TRAVELLING FIRE IN FULL SCALE EXPERIMENTAL BUILDING SUBJECTED TO OPEN VENTILATION CONDITIONS

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ABSTRACT

In the frame of the European RFCS TRAFIR project, three large compartment fire tests involving steel structure were conducted by Ulster University, aiming at understanding in which conditions a travelling fire develops, as well as how it behaves and impacts the surrounding structure. During the experimental programme, the path and geometry of the travelling fire was studied and temperatures, heat fluxes and spread rates were measured. Influence of the travelling fire on the structural elements was also monitored during the travelling fire tests. This paper provides details related to the influence of a travelling fire on a central structural steel column. The experimental data is presented in terms of gas temperatures recorded in the test compartment near the column, as well as the temperatures recorded in the steel column at different levels. Because of the large experimental data, only the fire test n°1 results are discussed in this paper.

Keywords: Structures; compartment fires; fire tests

1   INTRODUCTION

The response of a structure in fire is dependent on the fire exposure scenario. Small compartment fires behave in a relatively well understood manner, usually defined as a post-flashover fire, where the temperatures within the compartment are considered to be uniform. However, with modern architecture there is an important increase of open large-floor plan spaces, for which the assumption of post-flashover fire does not hold and there is instead a smaller localised fire that moves across the floor with time. The current design methods were developed using extrapolation of existing fire test data. These data come from small compartments tests for which a uniform distribution of gases and temperatures fit well. But as soon as large compartments are involved, this assumption does not hold anymore. After inspecting fires in large compartments that occurred the past two decades, the conclusion is that such fires have a great deal of non-uniformity. They generally burn locally and move across entire floor plates over a period of time. This

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phenomenon generates non-uniform temperatures and transient heating of the structure. This type of fire scenario is currently idealized as travelling fires [1].

In the EN1991-1-2 [2], only two models consider a non-uniform temperature distribution: the localised fire model and the advanced fire models (zone models and computational fluid dynamic models). Nevertheless, the localised fire method considers a static fire which do not translate the effect of a travelling fire (Figure 1a). For zone models, the situation starts as a two-zones model based on the the assumption of accumulation of combustion products in a layer beneath the ceiling, with a horizontal interface. Uniform characteristics of the gas may be assumed in each layer and the exchanges of mass, energy and chemical substance are calculated between these different zones. Although this model considers a non-uniform temperature distribution within the compartment, it does not translate the possible travelling nature of a fire. The CFD (computational fluid dynamic) models enable to solve numerically the partial differential equations giving in all points of the compartment, the thermo-dynamic and aero-dynamic variables. This tool is consequently complex (Figure 1b) and implies a high computational cost.
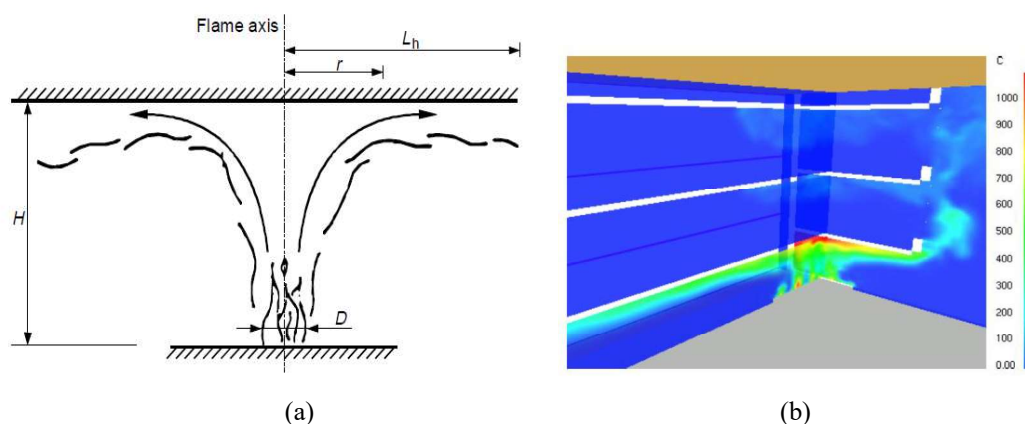

(a)   (b)

Figure 1. (a) Localised fire [2], (b) use of CFD in a case study with an atrium [1]

Travelling fires have been observed in several structural failures especially from 2000: The World Trade Center Towers [3] in New York City in 2001, the Windsor Tower [4] in Madrid in 2005, and the Faculty of TU Delft Architecture building [5] in Netherlands in 2008. The recent years have seen growing interest in investigating travelling fires which underlined the inadequacy of uniform heating in large compartments [6-12]. Further research effort is still needed, especially to extend the experimental results of such fire scenario.

2   EXPERIMENTAL PROGRAMME

During the experimental programme, three large-scale fire tests were conducted in a compartment with different boundary conditions having similar fire load (which can be observed on Figure 2a). The floor plan between the outer gridlines of the test structure was 15 m x 9 m as shown in Figure 3. The level of the ceiling from the floor finish surface was 2.90 m. The test compartment is a representative of a modern office building and represents a part of the entire office layout. The test compartment consisted of steel beams and columns as the main structural frame while hollow-core precast slabs were used for the construction of ceiling.. The fire load used for the three tests is also representative of an office building following references [2,10].

(a) Test 1: Opening area= 85.2 m^2.   (b) Test 2: Opening area= 30 m^2 (c) Test 3: Opening area= 10 m^2
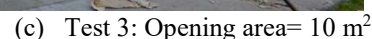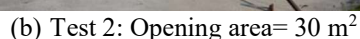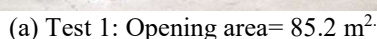
Figure 2 Different opening layouts were used for the three tests.
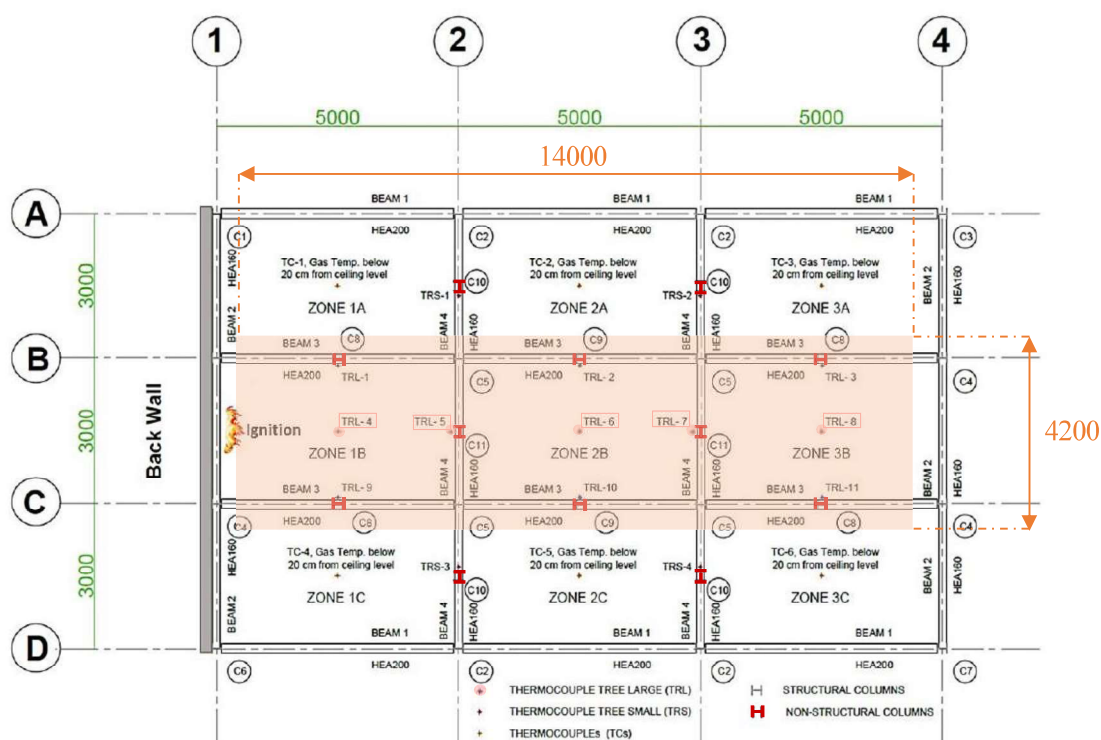

Figure 3. Layout plan of the structure and
location of the fuel load (dimensions given in mm)

2.1 Outline and formal structure

The structural steel frame of the test compartment was erected by Saverfield Ltd, local partner to FireSERT. The steel columns were separated into two categories, the structural columns and the dummy columns. The structural columns were part of the steel frame transmitting the loads to the foundation while the dummy columns were not part of the structural steel frame.

Table 1 Description of the steel structure

Description	Sections	Section Factor (m^{-1})	Length Height (m)	Protection Applied
Structural columns	HEA 200	209.5	3.5	Yes: R60
Dummy columns	HEA 200	209.5	2.7	No
Long beams	HEA 200	172.3	4.8	No
Short beams	HEA 160	138.0	3.0	No

All columns were fixed to the pre-existing reinforced concrete flooring via anchorage bolts. For the structural columns, four anchorage bolts were used while for the dummy columns, only two anchorage bolts were used for fixing purposes. The connections between the structural columns and beams were designed as fin-plates. The distance amongst the structural columns along the longer direction of the test compartment was 5000 mm while the same along the shorter direction was 3000 mm. The structural frame was laterally restrained using four diagonal bracings, two each along the longer and the shorter directions. The dummy columns provided for data acquisition purposes were anchored to the bottom flanges of the steel beams. The structural steel used for the construction of the test compartment was grade S355. Both the structural and dummy columns, as well as the beams provided along the longer direction, consisted for HEA 200 steel sections (see Table 1). On the other hand, the beams in the shorter direction consisted of HEA 160 steel sections. The ceiling consisted of 120 mm thick hollow-core precast concrete slabs spanning between the beams along the shorter direction of the test compartment. Keeping in view the usage of the test compartment, the main structural columns of the steel frame were protected using intumescent coating in order to maintain the structural integrity during the three fire tests. It can be seen in Figure 4, that only the structural columns are protected while the dummy columns are kept unprotected for data acquisition purposes.

2.2 Details of the fire load

The fuel wood source consisted of the species "*Picea abies*" with an average density 470 kg/m^3 having a moisture content of 15.22%. As the test compartment was a representative of an office building, Eurocodes propose a medium fire growth rate for such occupancy. In the frame of TRAFIR RFCS project, Gamba et al. [10] performed a series of fire tests with uniformly distributed cellulosic fire loads, aiming at defining an arrangement representative of an office building according to Eurocode 1. This work led to devise a well-established methodology, used to define the fuel load for the experimental campaign described in this paper. To achieve a medium fire growth rate for the office building, 9 layers of wooden sticks with an axis distance of 120 mm (90 mm intervals) were provided in three different directions. The wood sticks were 30 mm wide and 35 mm deep. The first layer of the wooden sticks was laid at 60° angle while the second was laid at an angle of 120°. The third layer was at 0° or 180° and the process was repeated in such a way the 6th layer of the sticks laid at 0° or 180° had a lateral offset of 60 mm with respect to the third layer as shown in Figure 4. The final layer, the ninth layer, of the fuel wood was at 0° or 180°, such an arrangement helped to visually observe the travelling behaviour of fire from one stick to another. The fuel load arrangement was kept same during all three tests while the boundary conditions were varied from one test to another.

Figure 4. Fuel load arrangement and steel columns (with and without fire protection)

The fuel wood was provided along the centre of the test compartment, as shown in Figure 4. The fire load was 14 m long stretching from wall to wall along the longer dimension of the test compartment. For convenience, a gap of 500 mm was maintained between the walls and the edge of the fuel bed at both ends. The width of the fuel bed was 4.2 m and was aligned with the centre line of the compartment. Such an arrangement of the fire load resulted in a distance of 2.4 m from the edge of the fuel bed to the centreline

of the columns provided along in the longer dimension along gridline A and D. The wood sticks were provided on a platform constructed using concrete blocks and gypsum fireboards as shown in Figure 4. The top surface of the platform was at a distance of 325 mm from the floor finish level.

3   DETAILS OF THE INSTRUMENTATION

The purpose of these large-scale tests was to investigate the dynamics of the travelling fires and to record fire related data. The recorded data included the compartment temperatures, temperatures in the structural steel components, the heat fluxes and the mass loss of the wooden fuel. For the purpose of data acquisition, intensive instrumentation was applied, which consisted of thermocouples, heat flux gauges, thin-skinned calorimeters, anemometer and the load cells (see detail of the large thermocouple trees, placed in the centreline of the compartment, in Figure 5, labelled TRL-1 to TRL-11)
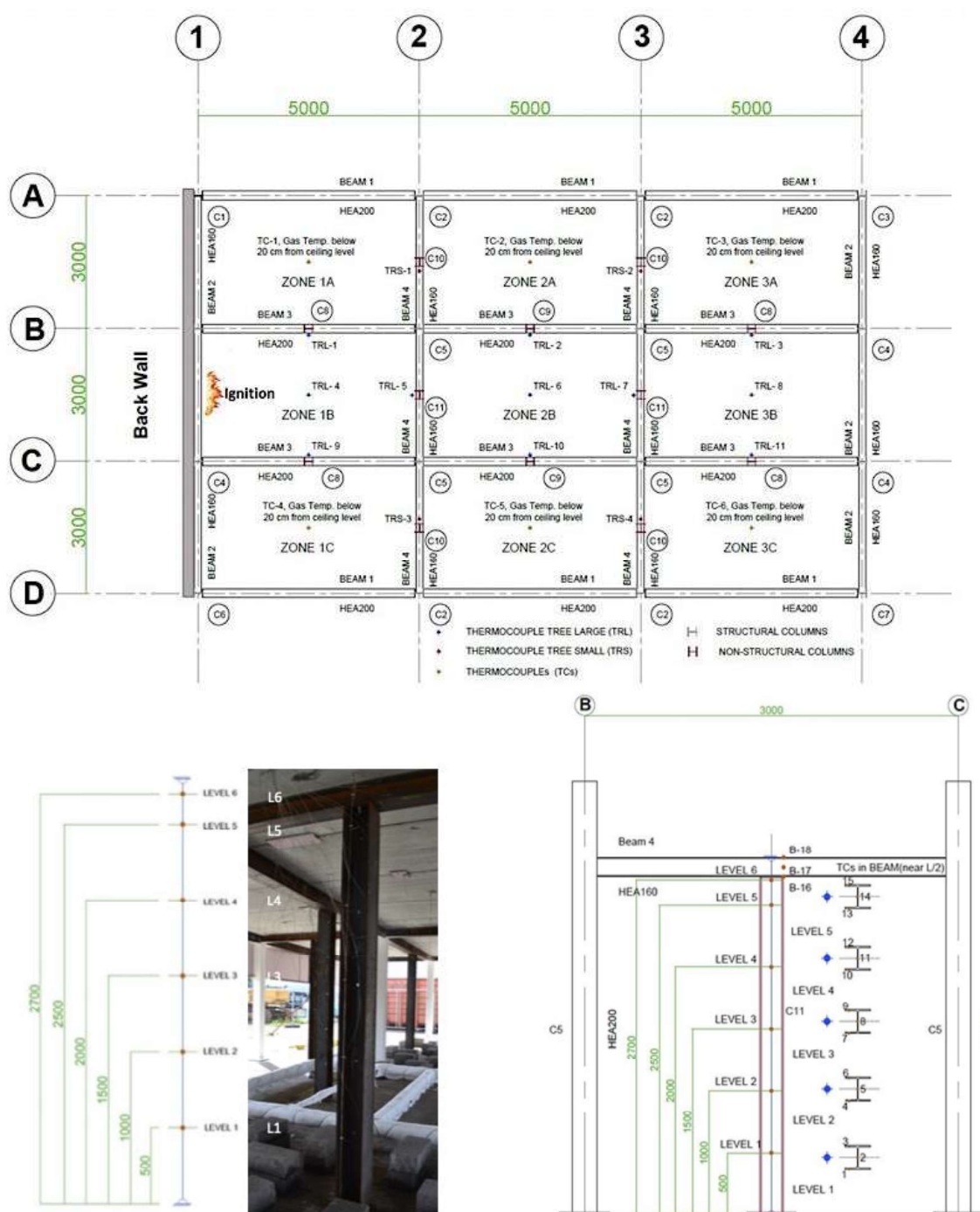

Figure 5. Location of the thermocouple trees in the test compartment and detail of the different levels of the thermocouples for the central zone

In addition to the data recorded in the compartment, temperatures were also recorded in the steel frame during the tests. Temperatures in the steel frame were recorded in the non-structural columns and the selected beams. All thermocouples were provided at 3 mm depth from the surface of the flanges and the steel web. The heat fluxes were monitored via Gordon Gauges (GGs) and the thin-skinned calorimeters (TSCs).

3.1 Mass loss recording

The mass loss was monitored in the middle of the test compartment between gridlines 2 and 3 using a steel platform as shown in Figure 6. The steel platform was 3 m long x 5 m wide and was supported using four load cells a shown in Figure 6. To avoid any damage to the platform during the fire tests, fire blanked was wrapped around the steel elements. The load cells were also protected using the fire blanket to avoid any damage resulting from rise in temperatures. On top of the steel platform, two layers of gypsum fire board were provided to support 4.2 m x 3.6 m of the wooden fuel. The layers of the fire board were placed 325 mm from the floor finish level and were aligned with other fire board panels used to support the fuel wood. Although the fire boards supporting the fuel wood above the steel platform were at the same level, these were kept segregated from the rest of the floorboards to ensure separation of the fuel wood for accurate measurement of the mass loss during the fire tests.
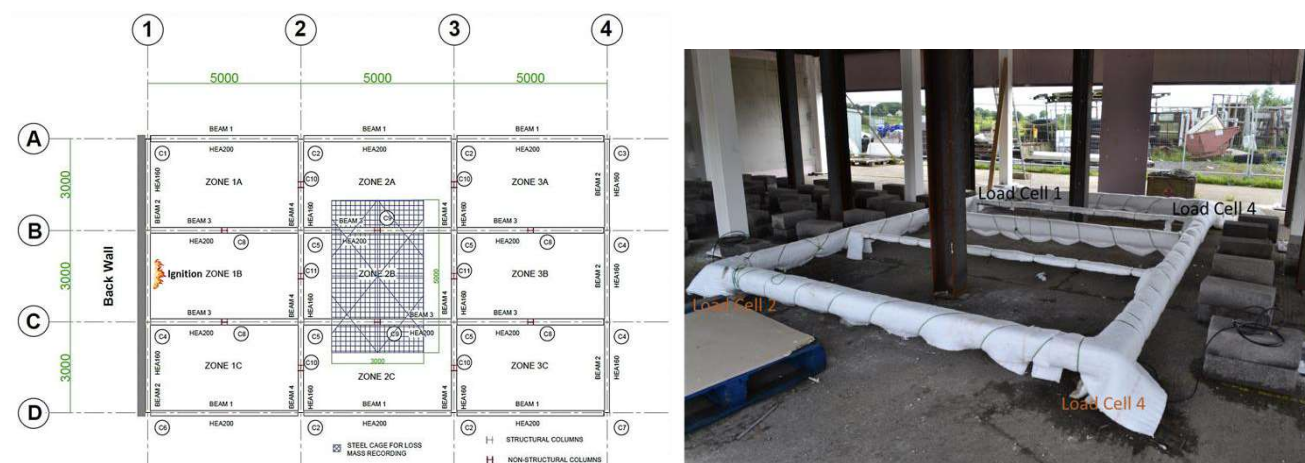

Figure 6. Position and arrangement of the mass loss recording though four load cells

3.2 Data logging system

All the assigned sensors were connected to the data logging system through extension cables. The extension cables were stretched along the roof and were connected with the data loggers stationed in the site office as shown in Figure 7. A layer of fire blanked was laid under these cables to evade any damage from the heat during the tests. Due to higher number of sensors applied, multiple data loggers were employed during the tests.

Figure 7. Extension cables for data sensors and data loggers

4   RESULTS AND DISCUSSION

In this paper only the first fire test results are presented. Figure 8 illustrates the travelling fire taking place along the length of the compartment through photographs and graphs plotting the evolution of gas temperatures in the compartment along the longer dimension, parallel to the path of the travelling fire, in five thermocouple trees (TRL-4 to TRL-8) equipped with six sensors each (as described in Figure 5). The first thermocouple tree was positioned in the middle of zone 1B at 1.5 m from the source of ignition. The remaining thermocouple trees (TRL-5 through TRL-8) along the centreline of the compartment were equidistant and positioned at 2500 mm centres.

The maximum temperatures recorded in TRL-4 were more than 1000°C after 20 mins from ignition but were measured for a very limited period of time, the gas temperatures quickly decreasing to reach the interval [800°C-900°C]. It is interesting to note that the plateau of the maximum recorded temperatures is longer at upper levels as compared to the lower levels. With the fire band travelling towards the next thermocouple tree, TRL-5, the temperatures recorded at TRL-4 reduce while the temperatures at TRL-5 increase. Temperatures recorded at TRL-5 reached the 900°C after 38 mins of the ignition. Similarly, the maximum recorded temperatures using TRL-6, TRL-7 and TRT8 at level 2 were 995°C, 975°C and 1000°C after 50 mins, 57 mins and 70 mins from ignition respectively as shown in Figure 8. It can be observed that the recorded temperatures vary along the height of the compartment, and that the TRL-6 to TRL-8 (placed in the second half of the compartment) present a shorter temperature peak than TRL-4 and TRL-5 (placed close to the ignition) from 2 m height.
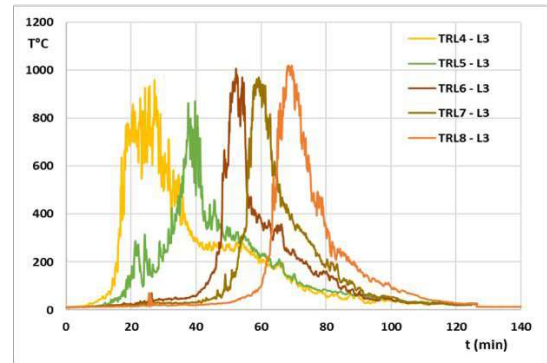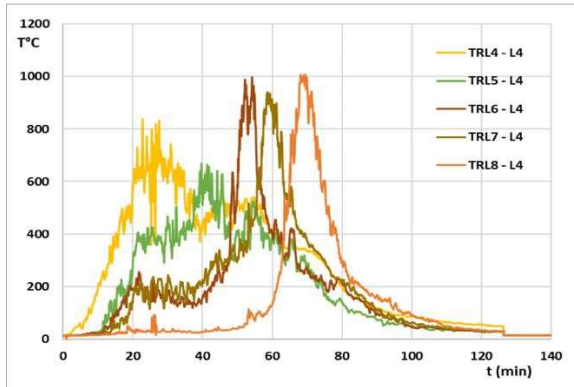

Time :12 min
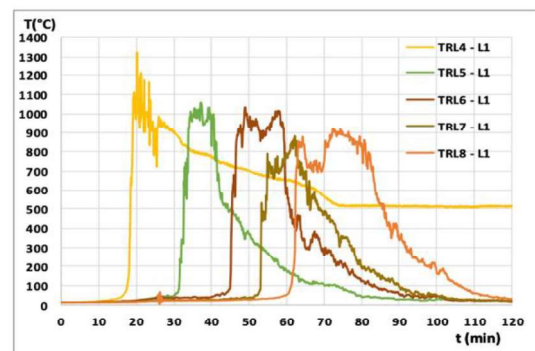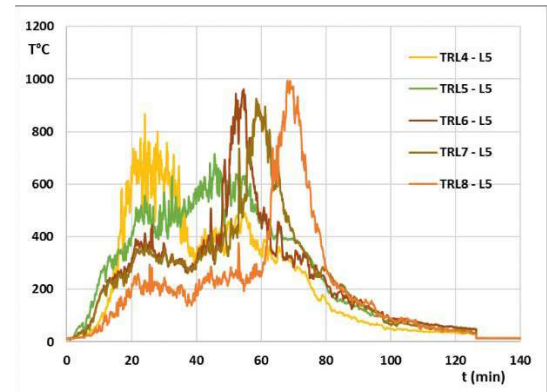

Height = 0.5 m
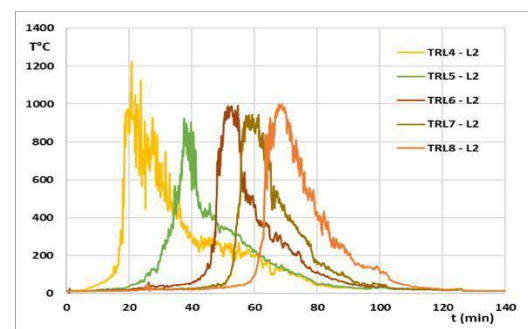
Height = 1.0m

Height = 1.5 m

Height = 2.0 m

Height = 2.5 m

Figure 8. Photographs of the fire and evolution of gas temperatures measured in TRL-4 to TRL-8 at 5 different levels

The maximum flame thickness (i.e. length of the fire along the longer dimension of the compartment) could be observed and is shown in Figure 9. The square markers correspond to a translation of the observations during the test, while the triangle markers correspond to inspection made from the video recording. The "travelling" behaviour of the fire (i.e. when the back end of the fire begins to travel) starts at 28 minutes from ignition for test n°1. This evolution suggests a fairly constant flame thickness of around 3.5 meters, with the lowest value occurring when the fire reaches the central bay of the compartment.
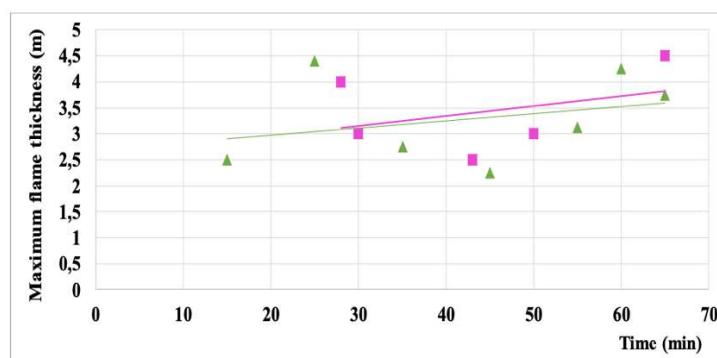

Figure 9. Evolution of the maximum flame thickness

4.1   Results of temperatures in the steel structure

Temperatures were recorded in the selected beams and the unprotected dummy columns. In this paper the column and beam along gridline 3 positioned between gridlines B and C have been selected for data presentation purposes, and thermocouples were placed as shown in Figure 5. During the test, it was observed that the fore end of the travelling fire reached the wooden fuel beneath the selected beam after 52 mins from ignition. The temperatures recorded at the ceiling level along the centre of the compartment (zone B) and the temperatures recorded in the compartment adjacent to the selected column using thermocouple tree TRL-7 are presented in Figure 10 and Figure 11, respectively. The temperature rises at higher levels L5 and L6 initiates earlier as compared to that at the lower levels. The temperature rise at L4 is earlier as compared to the remaining lower levels while it is slower in comparison with levels L5 and L6. This could be explained by the hot gases rising in the compartment, establishing in the upper part. For the bottom three levels, the increase in temperature is rapid as temperatures rise from 1000°C to 950°C within a few mins, translating the direct contact with the flames.
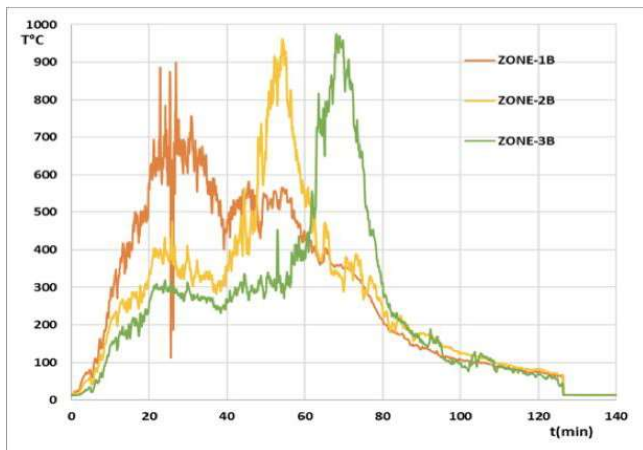

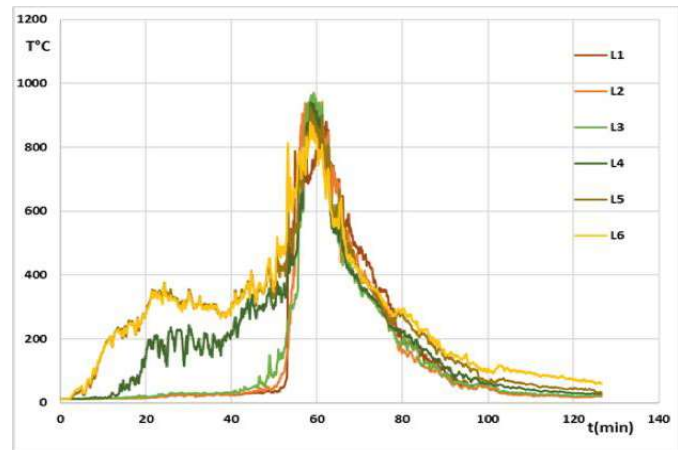Figure 10. Recorded temperatures at the ceiling level along the centre of the compartment (zone B)

Figure 11. Recorded gas temperatures in the thermocouple tree near the selected column and beam – TRL-7

The temperatures recorded in the flanges and the web of the column at level 3 are presented in Figure 12. Temperatures at level 2 rise after 52 mins from ignition while those at level 4 rise after 15 mins. For the first 50 mins from ignition, the rise in temperature at level 4 is slow while it rises significantly as the wooden fuel near the column starts to burn. The temperatures recorded across the section of the column at each level can be considered as uniform.

The temperatures recorded in the flanges and the web of the column (close to TRL-7) are presented in Figure 12. The label "LHS-F" corresponds to the flange closer to gridline C (i.e. those whose thermocouple number are 1, 4, 7, 10, 13 in Figure 5), "WEB-L" corresponds to the web and "RHS-F" corresponds to the flanges closer to gridline B (i.e. those whose thermocouple number are 3, 6, 9, 12, 15 in Figure 5). It can be seen that the steel temperature profiles are similar to the gas ones, with the following differences:

- The maximum steel temperature is 803°C at 63 minutes (versus 937°C at 58 minutes for gas temperature: this decrease, and delay translate the effect of the steel thermal inertia).
- The steel temperature descending branch is less steep than the gas temperature one (it reaches 500°C after around 80 minutes while the gas temperature one reaches this value after around 67 minutes).
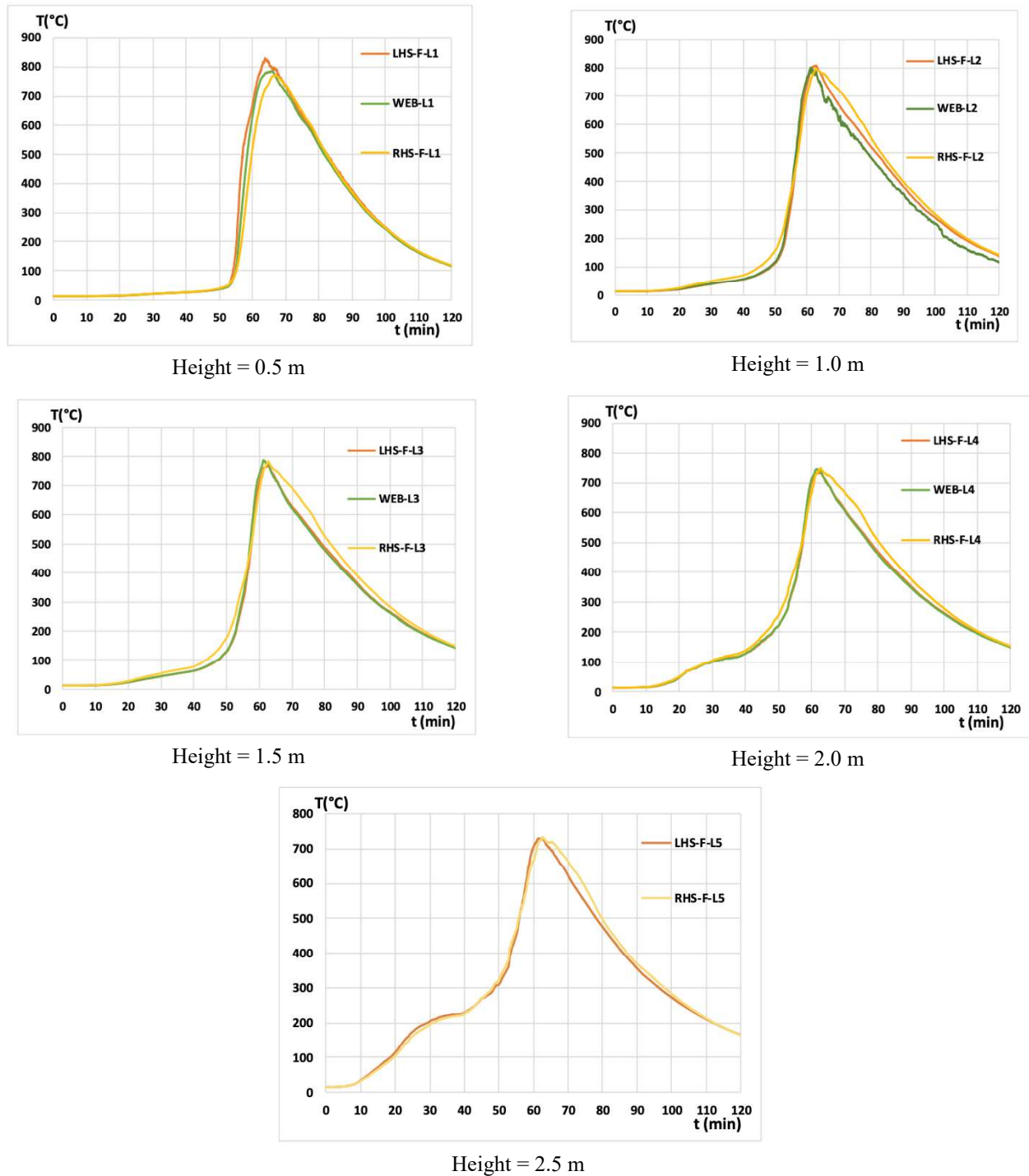- Also, the temperatures recorded across the section of the column at each level can be considered as uniform.

Height = 0.5 m

Height = 1.0 m

Height = 1.5 m

Height = 2.0 m

Height = 2.5 m

Figure 12. Steel temperatures at different locations along the height of the column close to TRL-7

4.2 Mass loss of the burning fuel

The mass loss data recorded during the test is presented in Figure 13. As observed during the test, a decrease in the mass of the fuel wood supported on the platform is seen once it catches fire after 37 mins from ignition. After 39 min, a uniform decrease in the wooden fuel mass is recorded. After 58 min from ignition, a slow reduction in the mass loss is recorded due to non-uniformity of the burning fuel. The mass loss recordings also comply with the observations during the test where most of the fuel wood provided on the platform was consumed after 64 minutes recoded in the selected column next to TRL-7.
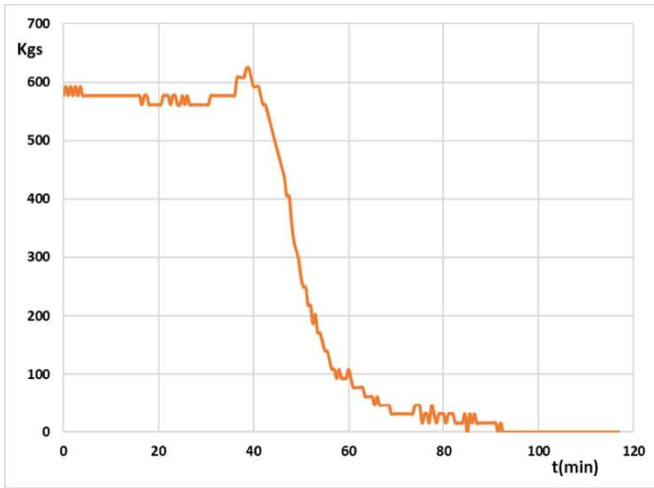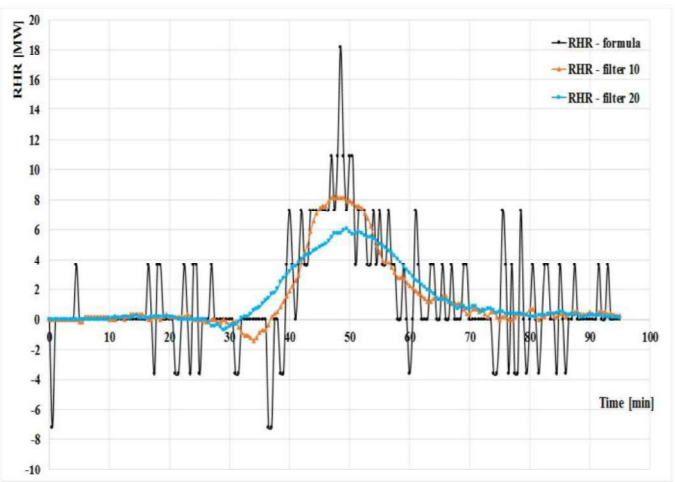
Figure 13. Recorded mass loss   Figure 14. RHR derived from the mass loss measurements

The mass loss rate [kg/s] is the variation of the solid fuel mass during the combustion process. It is possible to deduce the rate of heat release from the mass loss rate, since these two parameters are linked by the equations (1) and (2), Hu being the net calorific value [MJ/kg] and m being the combustion factor (considered equal to 0.8, following Eurocode 1). To evaluate the mass loss rate from the continuously measured mass, a backward finite difference scheme must be applied, which requires the definition of a fixed time step. There is no unique correct value for this time step; but the following consequences should be considered: a more important time step implies a smoother curve, while a less important time step translates in a more precise way the measurements but might provide unrealistic peaks (noise and outliers). Finally, a time step $\Delta t = 60$ seconds was considered as an acceptable compromise.

$$RHR(t) = H_u.m.MLR(t) \qquad (1)$$

$$RHR(t) = -H_u.m.\frac{dm}{dt} = -H_u.m.\frac{\Delta m}{\Delta t} \qquad (2)$$

As the mass loss rate is the derivative of an experimental signal, noise and outliers (for example negative values) are quickly generated. One method to cope with this is to filter the curve using, for example, a Savitzky–Golay filter. This digital filter that can be applied to a set of digital data points for the purpose of smoothing the data, that is, to increase the precision of the data without distorting the signal tendency. This is achieved, in a process known as convolution, by fitting successive sub-sets of adjacent data points with a low-degree polynomial. The simplest form of this approach, called running average , consists in computing the average for each subset. This approach is commonly used with time series data to smooth out short-term fluctuations and highlight longer-term trends or cycles. The RHR [kW] obtained by derivative of the mass loss using a time step of 60 seconds, the filtered RHR obtained with smoothing parameters of 10 and 20 are depicted in Figure 14. The filtered RHR with parameters 10 and 20 show maxima values of 8140 kW and 5850 kW, respectively. It also has to be noted that some discrepancies can be noticed with wooden fuel load, at the end of the combustion process. Indeed, the heat of combustion of wood is not perfectly constant: it is higher at the end of a test when only embers are left.

8   CONCLUSIONS

Three large scale tests were performed in real building dimensions were conducted to represent a realistic fire the travelling fire as realistic as possible. Instrumentation was installed to measure atmospheric

temperatures, surface temperatures, heat fluxes and temperature within the steel columns, beams and boundaries conditions of the surrounding compartment. In this paper only of the first of the three conducted tests is described and the evolution of the following results were presented: gas temperatures recorded in the central part of the compartment, along its length, maximum flame thickness, steel temperatures in a central beam and a central column, as well as mass loss data. The results obtained from the fire test demonstrated the non-uniform temperature distribution, leading to the heating of the nearby structural steel elements, resulting in a reduction of individual members' resistance, which could influence the global structural stability. The walls and precast slabs forming the boundary of the compartment retained its integrity despite a significant thermal gradient across the wall and slabs. In addition, all the connections and steel members performed very well and showed no signs of failure during the three conducted fire tests.

ACKNOWLEDGMENT

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