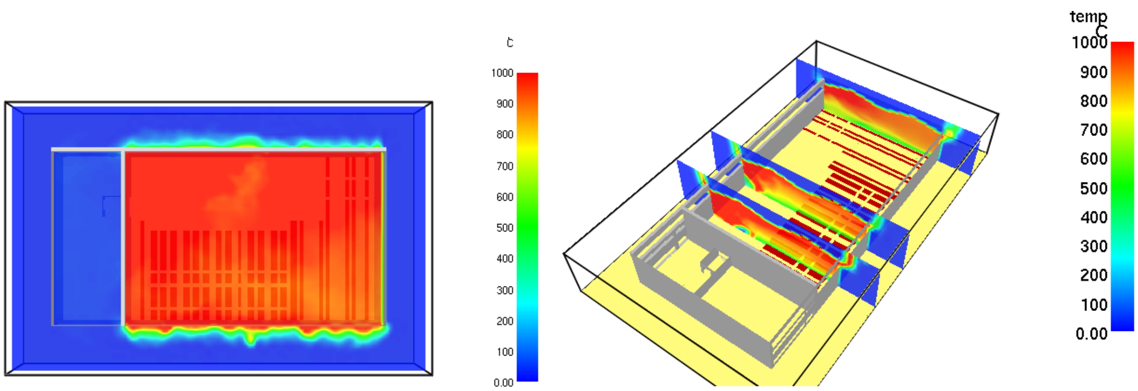
Sample results of an FDS fire scenario analysis in an industrial building used as a storage facility are given in Fig. 3a/b, Fig. 4a/b and Fig 5. The building has a floor plan of 80x40m with a height of 12m. It is divided in two main compartments, the main storage area and a two-storey office area. In the storage area the supplies (plastics in cardboard boxes) are stored in 6.25m high racks. The structural system consists of seven double-span steel frames.

Fig. 2 3-D model of building and rectilinear grid for CFD analysis



(a) (b)

Fig. 3 a) Heat Release Rate per Unit Volume b) Smoke distribution inside and outside the compartment



(a) (b)

Fig. 4 a) Temperature distribution under the roof b) Temperature distributions in the compartment

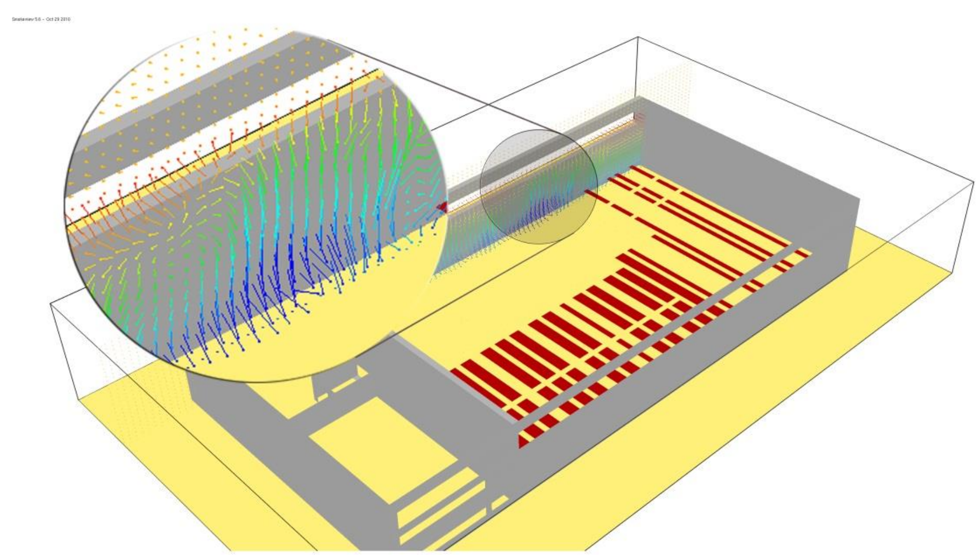


Fig. 5 Velocity vector field inside the compartment near the windows

5. SAFE PRACTICE IN CFD MODELLING

Despite the fact that CFD models have been verified and validated in multiple cases [3],[5],[6], they have limitations and if not used carefully they can be potentially misleading. Alike the advanced non-linear structural models, CFD models are very dependent on the values of the parameters used and they can be equally important as the actual mathematical model used in the analysis. The risk of incorrect results is higher though in CFD than structural models, due to the fact that modelers, especially the ones derived from the structural field, are not very familiar with the physical phenomena and behavior of fire. Therefore, it is necessary to perform extensive checks when using CFD models for fire analysis and design.

First of all, a sensitivity study to other parameter values has to be performed, before finalizing the model to be used for the analysis. The parameters in the analysis are literally hundreds, but at least the ones with the higher impact on the simulation need to be tested. Secondly, the results of the model ought to be confirmed by alternative means such as hand calculations, experimental data and expected physical behavior of the fire case. Thirdly, the model needs to be validated for similar scenarios so as to be confident of the validity of the method chosen to be applied. Also, third party reviews from experts in the field, would guarantee that the considered model is adequate for the purpose of the analysis and the results obtained can be safely used for any conclusions or design process that will be based on them. Last but not least, the designer needs to be aware of the model capabilities and limitations so as to interpret the results in their true context without extrapolating further than the approved field of its application. To conclude, CFD models are a breakthrough in fire study and analysis, providing cost-effective alternatives to expensive fire tests through simulations, and can be a very powerful tool in fire engineering when used rationally. And to quote George E. P. Box, “Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful” [7].

6. REFFERENCES

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ΣΧΕΔΙΑΣΜΟΣ ΚΑΤΑΣΚΕΥΩΝ ΕΝΑΝΤΙ ΠΥΡΚΑΓΙΑΣ ΜΕ ΤΗ ΒΟΗΘΕΙΑ ΤΗΣ ΥΠΟΛΟΓΙΣΤΙΚΗΣ ΡΕΥΣΤΟΔΥΝΑΜΙΚΗΣ

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ΠΕΡΙΛΗΨΗ

Στον Ευρωκώδικα 1 μέρος 2 παρέχονται κανονιστικές καμπύλες θερμοκρασίας-χρόνου και απλοποιημένα μοντέλα για τον υπολογισμό των φορτίων της πυρκαγιάς. Οι απλοποιημένες αυτές μέθοδοι όμως, είτε δεν εκφράζουν τις πραγματικές συνθήκες πυρκαγιάς, με αποτέλεσμα την υπερδιαστασιολόγηση, είτε έχουν περιορισμένο πεδίο εφαρμογής, καθιστώντας τες μη εφαρμόσιμες σε κατασκευές με ιδιαίτερη αρχιτεκτονική, ή σε μεγάλα βιομηχανικά κτίρια.

Μια εναλλακτική προσέγγιση είναι η χρήση της υπολογιστικής ρευστοδυναμικής, με ειδικούς κώδικες για την ανάλυση θερμικών ροών από φωτιά, όπως ο Fire Dynamic Simulator του NIST. Τα προσομοιώματα, σε συνδυασμό με τα στατικά μοντέλα μπορούν να αποτελέσουν το βασικό εργαλείο για τον σχεδιασμό με βάση την επιτελεστικότητα. Η ανωτέρω μέθοδος, εφόσον χρησιμοποιείται σωστά και εντός του πεδίου εφαρμογής της, μέσω της προσομοίωσης πολλαπλών σεναρίων πυρκαγιάς βοηθά τον μηχανικό α)στη μελέτη της εξάπλωσης της φωτιάς, του καπνού και των τοξικών αερίων εντός του πυροδιαμερίσματος και β) στην διερεύνηση της χωρικής και χρονικής ανάπτυξης των θερμοκρασιών στη περιοχή των δομικών μελλών. Τα εξαγόμενα αποτελέσματα μπορούν να χρησιμοποιηθούν για την μετέπειτα δομοστατική ανάλυση της κατασκευής. Στην εργασία παρουσιάζονται ενδεικτικά αποτελέσματα από την εφαρμογή της μεθόδου σε ένα βιομηχανικό κτήριο.