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Large Scale Travelling Fire Tests with Open Ventilation Conditions and Their Effect on the Surrounding Steel Structure– The Second Fire Test

ABSTRACT

In the frame of the European RFCS (Research Fund for Coal and Steel) TRAFIR (Characterization of TRAvelling FIRes in large compartments) project, three natural fire tests in a large compartment were conducted at Ulster University. The aim of this investigation was to understand the conditions in which the travelling fires develop and to study the impact of such fires on the surrounding steel structure. This paper provides details of the second fire test where the size of the openings was reduced to induce different ventilation conditions in comparison to the first fire test. During the test, behaviour of the travelling fire was observed and the gas temperatures at different levels and locations were recorded. The influence of travelling fires on the surrounding structure is studied in terms of the temperatures recorded in the selected steel columns and beams. The influence of change in the ventilation conditions is presented and highlighted through the comparison of results of the second fire test with those recorded earlier during the first fire test. It was found that the travelling fires produce non-uniform temperatures in the compartment irrespective of the ventilation conditions although the magnitude of this non-uniformity is related with the opening sizes. This non-uniformity exists along the length as well as along the height of the test compartment. It was found that for reduced opening sizes, more heat is retained within the compartment which induces higher temperatures in the surrounding steel structure. The transient heating of the surrounding structure caused by travelling fires should be considered while performing the structural fire design of large compartments. The results obtained during the test are state-of-the-art and will help in understating the behaviour of travelling fires and their influence on the surrounding structure which will help to devise fire design methods for future use.

Keywords: Travelling fire tests; steel structure; large natural fire tests; beams in travelling fires, columns in travelling fire

1 INTRODUCTION

With the changes in the modern architectural trends and designs, the layouts of the modern-day buildings have changed which challenges the existing engineering approaches and methods. Such changes in the architectural trends not only challenge the design approaches, but they are also more challenging from the structural fire engineering design prospective [1]. The traditional fire exposure conditions used for the structural fire design consider a post-flashover scenario where the temperatures within the compartment are deemed to be uniform and homogeneous. The current fire exposure conditions are based on the data acquired from the tests conducted in small compartments where the assumption of the uniform and homogeneous temperatures holds true. However, the modern architectural designs have more open spaces and large floor areas which makes the assumption of uniform and homogeneous temperatures within the compartment unrealistic. It has been observed during the accidental fires occurred over the last two decades that the temperatures in the large open-space compartments are not uniform and homogenous [1] [2]. Fires in the large open-space compartments initiate at a point (or multiple points), burn locally, and move across the floor with time. This behaviour of fire in large compartments generates non-uniform and non-homogeneous temperatures and results in the transient heating of the surrounding structure [1] [2]. Such types of fire scenarios are referred to as the travelling fires.

Although the standard time temperature curves ISO 834, hydrogen curves as well as the small compartment fires consider uniform and homogeneous temperature distribution, Eurocode 1 [3] provides two fire models considering non-uniform temperature distributions. The first of these models is the localised fire model while the second type is the advanced fire models. The localised fires in the Eurocode 1 are defined as the fires which involve a limited area of the fire-load in the compartment. Such fires do not represent the effect of a travelling fire in a compartment. The advanced fire models can either be the zone models or the computational fluid dynamics models (CFD). The details of the zone models are provided in Annex D of the Eurocode 1 [3]. The CFD (computational fluid dynamic) models enable to numerically solve the partial differential equations to give the thermo-dynamic and aero-dynamic variables at all points in a compartment [3]. CFD models may provide more accurate results as compared to the zone models, but these results come at a high computational cost.

It has been well documented that various travelling fire incidents have occurred since the beginning of the century. These incidents include the twin towers of the World Trade centre from the New York City during 2001 [4], the Windsor Tower of Madrid in 2005 [5], the Faculty of Architecture Building Delft University of Technology in Netherlands during

2008 [6]. There have been some efforts to study the behaviour of the travelling fires using the available literature, numerical investigations and experimental work including the ones listed in the references [2], [6] - [10], [15]. A detailed review of the work conducted on the travelling fires has been previously conducted by Dai, Welsh and Usmani [2]. These previous investigations are limited as they lack an in depth understanding of the travelling fires and their impact on the surrounding structure due to the absence of comprehensive experimental research. To build an understanding of the travelling fires and to study the conditions in which these fires develop, detailed experimental, numerical and analytical investigations are necessary. The experimental work conducted in this research will help to develop a better understating of the travelling fires and their influence on the surrounding structures. In addition to providing the state-of-the-art data and information, the results and findings from the experimental work can be used to calibrate simulation studies through CFD modelling to extend the scope of the experimental work by incorporating various factors influencing such fires. Further, this experimental work will support the improvement of analytical models to characterize the thermal impact from a travelling fire on a surrounding structure. It will help in devising guidance for fire design to better optimize the structures, resulting in economic and environmental benefits, while avoiding structural failures and safety issues.

2 THE EXPERIMENTAL PROGRAMME

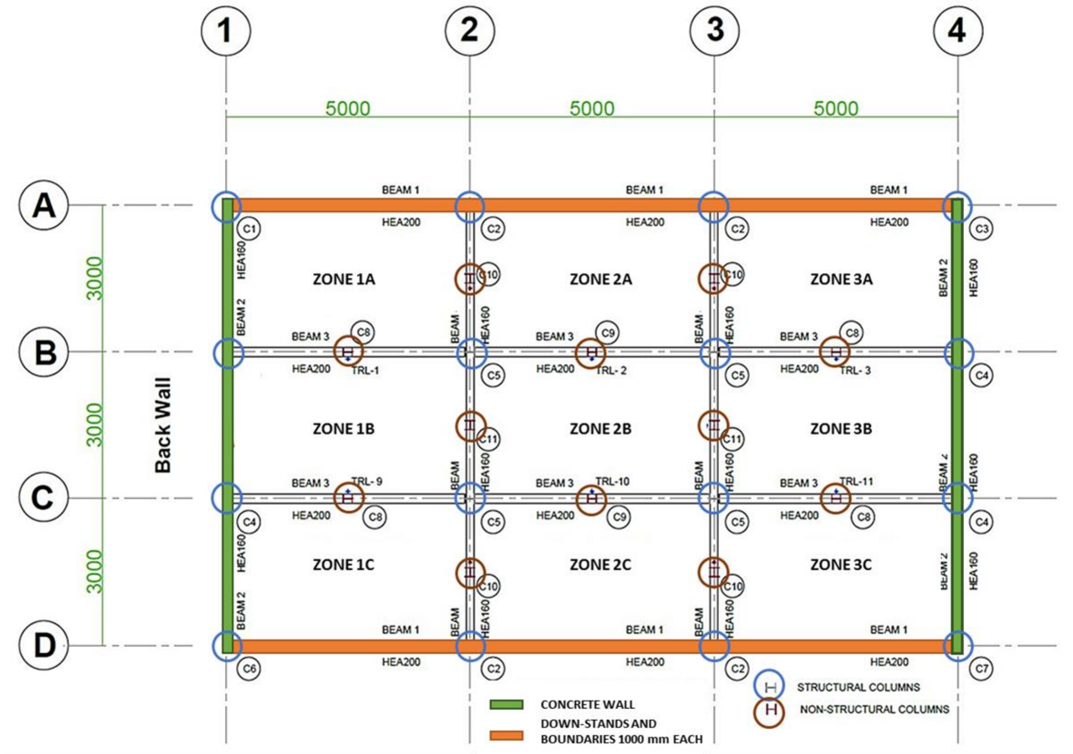
The experimental programme consisted of three large-scale fire tests conducted in a compartment built in the frame of the European RFCS TRAFIR project. During the experimental investigations, the fire load (which was calibrated to be representative of an office building according to Eurocode 1) was kept similar. However, the ventilation conditions were changed for each test, leading to different fire behaviours (see Table 1). This paper is focused on the second fire test (Test 2).

Table 1: Summary of the three large-scale fire tests

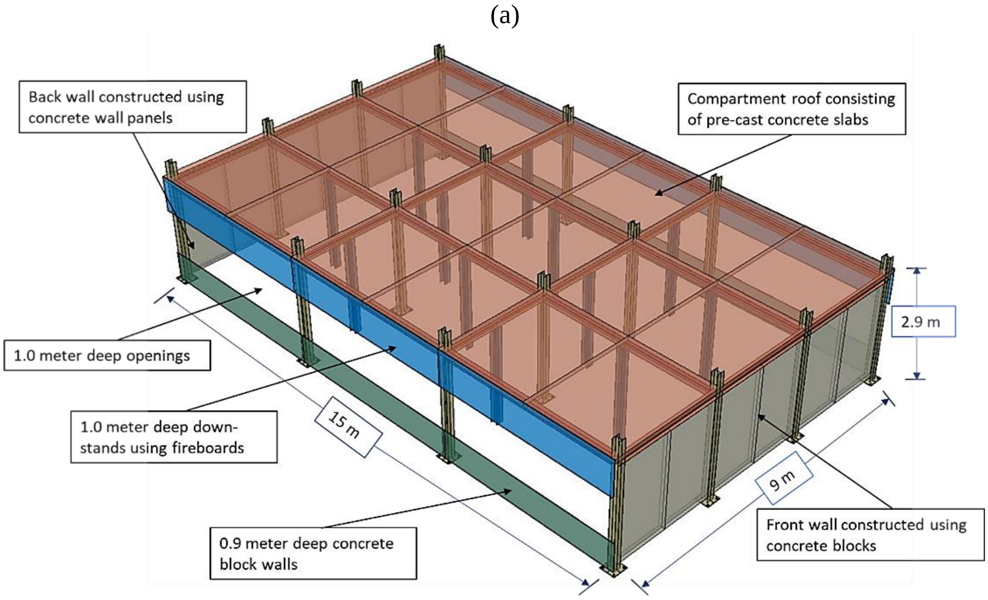
Test 1	Opening factor, O = 0.316 [$m^{1/2}$]	Travelling fire
Test 2	Opening factor, O = 0.073 [$m^{1/2}$]	Travelling fire
Test 3	Opening factor, O = 0.024 [$m^{1/2}$]	Travelling fire leading to flashover

2.1 Details of the Test Structure

The test compartment was a representative of a modern office building consisting of a floor area 15 m long and 9 m wide between outer gridlines (Figure 1 (a)). The ceiling level of the structure from the surface of the finished floor was 2.9 m as shown in Figure 1 (b). The structural frame of the compartment consisted of hot rolled steel beams and columns while the roof was constructed using 120 cm hollow-core pre-cast concrete slabs. The columns were categorised into two groups, the structural columns, and the dummy columns. The structural columns were part of the main structural frame responsible for supporting the loads while the dummy columns were provided only for data acquisition purposes. Both the structural and non-structural columns consisted of hot rolled HEA200 steel sections and were anchored to the thick pre-existing concrete floor. The structural columns were 3.5 m in height and extended beyond the roof, however, the dummy columns were erected between the concrete floor and the bottom flange of the steel beams and had lesser length of 2.7 m. The positioning of the columns along the longer dimension of the compartment was kept at 5 m intermediate distances while the same along shorter dimension were kept at 3 m as shown in Figure 1 (a). The dummy columns were provided between the structural columns along the gridlines ②, ③, Ⓑ and Ⓒ. These dummy columns have been identified as C8, C9, C10 and C11 in Figure 1 (a). In this article, only details related to C11 will be provided while discussing the test results. All the columns were fixed to the pre-existing concrete floor using anchorage bolts. In case of the structural columns, four anchorage bolts were used while for the dummy columns, only two anchorage bolts were used for fixing purposes. The beams of the test compartment consisted of two steel sections. Hot rolled HEA200 steel sections were used for the beams along the longer dimension while hot rolled HEA160 sections were used for the beams along the shorter dimension as shown in Figure 1 (a). The connection between the beams and the structural columns was designed as fin-plates. The structural steel frame was laterally restrained using two diagonal bracings along the longer and shorter dimension each. Once the steel frame was built, the hollow-core pre-cast slabs were used to cover the roof. The slabs were provided along shorter dimension of the compartment as shown in Figure 1 (c). Any gaps between the slabs were filled using fire blanket to make the roof airtight.



(a)



(b)

(c)

Figure 1: Details of the test structure, (a) the floor plan, (b) the schematic view, (c) the constructed test compartment

As mentioned before, in the frame of the European RFCS TRAFIR project, three large scale fire tests were conducted with same fire load and different ventilation conditions. This paper is focused on the second fire test (Test 2) where the boundary conditions were kept different as compared to the first fire test (Test 1) for which details are given by Nadjai et. al. [11]. During Test 1, a concrete wall was constructed only along the gridline ① while 1.0 m down-stands (made of fireboard) were provided in the longer direction along gridlines Ⓐ and Ⓓ. Due to such boundary arrangements, the total area of the openings was 87 m^2 which resulted in a fuel-controlled travelling fire. One of the aims of the research project was to assess the influence of the ventilation conditions on the fire scenario. For Test 2, it was aimed to reach a fuel-controlled travelling fire test but with opening sizes significantly smaller as compared to those used during Test 1. However, due to lack of research, defining the total opening area required to achieve such fire scenario was not straightforward: a priori (and simplified) simulations-based zone models were launched to evaluate which total opening area would lead to such situation without inducing a ventilation-controlled fire. To achieve this, a concrete block wall was constructed along the shorter direction of the compartment along gridline Ⓓ, like the existing concrete wall along gridline Ⓐ (the back wall). The wall constructed along gridline Ⓓ (the front wall) had no openings as shown in Figure 1 (c). To reduce the opening sizes along the longer dimension of the test compartment, 1 m deep concrete block walls were also constructed along gridlines Ⓐ and Ⓓ. These walls constructed along gridlines Ⓐ and Ⓓ have been referred to as the sill walls in this article. Such arrangement resulted in total opening size of 30 m^2 during Test 2. Hence, the size and arrangement of the boundary conditions during the second travelling fire test (Test 2) were different as compared to the first travelling fire test (Test 1).

As the test compartment was planned to be used for further experimental fire investigations, the structural columns were protected using intumescent coating (R60) to maintain the integrity of the structure. In addition to the structural columns, the back and the front concrete walls were also protected using fireboard (R60). A summary of the structural and non-structural elements and the protection applied is given in Table 2.

Table 2: Details of the construction elements and applied fire protection

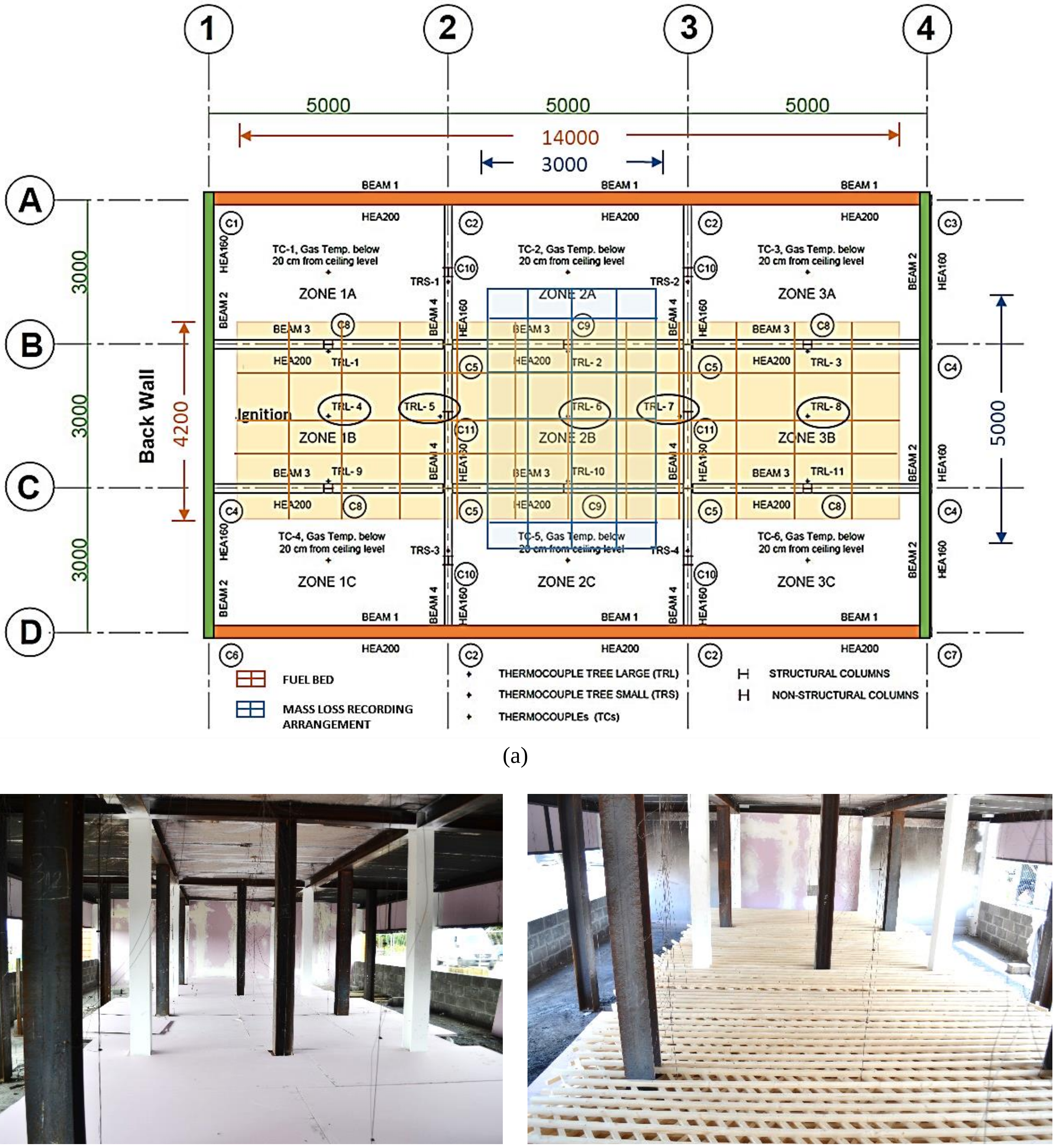
Description	Sections/Size	Section Factor (m^{-1})	Length Height (m)	Protection Applied
Structural columns	HEA200	211	3.5	R60
Dummy columns	HEA200	211	2.7	None
Long beams	HEA200	174	4.8	None
Short beams	HEA160	192	3.0	None
Back wall	9 m x 2.7 m	-	2.7	R60
Front wall	9 m x 2.7 m	-	2.7	R60
Sill walls	15 m x 1 m	-	1	None

2.2 Details of the Fire Load

The compartment considered during the fire tests was a representative of an office building. EN 1991-1-2 [12] provides a medium fire growth rate (t_α = 300 seconds) and a fire load density of 511 MJ/m^2 for such occupancies. During the earlier work packages of the TRAFIR- RFCS project, numerous experimental tests were conducted using uniformly distributed wood sticks to define an arrangement that would lead to an office fire as recommended in EN 1991-1-2. Details of the experimental work on the fuel load arrangement during the earlier work packages are given in the references [13] and [14]. The work presented in these references led to devise a fuel wood arrangement with a fire load density of 511 MJ/m^2 and a medium fire propagation. The results from these investigations have been used to define the fuel load for the experimental campaign described in this paper.

The fuel wood source used consisted of the species "*Picea abies*" with an average density 470 kg/m^3 having a moisture content of 15.22%. To achieve a medium fire growth rate for the office building and reach a fire load density of 511 MJ/m^2, 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 as proposed during in the earlier studies [13] and [14]. Overall, the width of the fuel wood was 4.2 m while its length was 14 m along the longer dimension of the test compartment as shown in Figure 2 (a). For convenience, a gap of 500 mm was maintained between the walls and the edge of the fuel bed at both ends. The fuel bed was aligned with the centre line of the compartment which resulted in a 2.4 m distance from the edge of the fuel bed to the centreline of the columns provided along in the longer dimension along gridlines Ⓐ and Ⓓ.

The fuel wood was not provided directly on the concrete floor, instead, a platform was constructed to support the fuel wood. The platform consisted of two layers of fire board which were supported on concrete blocks such that the top level of the platform was 325 mm from the floor finish level as shown in Figure 2 (b). The first layer of the wooden sticks was laid at 60° angle from gridline ④ while the second layer 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 (c). The final layer, the ninth layer of the fuel wood, was at 0° or 180°, which helped to visually observe the travelling behaviour of fire from one stick to another. For each test, the ignition was defined at a point located along the centreline at 0.5 m from its edge, i.e., at 1.0 m distance from the back wall.



(a)

(b)

(c)

Figure 2: Fire fuel details; (a) platform for providing fuel wood; (b) fuel wood provided in 9 layers

2.3 Details of the Instrumentation

In-line with the aims and objectives of this research, intensive instrumentation was conducted to record temperatures, mas-loss of fuel wood and heat fluxes during the fire test. Temperatures within the compartment and the surrounding structure were recorded using Type K-310 thermocouples with a bead size measuring 1.5 mm. The heat fluxes were measured using heat flux gauges and thin-skinned calorimeters while the mass-loss of fuel wood was recorded using load cells. Keeping in view the scope of the results presented, only details of the instrumentation related to the thermocouples is provided in this article.

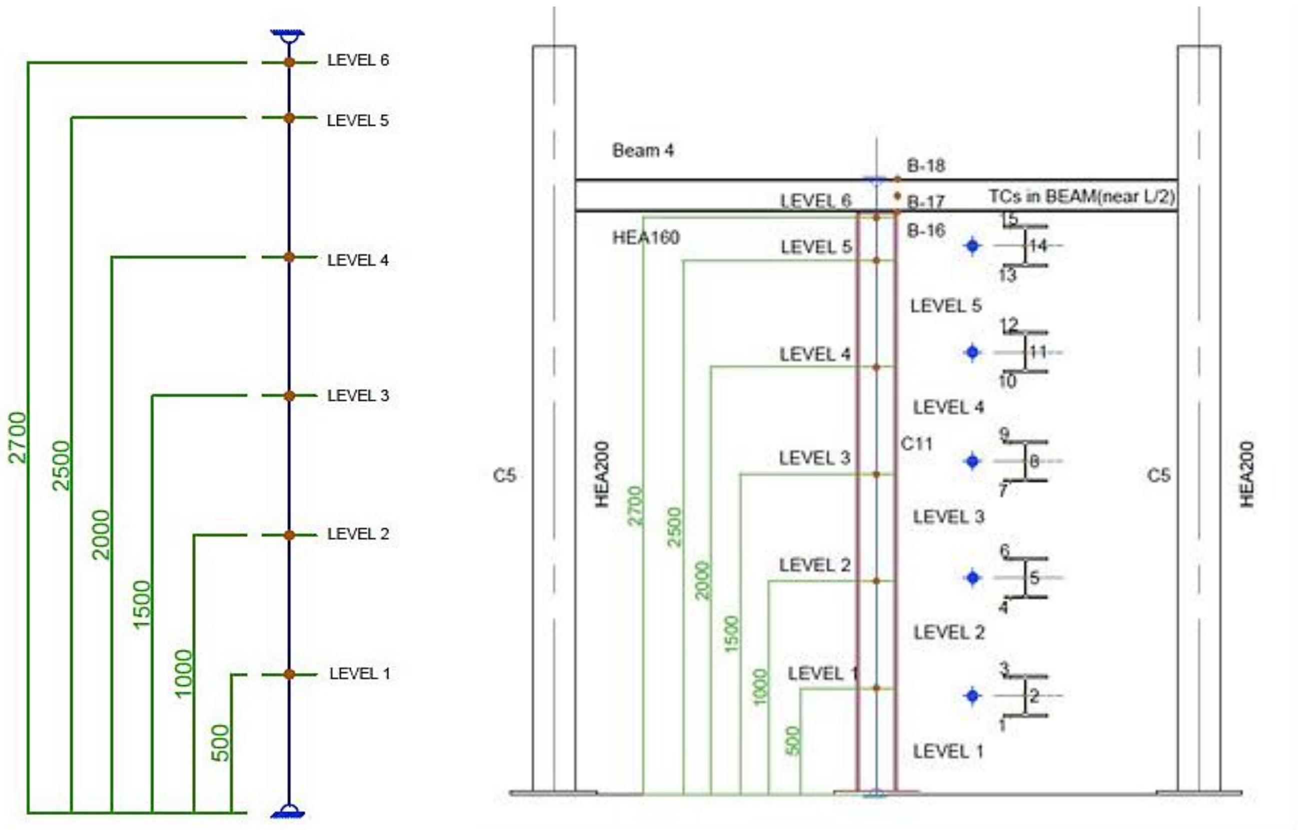
2.3.1 The Temperature Recordings

A significant number of thermocouples were employed to record the gas temperatures within the compartment during the test. Temperatures were recorded at the ceiling levels using individual thermocouples, while temperatures at different levels along the height of the compartment were recorded using thermocouple trees. Thermocouple trees used for temperature recording purposes were categorised into two groups, the small thermocouple trees (TRS) which consisted of three thermocouples and the large thermocouple trees (TRL) which consisted of six thermocouples each. The small thermocouple trees were provided outside the fuel bed while the large thermocouple trees were provided within the fuel bed as shown in Figure 2 (a). This paper will focus on the temperatures recorded within the fuel bed along the centreline of the test compartment using TRL-4 through TRL-8 which have been specifically identified in Figure 2 (a).

The positioning of the large thermocouple trees along the centre of the test compartment provided temperatures at six different levels during the test as shown in Figure 3 (a). Level 1 for each TRL was at 500 mm distance from the floor finish level and was therefore within the fire fuel bed. Level 2 and Level 3 were at 1000 mm and 1500 mm distance from the floor finish levels, respectively. Temperatures in the upper parts of the compartment were recorded at Level 4, Level 5, and Level 6. Level 4 and Level 5 were at 2000 mm and 2500 mm respectively from the floor finish level while Level 6 was closer the ceiling, at 2700 mm distance as shown in Figure 3 (a).

As mentioned previously, dummy columns were provided to record the steel temperatures. Two dummy columns were positioned along the centreline of the test compartment within the middle of the fuel bed. As shown in Figure 2 (a), these columns are labelled as C11 which are positioned adjacent to thermocouple trees TRL-5 and TRL-7 and are the focus of the research resented in this article. The temperatures in the selected columns were recorded at five levels, level 1 through level 5. The distance of these levels from the floor finish level is shown in Figure 3 (b) which is similar to that of the height of thermocouples provided in TRLs to record the gas temperatures. Three thermocouples were provided at each level in the dummy columns, two at each level were provided in the flanges while the third was provided in the steel web. The arrangement of the thermocouples was consistent at each level as shown in Figure 3 (c).

Temperatures in the beams were monitored at mid-span above the dummy columns as shown in Figure 3 (b). One thermocouple was provided in the bottom flange (B-16), one in the web (B-17) and one in the top flange (B-18) as shown in Figure 3 (d). For the data presentation purposes in this article, two beams along the shorter direction of the test compartment have been selected. The selected beams are placed along gridlines ② and ③ and span between gridlines Ⓑ and Ⓒ, as shown in Figure 1 (a) and Figure 2 (a).



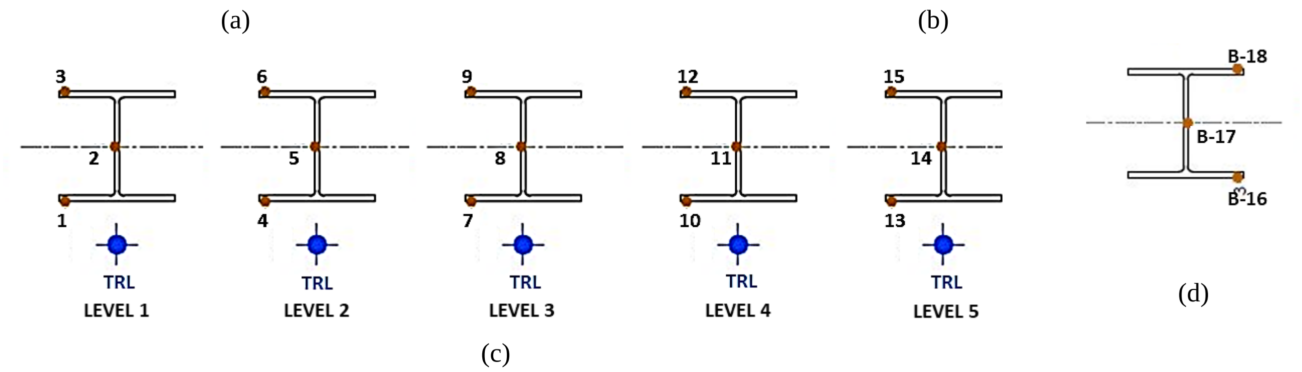


Figure 3: Details of thermocouples, (a) in the large thermocouple trees; (b) in columns and beams at different levels; (c) in columns, a closer view; (d) in beams, a closer view

2.3.2 The Mass Loss Recording

The mass loss of the fuel wood was monitored in the middle of the test compartment between gridlines ② and ③ as shown in Figure 2 (a). The steel platform used to measure the mass loss was 5 m long x 3 m wide and was supported on four load cells. To avoid any damage to the platform during the fire tests, fire blanked was wrapped around the steel elements to avoid direct exposure to heat. The load cells were also protected using the fire blanket to avoid any damage during the fire tests. 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 fuel wood. The layers of the gypsum fire board were at 325 mm distance from the floor finish level and were aligned with other fire board panels provided to support the fuel wood. Although the fire boards on the steel platform supporting the fuel wood were at the same level from the floor finish level, these were intentionally kept separate from the rest of the floorboards to ensure accurate measurement of the mass loss during the fire tests. Further details related to the arrangements for mass loss recording are provided by Nadjai. et al [11].

2.3.3 The Data Acquisition System

All the thermocouples were labelled and provided in the designated positions. As the length of the thermocouples used during the test was 3000 mm, extension cables were used to connect the thermocouples with the data acquisition system. The extension cables were stretched over the roof of the test compartment which connected the thermocouples and the data loggers. To protect the extension cables from direct exposure to heat during the fire test, a layer of fire blanket was provided between the cables and the roof slabs as shown in Figure 4 (a). As the number of thermocouples and other sensors used to record data was high, multiple data loggers had to be used for data recording purposes, Figure 4 (b).

(a) (b)

Figure 4: (a) Extension cables used for data recording purposes, (b) Multiple data loggers uses

3 RESULTS AND DISCUSSION

It has been stated earlier that three large scale travelling fire tests were conducted in the frame of the European RCFS-TRAFIR project. Details of the first fire test and results obtained have been presented earlier in a separate publication which can be found in the reference [11]. The results obtained during the second fire test (Test 2) are presented in the following sections.

3.1 The Travelling Fire Behaviour

The point of ignition being 500 mm from the edge of the fuel bed near gridline ①, the initial spread of the fire was in all directions forming a circle as shown in Figure 5 (a). After 6 min from ignition, the fire reached the backend of the fuel bed (the edge adjacent to gridline ①). The flames touched the ceiling level after 8 minutes from ignition. After 23 minutes from ignition, the width of fire-band was 4.2 meters as it reached to ends of the firewood parallel to gridlines Ⓐ and Ⓓ. After 24 minutes, the fire started to travel as the backend of the fire started to move along the length of the compartment. After 29 minutes from ignition, TRL-4 was fully engulfed in flames. The fire travelled ahead and entered Zone 2B after 32 minutes from the start of the fire test. The firewood provided on the platform to measure the mass-loss started to burn after 38 minutes from ignition as the platform was provided in Zone 2B. The thermocouple tree TRL-5 was fully engulfed after 42 minutes from the start of the fire test. At the same instance, the fore end of the travelling fire reached the centre of the test compartment while the centre of the travelling fire band reached the middle of the test compartment after 51 minutes from ignition engulfing the thermocouple tree TRL-6 as seen in Figure 5 (b). It should be noted that the fore end of the fire had also entered the Zone 3B at the same time after 51 minutes from the start of the test. With the fire travelling towards the fore end of the test compartment, majority of the fuel wood supported by the platform to measure the mass-loss was consumed after 59 minutes from ignition. This was the time when the thermocouple tree, TRL-7, was fully engulfed in flames. It was observed that majority of the fuel wood in Zone 3B was burning after 64 minutes from ignition and the thermocouple tree TRL-8 was found to be fully engulfed. The fuel wood continued to burn in Zone 3B until the 82nd min, the time when all combustive materials were consumed.

(a) (b)

Figure 5: Fire development and temperatures recorded at different intervals along the length of the test compartment: (a) early fire development; (b) fully developed fire in the middle of test compartment

The behaviour of the travelling fire is reflected in the recorded gas temperatures in the compartment presented for different time intervals in Figure *6* (a) through (f). The missing data for some thermocouples in Figure *6* is due to the malfunctioning of the sensors during the fire test. It is seen in Figure *6* (a) that after 15 minutes from ignition, gas temperatures throughout the test compartment are quite low (i.e., all below 350°C). The gas temperatures recorded at TRL-4, especially at upper levels, are relatively high as compared to those recorded using other thermocouple trees. Further, lower temperatures are recorded at further distances from point of ignition (e.g., TRL-7 and TRL-8). As the fire develops, the gas temperatures recorded at TRL-4 increase and reach almost 700℃, Figure *6* (b). Although temperatures recorded by TRL-5 through TRL-8 are lower as compared to those recorded at TRL-4, the overall gas temperatures recorded in the test compartment are higher after 30 minutes as compared to those recorded after 15 minutes.

As observed during the test, the travelling fire band was positioned closer to TRL-5 after 45 minutes from the start of the test. This has resulted in higher gas temperatures at TRL-5 which have exceeded 800°C (but remained under 900°C) at some levels as shown in Figure *6* (c). At the same time, the gas temperatures in TRL-4 have reduced due to the fire travelling towards the fore end of the compartment. The gas temperatures at some levels of TRL-4 which were 700°C after 30 minutes from ignition have now reduced to 600°C, refer to Figure *6* (c). Overall, the gas temperatures in the test compartment on average have increased at this stage of the fire test (after 45 minutes).

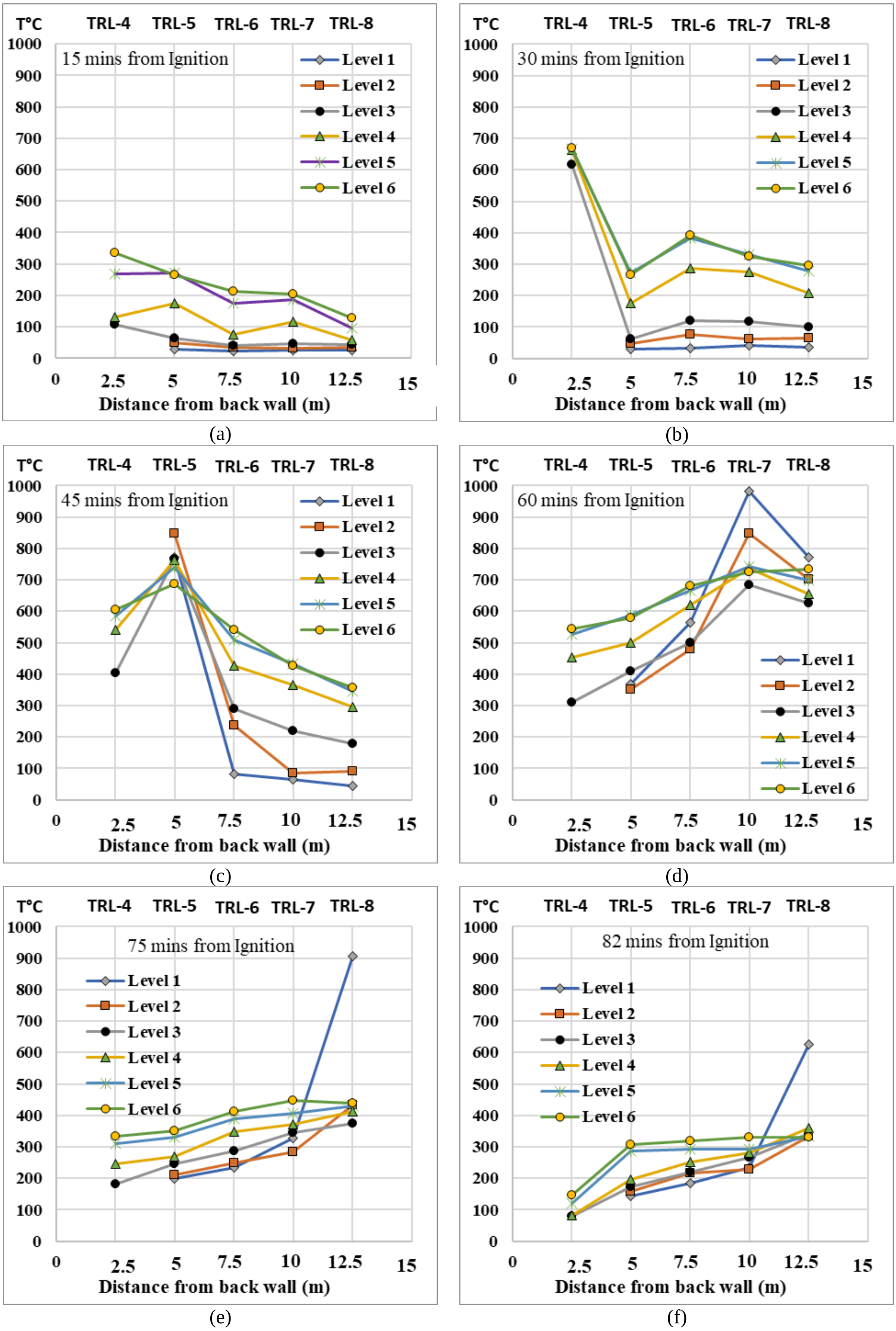


Figure 6: Fire development and temperatures recorded at different intervals along the length of the test compartment: gas temperatures after: (a) 15 minutes, (b) 30 minutes, (c) 45 minutes, (d) 60 minutes, (e) 75 minutes, (f) 82 minutes

The spread of the travelling fire band was relatively faster in the central zone (Zone 2B in Figure 2 (a)) as compared to the initial zone (Zone 1B in Figure 2 (a)). This was anticipated as the fire was developing in Zone 1B, which needs more time. After 60 minutes from ignition, the fore end of the fire band has already entered Zone 3B while the centre of the fire is still in Zone 2B. In other words, the travelling fire band has passed TRL-6 and is very close to TRL-7. This is seen in Figure *6* (d) where the recorded gas temperatures are highest at TRL-7. The gas temperatures recorded at TRL-8 and TRL-6 are also high after 60 minutes as these thermocouple trees are highly influenced by the closeness of the flames. At the same time, the gas temperatures recorded in TRL-4 and TRL-5 are relatively low as the fire band is at a higher distance from these thermocouple trees.

After 75 minutes from ignition, the fire band is concentrated in Zone 2C. At this time, majority of the fuel wood is consumed and the gas temperatures, including those in Zone 2C, have already reduced, refer to Figure *6* (e). It is interesting to note in Figure *6* (e) that gas temperatures recorded by the thermocouple at level 1 provided in TRL-8 is significantly higher as compared to other levels. This is because thermocouple at level 1 for all thermocouple trees was within the fuel bed. The thermocouple at level 1 in TRL-8 records high temperatures as this is within the fuel bed which is now a heap of embers. During the test, no flames were visible after 82 minutes, as a result the gas temperatures within the compartment have reduced below 375°C as seen in Figure *6* (f), except for the gas temperatures recorded by thermocouple at level 1 provided in TRL-8 which is around 620°C due to its positioning within the embers.

The other interesting observation made during the fire test was the width of the travelling fire band, i.e., the distance between the fore end and the back end (burnout) of the travelling fire along the centreline of the compartment from gridline ① towards gridline ④. As the fire started at a single point, it evolved in all directions initially forming a circle. The fire reached the backend of the fuel after 6 minutes while the fire continued to spread over the width of the fuel bed. The width of the fire band was 1 meter after 9 minutes and increased to 1.5 meters and 2 meters after 14 and 20 minutes respectively as presented in Figure 7. With the consumption of the firewood at near the back end of the compartment, the fire started to travel towards the fore end as a band (while it was “spreading” but not “travelling” beforehand). Generally, the width of the fire band was smaller in Zone 1B of the test compartment. The width of the fuel bed remained between 3 meters and 3.5 meters in the middle of the test compartment in Zone 2B from the 30th minute until the 50th minute as presented in Figure 7. Once the fire band entered Zone 3B, an increase its width was recorded which reached 5 meters after 62 minutes from ignition. At this point, most of the available fuel wood was burning, and it continued to burn for 12 more minutes over the same length as presented in Figure 7. With the consumption of the fuel wood, the intensity and width of the fire reduced. It was after the 82nd minute from ignition that all combustible materials were consumed, and no flames were visible. In addition to the observed fire band width, the trendline is also shown in Figure 7.

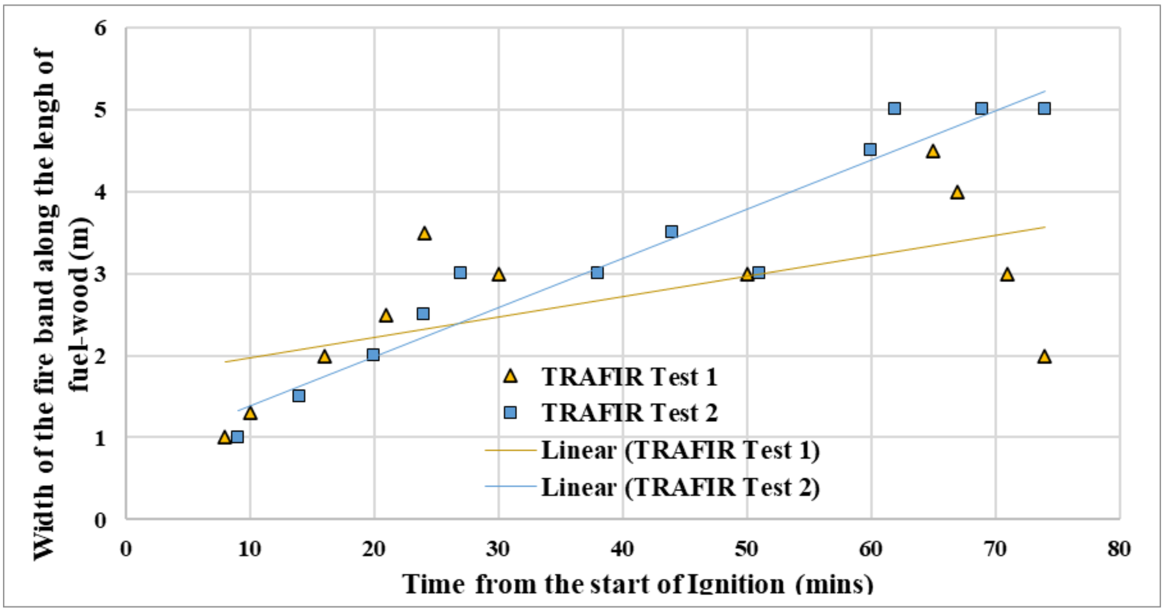
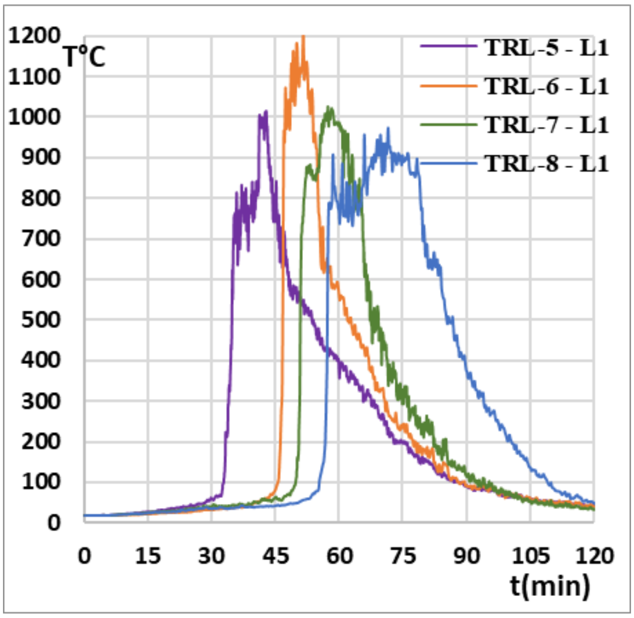


Figure 7: Fire-band width evolution during the fire Test 2 in comparison to fire Test 1

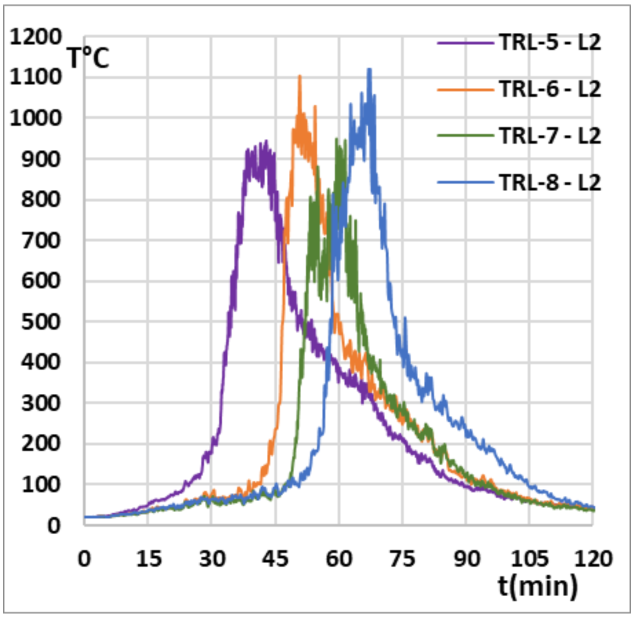
3.2 Gas Temperatures Recorded in the Test Compartment

The path of the travelling fire was along the middle of the test compartment starting near the back wall and travelling towards the front wall. The thermocouple trees along the centreline of the compartment were provided such that they recorded the gas temperatures in the compartment along the direction of the travelling fire. The gas temperatures recorded along the centreline of the test compartment using thermocouples trees TRL-4 through TRL-8 along the centreline of the test compartment are presented in Figure 8. The positioning of the thermocouple trees is shown earlier in Figure 2 (a) which shows TRL-4 closest to the point of ignition and is at 1.5 m from the source of ignition (or 2.5 m from the inner side of the back wall). On the other hand, TRL-8 is the farthest from point of ignition and is at 2.5 m from the front wall along gridline ④. The remaining thermocouple trees, TRL-5 through TRL-7, are positioned equidistant, at 2.5 m intermediate distances. As each thermocouple tree was equipped with a thermocouple at 6 levels, the data recorded is presented in Figure 8 (a) through (f). Any missing data for a thermocouple in Figure 8 is due to malfunctioning sensors. Following are the main observations from the gas temperatures recorded in the test compartment:

- The rise in temperature at upper level is earlier as compared to intermediate and lower levels. This can be seen in Figure 8 (e) and (f) where an increase in gas temperatures is recorded for level 5 and 6 within 5 minutes from the start of the test. This was expected as the hot gases rise and accumulate closer to the ceiling level which results in a rise of temperatures at upper levels of the test compartment.
- The rise in gas temperatures at level 4 also initiates at an earlier stage of the test, after 10 minutes from ignition. The initial rise in gas temperatures recorded at different thermocouple tree locations is very similar only with 5 minutes difference as shown in Figure 8 (d). This rise however is different at level 3. The rise in gas temperature at level 3 for thermocouple tree TRL-4 and TRL-5 initiates much earlier as compared to that recorded using TRL-6, TRL-7 and TRL-8, refer to Figure 8 (c).
- The rise in temperatures at the two bottom levels; level 1 and level 2, initiates late but this rise is sudden. It is seen in Figure 8 (a) and (b) that for the initial 30 minutes, the rise in temperatures at these levels is very low. However, after 30-32 minutes from the start of the test, a sudden rise in temperatures is recorded. This rise could have initiated at an earlier stage for levels 1 and 2 at TRL-4, however, the data could not be recorded as thermocouples at these levels in TRL-4 were found faulty. None-the-less, the rise in gas temperatures at these levels is directly related to the positioning of the travelling fire band. When the travelling fire band is away from these thermocouple trees, the rise in temperatures at lower levels is slow. As the travelling fire band gets closer to the thermocouple trees, a sudden rise in temperatures is recorded. It should be noted that the thermocouples at level 1 are embedded within the fuel bed while thermocouples at level 2 are at 20 cm from the top of fuel bed.
- It is interesting to see in Figure 8 that the maximum gas temperatures recorded at TRL-4 at the least amongst the maximum gas temperatures recorded using different thermocouple trees. Similarly, the maximum gas temperatures recorded at TRL-8 are the greatest amongst the maximum temperatures recorded using different thermocouple trees.
- The gas temperature curves for upper levels present a larger plateau as compared to the temperature curves for lower levels. Further, the gas temperature curves for TRL-4 and TRL-5 show larger plateau as compared to TRL-6. The plateaus for temperature curves at TRL-7 and TRL-8 are the smallest.



(a)



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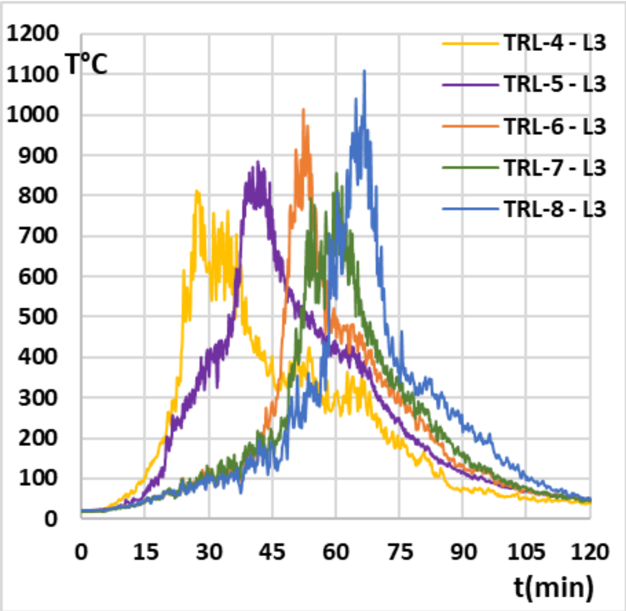

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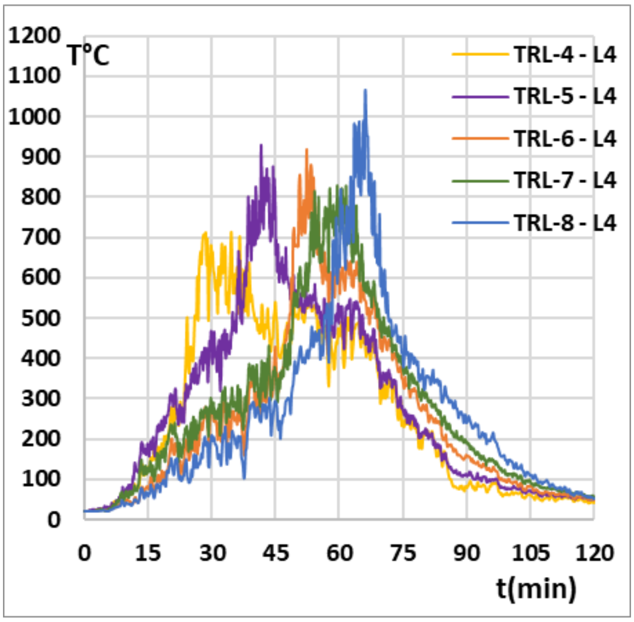

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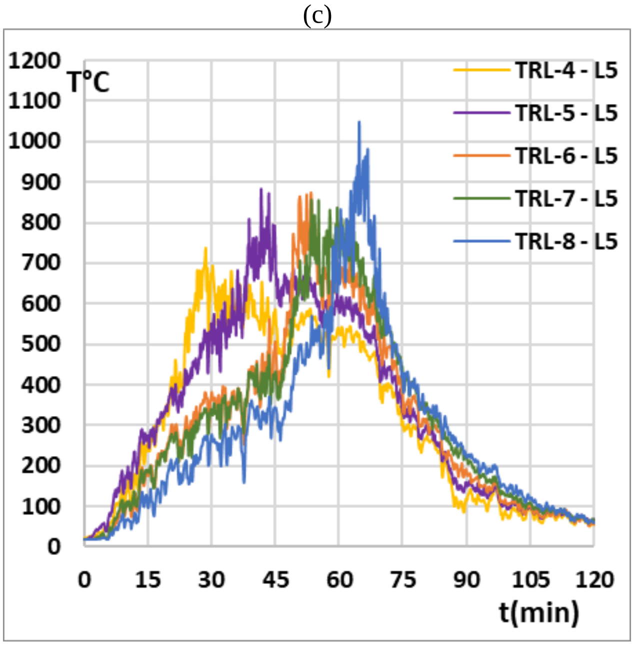
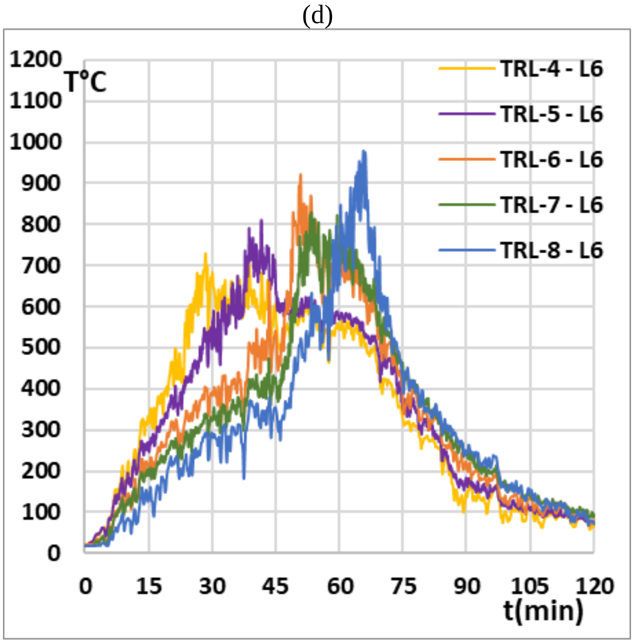


(e)



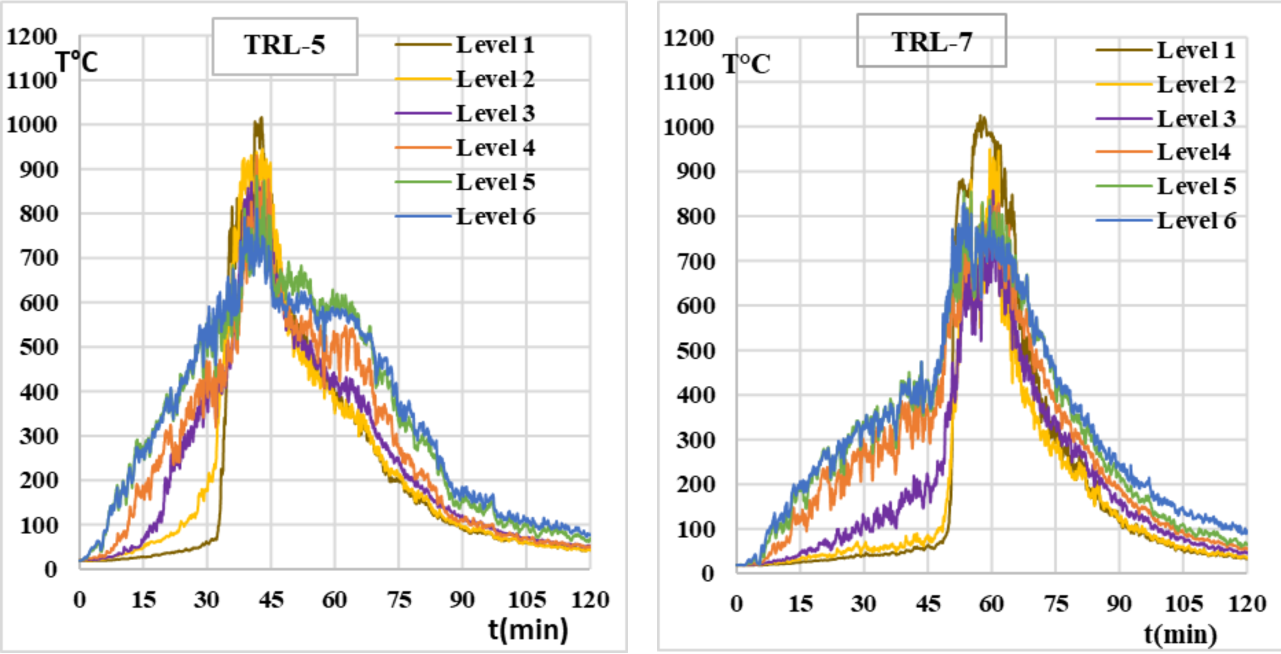
(f)

Figure 8: Gas temperatures recorded at different levels via thermocouple trees: (a) Level 1, (b) Level 2, (c) Level 3, (d) Level 4, (e) Level 5, (f) Level 6

- For upper levels, the increase in gas temperature is steady and slow while the decay phase is comparatively sharp as shown in Figure 8 (e) and (f). On the other hand, the rise in gas temperatures at lower levels is sharp while the decay part of the curve is uniform and slow as shown in Figure 8 (a) and (b).
- The gas temperatures recorded at different levels using thermocouple trees shows significant variations in the test compartment, highlighting a transient heating both longitudinally (i.e., along the path of the travelling fire) and vertically (i.e., along the height of the compartment).

3.3 Temperatures Recorded in the Steel Structure

In addition to the gas temperatures recorded within the test compartment, steel temperatures were also recorded in the test structure in the selected beams and the dummy columns. For data presentation purposes, the columns and beams along gridline ② and ③ positioned between gridlines Ⓑ and Ⓒ have been selected in this article. The columns and beams selected for data presentation purposes are adjacent to TRL-5 and TRL-7 shown earlier in Figure 2. The steel temperatures recoded in the column and beams are presented for different thermocouple positions shown in earlier in Figure 3. It was observed that the centre of the traveling fire band was concentrated near TRL-5 and TRL-7 after 47 and 58 minutes respectively from the start of the test. The gas temperatures recorded just next to the considered columns (i.e., in TRL-5 and TRL-7) are presented in Figure 9 (a) and (b) respectively. The gas temperatures recorded at level 6 provide the compartment temperatures in the surroundings of the beams.



(a) (b)

Figure 9: Gas temperatures recorded using; (a) TRL-5; (b) TRL-7

3.3.1 Temperatures recorded in the Steel Columns

Steel temperatures recorded in the dummy columns (C11) adjacent to TRL-5 and TRL-7 are presented in Figure 10 for all five levels (i.e., Level 1 to Level 5). It should be noted that temperatures in the steel column were recorded at 5 levels as shown earlier in Figure 3. Three labels shown in Figure 10 corresponds to different positions of the thermocouples. The label “LHS-F” corresponds to the flange of the column facing gridline Ⓒ. These thermocouples are identified as 1, 4, 7, 10 and 13 in Figure 3 (c). Similarly, the thermocouples identified as 3, 6, 9, 12 and 15 labelled as “RHS-F” are the ones provided on the flange facing the gridline Ⓑ. The remaining five thermocouples identified as 2, 4, 6, 8 and 10 are provided in the web and have been labelled with “WEB” in Figure 10. The thermocouples which were found faulty have been omitted from the data presented in Figure 10. The trend of the steel temperatures recorded in the columns present similarities to those recorded within the test compartment as the rise in temperatures at upper levels initiates earlier as compared to lower levels. In case of column adjacent to TRL-5, the rise in steel temperatures initiates after 33 minutes from the start of ignition at level 1. The column adjacent to TRL-7 is at a farther distance from the point of ignition, hence the rise in steel temperature at level 1 is recorded after 53 minutes from the start of the test. For both columns, the rise in steel temperature at level 1 is rapid once the travelling fire gets closer as shown in Figure 10 (a). The rise in steel temperature at level 2, 3 and 4 initiates after 18, 15 and 13 minutes from ignition for column adjacent to TRL-5. The rise in steel temperature is relatively rapid for level 2 while this is relatively slow for level 4 as shown in Figure 10 (b), (c), and (d). The rise in temperatures for column adjacent to TRL-7 at levels 2, 3 and 4 is similar to that for column adjacent to TRL-5. As the column adjacent to TRL-7 is at a higher distance from the point of ignition, the rise in temperature at level 2 is rapid and more pronounced after 30 minutes from ignition as shown in Figure 10 (b). On the other hand, the rise in temperature for column adjacent to TRL-7 at level 3 and 4 initiates after 22 and 15 minutes respectively as presented in Figure 10 (c) and (d). The gas temperatures recorded in the test compartment presented earlier in Figure 9 showed that the rise in gas temperatures at upper levels earlier as compared to that at lower levels. The steel temperatures recorded in the columns present a similar pattern.

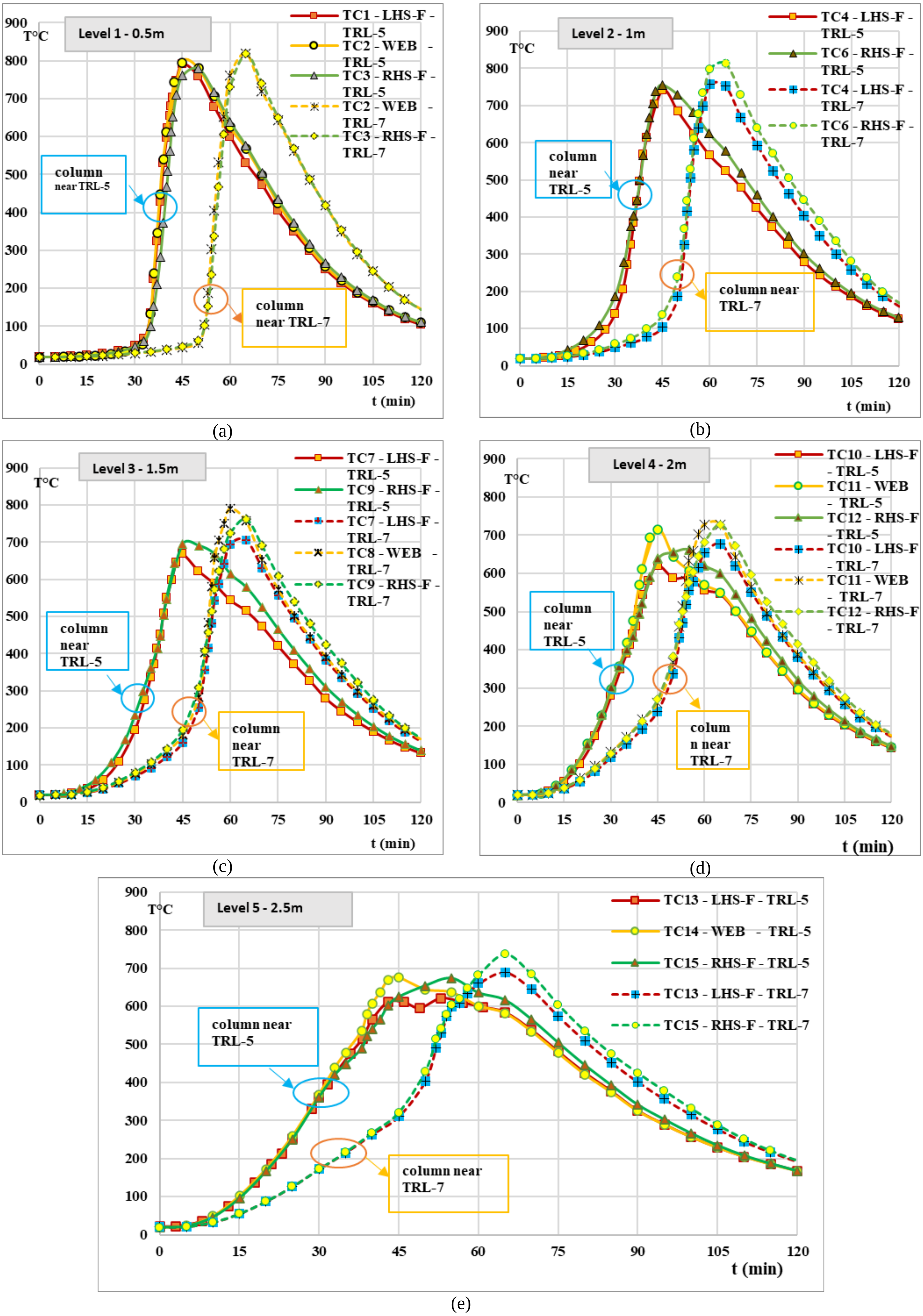


Figure 10: Steel temperatures recorded in dummy columns adjacent to TRL-5 and TRL-7 at; (a) Level 1: (b) Level 2: (c) Level 3: (d) Level 4: (e) Level 5.

At lower levels, the rise in temperature initiates after a longer time from the start of ignition while at upper levels, the rise in temperatures starts at earlier stages of the tests irrespective of the positioning of the column. It is seen in Figure 10 (e) that the rise in steel temperature at level 5 initiates after 10 minutes from the start of the test for both columns. This is comparatively faster for column adjacent to TRL-5 being closer to source of ignition while the same is slower for column adjacent to TRL-7. None-the-less, the rise in temperatures at level 5 initiates earlier as compared to the lower levels. It is also noticed in Figure 10 that steel temperatures across the section of the columns are quite uniform. It should be noted that higher maximum steel temperatures are recorded in column adjacent to TRL-7 as compared to those recorded in column adjacent to TRL-5.

3.3.2 Temperatures Recorded in the Selected Steel Beams

The beams considered for data presentation purposes consist of the hot rolled steel profile HEA160 provided along gridlines ② and ③ and located between gridlines Ⓑ and Ⓒ. The selected beams were instrumented with three thermocouples, one on each flange and one in the middle of the steel web, shown previously in Figure 3 (d). The gas temperatures in the compartment close to the beam thermocouples were recorded via thermocouples provided at level 6 in TRL-5 and TRL-7. The recorded gas temperatures at level 6 using TRL-5 and TRL-7 are presented earlier in Figure 9. For each beam, the recorded steel temperatures are presented using three curves in Figure 11. The labels "TC - B16 - BF" corresponds to bottom flange while the label "TC - B17 – WEB" corresponds to the middle of the beam web. The last label "TC - B18 – TF" corresponds to the top flange in Figure 11. The temperatures in the beam adjacent to TRL-5, being closer to the point of ignition, increase at an earlier stage of the test after 09 minutes from ignition. This increase in the recorded temperatures is relatively quick. However, for beam adjacent to TRL-7, a slower increase is recorded from the 13th minute until the 45th minute. As the travelling fire band moves across the compartment and gets closer, a sharp increase in steel temperature is recorded in the beam adjacent to TRL-7 as shown in Figure 11. In case of temperatures recorded across the section of the columns, it was found that the temperatures were fairly uniform, However, in case of beams, it is interesting to note that the temperatures measured in the flanges and the web are non-uniform. The temperatures recorded in the top flange in both steel beams are significantly lower as compared to those recorded in the bottom flange. The maximum steel temperatures recorded in the bottom flange, the web and the top flange are 675°C, 640°C and 550°C respectively for beam adjacent to TRL-5. Similarly, the maximum temperatures recorded in the bottom flange, web, and top flange for beam adjacent to TRL-5 are 700°C, 690°C and 600°C respectively as shown in Figure 11. The temperatures recorded in the steel columns and beams show the transient heating of the surrounding structure for travelling fire scenarios.

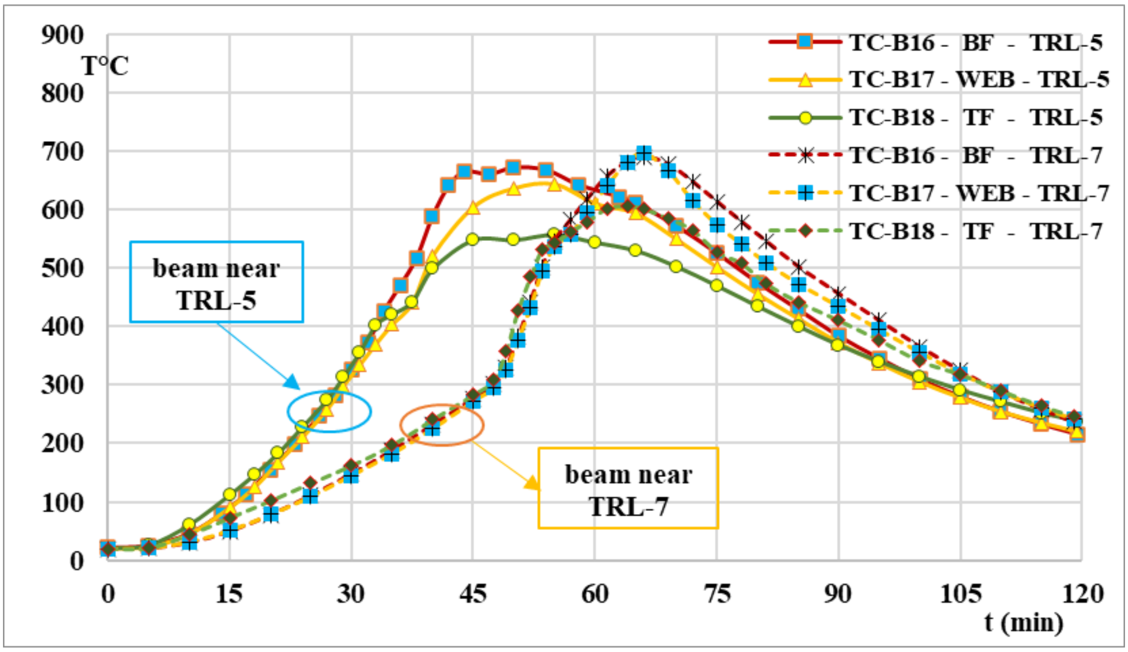


Figure 11: Evolution of temperatures in beams along gridlines ② and ③ adjacent to TRL-5 and TRL-7

3.4 Mass Loss of the Fuel Wood

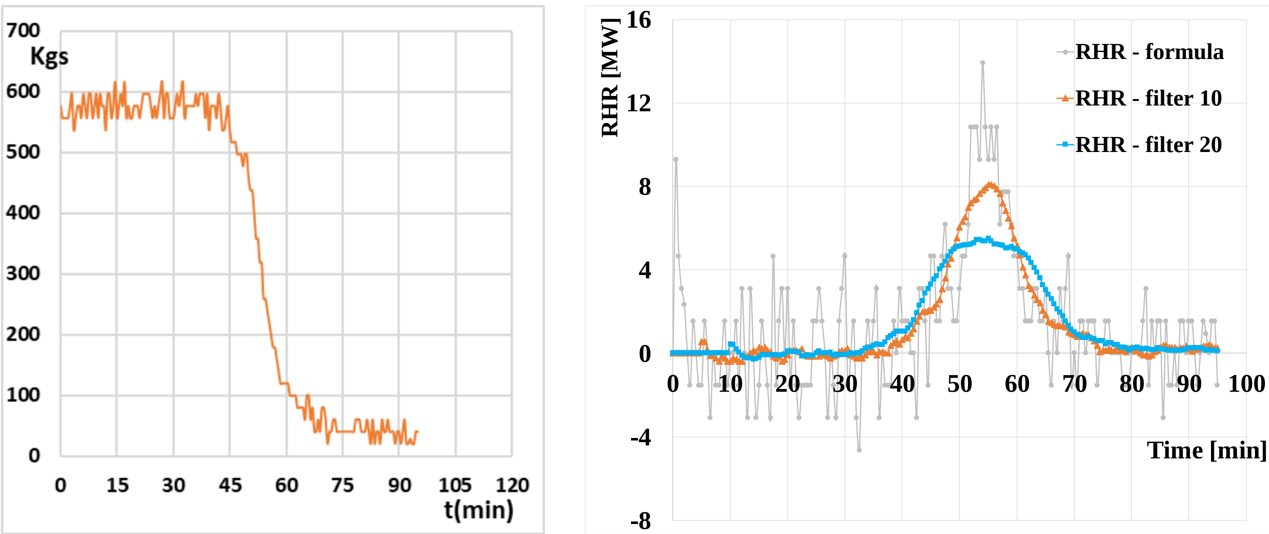
The mass loss data recorded during the test is presented in Figure 12 (a). During the test, it was observed that the fuel wood positioned above the steel platform to measure the mass loss started to burn after 38 minutes from ignition. For the initial few minutes, the burning rate was quite low, however, a sudden increase was noticed after 40 minutes. This observation complies with the data from Figure 12 (a): the recorded wooden fuel mass starts to decrease at around 40 minutes. During the test, after around 60 minutes from ignition, it was observed that the majority of the fuel wood on the steel platform was consumed: this is also in line with the change of slope in Figure 12 (a) at around 60 minutes.

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 of the fuel [MJ/kg] and *m* being the combustion factor (considered equal to 0.8, following EN 1991-1-2).

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

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

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 approach is commonly used with time series data to smooth out short-term fluctuations and highlight longer-term trends or cycles. The purpose of a Savitzky-Golay filter is to smooth the data through convolution, and to highlight the "long-term" trend. In this case, the simplest convolution filter was applied (also called "moving average"): each data subset being fitted by a horizontal line (average). In the frame of the TRAFIR project, the "filter 20" was chosen as the best choice: it allows to extract a clearer plateau value for the RHR which was in accordance with the other analyses conducted in the project (for example, the numerical modelling). This approach was also applied for the Test 1 and further details can be found in Nadjai et al. [11]. 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 12 (b). The filtered RHR with parameters 10 and 20 show maxima values of 8100 kW and 5505 kW, respectively.



(a) (b)

Figure 12: (a) Recorded mass-loss; (b)Approximation of the RHR, derived from the mass-loss measurements

4 COMPARATIVE ASSESSMENT OF TEST 1 AND TEST 2 RESULTS

Although this article provides a detail of the Test 2 results, a comparative assessment of the results obtained during Test 1 and Test 2 is presented in this part of the article. Readers may check the details of Test 1 which are available in the reference [11].

4.1 The Test Arrangements

The data recording arrangements during Test 1 and Test 2 were kept similar. These include the arrangements to record the gas temperatures in the compartment, the steel temperatures recorded in the steel structure and the arrangements for the mass-loss recording. In addition, the back wall constructed along the gridline ① and the down-stands provided along the longer dimension, gridlines Ⓐ and Ⓓ, were also similar. During Test 1, no walls were constructed along the gridline ④ as shown in Figure 13 (a). However, during Test 2, a concrete wall with no openings was constructed along the gridline ④. In addition to the down-stands provided along the longer dimension, along gridlines Ⓐ and Ⓓ, during Test 2, a 0.9 m high concrete wall (soffit) was constructed which further reduced the size of the openings along the longer dimension of the test compartment as shown in Figure 13 (b). The total size of openings during Test 1 was 87 m^2 which was reduced to 30 m^2 during Test 2.

(a) (b)

Figure 13: Boundary arrangements for (a) Test 1 – Only the back wall is constructed; (b) Test 2 – Additional front wall and 1 m deep concrete walls along the longer dimension

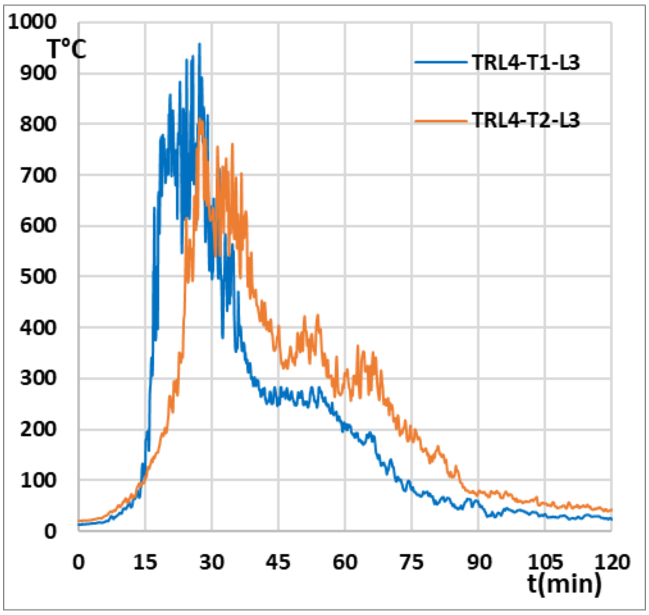
4.2 Comparison of the Travelling Fire Behaviour

The fire band width (i.e., the distance between the fore end and the back end (burnout) of the travelling fire along the centreline of the compartment from gridline ① to ④) noted during the first fire test (Test 1) are plotted against the same for the second test (Test 2) earlier in Figure 7. It should be noted that during Test 1, there were no soffit constructed along the longer dimensions of the test compartment as well as there was no wall constructed along the gridline ④, contrarily to Test 2. Influence of the walls during test can be seen in Figure 7. The width of the travelling fire band was very similar for Test-1 and Test-2 during the first 65 minutes. The width of the fire band was different towards the end of the fire tests. Due to the absence of wall along the gridline ④, the width of the travelling fire band started to reduce after 65 minutes. On the other hand, for Test 2, due to the concrete wall along the gridline ④, the width of the travelling fire band remained approximately 5 m until all the combustible material was consumed. During Test 1, the fire reduced gradually with the reduction in its length while in Test 2, the fire extinguished with reduction in the intensity over the 5 m length.

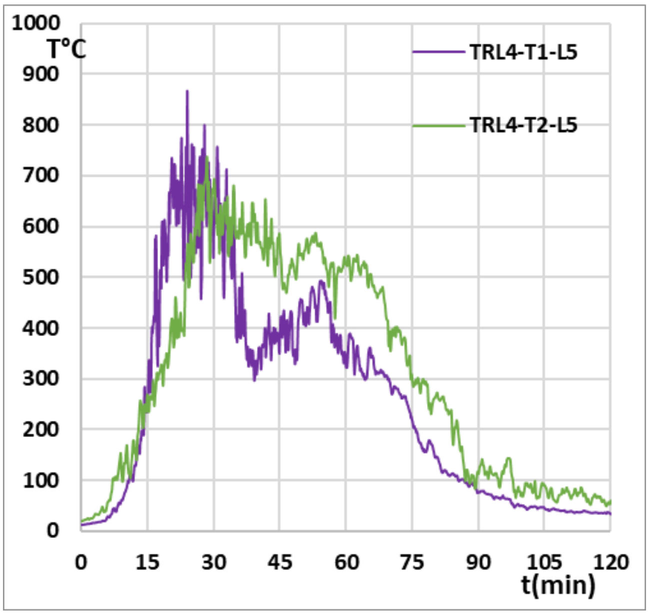
4.3 Comparison of Gas Temperatures

In this section, the recorded temperatures in the test compartment have been presented for Test 2 in comparison with those recorded during Test 1. As large number of thermocouples were employed to record the gas temperatures, comparison is presented only for selected thermocouples. The comparison presented is done only for TRL-4, TRL-6 and TRL-8 which are positioned in the middle of Zone 1B, Zone 2B and Zone 3B respectively as shown earlier in Figure 2. Further, two levels in each thermocouple tree have been selected, Level 3 is at 1.5 m while Level 5 is at 2.5 m from the floor finish level. The comparison of the gas temperatures can be seen in Figure 14: the labels "T1" and "T2" are provided for Test 1 and Test 2, respectively.

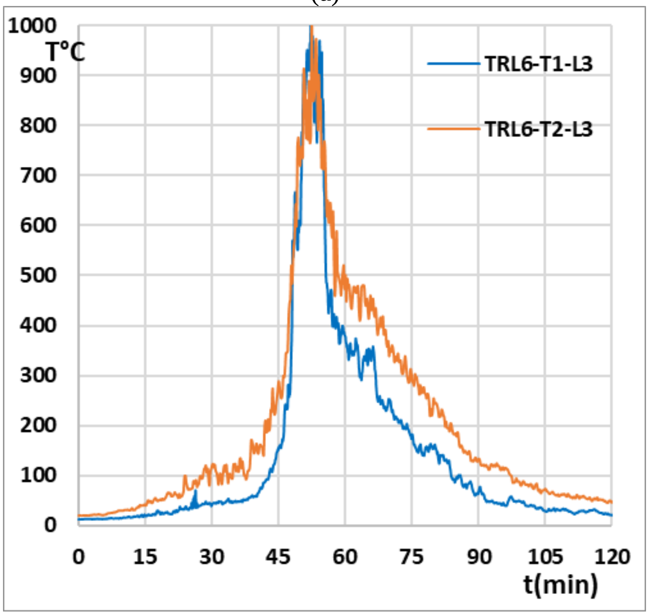
During Test 2, it was observed that the growing phase was relatively slower as compared to that observed during Test 1. This can be observed in Figure 14 (a), where the rise in gas temperatures is faster at level 3 in TRL-4 for Test 1 while the same is relatively slower for Test 2. It is also interesting to note that higher gas temperatures were recorded for Test 1 as compared to Test 2 at the same location. The gas temperatures recorded at level 5 in TRL-4 are very similar for Test 1 and Test 2 for the evolving phase, but differences exist for the phase when the fire travels away towards the fore end of the compartment as shown in Figure 14 (b). During Test 2 a gentler drop in temperatures was recorded at level 5 in TRL-4 as compared to sharp drop recorded during Test 1.



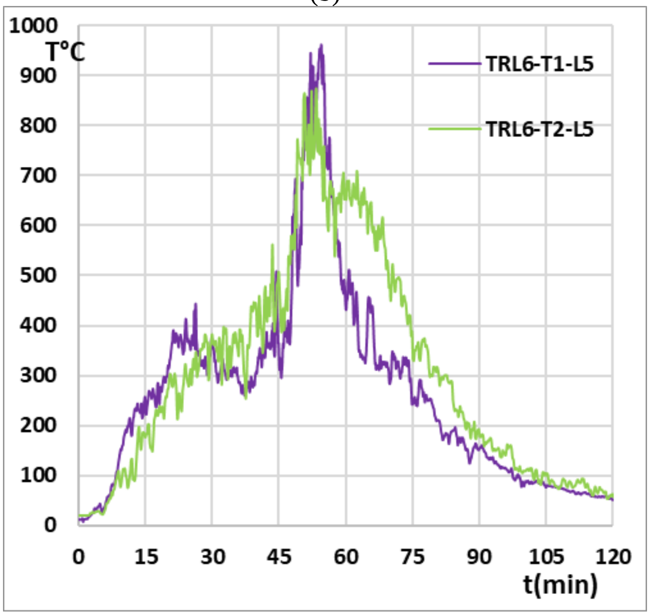
(a)



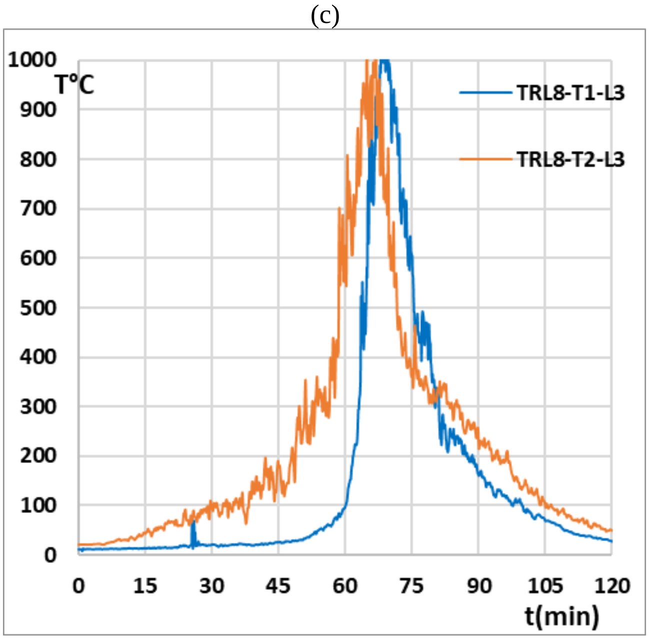
(b)

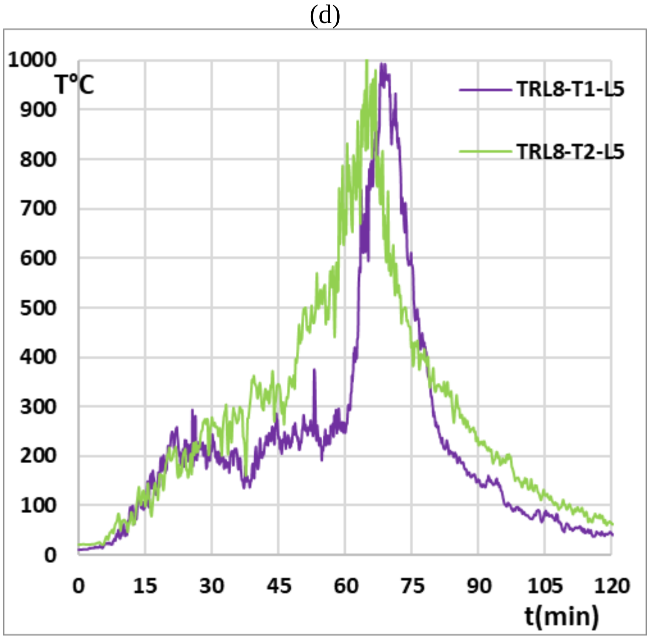


(c)



(d)





(e) (f)

Figure 14: Comparison of compartment temperatures, Test 1 vs Test 2; (a) TRL-4, Level 3; (b) TRL-4, Level 5; (c) TRL-6, Level 3; (d) TRL-6, Level 5; (e) TRL-8, Level 3; (f) TRL-8, Level 5

The gas temperatures recorded in the middle of the test compartment (referring to TRL-6) are very similar for Test 1 and Test 2: the similarities in the growing phase of the fire are closer to each other as compared to the decay phase as shown in Figure 14 (c) and (d). During the temperature reducing phase of Test 2, the decrease in gas temperatures is relatively slow as compared to that recorded during Test 1.

The temperatures recorded in the last zone of the test compartment, Zone 3B, are presented in Figure 14 (e) and (f). Differences during the growing and decay phases of the fire can be clearly seen. These differences are more dominant at level 3 as shown in Figure 14 (e). It is seen that the rise in gas temperatures at level 3 initiates at earlier stages during Test 2 as compared to Test 1. During Test 1, no concrete wall was provided along the gridline ④, which allowed the hot gases to escape. However, during the Test 2, due to the presence of the wall, the rise in temperatures was recorded at earlier stages as the hot gases were trapped within the test compartment. During Test 1, the increase in gas temperatures was only recorded once the travelling fire reached the area surrounding TRL-8, however during Test 2, increase at level 3 was recorded at earlier stages as shown in Figure 14 (e). It is also interesting to note that the decrease in gas temperatures during Test 1 was more rapid as compared to that recorded during Test 2 from the 80th minute onwards. Although for the initial 30 minutes the rise in temperatures at level 5 is similar for both tests, the rise in temperatures is more significant for Test 2 as compared to that recorded for Test 1, refer to Figure 14 (f). Again, this is the influence of the reduced openings of the test compartment by constructing additional walls along the gridline ④ and along the longer direction of the compartment. Similar to level 3, the reduction in temperatures at level 5 during Test 1 is more rapid as compared to that recorded during Test 2.

In general, the behaviour of the travelling fire and the recorded gas temperatures in the test compartment were found to be directly related to the ventilation conditions. It was noticed that the growing phase of the fire and the behaviour of fire in Zone 1B in terms of recorded gas temperatures were influenced more as compared to the middle part of the test compartment, Zone 2B. The influence of the change in boundary conditions was most seen in Zone 3B as this was directly affected by the adjacent concrete wall constructed along the gridline ④during Test 2. The width of the travelling fire band was also significantly longer during Test 2 as compared to that observed during Test 1.

4.4 Comparison of Temperatures in the Steel Structure

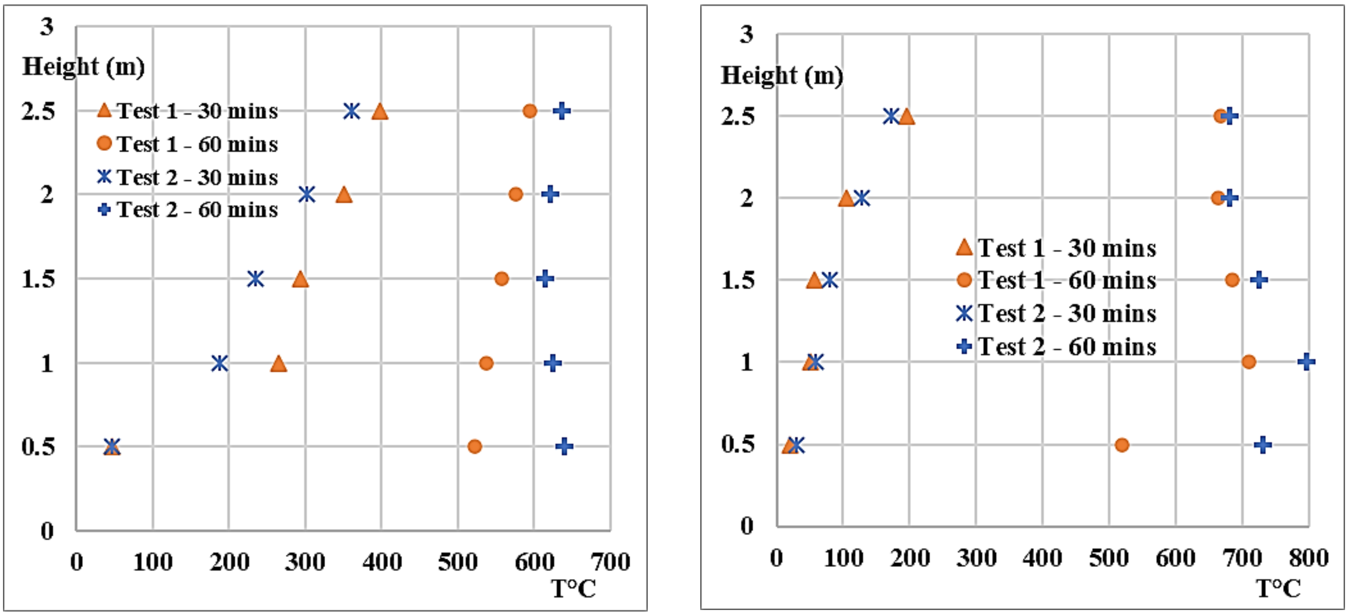
The influence of the variations in the size of openings has an impact on the behaviour of the travelling fire as well as the steel temperatures recorded in the structure.

4.4.1 Temperatures in the Steel Columns

Temperatures recorded in the steel columns during Test 2 were presented earlier in section 3. In this section, steel temperatures recorded during Test 2 after 30 and 60 minutes at all five levels in the steel columns adjacent to TRL-5 and TRL-7 are presented in comparison to those recorded during Test 1.

For the steel columns adjacent to TRL-5, after 30 minutes from the start of the test, temperatures recorded at level 1 (at 0.5 m) are similar during both tests as shown in Figure 15 (a), while the temperatures recorded at upper levels, level 2 through level 5, are higher during Test 1 (even though a similar trend is observed). This is related to the developing phase of the fire at earlier stages of Test 2 which was slower for Test 2 as compared to Test 1. The situation reverses after 60 minutes from the start of the test. Steel temperatures recorded at all levels during Test 2 were higher as compared to those recorded during Test 1, refer to the right part of the graph given in Figure 15 (a). The size of openings during Test 2 were significantly smaller as compared to Test 1, more heat was retained within the test compartment as a result, higher temperatures were recorded in the column adjacent to TRL-5.

In case of column adjacent to TRL-7, temperatures recorded after 30 minutes are similar for Test 1 and Test 2, as shown in Figure 15 (b). The recorded temperatures after 60 minutes are higher for Test 2. During both tests, temperatures recorded in the columns after 30 minutes were lower than those recorded after 60 minutes from ignition.

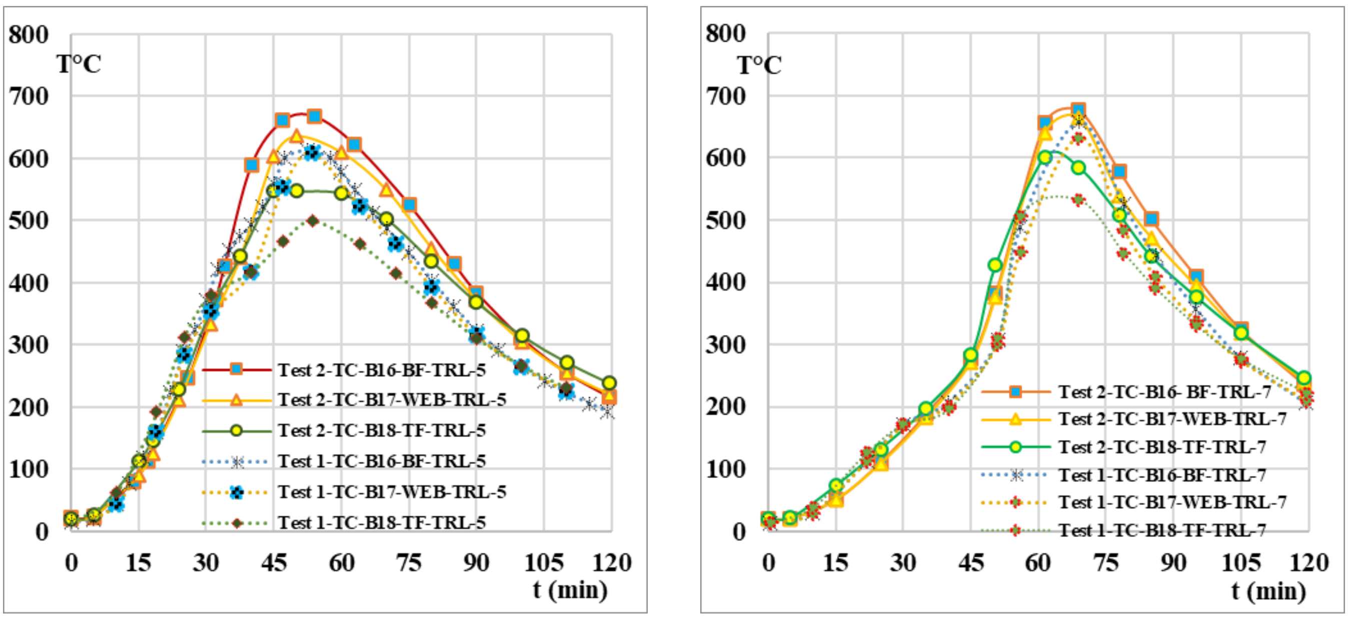


(a) (b)

Figure 15: Steel temperatures recorded during Test 1 vs Test 2; (a) Column adjacent to TRL-5, (b) Column adjacent to TRL-7

4.4.2 Temperatures in the Steel Beams

As mentioned previously, temperatures in the steel beams were recorded in the middle of the flanges and the web. The positioning of the thermocouples was kept similar during the experimental programme; hence a comparison of the recorded steel temperatures is presented for beams adjacent to TRL-5 and TRL-7. Temperatures recorded during Test 1 and Test 2 in the beam adjacent to TRL-5 are shown in Figure 16 (a). During both tests, the recorded temperatures in the bottom flange were higher as compared to those recorded in the top flange and the steel web. The steel temperatures recorded during Test 2 were found to be higher than those recorded during Test 1. During Test 1, the maximum temperatures recorded in the bottom flange were 550°C. However, the temperatures recorded in the bottom flange during Test 2 exceeded 670°C as shown in Figure 16 (a). A similar pattern is observed for the beam adjacent to TRL-7 where the temperatures recorded in the bottom flange were higher as compared to those recorded in steel web and the top flange during both fire tests. Further, the maximum temperatures recorded during Test 2 in the beam adjacent to TRL-7 are higher as compared to those recorded during Test 1 as shown in Figure 16 (b). It is interesting to note that the difference in temperatures recorded during Test 1 and Test 2 in the beam adjacent to TRL-5 is higher as compared to that recorded in the beam adjacent to TRL-7.

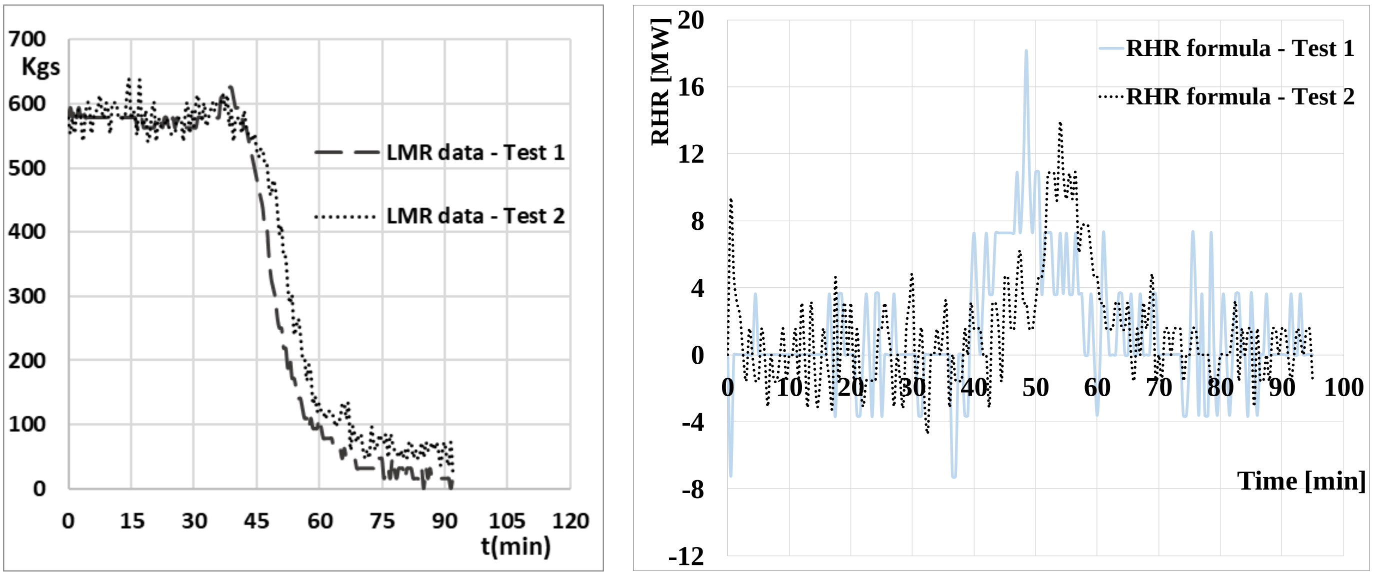


(a) (b)

Figure 16: Steel temperatures recorded during Test 1 vs Test 2; (a) Beam adjacent to TRL-5, (b) Beam adjacent to TRL-7

4.5 Comparison of Mass Loss of the Fuel Wood

The mass loss arrangements for Test 1 and Test 2 were similar as was the fire load. The burning of the fuel wood supported by the steel platform used to measure the mass loss started after 37 and 38 minutes respectively for Test 1 and 2. This can be seen in Figure *17* (a) where a reduction in the weight of the fuel wood supported by the steel platform was recorded at these times during the tests. The fuel wood supported by the platform was consumed after 64 minutes from ignition in Test 1. In case of Test 2, majority of the fuel wood was also consumed at the same instance, however, the burning continued for the reminder duration of the test. The approximated RHR derived from the mass loss measurements are fairly similar for Test 1 and Test 2, as it can be seen in Figure *17* (b). The only noticeable difference is a time shift for the whole curve which is delayed for around 5 minutes for Test 2 (which is in line with the temperatures observations described previously). Since the only significant change concerns the time occurrence, the applying of the Savitzky–Golay filter as described above leads to fairly similar results for Test 1 and Test 2: the filtered RHR with parameters 10 and 20 show maxima values of 8140 kW and 5850 kW for Test 1 and of 8100 kW and 5505 kW for Test 2, respectively.



(a)

Figure 17: Comparison for Test 1 and Test 2; (a) Recorded mass-loss; (b) Approximation of the RHR derived from the mass-loss measurements

5 CONCLUSIONS AND FUTURE RECOMMENDATIONS

Large-scale natural fire tests were conducted in a compartment representing an office building with steel hot rolled structural elements. The fire load used during the test was based on experimental investigations conducted upstream of the same research project. The details of the second fire test with reduced opening sizes were presented in this paper. The behaviour of the travelling fire, details of the recorded compartment temperatures and the details of the steel temperatures recorded in the selected structural elements were discussed. The details of the mass-loss data recorded during the experimental programme were also presented. Further, a comparison between the first fire tests (Test 1) and the second fire test (Test 2) was also presented in terms of the travelling fire behaviour, temperatures recorded in the test compartment and steel structure as well as the mass-loss recordings. Following are significant conclusions and lessons learnt during the second fire test (Test 2) and from the comparison of the two tests.

- The fire initiating at a single point in a compartment can travel across the compartment in different direction depending on the availability of the combustible materials. This develops non-uniform temperature distributions in the compartment with areas near the fire being at higher temperatures as compared to the areas away from the fire.
- The rise in temperatures at upper levels initiates at earlier stages of the fire as compared to those at the lower levels. During the test, the rise in temperatures at upper in the compartment were recorded at earlier stages of the test while the rise in temperatures at lower levels, especially at levels 1 and 2 (at 0.5 m and 1.0 m respectively from floor finish level) was recorded when the actual travelling fire band reached their vicinity.

- In a travelling fire scenario, not only temperatures along the length (or width) of the compartment are non-uniform, the temperatures along the height are also found to be significantly non-uniform. The non-uniform temperatures in the compartment have a transient effect on the temperatures recorded in the surrounding steel structure. For columns, temperatures recorded along the height at different levels were found to be non-uniform. At earlier stages, a rise in temperatures at upper levels was recorded. However, at lower levels, the rise in temperatures was recorded once the travelling fire band reached the vicinity. Further, when the travelling fire band approaches/reaches a column, temperatures in the column increase overall and reaches the maximum values. Once the fire band travels away from the column a gradual decrease in temperatures was recorded. Temperatures recorded across the section of the columns were found to be uniform for a given level.
- The temperatures recorded in the steel beams increased when the travelling fire reached the fuel-wood underneath. As the fire moved ahead and away from the beams, a decrease in recorded temperatures was recorded. The temperatures recorded in the bottom flange were significantly higher than those recorded in the web and the top flange which shows the non-uniform temperature distributions across the section of the steel beams.
- A significant influence of the change in ventilation conditions was observed during the experimental programme. The addition of concrete walls along the longer and shorter dimensions influenced the behaviour of the travelling fire. Although this influence was small on the travelling fire behaviour in Zone 2B, a higher influence was observed in the first and last zone of the test compartment, in Zones 1B and 3B.
- Decrease in the size of openings due to the presence of additional concrete walls resulted in retaining heat within the test compartment. As a result, higher temperatures were recorded in the beams and columns during Test 2 as compared Test 1. The gas temperatures recorded in the compartment showed a quick reduction in temperatures during Test 1. However, during Test 2, reducing branch of the curve was steadier.

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