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Experimental and Numerical Investigations on Steel Columns Compartment Subjected to Travelling Fires

Ali Nadjai, Naveed Alam[1] , Marion Charlier[2], James McGillighan[1], Olivier Vassart[2]

Correspondence

Prof. Ali Nadjai
FireSERT, Ulster University
School Built Environment
Shore Road
Newtownabbey, BT37 0QB
Email: a.nadjai@ulster.ac.uk

Affiliations

[1]Ulster University, Belfast, UK
[2]ArcelorMittal, Luxembourg

Abstract

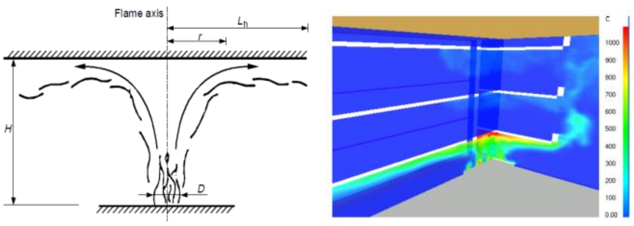
In the frame of the European RFCS TRAFIR project, three large compartment fire tests involving steel structure were conducted by Ulster University, aiming at understanding in which conditions a travelling fire develops, as well as how it behaves and impacts the surrounding structure. During the experimental 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 travelling fires on structural steel columns. The experimental data is presented in terms of the gas temperatures recorded in the test compartment near the column, as well as the temperatures recorded in the steel column at different levels. The scope of the experimental work is extended using CFD simulations with FDS software, which demonstrate with good agreement with measurements in the steel column exposed to travelling fires.

Keywords: Fire, Experimental, Steel, Compartment, Numerical

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 fire have a great deal of non-uniformity. They generally burn locally and move across entire floor plates over a period of time. This phenomenon generates non-uniform temperatures and transient heating of the structure. This type of fire scenario is beginning to be idealized as travelling fires [1].

In the EN 1991-1-2 [2], only two models consider a non uniform temperature distribution: the localized fire method and the CFD models. But the localized fire method consider a static fire which do not translate the effect of a travelling fire (Figure 1a). The CFD (computational fluid dynamics) 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)

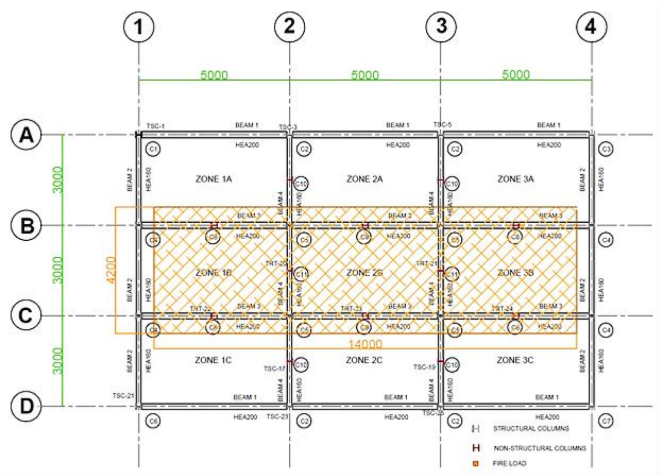
Figure 1 (a) Localised fire, (b) use of CFD in a case study with an atrium

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 [6-11]. 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. The floor plan between the outer gridlines of the test structure was 15 m x 9 m as shown in Figure 2. The level of the ceiling from the floor finish surface was 2.90 m.

(a)



(b)

Figure 2 (a) CPhotos of the test n°1, (b) layout plan of the structure and l ocation of the fuel load

2.1 Outline and formal structure

The structural steel frame of the test compartment was erected by Sav-erfield 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 Column	HEA 200	209.5	3.5	Yes (60 min)
Dummy Columns	HEA 200	209.5	2.7	No
Long Beams	HEA 200	172.3.	4.8.	No
Short Beams	HEA160	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 col-umns 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 brac-ings, 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 con-struction 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. On the other hand, the beams in the shorter direction consisted of HEA 160 steel sections. The roof consisted of 120 mm thick hollow-core precast concrete slabs span-ning between the beams along the shorter direction of the test compart-ment. 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 2 (a), that only the structural columns are protected while the dummy columns are kept unprotected for data ac-quisition purposes.

2.1.1 Fuel controlled fire test n°1

The boundary conditions for the fuel-controlled tests were designed by assuming the compartment to be a part of a large open plan office. To replicate such a scenario, a solid concrete wall was constructed along the shorter dimension of the compartment along gridline 1. In addition to the back wall, down-stands were provided along the longer dimension of the test compartment along gridlines A and B as shown in the sche-matic diagram in Figure 2 (b). Neither the wall nor the down-stands were provided along the shorter dimension of the test compartment along gridline 4. The back wall was constructed using precast concrete pro-vided by FP McCann Ltd, while the down-stands consisted of two layers of gypsum fire board panels having a thickness of 2x12.5 mm and a min-imum fire rating of 60 mins. The back wall and the down-stands were provided in such a way that they covered the whole length of the test compartment as shown in Figure 2(a). As the shorter direction of the test compartment along gridline 4 was kept open, it provided an escape route for smoke. During test n°1, the area of provided openings was 87 m^2. This paper only described the results of the test n°1, whose layout can be seen in Figure 2 (a).

2.1.2 Details of the fire load

The fuel wood source consisted of the species “Picea abies” with an av-erage density 470 kg/m³ having a moisture content of 15.22%. As the test compartment was a representative of a office building, Eurocodes propose a medium fire growth rate for such occupancy. In the frame of TRAFIR RFCS project, Franssen et al. performed a series of fire tests with uniformly distributed cellulosic fire loads [8], aiming at defining an ar-rangement 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 2(a). 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.

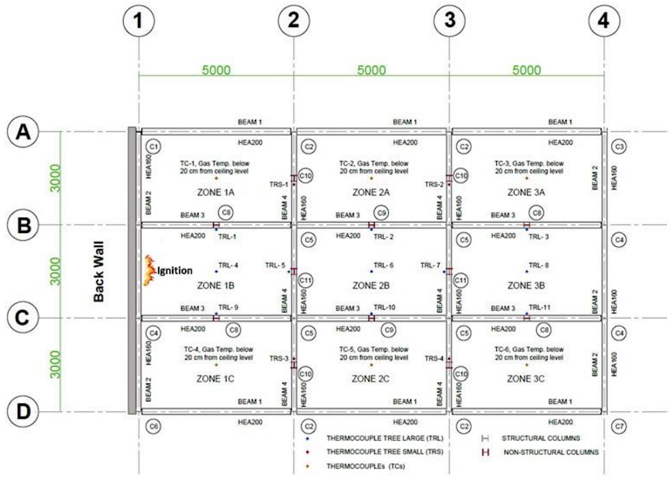
The fuel wood was provided along the centre of the test compartment, along zone B, as shown in Figure 2. The fire load was 14 m long stretching from wall to wall along the longer dimension of the test compartment. For convenience, a gap of 500 mm was maintained between the walls and the edge of the fuel 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 2. The top surface of the platform was at a distance of 325 mm from the floor finish level.

2.2 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 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 centerline of the compartment, in Figure 3).

2.2.1 Gas temperatures

The gas temperatures were recorded at different locations and levels using thermocouples. All thermocouples used for monitoring of temperatures in the compartment and in the test structure were type K-310 with bead size measuring 1.5 mm. The length of all thermocouples was 3 m. Thermocouples were provided in the form of trees as well as individual sensors. The thermocouple trees were divided into two groups, the ones within the central zone along the fuel bed between gridlines B and C and the ones in the outer zones, outside the fuel bed. The central trees within the fuel bed were equipped with thermocouples provided at six different levels. The first thermocouple was provided at 0.5 m from the floor finish level while the last one was provided at 2.7 m. In case of trees provided outside the fuel bed, only three thermocouples were provided at selected levels. In addition to the thermocouples trees, temperatures in the compartment at ceiling level were also monitored using thermocouples provided in each zone at 20 cm distance from the ceiling level



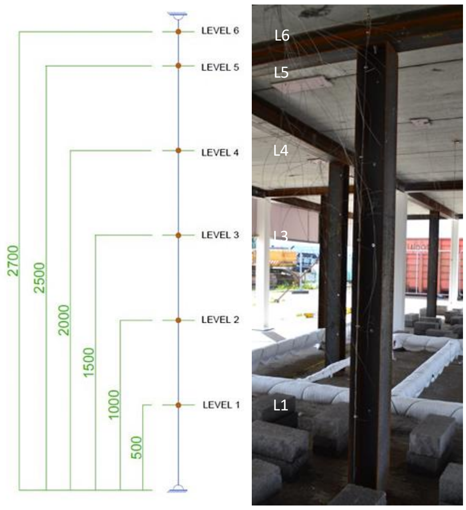
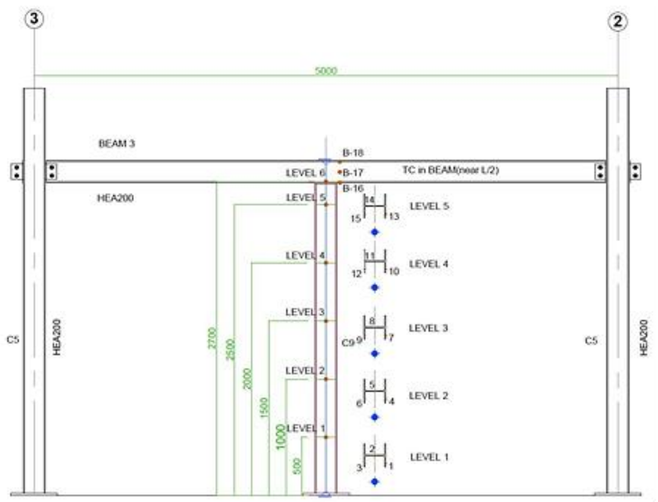


Figure 3 Location of the thermocouple trees in the test compartment and detail of the different levels of the thermocouples for the central zone

2.2.2 Steel temperatures

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 dummy columns (see Figure 4) and the selected beams. All thermocouples were provided at 3 mm depth from the surface of the flanges and the steel web.



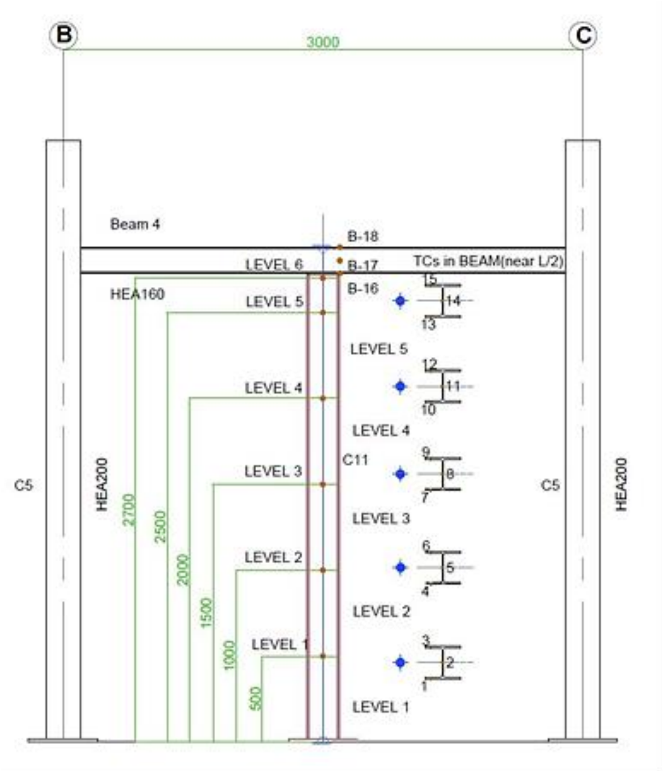


Figure 4 Thermocouple positioning in the central dummy columns

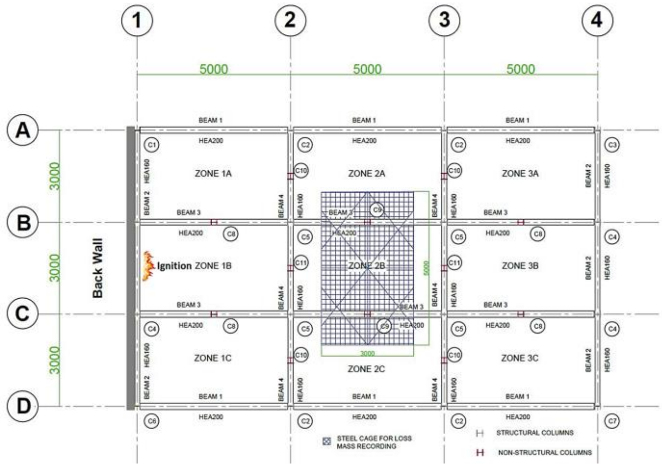


Figure 5 Position and arrangement of the mass loss recording though four load cells

2.2.3 Heat fluxes

The heat fluxes were monitored via Gordon Gauges (GGs) and the thin-skinned calorimeters (TSCs). These heat flux gauges were installed on a board which was positioned at 1.5 m from the edge of the fuel bed. The first GG and TSC were provided at 1 m level from the floor finish level while the second GG and TSC were provided at 2 m from the floor finish level. At each level along with GGs and TSCs, a thermocouple was also assigned to monitor the temperatures. The heat fluxes at the ceiling and fuel bed levels were monitored using nine and seven TSCs respectively along the middle of each zone as shown in Figure 3. For each TSC at ceiling level, an adjacent thermocouple was provided to record the gas temperatures. The positioning of the TSCs at ceiling level was kept similar during the three tests and were inspected after each test. As the TSCs provided within the fire bed were destroyed during Test1, a fresh set of the TSCs was provided during each fire test.

2.2.4 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 5. The steel platform was 3 m long x 5 m wide and was supported using four load cells a shown in Figure 5. 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 floor boards to ensure separation of the fuel wood for accurate measurement of the mass loss during the fire tests.

2.2.5 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 6. 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.

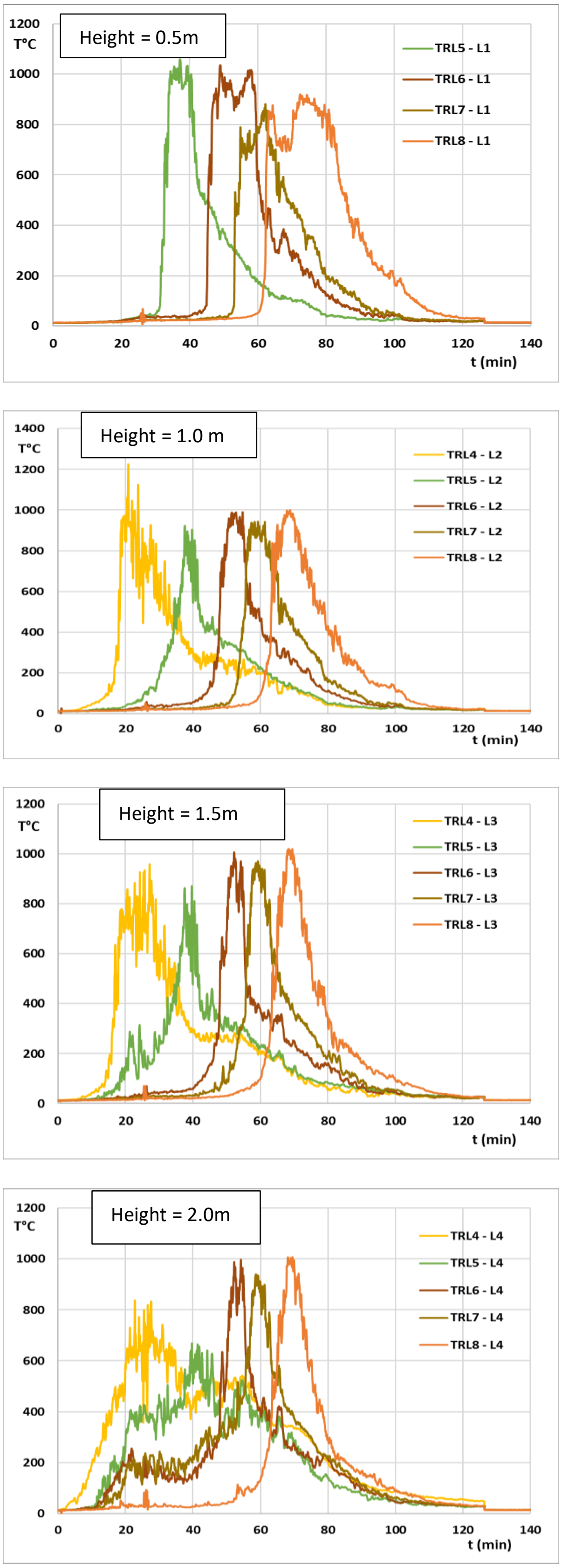
Figure 6 Extension cables for data sensors and data loggers

3 Results of Temperatures in the TC trees

Figure 7 illustates the travelling fire taking place along the length of the compartment. Temperatures in the compartment along the longer dimension, parallel to the path of the travelling fire within the fuel bed, were monitored using five thermocouple trees equipped with six sensors each as described in Figure 3.

Figure 7: Trevelling fire along the length oft he compartment

The first thermocouple tree, TRL4, was positioned in the middle of zone 1B at 1.5 m from the source of ignition. The remaining thermocouple trees (TRL5 through TRL8) along the centreline of the compartment were equidistant and positioned at 2500 mm centres. The recorded temperatures at different levels along the direction of the travelling fire are presented in Figure 8.



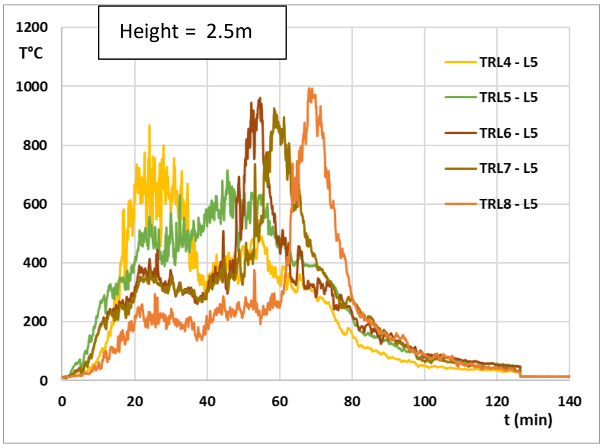


Figure 8: Recorded temperatures in the TC trees along the length of the compartment

The maximum temperatures recorded at TRL4 were more than 1000°C after 20 mins from ignition, at 2 m height, but thesehese temperatures reduced after a few mins as the fire travelled towards the fore-end. 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, TRL5, the temperatures recorded at TRL4 reduced while the temperatures at TRL5 increase. Temperatures recorded at TRL-5 reached the 900°C after 38 mins of the ignition. Similarly, the maximum recorded temperatures using TRL6, TRT7 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 is quite clear that the recorded temperatures vary along the height of the compartment, and that the TRL6 to TRL8 (placed in the second half of the compartment) present a shorter temperature peak than TRL4 and TRL5 (placed close to the ignition) from 2 m height.

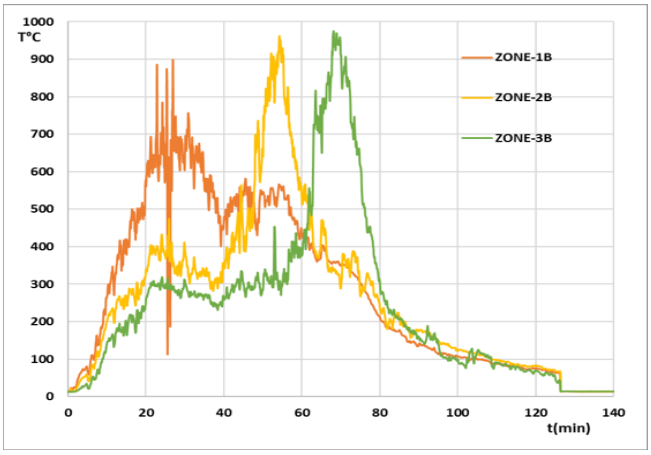


Figure 9 Recorded temperatures at the ceilling level along the center of the compartment

In addition to the temperatures recorded using the thermocouple trees, temperatures in the compartment at the ceiling level were monitored using individual thermocouples. The recorded temperatures at ceiling level in zone B along the centre of the compartment are given in Figure 9.

The temperatures in zone 1B reach the maximum values after 23 mins from ignition and gradually reduce with the fire travelling towards the fore-end of the compartment. The recorded temperatures in the centre of the compartment in zone 2B are 950°C after 50 mins from ignition while these are 980°C after 70 mins of ignition for zone 3B. In all cases, a gradual increase in temperatures is observed which reduces as the fire travels ahead.

4 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 as shown in Figure 4.

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 in the compartment adjacent to the selected column using thermocouple tree TRL7 are presented in Figure 10. The temperature rise 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. For the bottom three levels, the increase in temperature is rapid as temperatures rise from 100°C to 950°C within a few mins.

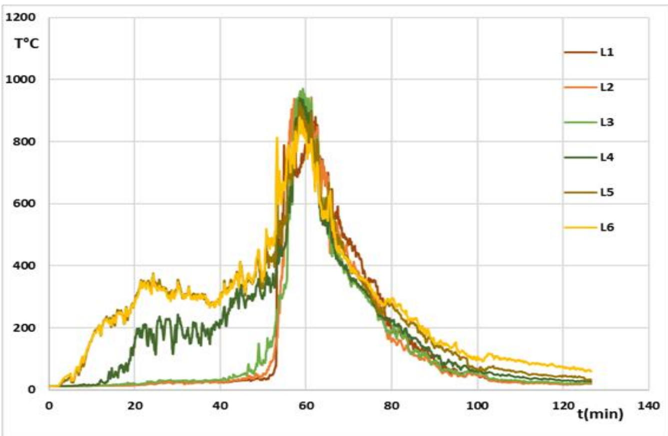


Figure 10 Recorded gas temperatures in the thermocouple tree near the selected column and beam – TRL7

The temperatures recorded in the flanges and the web of the column at level 3 are presented in Figure 11. 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.

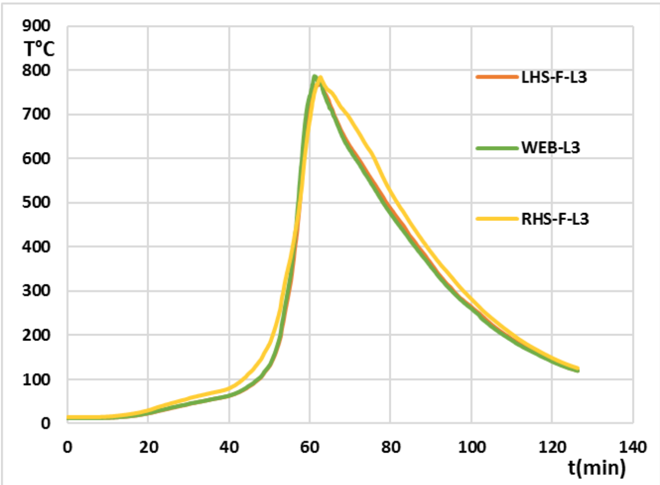


Figure 11 Temperatures recoded in the selected column along gridline 2 positioned between gridlines B and C at level 3

5 Mass loss of the burning fuel

The mass loss data recorded during the test is presented in Figure 12. 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 the 39th min, a uniform decrease in the wooden fuel mass is recorded. After 58th 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 mins

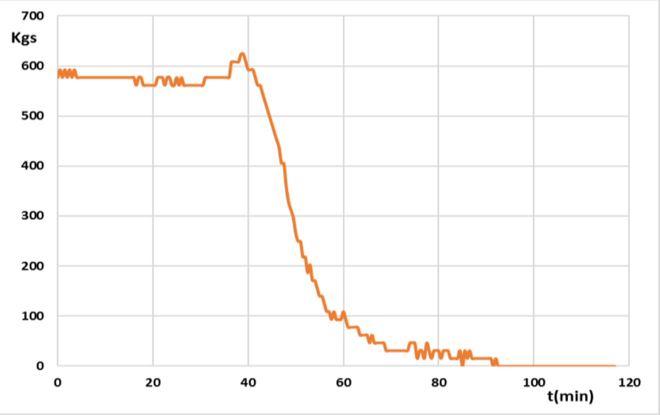


Figure 12: Recorded mass loss

6 CFD simulations (Simplified Approach)

Several CFD simulations were launched with FDS software to calibrate the model for thelarge scale tests. These CFD simulations consider a simplified representation of the continuous fire load consisting of discrete volumes based on a regular arrangement. Simplification was targeted, as modelling the real wood stick size in CFD requires a very fine mesh and therefore a very significant computational time for real building dimensions. Such approach was also used by Degler et al. [11], Horová [7] and Charlier et al. [12].

As explained previously, the steel temperatures were recorded at five different levels on unprotected column placed in the centerline of the compartment, with three thermocouples provided at each level such that one is positioned in the web while the others are positioned in the flanges. This experimental data is compared with numerical results in a simplified manner: the CFD output "adiabatic surface temperature gas" was used to evaluate the related steel temperature using subsequently the incremental formula from EN1993-1-2 (section 4.2.5.1) [13]. The modelled compartment is represented in Figure 13.

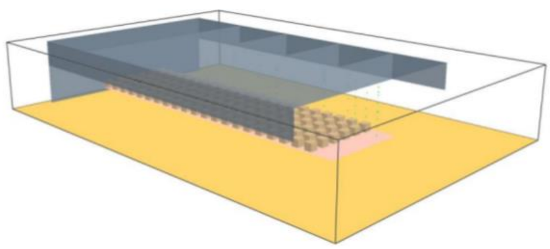


Figure 13: Modeled compartment in FDS for test No1 (example with 0.32m size cubes)

This method considers a constant temperature through the section for a given height. The comparison of the results is encouraging as it is shown in Figure 14.

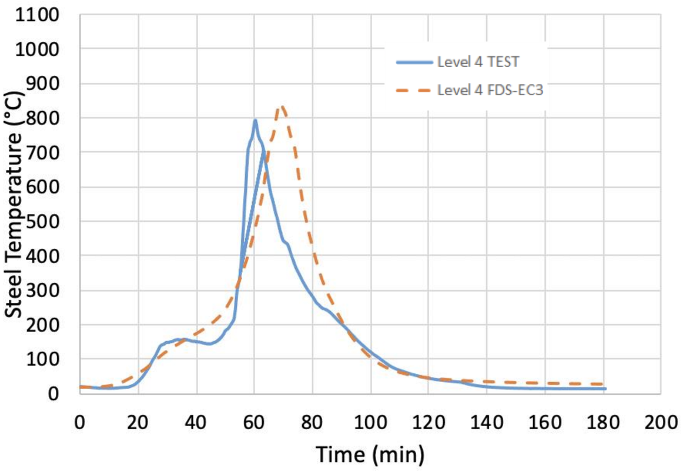


Figure 14 Steel temperature measured during test versus steel temperature obtained using FDS results in central column at 2m height.

8 Conclusions

Three large scale tests were performed in real building dimensions were conducted to representation the travelling fire as realistic as possible. In this paper only of the first of the three conducted test is presented..

Instrumentation was installed to measure atmospheric temperatures, surface temperatures, heat fluxes and temperature within the steel columns, beams and bounderies conditions of the surrounding compartment. The fuel mass loss rate was also considered as well as the thermal feedback from surroundings, which depends on the ambient oxygen concentration.

The results obtained from the fire test demonstrated the non-uniform temperature distribution, leading to the heating of the nearby structural steel elements, which resulted in a reduction of individual members' resistance, which could influence the global structural stability.

The comparison of measured steel temperatures and FDS software is in a good agreement with the experimental results.

The walls and precast slabs forming the boundary of the compartmentretained 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.

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