Modelling Real Fire by FDS and 2-Zone Model for Structural Post-Fire Assessment

Tom Molkens[1(✉)] and Barbara Rossi[1,2]

[1] Department of Civil Engineering, KU Leuven, Technology Campus de Nayer,
Jan Pieter de Nayerlaan 5, 2860 Sint-Katelijne-Waver, Belgium
`tom.molkens@kuleuven.be`
[2] Department of Engineering Science, University of Oxford,
Parks Road, Oxford OX1 3PJ, UK

Abstract. Post-fire resistance assessment of industrial structures is of prime importance to companies having to deal with such accidental situations. Most of the time, the structure or at least a major part of it still stands. Being able to quickly assess the temperature it was once submitted to, is very important to reevaluate its load-bearing capacity. The latter is to help take wise decisions regarding its dismantling or replacement and to avoid unnecessary delays during which the industry can no longer carry out its business. This paper describes a quick methodology to do so and demonstrates its accuracy with a case-study. Although full-scale fire experiments are reported in the literature, they are mostly under-instrumented, in such a way that few information is usually available. However, in 2018, a full-scale and fully instrumented fire experiment was conducted by Tongji university on a steel frame single-story building. This case study is simulated in the present paper using two different numerical simulation techniques, namely 2-Zone model using Ozone and Computational Fluid Dynamics using Fire Dynamics Simulator (FDS). Through the FDS model, several features of the test can be thoroughly modeled to increase the accuracy of the results, however increasing the calculation time. While the 2-Zone model delivers quick and accurate results (time versus temperature development) especially if the model can be calibrated by the use of tests or based on visual observations reported by the fire brigade during the fire.

Keywords: FDS · 2-Zone model · Single story · Real fire · Post-fire assessment

1 Introduction

Post-fire load bearing assessment of industrial structures is of high economic importance for most companies, which must deal with such accidental event. In many cases, the structure exposed to the fire still stands and can be reused. And, therefore, the financial as well as time consequences for the company can be reduced. To obtain a better insight in the temperature development of load-bearing elements reached by the fire, there is a need for fast and reliable predicting models further evidenced by observations made during and after the fire by, for instance, the fire brigade. In the perspective of the structural response, pyrolysis with a gasification stage followed by

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combustion is of no interest. Nevertheless, the assessment should at least provide insight into the real temperature development that took place, based on a limited set of data.

This paper deals with post-fire situations, hence the fire-load can be well described which is most of the time not the case, especially in a design. The knowledge of the thermal load on a structure and its initial boundary conditions [1] are the main parameters to start with a resistance verification in case of fire. To obtain an idea of the temperatures reached in the structural elements during and after the fire, measurements (based on tests), photos and videos can be of great help but, most of the time, only some external visible parameters can be used, like, for instance, the melting or degradation temperature of the materials included in the building. The accuracy of such an evaluation is high enough when the considered material is fully accessible and not influenced by the surrounding environment. On the contrary, the temperature reached by non-visible parts of the structure (like the upper flange of a beam for example) can rarely be estimated. To fill this lack of knowledge, a simulation of the effect of a real fire on a structure can be done by the for example 2-Zone models or using Computational Fluid Dynamics (CFD). Validation can be made using the collated (visual) information to evaluate the accuracy of the model.

2 Reference Full-Scale Fire Tests

Only very few well instrumented and controlled fire tests on buildings are available to study the accuracy of simulations. On several occasions, the carried test did not lead to the expected conclusions because of environmental parameters. For example, during a previously executed real scale fire test in Belgium, in collaboration with KU Leuven, it was not possible to foresee the location of collapse due to a change in the wind direction during the test [2]. In France, a warehouse was set into fire in the scope of the National project Flumilog [3] and, there too, a strong influence of the wind was noticed.

Recently, new data on the experimental study of a full-scale steel portal frame submitted to a real fire were published in [4] and [5]. This study was mainly done in collaboration with Tongji university, which is the reason why we will name it the Tongji-experiment in the present paper. Photos of the tested building were taken each 5 min, hence there is a possibility to compare our simulations against visual observations during the fire. Gas temperature data at 4 locations inside the compartment were also registered. Thermocouples were placed at four levels on columns, beams and rafters. All the measurements were published in [4]. The fire load was obtained via wooden cribs and is therefore supposed to be well-known. Based on this, a model of the test was prepared using an Fire Dynamics Simulator (FDS) version 6.7 software [6] to simulate the effect of the fire on the building. In this article, the focus will be put on how the combustion parameters can be obtained in a rather straightforward way and on the results of an advanced pyrolysis study.

3 The Tongji Experiment

3.1 Geometrical Information

An extensive description of the experiment and the recorded measurements can be found in [4] and [5], some data needed to understand the test will be described here below and illustrated in Fig. 1(a). Two steel frameworks were erected with a span of 12 m, a roof eave at 5.4 m and a roof ridge at 5.8 m. The building skin was made of sandwich panels i.e. rock wool insulation core in between two thin-walled steel sheets. An inner partition wall was added with a fire rate of 3 h (ISO834 fire), with an opening along the edges of 0.3 m on top and 0.15 m on the sides as well as a door of 1.0 by 1.8 m. By doing so, a fire compartment of 4.0 by 6.0 m is created. There is one window opening of 1 m wide and 0.8 m height. The authors do not provide information on the type of window that was used hence single glazing will be considered as well as the following assumption (based on the Luxemburg rules for Fires Safety Engineering purposes [7]): in combination with a smoke temperature of 100 °C or 250 °C, the window opening reaches 50% and 90%, respectively. It is worth pointing that, at this stage, it was already demonstrated in [8] that the stress distribution in the glass does not fluctuate a lot between 250 °C and 400 °C, and therefore neither does the failure risk. In the compartment next to this one, one external door of 2.0 by 3.0 m was included.

Another important statement at this stage concerns the opening factor O of the compartment which will be rather small. At the beginning of the fire, when the glazing is still intact, O is given by:

$$O = \frac{A_v\sqrt{h_{eq}}}{A_t} = \frac{1 \cdot 1.8\sqrt{1.8}}{2 \cdot 4 \cdot 6 + 2 \cdot 5.6 \cdot (4 + 6)} = 0.015 \qquad (1)$$

Where A_v = area of vertical openings, A_t = total area of enclosures and h_{eq} the weighted average of the window heights = $(\Sigma A_{vi} h_i)/\Sigma A_{vi}$.

The factor O is lower than the minimum boundary of 0.02 recommended in [9]. However, due to the glass breaking, the window opening reaches 90% of its theoretical surface, hence the opening factor increases up to 0.02 after this phenomenon. Equation 1 becomes Eq. 2 and it can be presumed that the fire will be ventilation controlled:

$$O = \frac{A_v\sqrt{h_{eq}}}{A_t} = \frac{(1 \cdot 1,8 + 1 \cdot 0.8)\sqrt{1.49}}{2 \cdot 4 \cdot 6 + 2 \cdot 5.6 \cdot (4 + 6)} = 0.020 \qquad (2)$$

Thermocouples were placed on trees (= vertical steel bar with thermocouple devices attached at different levels) between the wooden piles as well as on the steel elements (locations 1# and 4#), where 4 positions were measured: at 1/4th 2/4th, 3/4th and on top of the element; in the neighbouring compartment (locations 2# and 3#), where 2 positions were measured: at half and on top of the element.

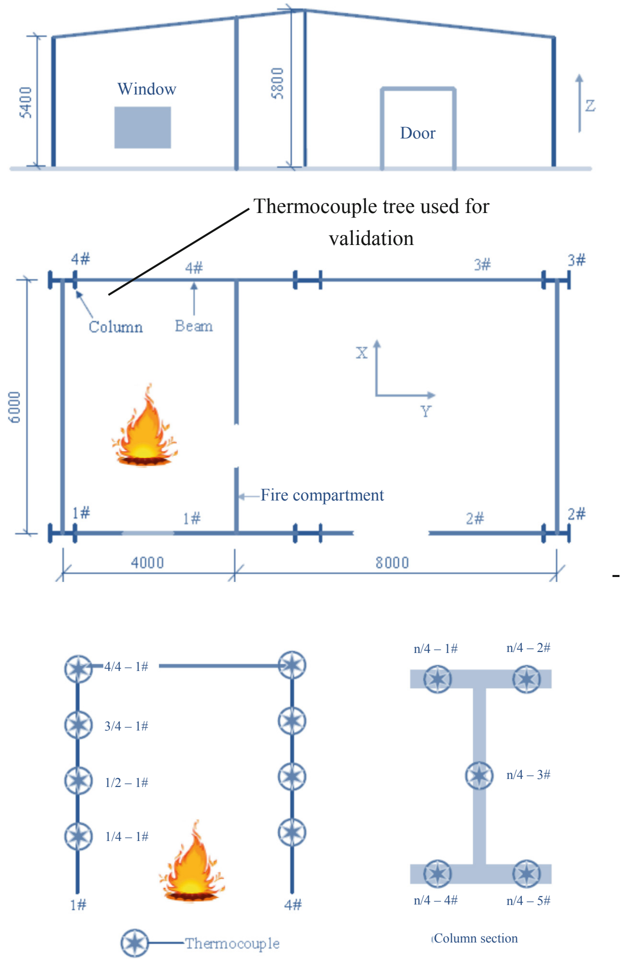

Fig. 1. Overview of the structure and fire compartment (a) and measurement equipment (b) [5]

3.2 Fire Load

Following the description, a fire load of 81900 MJ was present. It was made of four piles of wooden cribs. Nevertheless, our calculation revealed an overprediction of that load, which was, in the meantime, confirmed by the authors themselves. Indeed, four piles of wooden cribs were present, each pile made of 20 layers with 15 sticks on each layer. Depending on the layer, the wooden lengths were ranging between 1.5 and 2 m, with a cross-section of 50 by 50 mm^2. Considering a combustion heat for wood of 17.5 MJ/kg and a mass density of 440 kg/m^3, we obtain half of the fire load provided in [4]. This can be worked out as the product of [the number of sticks] by [half of the number of layers] by [the length of parallel and perpendicular layers] by [the gross section] by [density] by [combustion heat] as expressed in Eq. (3). The difference with the reference article is that the authors used the gross volume of the piles instead of its net volume. With a floor area of only 24 m^2, the fire load density is 40425/24 = 1684 MJ/m^2.

$$\text{Fire load} = 4 \cdot 15 \cdot 10 \cdot (1.5 + 2) \cdot 0.05^2 \cdot 440 \cdot 17.5 = 40425 \text{ in } [\text{MJ}] \tag{3}$$

The measured heat release rate was about 5 MW per pile, a similar value is obtained by the application of the annex E of Eurocode 1 [9]. However, in [4], it is stated that the total heat release rate was (4 times 5) 20 MW. Nevertheless, with a ventilation-controlled fire, this will not be the case and the prescriptions of the Eurocode 1 limit the heat release rate to Eq. (4):

$$\text{HRR} < 0.10 \cdot m \cdot H_u \cdot A_v \cdot \sqrt{h_{eq}} = 4.45 \text{ in[MW]} \tag{4}$$

4 Fire Models

4.1 2-Zone Model

In the reference article [4], a simulation was made using a parametric fire method. It is worth pointing that this method can be used as the fire load $q_{t,d}$ (based on the total surface of the surroundings) is lower than 1000 MJ/m^2. Presently it is 1684 MJ/m^2 of floor surface (initially estimated as double). For this reason, a simulation of the experiment as a 2-Zone model using the well-known Ozone software version 3.0.1 [10] was carried out. The 2-Zone model automatically becomes a 1-zone model if one of the following four criteria is met: the upper layer temperature is ≥ 500 °C; the combustible in the upper layer and the upper layer temperature is $\geq$ the ignition temperature of 300 °C; the interface height is ≤ 0.2 of the compartment height or at least the combustion area is $\geq 1/4^{\text{th}}$ of the floor surface.

A user-defined fire characterised by the previously described geometry of the fire compartment was introduced, with a t_α of 300 s, a heat release rate of 500 kW/m^2, a fire load of 1684 MJ/m^2 and a danger of fire activation equal to 1. The heat release rate (HRR) and the temperature of the upper layer (Ozone) are respectively presented in Figs. 2 and 4.

A comparison between the visual observations during the test and those preliminary calculations was also made. It shows that 5 min after ignition, the fire was seriously developing but that the glazing of the window was still intact. In other words, the flashover occurs 300 s after ignition, despite the intact glazing. The Ozone calculation leads to a flashover after only 60 s seen that, at that time, it automatically switched from 2 to 1 zone.

As for the post-fire simulations, it can be noticed from Figs. 2 and 4 (Ozone shifted), where the Ozone upper layer temperatures and the measured steel temperatures in the column 1# are provided, that the tool is appropriately predicting the smoke temperature. Note that, the Ozone temperature-time relation is shifted by 500 s which is the ignition time and that the smoke temperature is compared to the steel temperature causing a

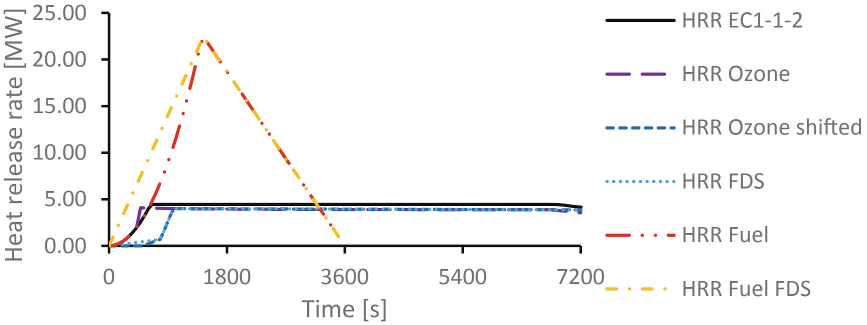

Fig. 2. HRR obtained by Ozone, application of EN1991-1-2 or a fuel-controlled fire

slight decrease. The visual observations become rather important to define this so-called shift. Indeed, since glazing is still intact after 800 s (ignition time + 300 s), the smoke temperature at that moment should still be around 250 °C i.e. the failure criteria for glass. Using Ozone, this happens after 286 s.

On the one hand, the smoke temperature calculated by Ozone is slightly in advance compared to the steel temperature (which may be expected). But, on the other hand, this is not the case for the thermocouple situated at 3/4th of the column height. After 900 s or 15 min of fire (= after ignition), a peak temperature over 1100 °C is measured as can be seen in Fig. 4.

Moreover, the structure starts to fail, the wall cladding tears apart leading to an extra amount of oxygen at that location with higher HRR and temperatures. It is also clear that, after 19 min of fire, the shape and volume of the compartment have

Fig. 3. Visual observations during the test [5]

drastically changed, see Fig. 3. Due to the extra amount of oxygen and the changes in shape, the interesting time range is limited to about 15 min and definitely lower than 19 min after fire ignition [5]. It is the area shaded in light grey in Fig. 4.

After a thorough study of the articles [4] and [5], which both describe the same experiment, it came out that the reported measured steel temperatures beneath 800 s were different. After feedback of the authors, it became clear that the results as they are presented in the journal article are more reliable.

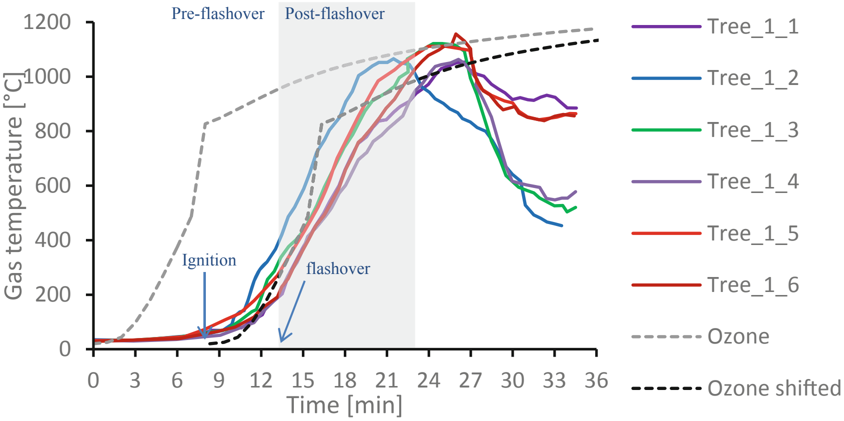

Fig. 4. Measured temperature development on the steel Sect. 1# [5] together with the Ozone evaluation of the upper layer temperature

4.2 FDS Model

FDS or Fire Dynamics Simulator [6] is a widely used powerful tool for the description of the fluid behavior in case of fire. Through the use of computational fluid dynamics, it is possible to go much further in detail in the simulation but on the other hand this numerical tool requests also much more information to describe the fire and the boundaries.

General Introduction to the Model. The smallest dimension of the wooden cribs is 50 mm. For that reason, the minimum mesh size was put equal to 50 mm. A mesh sensitivity check was executed with a finer mesh of 25 mm cubes till 15 min, the comparison will be shown later on in this section. The FDS version 6.7 [6] was used. The numerical domain was limited to the combustion area except for the wall with an opening, where an extension of 1.5 m outside was considered. The geometry of the model is shown in Fig. 5.

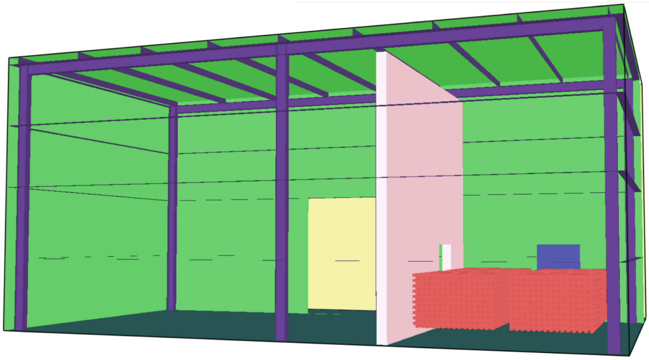

Fig. 5. FDS Model of the structure, with view on fire load, window, door and gate

The floor is made of concrete, sandwich elements are used for the walls, the roof and the open space for the external part. Standard material characteristics were collected out of the literature as presented in Table 1 as they are not provided in [5].

Table 1. Material characteristics

Description	Material	Thickness [m]	Conductivity [W/mK]	Specific heat [J/kgK]	Density [kg/m^3]	Backing
Floor	Concrete	0.15	1.6	1000	2300	Exposed
Fire wall	Cellular concrete	0.20	0.14	840	550	Exposed
Profile	Steel	0.01	45	600	7850	Exposed
Sheet	Steel	0.0005	45	600	7850	Exposed
Insulation	Wool	0.075	0.037	1030	60	Exposed

Applied Fire Load. The global physical reaction of the wooden cribs was introduced as $C_{3.4}H_{6.2}O_{2.5}$ with a soot yield of 0.015 and a heat of combustion equal to 17.5 MJ/kg. No attention was paid to travelling fire due to the relatively small size of the compartment.

Uniformly Distributed Fire Load. As first simulation was used as upper bound: the combustion product develops the highest possible HRR. The combustible amount of energy was previously calculated as 40425 MJ. In the assumption of a linearly increasing heat over a period of 1440 s (time of maximum reached temperature in the compartment) and decreasing over 2160 s, the energy over time is 22458 kW. This is more or less the description of a fuel-controlled fire with a quadratic growing stage as mentioned in [9] with the formulation of Eq (5).

$$Q = \left(\frac{t}{t_\alpha}\right)^2 \text{ in [MW]} \tag{5}$$

After reaching the peak value a linear decrease is assumed. The difference between the quadratic increase using Eq. (5) with a t_{α} = 300 s (moderate growing rate) and the linear approach can be seen in Fig. 2, respectively "HRR Fuel" and "HRR Fuel FDS".

In sum, as long the fire acts in an enclosed space, it is ventilation-controlled and the previously calculated HRR versus time curve are valid (see section about the 2-Zone model). So, except for the fuel-controlled fire simulations, the fire load will be based on the shifted Ozone curve of the HRR (Fig. 2) which is almost the one of EN 1991-1-2.

Local Fire. It could be assumed that the behavior of the four "piles" of interlaced and layered sticks (or cribs) could better be modelled using four separate local Hasemi-fires. In [9], the HRR can be calculated on the roof where the flame does not touch the ceiling. With a position of the fire load based on the experiment and the FDS simulation (Fig. 5), a quasi-uniform HRR can be obtained at the roof level. For the size of the fire load, an equivalent diameter of 1.96 m was calculated. The Fire height is taken equal to 1 m from the top of the wood pile.

4.3 Parameters Investigated in the FDS Model

Geometry of the Fire Load. Based on [11], where a simplified predefined heat release rate pro unit area (HRRPUA) is provided, several simulations were presently done, in which the geometry of the fire together with the condition which control the fire (fuel or ventilation) leads to different HRRPUA are as follows:

- For a crib under the condition of a fuel-controlled fire, we have:
  $22458/[4 \cdot 15 \cdot 10 \cdot (1.5 + 2.0) \cdot 4 \cdot 0.05] = 54 \text{ kW/m}^2$,
  since cribs are presumed to burn on four sides.
- For a crib with a ventilation-controlled fire:
  $4450/[4 \cdot 15 \cdot 10 \cdot (1.5 + 2.0) \cdot 4 \cdot 0.05] = 10.60 \text{ kW/m}^2$,
  under the same conditions as above.
- Pro pile for a ventilation-controlled fire:
  $4450/[4(1{,}5 \cdot 2{,}0 + 2 \cdot (1.5 + 2.0) \cdot 1)] = 111{,}25 \text{ kW/m}^2$,
  it is assumed that the burning face corresponds to the top and the four sides.

Window Breaking. In Sect. 3.1, it was shown that *O* is rather low and could impact the fire development. For that reason, several fire glass-breaking scenarios were investigated:

- With no glass at all (upper bound), refer to the last section about the thermocouple devices.
- With the glass consisting of an upper (from 1.4 till 1.8 m) and lower part (from 1.0 to 1.4 m) and breaking at a temperature of 250 °C (the temperature being controlled at 0.05 m out of the glass (to the fire).
- Same as above. At this moment no longer a simple temperature device is used but a thermocouple device. The difference between these two will be discussed in the last section about the thermocouple devices.

Mesh Size. For the models with cribs of 5 by 5 cm, a mesh size of 5 cm in all directions is used which can be doubled or tripled (going up to 0.15 m) when a pile is considered. The latter value was kept as the maximum value due to the size of the roof girders (the height of which is 0.15 m). In the simulation, a perfect cubic mesh geometry was used.

Thermocouple Devices. Since no specification about the used devices could be found in [5], traditional temperature devices measuring the temperature of the gases were firstly included in the first two models. In [4] however, it is mentioned that k-type thermocouples were used thermocouples were then used in the subsequent simulations. The default setting parameters for a FDS thermocouple were used (i.e. diameter 1 mm, emissivity 0.85, density 8909 kg/m^3 and specific heat 0.44 kJ/kg/K for nickel).

5 Results

Eight simulations were conducted in total, as can be found in Table 2. One can find, in order of appearance, the type of HRR: simplified model based on measurements of time and temperature (fuel-controlled) or the so-called shifted 2-Zone Ozone model (ventilation-controlled); the fire load: cribs or pile; the scenario of window openings: (a) completely open from the start, (b) one glass panel or (c) failure in two steps; the type of temperature measurement devices: T = Temperature and TC = thermocouple device; and, last, the mesh size (Mesh) in [m]. Three time-related information are provided too; the simulation time (stopped after about 35 min), the average of the achieved simulation time in seconds per day and the total simulation time needed in days.

Table 2. Overview of FDS models

#	HRR	Fire	Window	Dev.	Mesh [m]	Time [s]	CPU [s/day]	CPU [days]
1	Meas.	Cribs	(a)	T	0,05	2153	9	227
2	Ozone	Cribs	(c)	T	0,05	2131	23	93
3	Ozone	Pile	(c)	T	0,05	2131	27	80
4	Ozone	Pile	(b)	TC	0,05	2117	22	98
5	Ozone	Pile	(b)	TC	0,1	2100	263	8
6	**Ozone**	**Pile**	**(a)**	**TC**	**0,1**	**2100**	**263**	**8**
7	Ozone	Pile	(b)	TC	0,15	2100	2100	1
8	Meas.	Pile	(b)	TC	0,15	2135	1068	2

The first model cannot capture in a proper the delay of the ignition or the temperature development because of the limited ventilation conditions which are presently not properly modelled. In the second model, thanks to the shifted HRR, a better approximation of the start of the fire is obtained. However, the opening scenario (c) leads to heavily fluctuating temperatures. Simulating the fire load using solid volume instead of bricks delivers better results. The temperatures are well predicted till about 500 °C. Changing to one glass panel does not influence the results. The same can be concluded when increasing the mesh size to 0,15 m. It should be noted that if the HRR is calculated with glass breaking, it is redundant to include the window in the simulation.

Hence, the next simulation, which is the one depicted in Fig. 6, was done with an open window (scenario (a)) from the start. In this figure, the measured temperatures of tree #1 are provided together with the original and shifted 2-Zone Ozone simulation in grey and black dashed lines, respectively. The FDS calculated gas or thermocouple temperature are provided as dotted lines, for the simulation #6 (in bold).

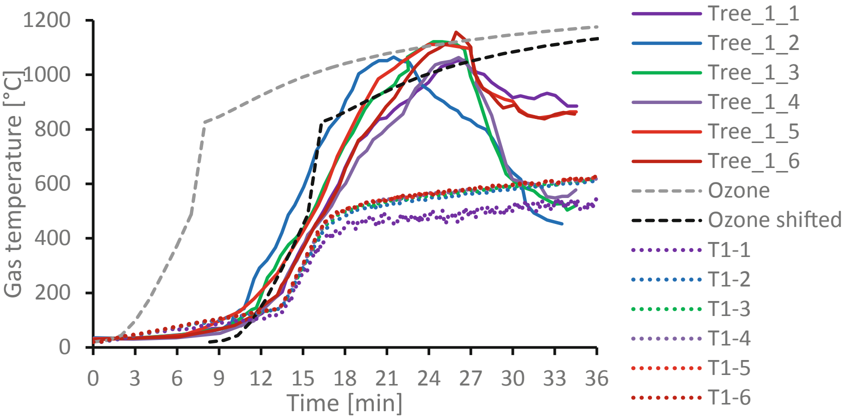

Fig. 6. Temperature measurements, Ozone and FDS for ventilation-controlled, pile fire without glass panel and 0.10 m mesh size

Out of Fig. 1, one can notice that FDS, 2-Zone Ozone and the experiment itself deliver comparable results until about 450 °C. The simulation #6, though delivering the best agreement with the measured results, is however not able to capture the post-flashover behavior in an accurate way. The obtained temperatures remain at about 400 °C too low compared to the test or to the 2-Zone Ozone results. Solving energy and mass equations for such a large compartment (compared to the cell size) is probably causing the large discrepancy, however this should be properly and more thoroughly investigated.

6 Conclusions

This paper describes a quick methodology to obtain the temperatures reached in a structure during a fire and demonstrates its accuracy with a case-study. The case study is a steel frame single-story building submitted to a real fire. It was simulated in the present paper using two different numerical simulation techniques, namely 2-Zone model using Ozone and Computational Fluid Dynamics using Fire Dynamics Simulator (FDS).

Today, even though FDS is considered inappropriate to simulate flashover in large compartments, it still stays a powerful instrument to study more local effects. As such it can deliver valuable and helpful results for post-fire assessment. Through the FDS model, several features of the test can be thoroughly modeled to increase the accuracy of the results, however increasing the calculation time. Despite the sometimes immense required computing time, one herein demonstrated that the FDS model could predict the temperature development in a very accurate way, however, in this case, till a relatively limited temperature of about 450 °C. One of the simplest FDS model delivers the best fit with the measured temperatures, i.e. using a solid burning volume and the least fine mesh. As mentioned in the paper, since the calculated heat release rate took the glass breaking into account, all openings were set open from the beginning of the simulation, without breaking scenarios.

The 2-Zone model delivers quick and accurate results (time versus temperature development) especially if the model can be calibrated by the use of tests or based on visual observations reported by the fire brigade during the fire. The results are filling the gaps between what can be easily observed after the fire (or during, by the fire brigade) and what remains unknown. Looking towards time efficiency and accuracy, the 2-Zone model performed well, even till collapse of the building.

For post-fire assessment purposes, it can therefore be concluded that, only under very particular circumstances, an advanced modelling of the fire and the compartments will have to be carried out. A simpler model, such as the 2-Zone model presented in this paper can advantageously be used. However, a number of information are required to calibrate the model such as the temperature attained by some elements of the structure for example as well as the heat release rate per unit area. In the Tongji experiment, a big amount of data was available but, in most cases, only a few information will be available, and one has to base the iteration process only on a few specific known times (like failure or flashover) or temperatures. Herein, the time of glass breaking was, in this specific case-study, an important parameter used to validate the simulation.

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