LARGE SCALE FIRE TEST: TRAVELLING FIRE WITH FLASHOVER UNDER VENTILATION CONDITIONS AND ITS INFLUENCE ON THE SURROUNDING STEEL STRUCTURE

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LARGE SCALE FIRE TEST: TRAVELLING FIRE WITH FLASHOVER UNDER VENTILATION CONDITIONS AND ITS INFLUENCE ON THE SURROUNDING STEEL STRUCTURE

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ABSTRACT

In the frame of the European RFCS-TRAFIR project, different natural fire tests in large compartment were conducted by Ulster University, involving steel structure and aiming at understanding the conditions in which a travelling fire develops, 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. This paper presents the selected experimental data from the third fire test in terms of gas temperatures recorded in the test compartment at different positions and levels. The paper also presents the influence of the traveling fire with flashover on the surrounding structure via temperatures recorded in the selected steel columns and beams. The temperatures in the test compartment were found to be dependent on the positioning of the travelling fire as well as on the height from the floor level. It was found that the non-uniform temperatures in the compartment lead to transient heating of the nearby structural steel elements which is different from a standard furnace test. These non-uniform elevated temperatures result in a reduction of the fire resistance of the structural elements which may influence the global stability of the structure. The results obtained during the test and lessons learnt will help to understand the behaviour of the travelling fires and their influence on the structural members. This knowledge will help to reduce the travelling fire associated risks in future.

Keywords: Travelling fire tests; Natural fire tests; Steel Structure; Large-scale compartment tests, Travelling fire with flashover

1 INTRODUCTION

It is well established that the response of a structure subjected to fire is dependent on the fire exposure conditions. Small compartment fires behave in a well understood manner defined as a post-flashover fire

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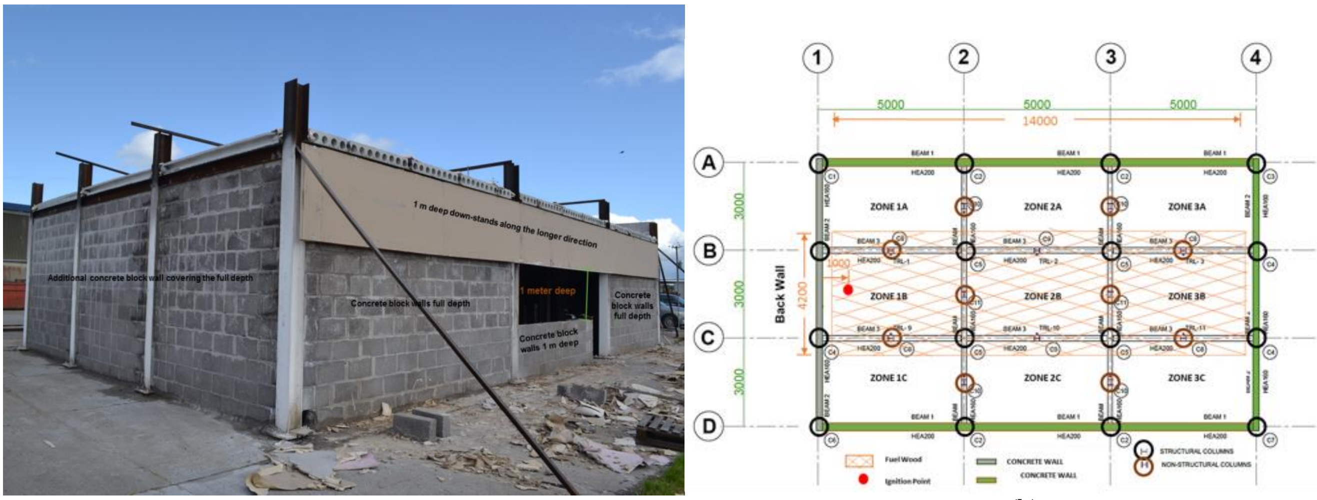
with uniform temperatures. Over time, the building designs have evolved and with modern architecture, there is an increase of open large-floor plan spaces, for which the assumption of post-flashover fire and uniform temperatures does not hold [1,2]. Instead, there is a smaller localised fire that moves across the floor starting in a certain area or a point. The current standard fire as well as the compartment fire exposure conditions have been developed by using data from small compartment tests. The existing test data is available from small compartment tests, the concept of a uniform distribution of gas temperatures fits well when dealing with similar scenarios. In case of large compartments, the assumption of uniform temperature distribution does not hold, and more research is needed to address such cases. During recent fires, the travelling fires have been observed and investigated, which include the destruction of the World Trade Centre Towers in New York City in 2001 [3], the Windsor Tower in Madrid in 2005 [4], and the Faculty of TU Delft Architecture building in Netherlands in 2008 [5]. The detailed investigations on the fire events in large compartments have revealed that such fires have a great deal of non-uniformity unlike the small compartment fires. They generally burn locally and move across floor which generates non-uniform temperatures and transient heating of the surrounding structure and are idealized as the travelling fires [1,2].

Although majority of the fire exposure scenarios provided in the design codes consider uniform temperatures within the compartment, there is also some guidance available related to non-uniform temperatures. In the EC2 (EN1991-1-2) [6], two models are provided which consider a non-uniform temperature distribution, the localised fire model, and the advanced fire models (zone models and computational fluid dynamic models). Although the localised fire is assumed to be static, it is possible to consider several localised fires, one localised fire spreading to other localised fires. Such effect covers a fire spread but does not directly allow to fully capture the science behind the travelling fires. For zone models, the situation starts as a two-zone model which assumes 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 [6]. Although this model considers a non- uniform temperature distribution within the compartment, it does not translate the 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. These models are consequently complex and imply a high computational cost. Further, these modules need further refining through comparisons with experimental data. The recent years have seen growing interest in investigating travelling fires which underlined the inadequacy of uniform heating in large compartments [6-13]. Further research efforts are needed, especially to extend the experimental data related to such fire scenarios which is scarce, limited, and partial.



(a) (b)

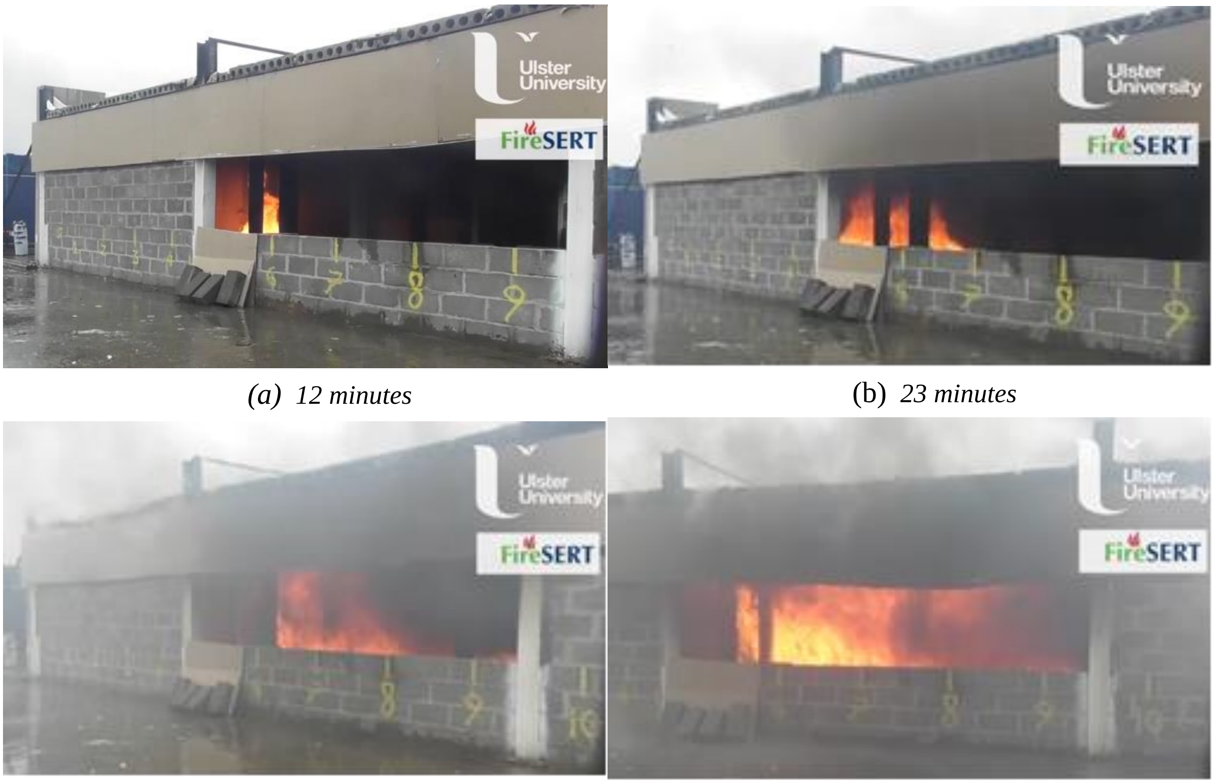
Figure 1: Test 3 compartment, (a) Perspective view, (b) Plan with boundary conditions

Large scale travelling fire tests were recently conducted by Ulster University which included the fuel controlled and ventilation-controlled fire scenarios. The details of the two fuel-controlled travelling fire tests (Test 1 and Test 2) with different opening sizes were published by Nadjai et al. [14,15] and Alam et al. [16]. Details of the test compartment, instrumentation, fire load and other arrangements are available in the references [14 - 16]. The third tests, Test 3, was conducted to achieve a ventilation-controlled travelling fire scenario. To reduce the opening sizes during Test 3, the height of the soffit was increased along the longer dimension between gridlines 1 & 2 and between gridlines 3 & 4 by adding extra layers of concrete blocks. In these zones, no opening were provided, while the central part of the long walls (between gridlines 2 & 3) was kept identical to Test 2. Hence, the height of the openings between gridlines 2 & 3 remained 1 meter. Such provision of the boundary openings provided a total opening area of $10m^2$ in the test compartment as seen in Figure 1. The selection of opening sizes was conducted based on the outcomes of analysis using OZone software.

2 GENERAL FIRE SPREAD AND OBSERVATIONS DURING TEST 3

The fuel wood arrangement was similar for all three tests and the ignition was triggered using the same approach and position as done during the previous tests [14-16]. Photos taken at different time intervals during Test 3 have been shown in Figure 2. Following observations were made during the Test 3.

- Similar to the previous tests (Test 1 and Test 2), the fire initially spreads in all directions creating a circle around the point of ignition and after 10 mins, the fire flames touch the ceiling of the compartment. It was observed that the fire reaches the back end of the fuel after 9 mins. At this point, the flame thickness is 1 m. After 20 mins, the flame thickness is approximately 1.5 m.
- The fire spreads across the entire width of the fuel bed after 27 mins from ignition. The edges at the back end of the fuel is consumed after 29 mins from ignition. This initiates the travel of the fire towards the fore-end of the fuel bed.
- The travelling fire enters zone 2B of the test compartment after 37 mins. The flame thickness is approximately 2.5 m after 40 mins. The spread of the fire from one stick to another in the central part of the test compartment is steady. Similarly, to the previous tests, the number of sticks burning in the upper layers is higher than the number of sticks burning in the lower layers.
- The fire reaches the centre of the test compartment after 48 mins. At this point, the flame thickness is approximately 3.5 m.
- The flame thickness increases to 4 m after 52 mins from the start of the test. As the travelling fire reaches the centre of the compartment, its length extends to 5 m. The intensity of fire is significantly higher at this point. After 55 mins from ignition, flames escape through the openings of the compartment, which confirms a ventilation-controlled fire.
- After 56 mins, the spread of the travelling fire from stick to stick slows down significantly and the fire remains concentrated in the central part of the test compartment.
- The centre of the travelling fire reaches the middle of the compartment after 57 mins from ignition. After 58 mins, a small part of the fuel bed area near the fore-end of the compartment, (isolated from the actual travelling fire), catches fire. This separate fire at the fore-end of the compartment continues to burn until the 64th min. The intensity of the fire near the fore-end is higher until majority of the fuel wood is consumed. With the consumption of the fuel wood towards the back end of the central zone, the remaining fuel in the last part of the compartment starts to burn, joining the isolated fire. The intensity of the fire reduces after 85 mins.
- The fuel wood in the last compartment continues to burn until the 100th min with moderate intensity. From here onwards, the intensity of the fire reduces further. After 111 mins, no flames were visible as the fuel was totally consumed. The data acquisition continued further to obtain a dataset of more than 120 mins.
- Given the observations detailed above, the evolution of the maximum flame thickness is evaluated and represented in Figure 3. The data in Figure 3 is selected such that only “travelling fire” flame thicknesses are displayed (i.e, no point corresponds to the growing stage of the fire, when the back end hasn’t start travelling yet).



(a) *12 minutes* (b) *23 minutes*

(c) *45 minutes* (d) *55 minutes*

Figure 2: Travelling fire along the compartment length after, (a) 12 mins, (b) 23 mins, (c) 45 mins (d) 55 mins

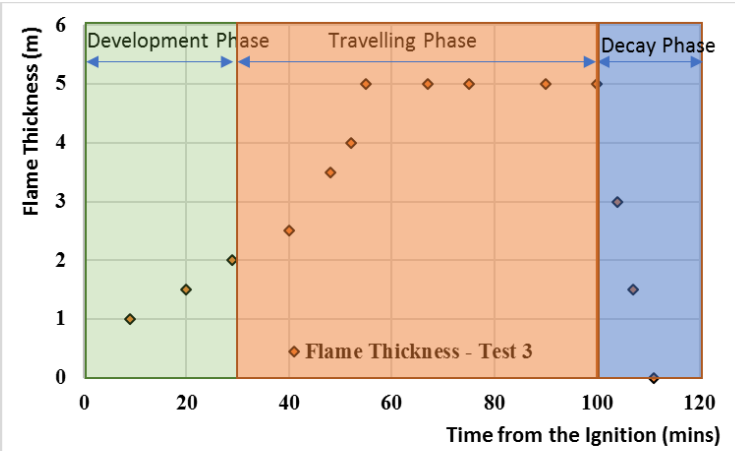


Figure 3: Evolution of the maximum flame thickness during Test 3

3 INSTRUMENTATION

The instrumentation and fuel load during all the fire tests was kept similar as mentioned before. Details of the instrumentation and fuel load for Test 3 shown in Figure 4 are similar to the arrangements made during Test 1 and Test 2 available in the references [14], [15] and [16].

Gas temperatures in the compartment were recorded using thermocouples provided as individual sensors or in groups in terms of thermocouple trees. In this paper, details of the thermocouples provided along the centreline of the test compartment have been provided. The thermocouples along the centreline of the test compartment were provided as thermocouple trees, TRL-4 through TRL-8 as shown in Figure 4 (a). The first thermocouple tree, TRL-4, was positioned at 1.5 m from the back wall while the remaining thermocouple trees were positioned at 2.5 m intervals. The thermocouple trees along the centre were provided with six thermocouples each. The positioning of the first thermocouple from the floor finish level was 0.5 m (L1). The thermocouples at L2, L3, L4 and L5 were at 1.0 m, 1.5 m, 2.0 m, and 2.5 m respectively. The last thermocouple at L6 was provided at 2.7 m from the floor finish level, Figure 4 (c).

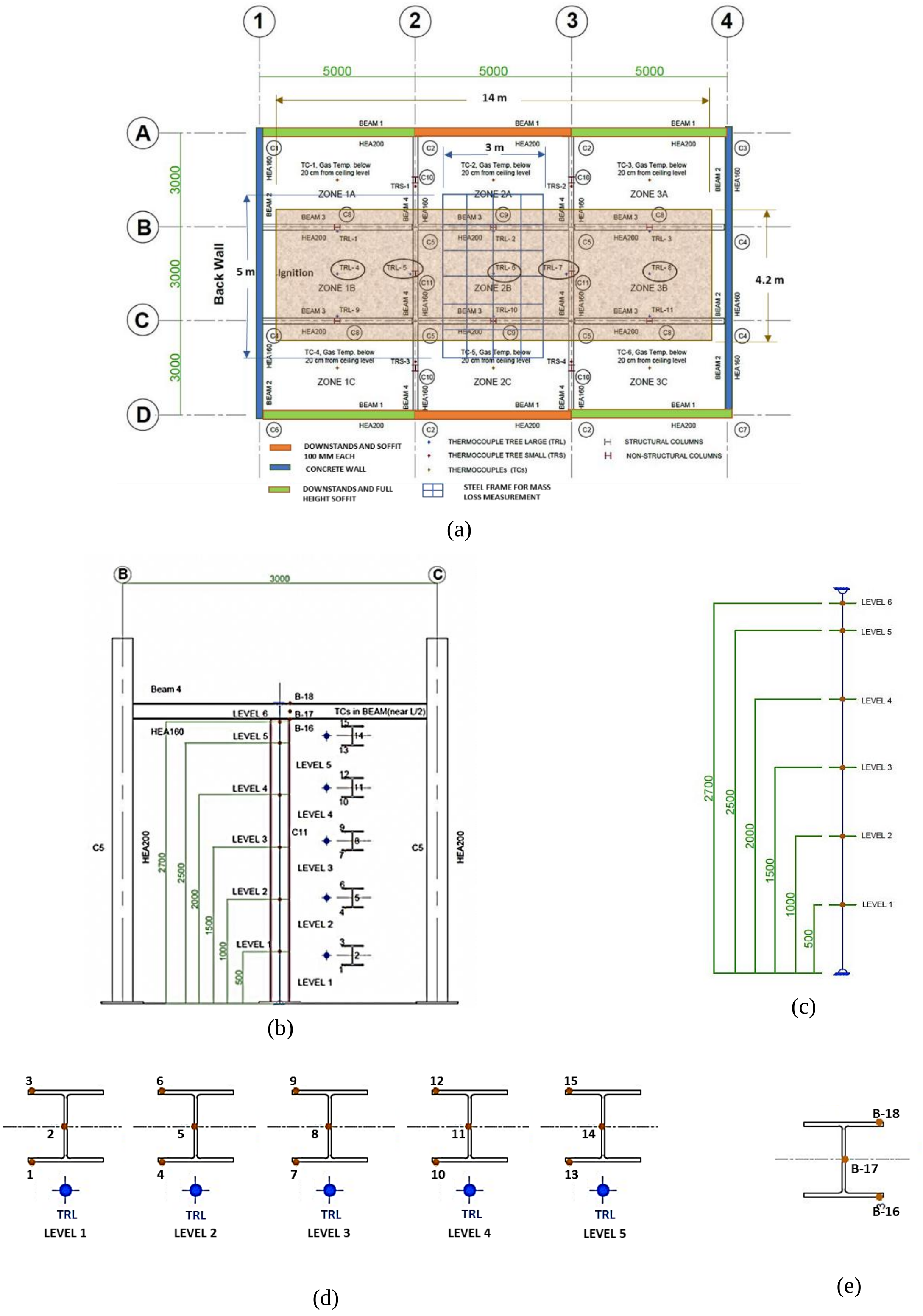


Figure 4: Details of thermocouples, (a) positioning of thermocouple trees (b) thermocouples in beams and columns, (c) thermocouples in large thermocouple trees; (d) thermocouples in columns; (e) thermocouples in beams

To analyse the influence of the travelling fire on the surrounding steel structure, temperatures were monitored in the columns and beams. Details of the instrumentation and recorded temperatures in the dummy column and beam adjacent to TRL-7 have been provided in this article. The column has been identified as C11 while the beam has been identified as BEAM 4 in Figure 4 (a). In total fifteen thermocouples were used in the column and three were used to recorded temperatures in the beam as shown in Figure 4 (b) & (d) and Figure 4 (e) respectively. The column and beam mentioned herein are between the gridlines Ⓑ and Ⓒ provided along the gridline ③ and are adjacent to thermocouple tree TRL-7.

4 GAS TEMPERATURES WITHIN THE FUEL BED ZONE, *TRL-4 THROUGH TRL-8*

The recoded data in the middle of the test compartment within the fuel bed using thermocouple trees TRL-4 through TRL-8 has been presented in Figure 5. The data presented is for thermocouples provided at L1, L3, L4 and L7. The gas temperatures at higher levels starts to rise much earlier as compared to those at lower levels, translating the hot gas layer. It should be noted that thermocouple at L1 (0.5m from the concrete floor level) lies within the fuel load. The following observations can be made from Figure 5:

- Temperatures recorded at L1 are lower as compared to temperatures recorded at higher levels, L3, L4 and L6.
- Temperature recorded in TRL-4 are lower as compared to temperatures recorded using other thermocouple trees. This could be explained by the fact that the fire is still developing at this location. As detailed above, the fire reaches the entire width of the fuel bed only after 27 mins from ignition and the temperature peaks in TRL-4 occur at 28 mins approximately. Similarly, the temperatures recorded at TRL-5 are lower as compared to those recorded using TRL-6 through TRL-8, however, these temperatures are higher as compared to those recorded in TRL-4.
- For Test 1, temperature profiles at L1 and L3 were quite distinct (i.e., shifted in time). For Test 3, such observation can only be made for L1 (at other levels, some coincidence observations can be made). This may result due to the progressively reduced openings from Test 1 to Test 3, enhancing the accumulation of smoke within the compartment and therefore merging the temperature profiles.
- The temperature profiles from TRL-6 and TRL-7 coincides to a certain extent at L4 (while the temperatures from TRL-8 are lower) with those recorded during Test 1. Similarly, the similarities in temperatures are more between Test 3 and Test 2 as compared to Test 3 and test 1. Furthermore, the beginning of the temperature profiles from TRL-6 through TRL8 coincides to a certain extent at L3, L4, and L6 for Test 3 and Test 2. Also, the peak temperatures measured at TRL-6 through TRL8 are in the same order of magnitude at L6 for Test 3 and Test 2.
- Globally for Test 3, the maximum gas temperatures recorded are around 1000°C. The following remarks can be made excluding L1 which is within the fuel bed.
  - TRL-6 through TRL-8 present maximum temperatures between 900-1000°C and are reached at all levels.
  - TRL-5 presents maximum temperatures around 800-900°C and are reached at all levels.
  - The maximum temperatures in TRL-4 are recorded between 750°C and 900°C.
- In case of Test 2, the maximum gas temperatures recorded in TRL-4 through TRL-8 were 1000°C - 1100°C at L1, and between 800°C - 900°C at other levels, i.e., there was a tendency to encounter higher temperature at lower levels.
- For Test 3, the same order of magnitude is reached, whatever the level.
  - The TRL-8 shows a longer period of high temperatures. The period during which temperatures above 600°C are recorded in thermocouple trees is: TRL-4: around 12 mins, TRL-5: around 20 mins, TRL-6: around 25 mins, TRL-7: around 20 mins, TRL-8: around 35 mins (from around 65 to 100 mins).
- The longer duration for TRL-8 can be explained as during the test after 58 mins, a small part of the fuel bed area near the fore-end of the compartment caught fire. This separate fire at the fore-end of the compartment continued to burn until the 64th min, generating a high intensity of the fire near the fore-end, which then reduced after 85 minutes.

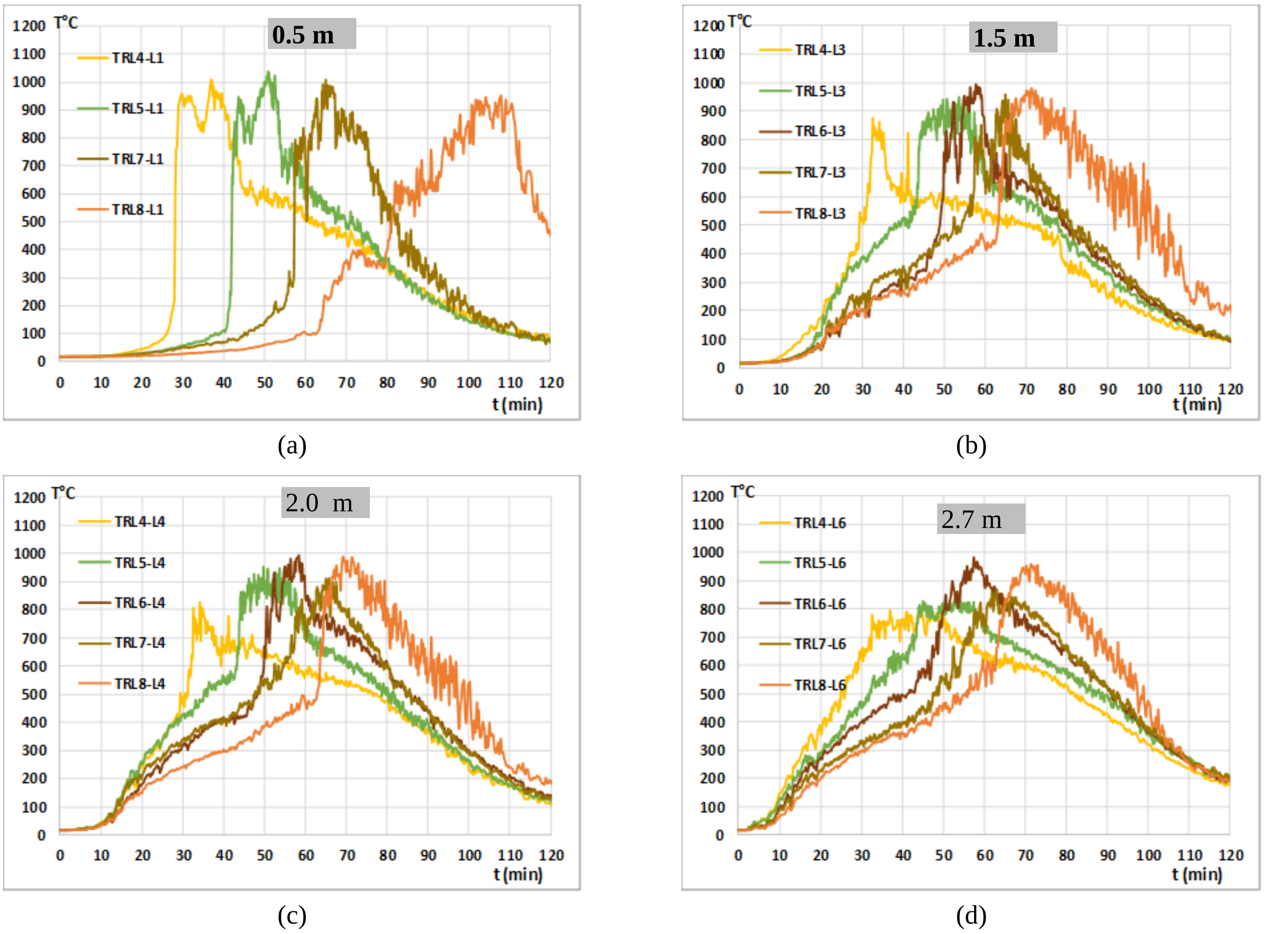
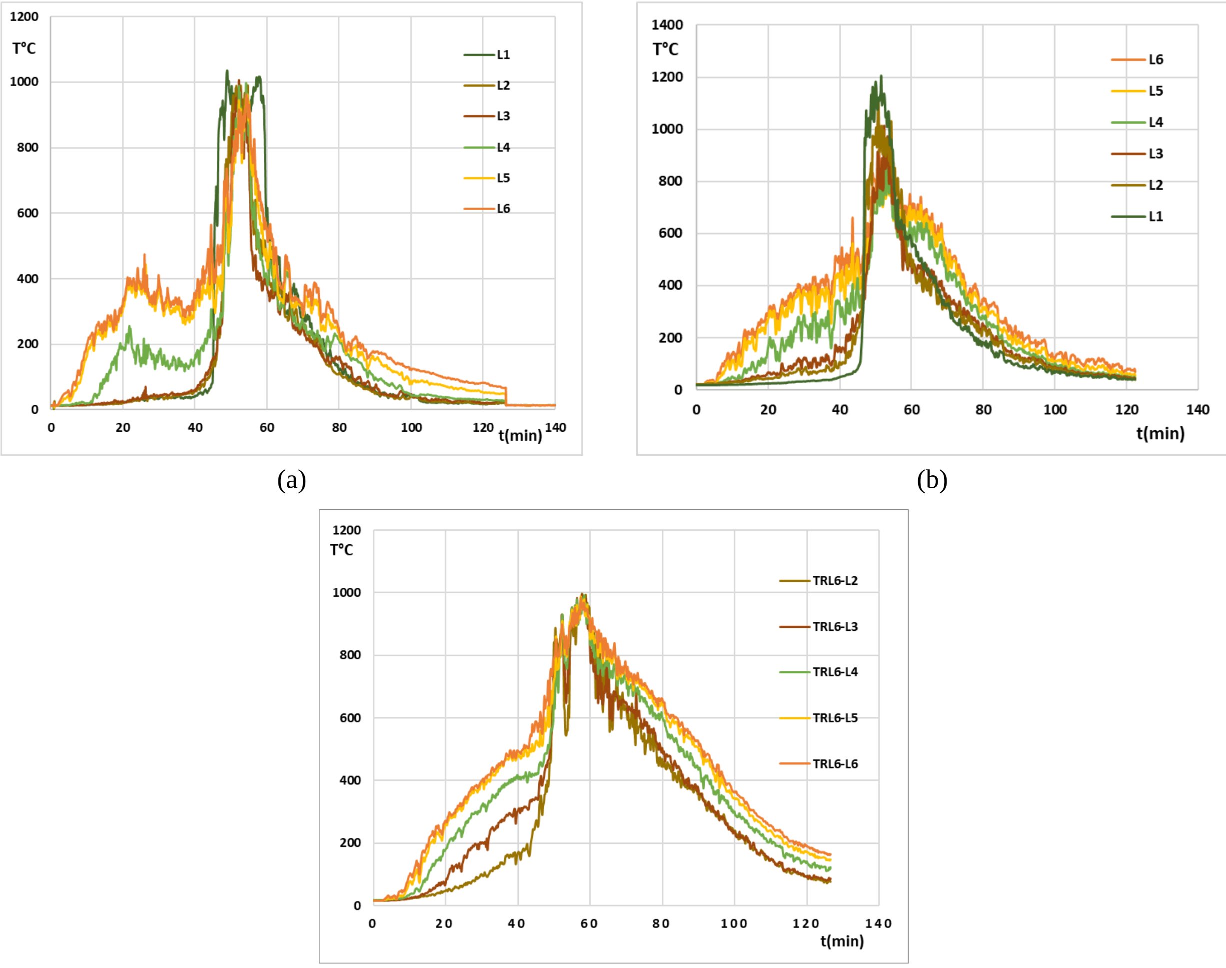


Figure 5: Gas temperature measurements during Test 3 at (a) L1, (b) L3, (c) L4, (d) L6

The thermocouple tree TRL-6 is positioned in the middle of the compartment (both along length and width). Following the observations during the tests, it is known that the centre of the travelling fire reaches TRL-6 after 48 mins during Test 3 (the same was reached after 49.5 and 51 mins during Test 1 and Test 2, respectively). The flame thickness at this point during Test 3 was approximately 3.5 m (the same was 3 m for both Test 1 and Test 2). The comparison of the temperatures recorded in the middle of the test compartment using TRL-6 is made and presented in Figure 6. For comparison purpose, L3 (around mid-height) at 30 mins is considered. At L3 after 30 mins, 40°C are measured for Test 1 while the same is 110°C for Test 2 and 200°C for Test 3. The maximum recorded gas temperature in TRL-6 is approximately 1000^{o} C during Test 3 (versus 1000°C and 1100°C for Test 1 and Test 2 respectively) after around 58 mins from ignition (nevertheless, measurements at L1 are not considered when finding this maximum). During the peak, contrarily to Test 2 where the higher temperatures are encountered for the lower levels, the temperatures are coinciding (around 1000°C). After the peak, the recorded temperatures reduce as the fire travels towards the end of the compartment. During the whole duration of the test, the higher temperatures are recorded at upper levels, and lesser temperatures for lower levels. It was observed that temperatures measured at upper levels (L6) start to increase at earlier stages of the test due to a hot layer of gases in the upper part of the compartment. It is interesting to note that during Test 1 and Test 2, temperatures at lower levels, especially at L1 and L2, rise suddenly at 45 mins from ignition. In case of the ventilation-controlled Test 3, the rise at lower levels, L1 and L2, is gradual and initiates at earlier stages of the test. During Test 3, due to limited opening sizes, the heat was retained within the compartment as a result, the temperatures of the compartment at all levels, including the lower levels, increased even at earlier stages which is different from the fuel-controlled Test 1 and Test 2. It is also noticed in Figure 6 that sharp decrease in temperatures is recorded for fuel-controlled Test 1 and Test 2. However, due to smaller openings and retaining of the heat, the temperatures recorded during Test 3 show a gradual decrease and remain higher until the recording is discontinued.



(a) (b)

(c)

Figure 6: Gas temperature measurements made in TRL6 during; (a) Test 1, (b) Test c, (c) Test 3

5 TEMPERATURES RECORDED IN THE SURROUNDING STRUCTURE

The temperatures were monitored in beams and unprotected non-structural columns of the steel structure. Within the fuel bed zone, the column and beam (hot rolled, HE 200 A) placed adjacent to TRL-7 have been selected for data presentation purposes. The selected beam and column are along gridline ③ between gridlines Ⓑ and Ⓒ has been selected for data presentation purposes.

5.1 In columns adjacent to TRL-7 with comparison with column adjacent to TRL-5

For the column next to TRL-7, the temperatures recorded during Test 3 are presented in Figure 7. The thermocouple label “LHS-F”, “WEB”, “RHS-F” correspond to the flange near gridline Ⓒ (thermocouples 1,4,7,10,13), the section web (thermocouples 2,5,8,11,14) and the flanges near gridline Ⓑ (thermocouples 3,6,9,12,15) respectively. The faulty thermocouples 1 and 5 are not considered during the discussion below. The temperatures recorded using TRL-7 are presented in Figure 7 (a). It is clearly seen in Figure 7 that the steel temperature profiles are similar to the recorded gas temperatures, with the following differences:

- The maximum temperature recorded in the column adjacent to TRL-7 during Test 3 is 834°C after 70 mins (it was 833°C after 60 mins for Test 2 and 803°C after 63 mins for Test 1). For this column, the recorded temperatures are slightly higher for Test 2 and m as compared to Test 1. It can nevertheless be noted that the maximum temperatures are reached during Test 3 due to smaller opening sizes. The maximum gas temperature during Test 3 is 1010°C after 65 mins (it was 1021°C at 58 mins for Test 1 and 937°C after 58 mins for Test 2).

- At the exception of L1, the steel temperature descending branch is less steep than the gas temperature one (steel reaches 500°C after around 95 mins while the gas temperature reaches the same after 85 mins).
- During the decay phase of Test 3, the steel temperatures recorded at L1 decrease faster than other levels (this phenomenon was also observed for Test 2 and not for Test 1).
- Temperatures recorded across the section of the column at each level are uniform as seen in Figure 7. Similar observations were also made during Test 1 and Test 2.

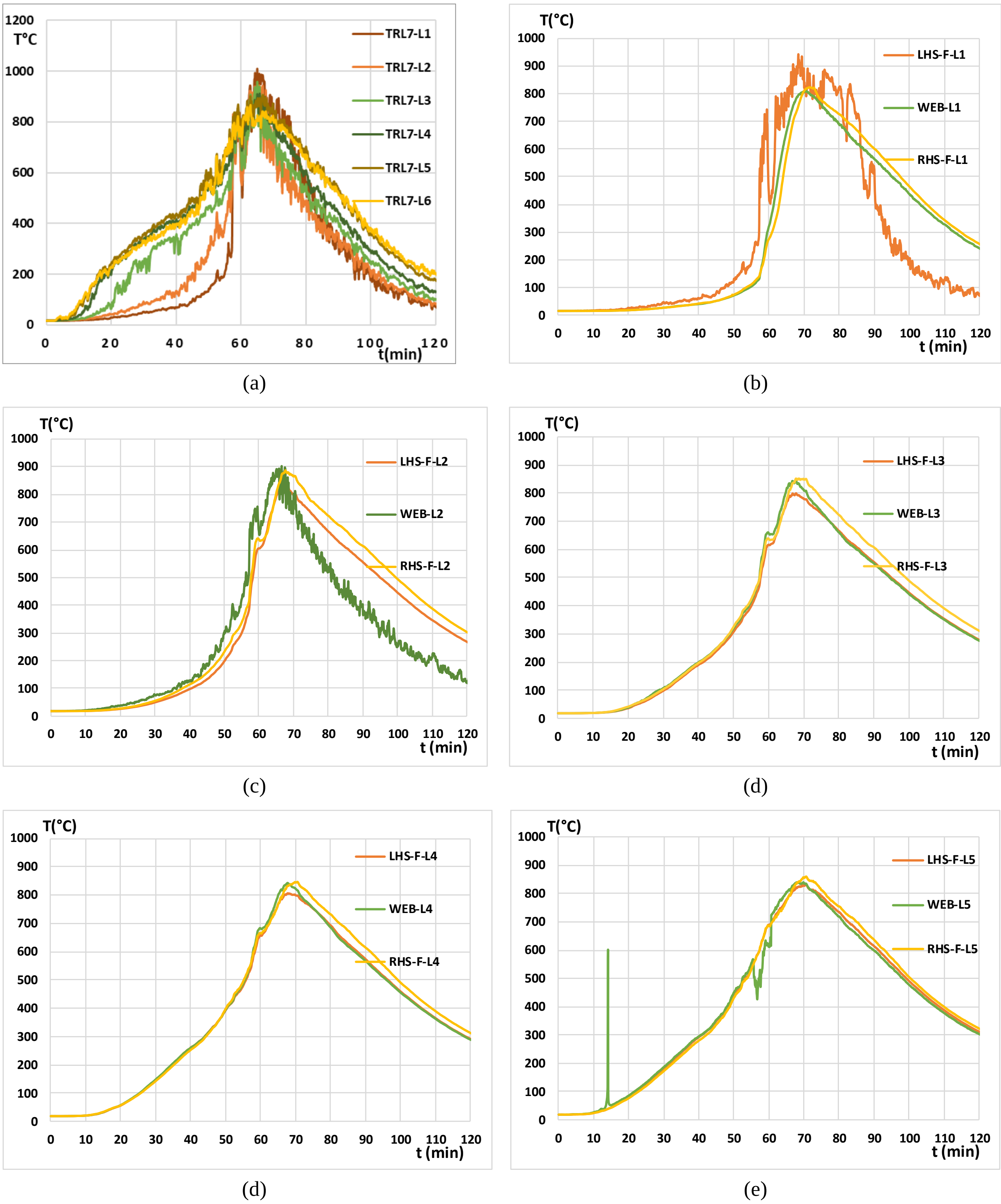


Figure 7: Temperature recordings Test 3: (a) using TRL7, (b) Column L1, (c) Column L2, (d) Column L3, (e) Column L4, (f) Column L5

Temperatures were also recorded at similar points in the column adjacent to TRL-5. Due to space constraints, these have not been presented in this paper, however, a comparison of the maximum temperatures recorded in columns adjacent to TRL-5 and TRL-7 is presented in Table 1. In addition to the maximum recorded temperatures, Table 1 also provides the temperature difference between these values (Δ = TRL7 - TRL5). Also, within each column, the maximum temperature gradient (Δ) is also presented in Table 1. The following observations have been made:

- The maximum steel temperature is 887°C after 68 mins for the column adjacent to TRL-7 (it was 838°C after 63 mins for Test 2 and 799°C after 63 mins for Test 1) while it is 890°C after 56 minutes for the column adjacent to TRL-5 (versus 781°C after 49 mins for Test 2 and 731°C after 46 mins for Test 1). While there was no significant change during comparing Test 1 and Test 2 recorded temperatures, it appears the lower opening factor during Test 3 results in higher steel temperatures (nearly 100°C more).
- For Test 2, the maximum temperature gradient within each column (Δ) was almost identical whereas for Test 1, a lower gradient was observed in column next to TRL-7 as compared to column next to TRL-5. For Test 3, the tendency is same as that for Test 1. This could be explained by the flame thickness which is lesser near TRL-5 as compared to TRL-7. For a similar 'rate of heat released density', a thicker flame (and therefore a bigger diameter if the fire is represented as a localised fire) implies a higher flame length, implying a lower gradient in temperatures for the given heights.
- In previous tests, the gas temperatures from TRL-5 and adjacent column were globally lower than the ones recorded further away in the compartment, which was different in case of Test 3. When looking at the differences between maximum temperatures recorded in the two columns for each level (Δ =TRL-7 – TRL-5), one can see these values are very low, highlighting very similar steel temperatures in TRL-5 and TRL-7. Having less openings compared to previous tests, more heat is contained within the compartment, limiting the differences in the columns.
- When evaluating the period during which higher temperatures (arbitrarily chosen above 600°C) are encountered, it can be observed that this period is quite similar for the column adjacent to TRL-7 (from 60 to 90 mins, i.e. for approximatively 30 minutes) and for the column adjacent to TRL-5 (from 45 to 80 mins, i.e., for approximatively 35 minutes). This period was 20 mins for Test 2, and 15 mins for Test 1, implying that the reduction of opening sizes, elongates the heating time.

Table 1: Maximum steel temperatures measured during Test 3 in columns adjacent to TRL7 and TRL5 (flanges)

	Level 1	Level 2	Level 3	Level 4	Level 5	Δ
TRL5	806°C	890°C	882°C	852°C	850°C	84°C°
TRL7	824°C	887°C	853°C	846°C	859°C	63°C°
Δ (TRL7-TRL5)	18°C	3°C	29°C	6°C	9°C	

5.2 In beam adjacent to TRL-7 during Test 3 and comparison with the previous tests

Each beam was instrumented with three thermocouples, two on the flanges and one on the steel wed as presented earlier in Figure 4 (e). The beam used for data presentation is along gridline ③ between gridlines Ⓑ and Ⓒ in Figure 4 (a). For the beam temperatures presented in Figure 8 (a), "BF", "TF" and "Web" correspond to the bottom flange, the top flange and the web of the beam. The temperatures recorded in the beam follow the same trend as the ones recorded at L5 and L6 of TRL-7. The temperatures in the beam are non-uniform. Similar to the previous tests, temperatures recorded in the top flange are significantly lower than those recorded in the bottom flange. The maximum steel temperatures reached at the bottom flange, the web and the top flange are 783°C, 782°C and 760°C respectively as seen in Figure 8 (a).

The average temperatures recorded in the beam along gridline ③ between gridlines Ⓑ and Ⓒ during all three tests is presented in Figure 8 (b). It can be observed that the temperature recordings are similar for Test 1 and Test 2. However, for Test 3, higher steel temperatures are recorded, and these elevated temperatures are maintained for a longer period. It can be clearly seen that steel temperatures are not affected by the change in ventilation conditions from Test 1 (opening factor 0.316 [$m^{1/2}$]) to Test 2 (opening factor 0.073 [$m^{1/2}$]), while these are significantly affected for Test 3 with smaller openings (opening factor 0.024 [$m^{1/2}$]).

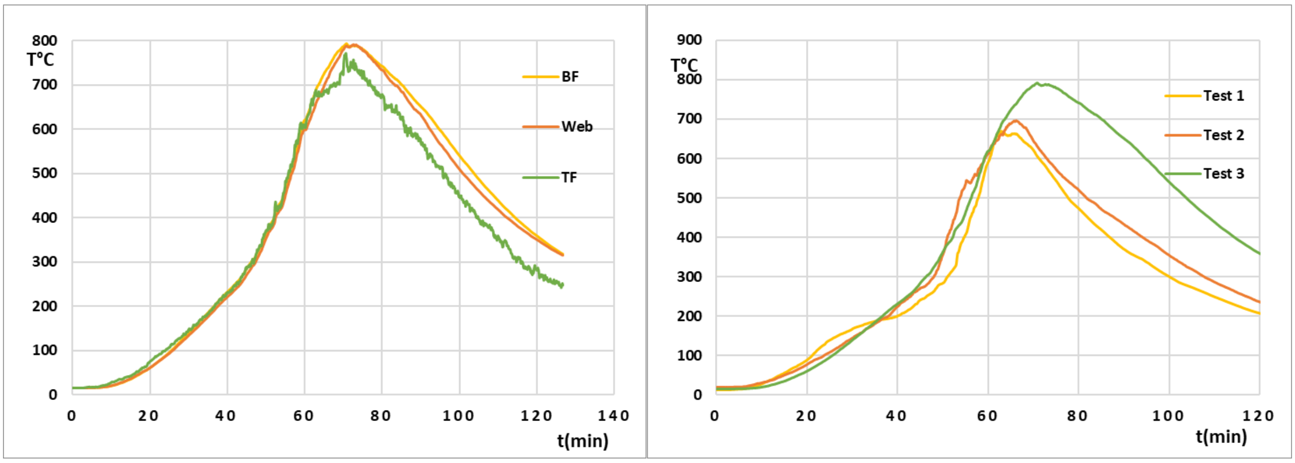


Figure 8: (a) Temperatures recorded in beam adjacent to TRL7, (b) average temperatures recorded in the selected beam during all three tests

6 CONCLUSIONS

Three large scale natural fire tests were conducted in a building with large dimensions. A fire load representative of an office building, defined according to a well-established methodology was used for the three tests, only the ventilation was varied to assess its influence on the fire behaviour. The main objectives of this experimental campaign were to understand in which conditions a travelling fire develops, as well as how it behaves and impacts the surrounding structure. Instrumentation was installed to measure compartment temperatures, heat fluxes and temperature in the steel columns, and beams. This article presented details of Test 3 in terms of gas temperatures recorded in the central part of the compartment, along its length. The details related to the maximum flame thickness, steel temperatures in selected central beams and columns were also provided. Following are major conclusions from the travelling fire Test 3.

- For the fire initiating at a single point, its developing phase consists of increase in the volume of fire in all directions making a circle around the point of ignition. Once the fire is well developed, it continues to travel along the fuel bed. In the case of the test conducted during this research, the fire travelled in the forward direction towards the fore end of the compartment. However, the fire could travel in any direction depending upon the availability of the fuel.
- The rise in temperatures at higher levels starts at the initial stages of test while the rise at lower levels starts once the fuel wood starts to burn locally. The temperatures in the compartment were found to be dependent on the positioning of the travelling fire. The parts of the compartment around the fire are hotter while the parts away from the fire were at lower temperatures.
- The results obtained 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. Such transient heating of the columns should be considered when analysing the stability of a structure subjected to travelling fires.
- All the connections and steel members performed well and showed no signs of failure during the fire test.

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