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Can fire cause the collapse of Plasco Building: A numerical investigation

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Abstract

Since the tragic event of the World Trade Centre (WTC), efforts to understand realistic fire behaviour in tall buildings are accelerated. It is critical to understand the fire dynamics involved in a compartment fire before performing a forensic investigation of a fire accident. In this paper, various fire scenarios are considered to simulate the behaviour of fire in a high-rise building and demonstrated the case of the Plasco Building using computationally fluid dynamics (CFD). Two fuel distribution patterns are assumed with different packing densities as clothes placed throughout the compartment in a scattered form (similar as in racks) and densely packed as stacked (stored in cartons). It is observed that the distribution of the fuel highly influences the duration of the fire, peak temperatures, and the severity of the fire. The fuel distribution also affects the spread of the fire in both horizontal and vertical directions, which helps in understanding probable fire scenario responsible for the collapse of a building. A case of subsequent heat transfer analysis in an OpenSEES FE model is conducted to represent the extent of temperature reaching the structural elements where temperature data from FDS are used as thermal boundary conditions. Large variations in the temperature of the structural members have been observed between two fuel distributions, which can be a governing factor while analysing structural behaviour in fire conditions. This paper provides insight into performing a forensic investigation of fire collapsed high-rise buildings based on visual evidence.

Keywords: fire behaviour, CFD, forensic, finite element, fire load

1. Introduction

Over the last century, several structures collapsed or were severely damaged due to fire [1]. The tragic event of the WTC garnered significant attention from the structural engineering community. Researchers have suggested proactive measures to avoid such incidents either by upgrading the existing fire safety strategies or improving the strength of the structural members to sustain such fire accidents, and use of performance-based design (PBD) methods is also suggested. Usmani et al. [2] investigated the collapse of the WTC Twin Towers and concluded that only the fire effects were severe enough to cause its collapse without including the impact of the airplane in their study. Nearby building WTC 7 was also collapsed where the fire was ignited from the collapse debris of WTC 1 [3,4]. It was the first reported tall building (taller than 15 stories) that collapsed primarily due to fire. More recently, in another fire incident, the Plasco Building in Iran collapsed where a fire was caused by a short circuit [4,5,] and the whole building crumbled to the ground within three hours of fire ignition. However, it leads to a question: what kind of fire scenarios are responsible for the collapse of these tall structures?

Fire resistance design of structures is principally based on the provisions of locally adopted codes that are usually based on the building codes. In the prescriptive design method, a fire scenario is defined using idealized fire curves such as a standard time-temperature curve [7]. It is well-known that these curves do not represent real fires, although traditionally considered to be a conservative representation of a real fire scenario. Modern materials and architecture have changed so fundamentally that this assumption is being seriously questioned, particularly in the context of high-rise buildings. The realisation of the inadequacy of the current approach to represent the likely fire hazard has provoked a need of new thinking and method for developing realistic fire scenarios that could account more faithfully for features of real fires. In addition to the heat generated from the fuel, the fire spread behaviour is also an important feature that is required to represent real compartment fire scenarios. Fuel quantity and its distribution within the building can greatly influence the fire intensity and its spread behaviour. An experiment conducted at Ulster University demonstrated the influence of the fuel load and ventilation on the fire behaviour in large compartments[8].

While investigating the collapse of a building due to a fire, it is important to understand the fire behaviour inside the building. Fire behaviour is highly unpredictable, which depends on a number of factors such as ventilation conditions, quantity and type of the combustibles, fuel distribution and so on. To analyse the fire spread in a corridor, McGuire [9] performed a series of experiments using a range of materials for ceiling, floor, and wall lining. He evaluated the flame spread indexes of each material. Sun et al. [10] carried out a review study to understand the fire dynamics in a tall building, but their study was limited to the fire spread due to combustible façade material. Chow et al. [11] conducted a survey to estimate the fire risks to the hotel buildings in Hong Kong. The major parameter in their study was fuel load (mass of fuel per unit surface area). Their study does not provide any insight into the influence of the fuel distribution pattern or packing density of the fuel on the fire severity.

The reasons for the fire spread within the Plasco Building, which led to its collapse, are unclear mainly because of the ambiguous data in terms of the building architecture, actual fuel load and its packing and distribution. In previous studies, while investigating the collapse of the Plasco Building realistic fire load was not considered. The structure was either assumed to be exposed to a constant temperature or standard fires [6,12]. These fire loads are far from reality and do not provide any information for factors affecting the fire behaviour, such as fuel distribution, and building geometry, which might be one of the deterministic factors for the collapse of the Plasco Building[13]. Estimating the accurate fire load facilitates establishing realistic fire scenarios, which is an essential prerequisite for the development of the PBD approach. The implementation of the fire curves such as standard and parametric fires may produce misleading fire scenarios, for example, in the presence of high fuel load at each floor and combustible façade around the perimeter of the building, the fire can be considered as fuel-controlled [14]. In contrast, the standard and parametric fire curves can only represent ventilation-controlled fire scenarios [15]. According to Thomas' curve for Regime II, fuel-controlled fire is highly unpredictable, and standard curves cannot represent such fires. To investigate the collapse of Plasco Building, fuel-controlled fire scenario may be the most suitable because of its unique fuel distribution patterns and ventilation conditions. Various studies have emphasised the effects of fire load and ventilation on fire behaviour [16–18]; however, limited attention has been given to the effects of fuel distribution and its packing and building geometry

Since the last few decades, the capabilities of the CFD in fire modelling have been used extensively; however, it has been reported that the CFD simulations are highly sensitive to certain parameters, which are essential to develop a model [19]. Therefore, to obtain a realistic fire scenario, the user must be aware of the uncertainties involved in the CFD modelling and enough information necessary to define the fire spread phenomena within the building. To simulate the fire behaviour of Plasco fire accident, a computational tool for fire modelling: FDS [20] is used in this study - developed by NIST [21].

In this paper, a numerical study is performed to evaluate the effects of the fuel load distribution on the temperatures reaching structural components. It also discusses how the distribution of fuel load affects the fire spreads to adjacent rooms (horizontal fire travel) and upper floors (vertical fire travel). The prime motive of this paper is to understand the fire spread behaviour in a high-rise building and the effects of fuel distribution and its packing on the overall fire behaviour using computational modelling of the Plasco Building accident as a case study. The necessary information of the Plasco Building, such as building architecture, ventilation, and fire load, is obtained from the literature [5,6]. It enables the reader to conduct forensic studies of fire accidents by verifying data with the evidence available in the literature.

2. Fire accidents in tall buildings

According to a survey conducted by NFPA, more than half of the high-rise building fire incidents occurred in hotel-type buildings. These buildings were severely damaged but did not completely collapse [22]. The fires in office buildings might lead to higher damages to the structures. The main reasons for the collapse or failure of these office buildings are the tendency of the fire to quickly travel in both horizontal and vertical directions. The travelling behaviour of fire in office buildings is exacerbated due to the availability of high amount of fuel load such as furniture, paper, and plastics [1]. Open-floor plans of office buildings may also enhance the fire intensity and turns it into an uncontrolled fire [1]. According to a report published by NFPA [1], the likelihood of floor-to-floor fire travel in tall buildings is 3-4 times lower than the short buildings. The report also states that the probability of spreading of fire in tall buildings beyond the room of origin is 50% lesser than short buildings, which is attributed to adequate fire barriers due to compartmentation. Therefore, it is intriguing to identify the conditions that lead fire in high-rise buildings to spread vertically and horizontally as in the Plasco Building. Other than the collapse of the three towers of WTC and the Plasco Building, a 26-storey building in São Paulo, Brazil (2018) collapsed after being engulfed in flames. It was witnessed that the flames spread quickly from one of the lower floors and set an adjacent building on fire. According to the São Paulo fire department, the modifications made by the residents increased the fuel load (temporary wooden partition) had allowed the fire to spread more quickly. The lifts had also been removed, and those empty air shafts formed a chimney and helped fire spread. In most of the buildings that were collapsed in the fire, the fire load was significantly higher than the intended or designed fire load. Additionally, the distribution of the fire load also played a significant role and contributed to the rapid fire spread within the floor and across the floors.

Fire can spread in both horizontal and vertical directions from its origin. Undoubtedly, the main reasons for rapid fire spread were the amount, distribution and packing of the fire load. In addition to the fuel load and its distribution, fire spread depends on many other factors such as the location of vertical openings (elevator shafts, stairways), interconnected false ceilings, combustible interior finish, presence of power and communication cables, combustibles materials in the elevator shafts or false ceilings or false floors and so on. Fire travel behaviour and factors affecting its spread in a high-rise building are discussed in subsequent paragraphs. This section also discusses the fire behaviour in real fire accidents.

2.1. Vertical fire spread

The phenomenon of fire spread to the floors above the floor of origin is not uncommon. The fire may travel vertically to upper floors in a high-rise building either through windows or any vertical openings (stairways or elevator shafts) and façade. There are some fire incidents where fire was observed on lower floors as well, that was mainly due to the combustible façade [23]. The fire in the Grenfell Tower (2017), London, is an example of a façade fire, where more than 70 people died, and the structure was severely damaged.

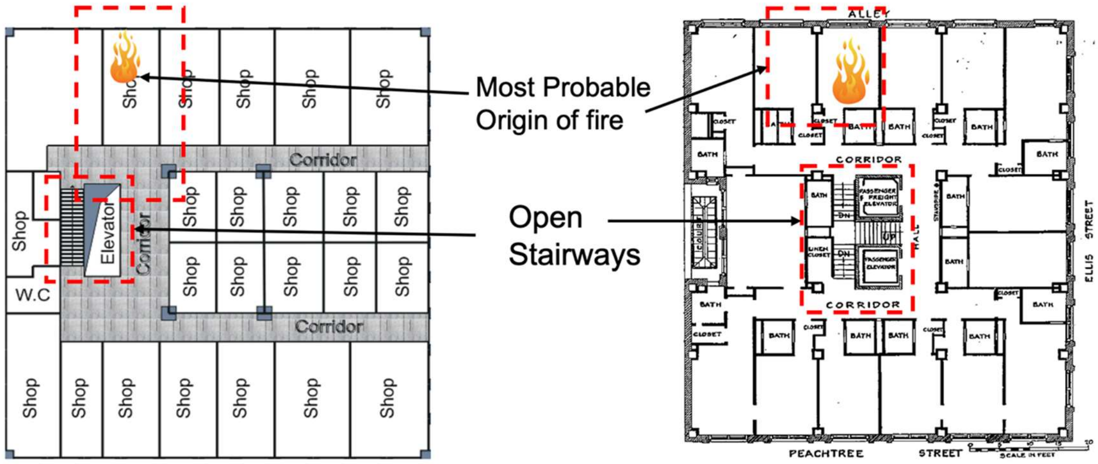
In one of the earliest fire incidents for high-rise buildings: the MGM Grand Hotel fire, around 85 people died [24]. Although the fire broke out at the 2nd floor (casino level) of the MGM Hotel in a restaurant, heat and smoke had travelled rapidly to upper floors through stairways and elevator shafts and activated the sprinklers at the top floor (26th floor). The breaking of the windows was another way for the fire to reach the upper floors. Satoh and Kuwahara [25] investigated the propagation of fire from the lower floors to the upper floors in a high-rise building through windows. Usually, the failure of the window's glazing can occur at 280 to 320 °C [26] that may cause the fire to spread vertically to the upper floors as observed in the Hilton Hotel fire accident in Las Vegas in 1981 [27]. The fire can reach upper floors through windows or façade which might be the most probable scenario in the case of the Plasco Building. Due to the openings created by the failure of windows, more air is drawn and fire behaviour might eventually turn from 'ventilation controlled' to 'fuel controlled' (regime II to Regime 1 of Thomas's Curve) [15], and instantly a very fast-growing fire can be observed.

The vertical spread of fire in a tall building can be understood from scientific principles and phenomena observed in previous fire accidents. Due to the lower density, fire (and smoke) has a natural tendency to travel in upward direction. The stack effect is another factor that contributes to the vertical movement of fire. It causes entrainment of air due to temperature differences between two regions of a building. Vertical openings such as stairways and elevator shafts support the stack effect. The flames (fire) travel towards the openings due to the stack effect and reach upper floors through these openings, as was observed in the Plasco Building. In terms of the current fire protection strategies, special attention must be given to vertical openings to overcome the stack effect[26]. Limiting continuous shaft heights and making the exterior walls airtight to reduce the effects of wind are a few of the primary design considerations that could be used to limit the fire travel in the vertical direction. However, all these provisions were not considered for constructing the Plasco Building, which might have supported the fire propagation in the vertical direction.

2.2. Horizontal fire spread

Once a fire becomes fully developed in a compartment, it can spread to the adjacent area and lead to the horizontal spread of fire. In the absence of fire barriers (or compartmentation), fire can keep spreading until it reaches flashover or travel across the whole floor plate. If compartments are made using barriers such as walls, in that case, fire can still travel horizontally through false ceilings (later section discusses how this could have happened in the case of the Plasco Building). False ceilings or attics play a critical role in spreading the fire in the horizontal direction especially for structures with compartmentation. Fire travel through the false ceiling can be one of the most severe hazards in terms of safety as it permits fire propagation undetected by firefighters, and if the false ceilings do not have any separation, it can support the fire to spread to the entire floor.

The horizontal fire travel is more common for buildings with large open-plan architecture as in the case of the WTC 1, 2, and 7 [3,4]. Travelling fires are often observed in a large open space where it is difficult to achieve a flashover as all fuel cannot burn simultaneously; instead, fire travels from one location to the other and spreads in all directions. In the Plasco Building case, the floor plan was typical for all floors above the 6th floor as shown in **Fig. 1a**. Two scenarios are favourable for the fire to propagate throughout the floor. Firstly, floors might not have partition walls which permit the fire to travel across the whole floor. In this case, the fire propagation can simply be described as travelling fire or fully developed fire, which would depend on fuel distribution, the density of the fuel, and the velocity of the fire spread. If the velocity of fire spread is nearly equal to the velocity of burnt-out fuel, it would be considered a travelling fire [28]. Another possible scenario is that the shops were separated by partition walls which limit the fire propagation. It raises a question that in the presence of fire barriers, what favours the fire to travel in the horizontal direction as the fire was observed throughout the entire floors above the 10th floor of the Plasco Building (**Fig. 1a**). The Plasco building had continuous false ceilings at each floor, as reported by Ahmadi et al. [5] It can be deduced that the only possible scenario for the fire to travel within the floor was through false ceiling once it was damaged. The damaged false ceiling in a compartment fire was observed in many previous fire incidents. The fire that occurred in the Stardust nightclub fire, Ireland (1981) reached to ballroom from an alcove through false ceilings and took the lives of 48 people [29]. A survey was conducted by Chow and Kot [11] on hotel fires in Hong Kong. It was found that the false ceiling of one of the hotels was severely damaged by a relatively small fire which was later extinguished by sprinkler systems. However, in the Plasco Building, no automatic sprinkler system was installed, and the manual fire hose reels were also not operational; therefore, the fire could have travelled horizontally once the false ceiling gets damaged.



(a) **(b)**

Fig. 1 (a): Floor plan of 10th Floor of Plasco Building (Typical from 6th to top floor) [5] (b): Floor plan of 3rd Floor of Winecoff Hotel [30]

3. The collapse of the Plasco Building

3.1. Buildings' Structural detail

The Plasco Building was constructed in 1962 and was a landmark high-rise building in Tehran, Iran. The building had two separate structural blocks; the 16-storey main tower stood beside a 5-storey building (**Fig. 2**). The 16-storey building included a basement floor and fifteen floors above the ground level. There was no emergency evacuation plan or in other words, there was no fire safety strategy for this building, although when it was constructed it followed the design codes of that period. Due to the lack of structural drawings and other information during the fire incident, many field inspections were conducted by researchers and engineers to establish the details of all structural members. All the structural members were welded built-up sections, meaning that they were made by welding multiple steel profiles such as U and L-shaped profiles. The flooring system comprised of a concrete slab with a thickness of 120 mm, which was supported by a series of ceiling trusses in both perpendicular directions forming a dense steel grillage structure. The structure details are discussed in depth by Behnam [6].

Fig. 2: Detail of the Plasco Building [31,32]

3.2. Fuel in the Plasco Building

The 16-story building was initially designed to use as a commercial building under normal loading conditions; however gradually, it turned into one of the largest garment distribution and production centre with large static and fire loads coming from the garments. At the time of the fire incident, the Plasco Building consisted of a shopping centre on the ground floor and restaurants, workshops, and storage for clothing material on upper floors as reported in the investigation reports [5,33]. Therefore, the primary fuel was the fabric material on the fire floors.

The use of the Plasco Building was changed from regular business activities to storage and manufacturing facility, especially on the upper floors (where the fire broke out and spread). The change in occupancy resulted in a much higher fire load than the intended [26]. Behnam [6] argued that at the time of the fire, the fire load was almost four times higher than the designed fire load of the building. It is mentioned in the modern codes and standard to specify the "use of building" which should not be changed until necessary changes to the new occupancy types have been carried out. In NFPA 13, it is explicitly mentioned to have "Owner's certificate" before carrying out any fire protection design [34]. Owner's Certificate includes all information of the building such as occupancy type, permitted fuel and so on. However, in case of the Plasco Building, the fuel load and the "use of building" was keep changing throughout the lifetime which was overlooked by the owner despite the local codes and warnings from the Tehran Fire Safety Department (TFSD) [35].

Due to the change of its occupancy, the static load at each floor was also increased. Not only the fire load and static load but also the fuel distribution and consequential fire travel behaviour might have played a vital role in triggering the collapse of the Plasco Building. This paper analyses the possible fire scenario that might be responsible for the collapse of the Plasco Building by arguing the conditions that favour the fire spread.

3.3. Fire accident

On January 19, 2017, a fire broke out due to an electrical short circuit on the 10th floor of the north-western side of the 16-storey Plasco Building. The electrical wiring was outdated according to the firefighters [35]. The fire reached the upper floors and adjacent floors in early stages of the fire. During a fire incident, smoke and heat can reach the upper floors through stairs or façade of the building. Flames can also spread horizontally within the `inuous false ceilings and open stairways [5] which favoured the fire to spread in both horizontal and vertical directions, respectively. In one of the deadliest incidents, where fire travelled in the vertical direction and reached upper floors of a hotel in the US: Winecoff Hotel ("it was *claimed as fire-proof*") [36]. In the Winecoff Hotel, the fire was originated from the mattresses in a room on the third floor, which was near the stairways. In later stages, the fire reached up to the thirteenth floor in the 15 storeys hotel. It was reported that 119 people died during the fire incident. After this accident, the word "*fire-proof"* was eliminated from the NFPA codes. As shown in **Fig. 1** [5], besides being a steel frame structure, the Winecoff Hotel fire was quite identical to the fire in the Plasco Building (**Fig. 1a**) particularly in terms of the origin of the fire which was near the stairways, and only one stairway was serving all floors of the building (**Fig. 1b**). Unfortunately, both buildings were not equipped with sprinkler systems which also fuelled the fire spread. In the Winecoff Hotel, only the floor of the fire origin and stairway were damaged while the rest of the structure was unaffected and the entire building did not collapse. However, the fire load on the Plasco Building was much higher, which raised the temperatures of structural members and reduced their load-carrying capacity significantly that might lead to the collapse of the whole building. The current numerical study suggests that it was not only the amount of fire load but also its packing and distribution that facilitated the fire spread throughout the floors.

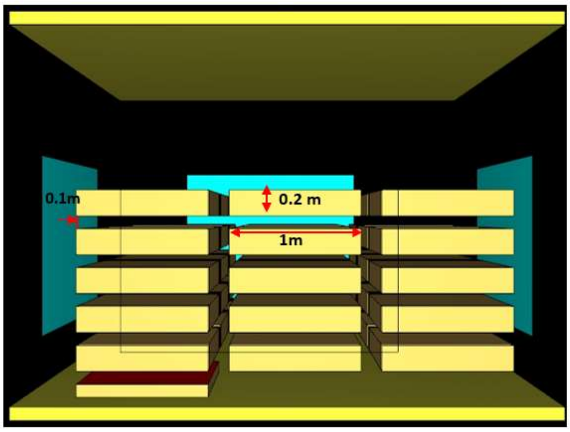
4. Fire modelling of a compartment

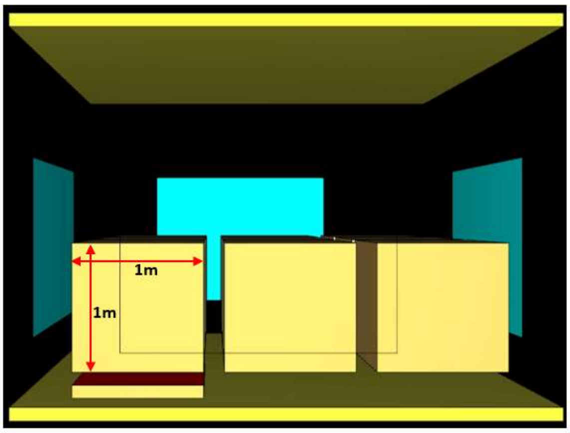
In this study, a compartment with a similar fire load as was reported in the Plasco Building is simulated for 60 minutes of fire (when the heat release rate reached the steady-state). This paper primarily investigates the effects of the distribution and packing of the fuel load on the severity and the spread of fire. In the present paper, a fire load of 1910 MJ/m^2 [6] is used to perform CFD analysis using FDS software to understand fire behaviour and to obtain realistic thermal boundary conditions for sequential heat transfer and thermomechanical analyses. The building was occupied primarily by garment businesses, and high volume of fabric material was stored on the premises. Therefore, nylon is considered as primary combustible (fuel of fabric type) to adopt a simpler chemical kinetics model in CFD analysis as the material properties of the nylon is well defined in the SFPE Handbook [37] based on experimental studies.

4.1. Fuel Distribution

Fire load is the major criteria to estimate the fire risk for any kind of occupancy [38,39], which is generally defined in statistical terms [40,41]. The standard calculation methods for fire load ignore the effects of its packing and distribution, which may greatly influence the fire behaviour and can be vital for structural integrity in fire accidents. To investigate the fire behaviour in collapsed structures, a CFD model is usually developed and validated based on available information such as building plans, visual evidence, and possible fuel load. It is also necessary to learn how fire can travel, and how fuel distribution and packing can affect the fire severity. In the case of the Plasco Building, unlike the WTC towers, insufficient data is available that could provide a clear picture of the amount of fuel load and its distribution within the building. The data in the literature or reports from the Fire department [33] is primarily based on the testimonies of witnesses or fire department personnel. Therefore, no well-structured fire investigation is found in the literature so far.

Fig. 3 represents two probable ways of storing goods, which are often used in practice and can result in two distinct cases of fuel distribution. Case1- where fuel load is distributed in the form of small stacks (as in racks, see **Fig. 3a**), and Case 2- where the same fuel load is supposed to be densely packed in large cartons (see **Fig. 3b**). Both methods of storing cloth fabric can produce fire scenarios that have entirely different fire behaviour and effects on structural integrity. Ventilation conditions were kept the same for both cases.





(a) **(b)**

Fig. 3: Fuel Distribution Cases a) Case 1: Small staked b) Case 2: Densely packed in cartons

In FDS simulation, only a portion of the 10th floor, where the fire was broke out, is modelled as a compartment to understand the effect of fuel load distribution on fire behaviour. The dimensions of the modelled compartment are 7×5×3 m^3. All sides of the compartment are provided openings as in the Plasco Building, windows were open from all sides or burned down during the fire as shown in **Fig. 4** (Images are taken from various news agencies [32,42,43]). Adiabatic surface temperatures (AST) were recorded on the surface of structural members [44], which were used as a thermal boundary condition to conduct sequential heat transfer analysis. For Case 1, stacks of dimension 1×1×0.2 m^3 were placed with a gap of 0.1m between each stack, and for Case 2, blocks of 1×1×1 m^3 were distributed within the compartment. The fire load present in the compartment ignited and continued to burn until the end of the analysis (one hour). A burner of 1 × 1 m^2 was placed at one corner of the compartment and initiated for 30 seconds to ignite the fire. The pyrolysis model available in FDS is not feasible and practical to simulate the fire behaviour within a compartment as it requires a complex stoichiometry model. Therefore, the ignition temperature of the fuel surface (230 °C in case of nylon) was set for its ignition, which is a valid approximation for such kind of study. **Fig. 4** shows the temperature contours at the centre of the compartment (X=2.5 m) after 45 minutes since the ignition. A significant temperature difference is observed between both cases of fuel distributions. It can be seen from **Fig. 5** that the maximum temperature for Case1 is significantly lower than Case 2, which were around 980 °C and 1270 °C, respectively.

Fig. 4: Ventilation from all sides of the building [31,32,42].

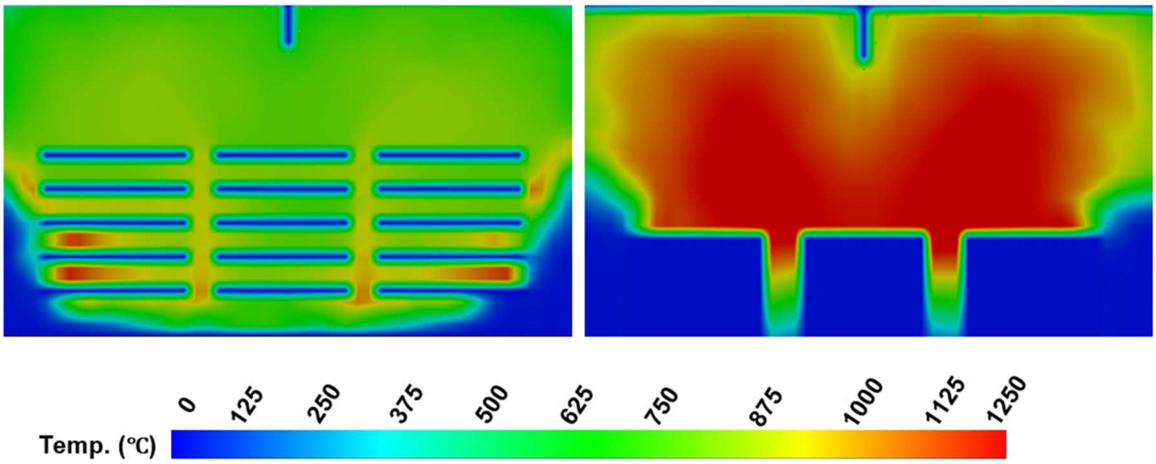
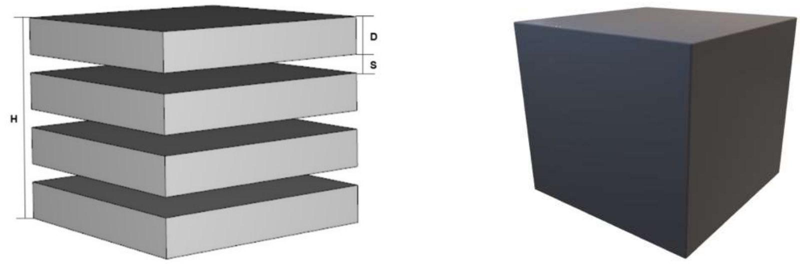


Fig. 5: Temperature Contours (°C) at 45 minutes a) Case 1 b) Case 2

The above observed phenomenon is counter-intuitive, but it can be explained using fire dynamics principles and difference in the burning rate between both cases. The burning rate depends on several factors such as surface area, thickness, the fuel's porosity, and so on. Burning rate of fuel also affects the temperature within the compartment, which is illustrated in detail in the subsequent paragraphs.

When surface-controlled burning of fuel is considered, the burning rate would be higher for Case 1, which is attributed to the higher surface area compared to Case 2, as shown in **Fig. 6**. This phenomenon can be understood by representing Case 1 and Case 2 fuel distribution analogous to wood cribs and solid blocks of wood, respectively. The burning rate is numerically expressed as Equation 1, where the burning rate ($\dot{m}$) is inversely proportional to the thickness of fuel (D) [37]. Block [45] deduced a similar inversely proportional relationship between the burning rate and the thickness of the fuel bed by conducting theoretical and experimental studies (Equation 2). According to an experimental study performed by Gross and Robertson [46], a considerably higher burning rate was observed for fuel distribution with higher surface area under unrestricted ventilation conditions. This behaviour validates the observations made in this study as Case 1 has a higher burning rate due to the availability of higher fuel surface area compared to Case 2. The higher value of fuel porosity in Case 1 also contributes to an increase in the burning rate of fuel and can be expressed as Equation 3 [37]. Gross [47] confirmed this phenomenon by conducting an experimental study for diffusion-limited combustion, where the fuel burning rate increased with an increase in the fuel porosity. In this study, Case 1 has higher surface area and porosity and lower thickness compared to Case 2; therefore, the observed burning rate is significantly higher for Case 1.



(a) **(b)**

Fig. 6: Thickness and porosity for the arrangement of fuel load (a) Scattered (b) Carton

$$\dot{m} = \frac{4}{D} m_o v_p \left(\frac{m}{m_o}\right)^{1/2} \quad (1)$$

Where m_o is initial mass and v_p is the regression velocity which depends on the type of the material [37].

$$\dot{m} = \frac{C}{D^{0.5}} \quad (2)$$

Where *C* is the material property and is independent of the size and geometry of the fuel.

$$\dot{m} = 4.4 \times 10^{-4} \left(\frac{S}{H}\right)\left(\frac{m_o}{D}\right) \quad (3)$$

where *S* is the distance between the stacks (porosity between the fuel) and *H* is the total height of the fuel load.

Hot products of combustion such as gases and soot rise above due to buoyancy and escape the compartment, which allows drawing in cool air from outside as illustrated in **Fig. 7**. This phenomenon was experimentally studied by Kawagoe and Sekine [48], and Odeen [49]. They proposed a correlation to calculate the heat losses due to the replacement of the hot gases with the outside cooler air as illustrated by Equation 4. Kawagoe and Sekine [48] calculated the flow rate of the incoming and outgoing air by using Bernoulli's equation at the openings (difference of gases coming in and going out is equal to the difference of the quantities of the gases consumed and produced during the combustion). They found that the heat loss to the atmosphere (Q_L) is directly proportional to the burning rate ($\dot{m}$) [50]. It was reported in their study that the rate of incoming air ($\dot{m}_{in}$) and outgoing gases ($\dot{m}_{out}$) are also a function of the burning rate [50] as illustrated in Equation 5 and 6. In other words, the volumes of the cool air coming in and hot gases going out increases with an increase in the burning rate. Therefore, as the burning rate is much higher for Case 1 compared to Case 2, more hot air escapes from the compartment in Case 1, and to maintain the equilibrium at the neutral plane (where the pressure difference is zero), an equivalent volume of cool air is drawn inside the compartment. Due to the exchange of hot and cool air, heat losses observed for Case 1 are higher than Case 2, which eventually results in a reduced overall compartment temperature for Case 1, as shown in **Fig. 5**. The authors recommend conducting more experimental studies to understand the above observed phenomenon.

The CFD calculation results for the mass flow rate at the opening are presented in **Fig. 8**. A higher mass flow rate is obtained for Case 1 compared to Case 2, which confirms the empirical relation proposed by Kawagoe and Sekine [48]. Therefore, it can be concluded that due to higher heat losses in Case 1, lesser overall compartment temperature is observed.

$$Q_L = \dot{m}G_o(T_g - T_a)C_p \qquad (4)$$

Where G_o is the volume of the combustion gases produced by the fire. T_g and T_a are the gas temperature and outside air temperature, respectively. C_p is the specific heat of the hot gases.

$$\dot{m}_{in} = \dot{m}L\rho_a \qquad (5)$$

$$\dot{m}_{out} = \dot{m}G_o\rho_a \qquad (6)$$

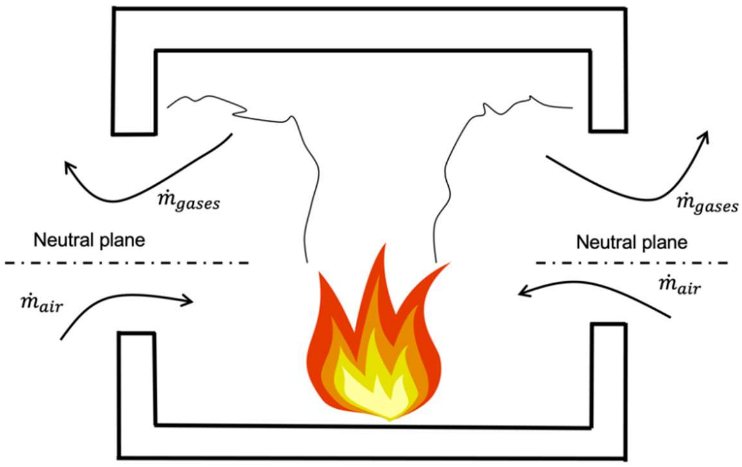


Fig. 7: Compartment fire mass flow of hot gases and cool air

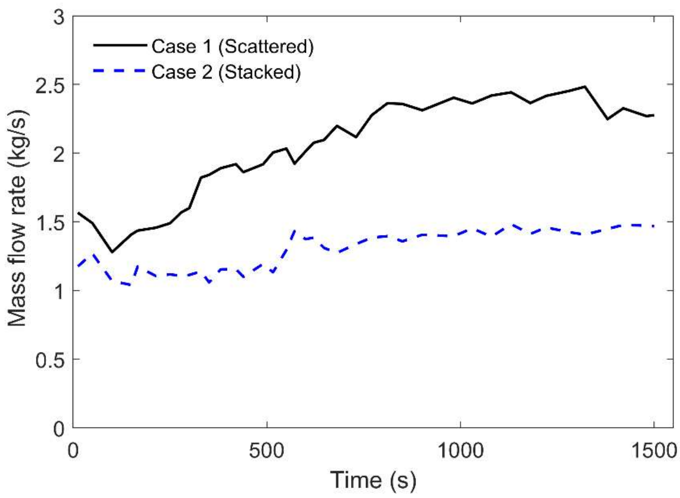


Fig. 8: Mass flow rate at the opening for both Cases from the CFD calculation

The flow rate of the gases for Case 1 and Case 2 can be represented using the velocity profile obtained from the CFD simulation (**Fig. 9**). These results are in confirmation with Equations 5 and 6 proposed by Kawagoe and Sekine [48], where the airflow rate is directly proportional to the burning rate. As seen in **Fig. 9** for Case 1, the hot gases are leaving the compartment with an average velocity of more than 5 m/s, which is significantly higher than the average velocity of 3.0 m/s for Case 2. As a result, the hot gases stay inside the compartment of Case 2, resulting in lower heat losses and relatively higher compartment temperatures compared to Case 1. Due to the burning of fuel at multiple levels in Case 1, the air is drawn at various levels that enhance the burning rate. On the other hand, for Case 2, the high velocity of gases can be found only in the upper zone of the compartment because most of the burning is taking place at the upper level. It is noteworthy that in Case 2, the high-velocity gases are travelling through the gap between the fuel load as shown in **Fig. 8**, which are responsible for creating large-scale vorticities at the upper zone of the compartment. These large-scale vorticities could essentially be another reason for obtaining higher temperatures in the upper zone in Case 2.

Fuel burning rate also affects the duration of the fire. As the burning rate for Case 2 is lower than Case 1, a longer burning time is observed for Case 2, and prolonged fire exposure for structural elements could be detrimental for structural integrity. The longer duration of fire (τ) in Case 2 with the same fire load (L) as in Case 1 can be explained using the correlation proposed by Law [51] (Equation 7), where fire duration is inversely proportional to the mass flow rate or rate of burning of fuel ($\dot{m}_f$).

$$\boldsymbol{\tau = \frac{L}{\dot{m}_f}} \qquad \textbf{(7)}$$

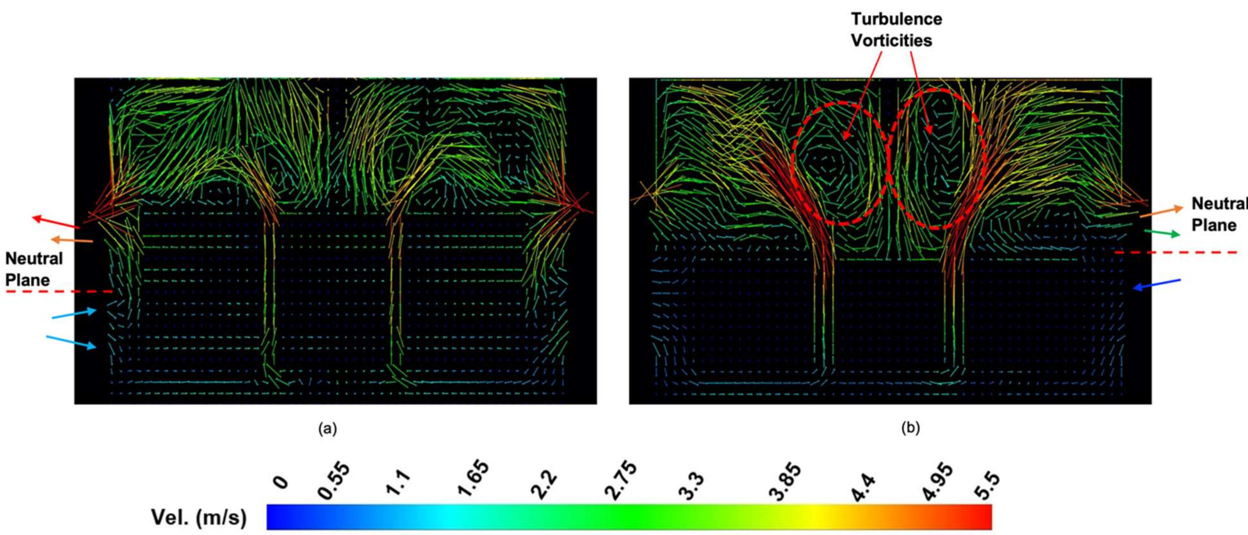


Fig. 9: Velocity contours (m/s): (a) Case 1, (b) Case 2

Fig. 10 shows that a higher magnitude of heat release rate (HRR) is obtained for Case 1 against Case 2, which is mainly attributed to the higher mass burning rate in Case 1. HRR is proportional to the heat of combustion (h_c) of a fuel and mass loss rate ($\dot{m}$) as illustrated by Equation 8. From equations 1, 2, and 3 a higher burning rate was obtained for Case 1, therefore the HRR for Case 1 is also higher. The velocity of the surrounding air influences HRR, it increases sharply with an increase in the velocities of the surrounding air. In an experimental study carried out by Lönnermark and Ingason [52], the authors tested the wood cribs in a tunnel and found that the fire growth rate increased by 5 to 10 times by increasing the surrounding air velocity three times. In the current analysis, the maximum HRR recorded for Case 1 is 1.25 times higher than Case 2 as shown in **Fig. 10**. This behaviour is supported by the information presented in the velocity contours (**Fig. 9**).

For Case 2, lower HRR was observed because of a relatively slower burning rate, however, higher temperatures were obtained, as explained earlier in this section. Both the higher temperatures and longer duration are more critical for a structure's performance in a fire.

$$\boldsymbol{HRR} = \Delta \boldsymbol{h_c} \times \dot{\boldsymbol{m}} \qquad \textbf{(8)}$$

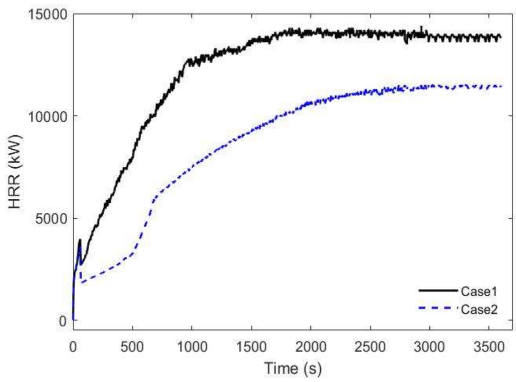


Fig. 10: Heat release rate for both cases

4.1.1. Variation of HRR for different fuel packing density

In the previous section, analytical and numerical correlations are presented to illustrate the variation of HRR due to the difference in fuel porosity and surface area. A small-scale calorimeter test has been carried out to indicate the HRR for two cases. To represent Case 1, a solid block of wood of 10×10×3 cm^3 (**Fig. 11a**) was exposed to irradiation of 50 kW/m^2 and for representing Case 2, 12 sticks of 10cm long and diameter of 1cm (**Fig. 11b**) of the same material were placed up to a height of 3 cm and exposed to the same irradiation. HRR was calculated based on oxygen calorimetry [53]. As shown in **Fig. 12a**, significantly higher HRR was obtained for the case when fuel was placed in the form of sticks compared to solid block. These results are intuitive and confirm the well-established analytical and numerical methods which were developed by conducting FDS simulations and using fire dynamics principles. **Fig. 12b** shows the ratio of the remaining mass (m_r) to the original mass (m_0). It is clear from this experiment that the HRR and mass consumption rate are much higher in sticks compared to solid block as shown in **Fig. 12b**. The mass-loss rate was lower for block, however, it kept burning for a longer period which justifies the correlation suggested by Law (Equation 7). The experiment described above provides a relatively qualitative indication, and therefore it is not reasonable to draw definitive conclusions based on small bench-scale tests. The authors strongly recommend carrying out experiments for such cases at a compartment scale.

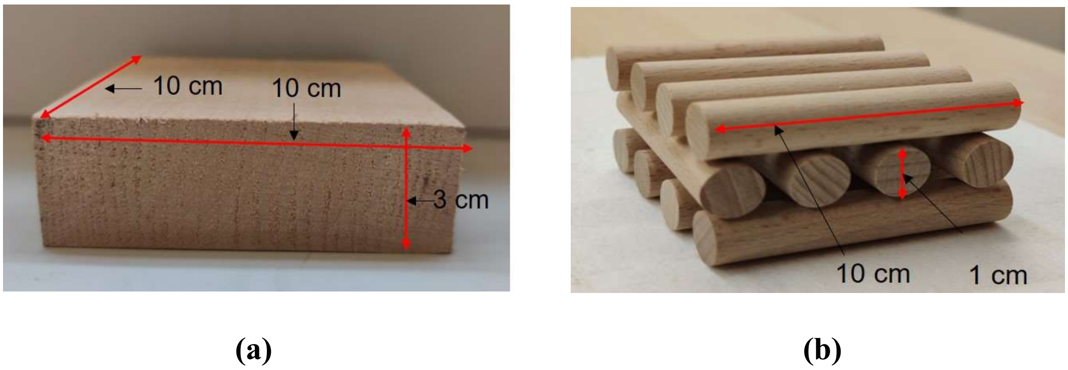


Fig. 11: a) Block b) sticks used in the experiment

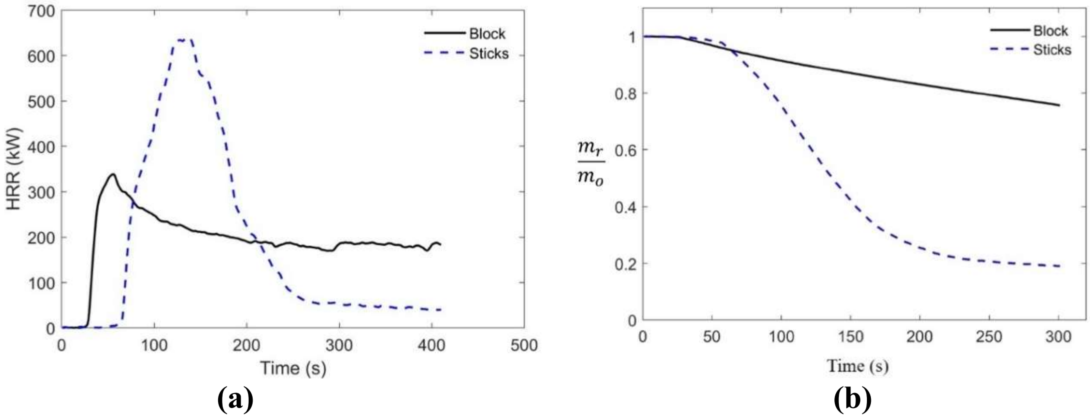
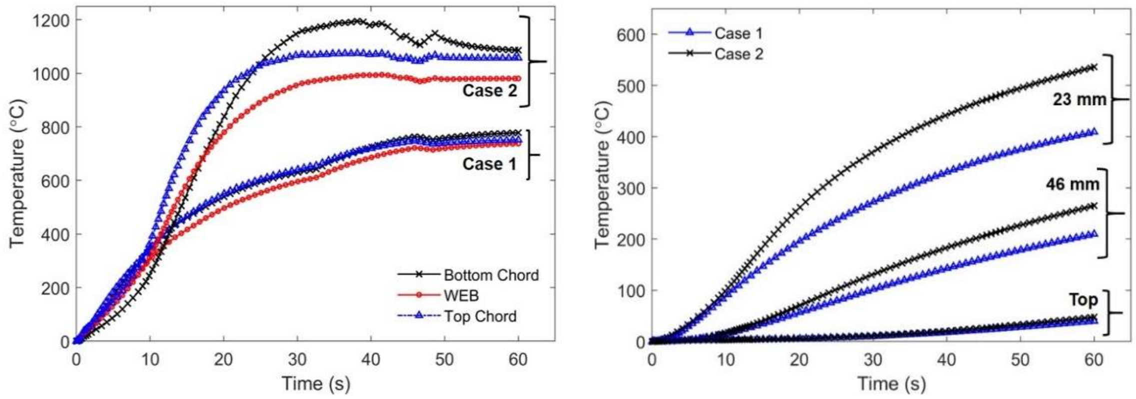


Fig. 12: a) HRR b) mass ratio for both the cases

5. Surface Temperature at structural elements

The transient temperatures obtained from the CFD analysis are used for performing heat transfer analysis of the structural members. Heat transfer analysis is performed to estimate the difference in the temperature of structural elements and consequential strength reduction due to consideration of different fuel distribution. A heat transfer model of a concrete slab-steel truss assembly similar to the Plasco Building is developed in OpenSEES (an opensource FE software) [54]. A concrete slab of 130 mm thick and a 400 mm deep steel truss are considered in this paper. The section details used are similar as used by Behnam [6]. The temperatures in the form of AST [55], which are obtained in section 3 after conducting CFD analysis, are used as thermal boundary condition for conducting heat transfer analysis. A convection coefficient of 25 W/m^{2}K and an emissivity of 0.7 are used as per the Eurocodes for steel [56] for fire-exposed surfaces. **Fig. 13** shows the surface temperatures of the truss members and concrete slab for both the cases after performing heat transfer analysis.

Fig. 13 (a) represents the time-temperature behaviour for both cases at various locations on the steel truss. The overall temperatures reached for Case 2 were significantly higher compared to Case 1 (refer section 3.1). After 60 minutes of the fire exposure, the difference between the maximum temperatures reached was around 400 °C between the two Cases. It is noteworthy that an additional 400 °C rise in temperature in Case 2 can adversely affect the building's structural performance and might help in determining the correct fire load distribution that could have caused the collapse of the Plasco Building. It is interesting to note from **Fig. 13 (a)** that the temperatures for Case 1 are higher in the beginning compared to Case 2, which is due to the higher fuel burning rate for Case 1. Whereas, at later stages, due to the higher burning rate, cool air starts replacing the hot air which resulted in reduced overall temperature reduction for structural members as shown in **Fig. 13(a)**. **Fig. 13(b)** shows the variation in temperatures with time across the depth of the slab. Thermal gradients are observed inside the slab for both cases. The difference in overall temperature is quite high for both cases, for example, the temperature at 23mm inside the bottom face of the slab (reinforcement level) is around 560 °C and 410 °C for Case 1 and Case 2, respectively. The current analysis is performed for one-hour fire duration where the top face of the slab is assumed to be at ambient temperature. Higher structural temperature and thermal gradient in Case 2 compared to Case 1 present a severe fire scenario for analysing the structural performance of the building.



(b) **(b)**

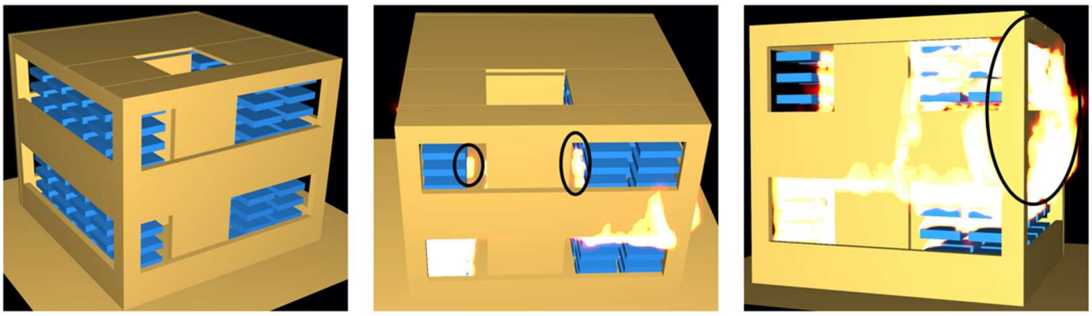
Fig. 13: Temperature Vs Time a) Truss temperatures b) Slab temperatures

6. Fire spread in the Plasco Building

Before performing the CFD simulation of a whole building for a fire investigation study, it is critical to understand and verify the fire spread in horizontal and vertical directions with the actual data and visual evidence present in the literature. In this section, ventilation conditions (around the perimeter) and fuel load of the Plasco Building [6] are considered to ascertain how fire travels vertically and horizontally from the floor of origin to upper floors and adjacent floors.

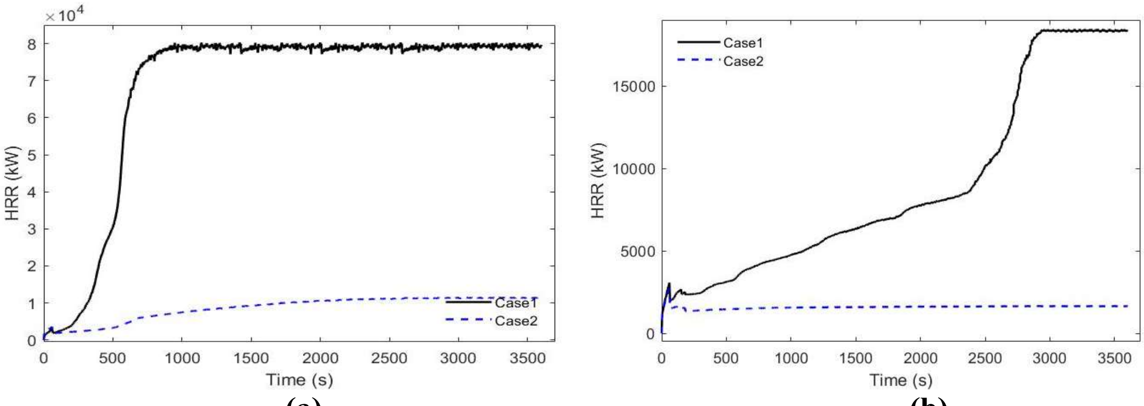
6.1. Numerical modelling of vertical fire spread in a building

To determine the possible fire scenarios based on the fuel distribution, a two-floor building (one room at each floor) with one vertical opening (as stairways) and similar ventilation condition as in literature [5,6,35], is simulated for both the cases. To demonstrate the vertical fire spread, each room of 7 × 7m2 floor area and floor to floor height of 3m was generated in FDS. A vertical opening of 2×2m is provided near the origin of the fire to demonstrate the effects of stairways on the vertical spread of fire. **Fig. 14** shows the fire spread behaviour for Case 1. Once the fire started, it grew, and flames could be seen coming out through windows and were able to reach the upper floors from both vertical openings and windows as shown in **Figs. 14b** and **14c**. Within 25 to 30 minutes, the fire started to grow rapidly, and the flame front became significantly large. The fire entered the upper floors through multiple locations and ignited the combustibles. At that moment, the HRR increases at an exponential rate before reaching a steady-state [57] as shown in **Fig. 15a**. Similar vertical fire spread behaviour was observed in the Plasco Building, verified with the available investigation reports and interviews from fire department personnel and witnesses [33]. In the Plasco Building, windows were present all around the perimeter of the building, and according to the report [33] and testimonies, the fire reached from the 10th to the 15th floor (top floor) within 22 minutes (before the firefighting operation began). It can also be interpreted from the simulation results that at later stages, the fire was freely spreading and might ignite the combustibles at multiple locations on the upper floors, which may have resulted in multiple local flashovers at the very early stages of the fire. Therefore, it took only three hours for the Plasco Building to collapse compared to the collapse of the WTC 7 [3] where it took seven hours after the fire broke out [5]. To further verify the fire spread through the open façade (openings) to the upper floors, a CFD simulation was performed. The north-west corner of the Plasco Building from the 10th to 15th floors was simulated where the fire could be seen to reach the top floor at the early stages of the fire as shown in **Fig. 16**. This vertical fire spread can be verified with the photographic evidence of the Plasco Building (**Fig. 16b**). This simulation is performed just to represent the vertical fire spread, whereas, to reconstruct the whole fire incident of the Plasco Building, authors recommend performing a detailed forensic study by modelling the whole building.



(a) (b) (c)

Fig. 14: Case 1 Vertical propagation a) Two Floor geometry (b) fire spread from the opening (c) multiple ignitions



(a) **(b)**

Fig. 15: HRR for both Cases a) Two floors geometry, b) Single floor with wall partition

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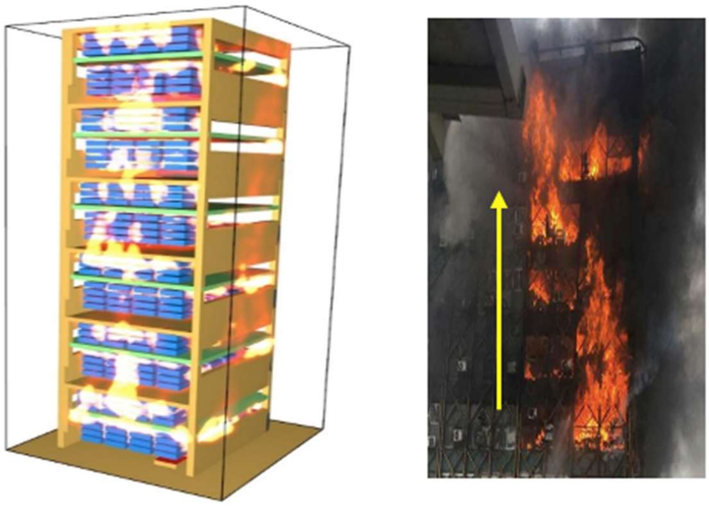
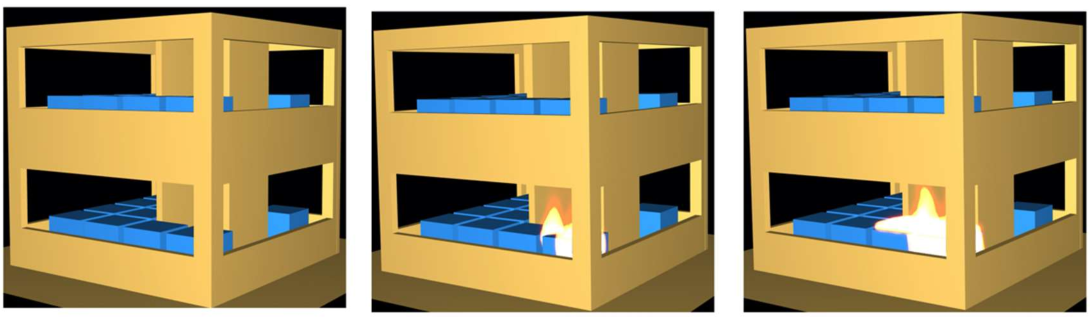


(a) (b)

Fig. 16: (a) 6 floors CFD model with false ceilings (vertical fire spread), (b) photographic evidence

For Case 2 fuel distribution, the fire could not reach the upper floors as shown in **Fig. 17**. This behaviour is attributed to the fact that the flames are not high enough to reach the ceiling or enter through openings. According to Hasemi's [58] fire model for localized fire, flame height depends on HRR and the diameter of the fire. **Fig. 15b** shows the HRR obtained for both cases. For Case 2, the HRR is significantly lower compared to Case 1 as a result flames do not reach the upper floor. Another reason is the height of the stored fuel load. For Case 2, the fuel load was stored with a lower height compared to Case 1, where fuel was about to touch the ceiling. Due to the lower height of the fuel, flames were not able to reach the ceiling and stayed within the floor as shown in **Fig. 17**. Consequently, multiple floors (10^{th} to 15^{th}) are not simulated for Case 2 distribution.



(a) (b) (c)

Fig. 17: Case 2 Vertical propagation (a) Two Floor geometry (b) Initial vertical spread (stairways) (c) Spread after 5 minutes

In the Plasco Building, the windows coverings were combustible (**Fig. 2** [42]), which burnt down at the early stages of the fire. In the simulation of Case 1 (section 3.1), large vorticities are observed in upward fire flows, as shown in **Fig. 18** (red circles), which caused the fire to reach the upper floors. In a numerical study, Satoh and Kuwahara [25] observed that large scale vorticities in the upward motion of the hot gases were because of the entrainment of cool air and verified this behaviour with the experimental study of Hayeshi [59]. Due to the oscillatory motion within the gases or flames, the flames adheres to the exterior wall [60] and enter the upper floor through windows

This oscillatory motion was observed for Case 1 fuel distribution and can be seen in **Fig. 18.** The oscillatory motion is influenced by HRR, it gets accelerated as with an increase of HRR [61], as observed for Case 1, where HRR was much higher than Case 2 (**Fig. 15a**). The fire was able to reach the upper floors due to high oscillatory motion. HRR for Case 1 increased tremendously, once both floors reached to flashovers, the peak HRR reached to nearly 80 MW as shown in **Fig. 15**.

From the above discussion and CFD simulations, it can be deduced that factors such as buoyancy, stack effect, oscillatory motion, and most importantly the height of the fuel influenced the fire to reach the upper floors.

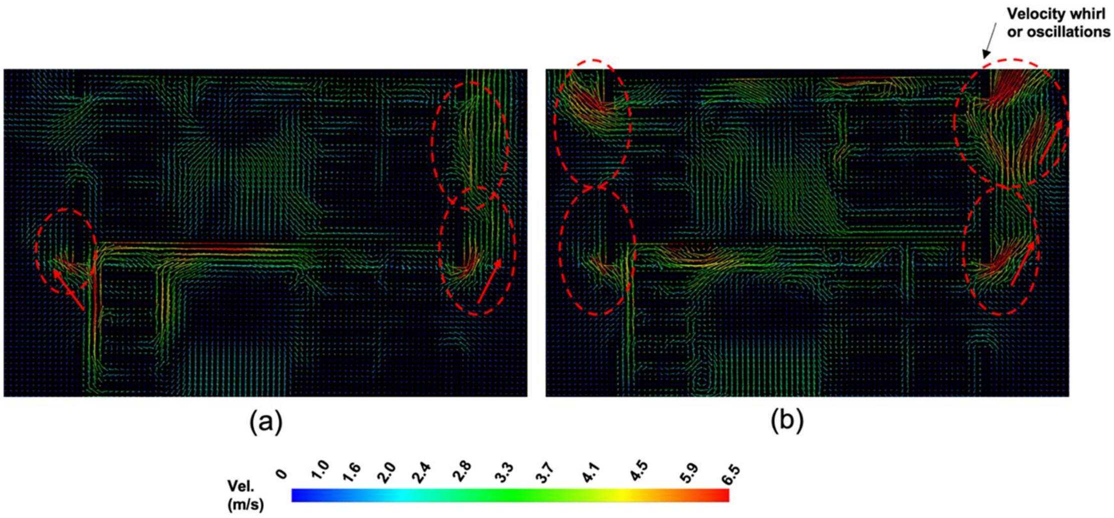


Fig. 18: Velocity contours (m/s) for Case1 at Y = 2.2: (a) at 500 sec, (b) at 600 sec

6.2. Numerical modelling of horizontal fire spread in a building

To verify and understand the horizontal fire spread, authors performed a simulation for a small building where a concrete wall is used for compartmentations (**Fig. 19**). False ceilings were also attached, which were assumed to be failed after a certain duration of exposure to the fire. In the simulation, the false ceilings were removed progressively using control devices in FDS [20] to capture the effects of the fire spread through false ceilings.

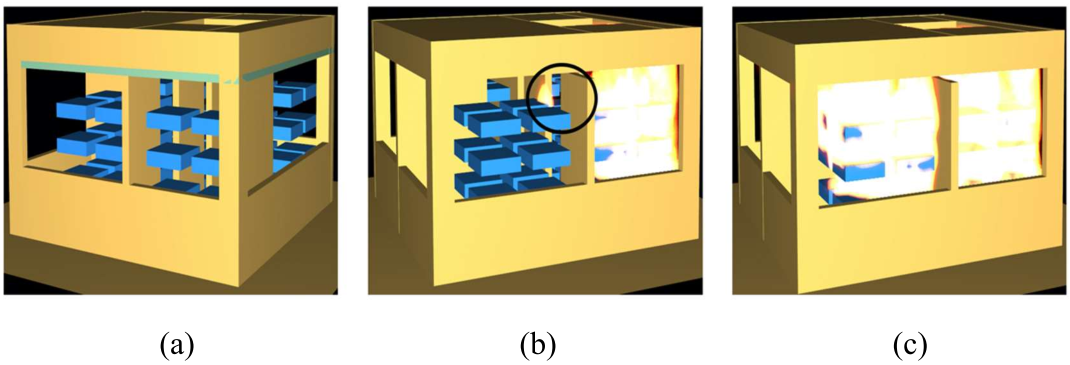
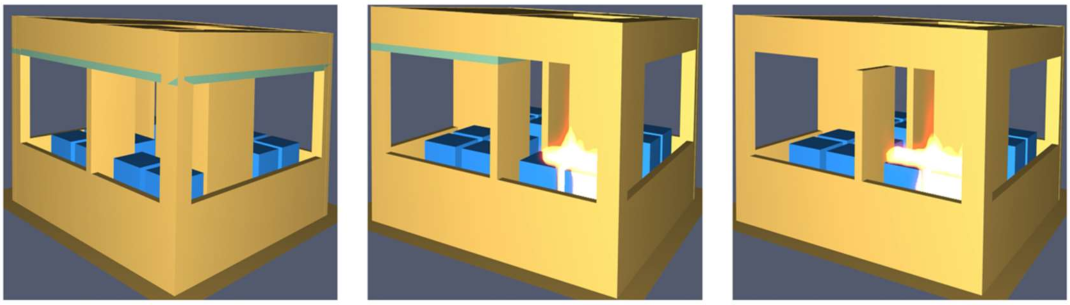


Fig. 19: Case 1 Horizontal propagation a) Compartment with wall and false ceiling, b) Horizontal spread, and c) Horizontal spread after 450 seconds



(a) (b) (c)

Fig. 20: Case 2 Horizontal propagation a) Compartment with wall and false ceiling, b) Horizontal spread, and c) Horizontal spread after 450 seconds

Fig. 19 and **20** show the geometry used for the CFD simulation to verify the fire spread to adjacent rooms for both cases of the fuel distribution. For Case 1 as shown in **Fig. 19b**, after the removal of the false ceiling in the simulation, it took less than 8 minutes for the fire to reach another room and the top surface of the fuel in the adjacent room ignited. In Case 1, the fire propagated to the entire floor horizontally, and a peak HRR of 20 MW (**Fig. 15b**) was recorded. For Case 1, at early stages, the HRR increases steadily, whereas at later stages, (**Fig. 14b**) it increases rapidly when the fire reached the adjacent compartment resulting in the sequential local flashover. On the other hand, the flames for Case 2 (**Fig. 20**) are not high enough to reach the adjacent room, it might be mainly due to lower HRR (10 MW) [58] (**Fig. 14b**) and comparatively lower height of the fuel. Evidently, these simulations represent that not only the failure of the false ceilings that would accelerate the fire propagation but also the height of fuel which plays a critical role to determine the ignition of the fuel in the adjacent room. Once the fuel in adjacent compartments ignited, multiple flashovers can be obtained. The distribution of the fuel affects the timing, growth rate of the fire, and travelling behaviour of the fire to the remaining floor area. The current simulation also suggested that the fuel distribution governs the fire spread behaviour in the horizontal direction. Authors recommend performing such experimental studies to understand the fire spread in modern buildings for obtaining realistic fire scenarios as fire accidents are occurring each year.

In short, to conduct a forensic study through computer modelling approach, it is necessary to have a great deal of information available beforehand. Besides having a proper layout of each floor, detailed information of the combustibles, fuel distribution, ventilation conditions such as windows, doors, or any other openings, and their size and location are required. In the case of the Plasco Building, the information of most of these factors is not available. However, based on the limited available data, this paper provides an investigation study for fire spread behaviour in the Plasco Building considering two possible fuel distribution patterns. This paper provides an insight into fire travelling behaviour in high rise buildings by considering the case of the Pasco Building accident and develops a basic understanding to perform realistic fire simulations. This study also provides an insight that how fuel might have been distributed in the Plasco Building as temperatures for Case 2 were much higher to make the structure collapse, but the probability of spreading fire within the floor and to upper floors is low. Case 1 supports the propagation of fire both horizontally and vertically, but temperatures observed inside the compartment were much lower compared to Case 2, though still high enough to cause a structural failure. Therefore, the fuel might have spread all over the floors as a combination of both fuel distributions, which are generally found in storage areas and workshops. The rate and probability of propagation of fire in both horizontal and vertical directions would also be influenced by the height of fuel (fuel distribution methods).

The outcomes and reasoning from the current study and visual evidence of any incident would greatly help to investigate fire behaviour in any high-rise building and to conduct a subsequent thermomechanical analysis to determine the structural response in a real fire scenario.

Conclusion

The current study presents the effects of different fuel load distribution on fire behaviour. Previous studies for simulating the collapse of Plasco Building and other high-rise buildings were mainly performed using parametric curves. The fire spread behaviour (horizontal and vertical travel) and temperature differences in the structural members due to different fuel distribution cannot be represented using these curves. By simulating two dissimilar cases of fuel distribution, where fuel load and ventilation conditions were kept the same for both cases, fire behaviour was observed to identify the possible horizontal and vertical spread of the fire. The fire spread is verified with a case of the Plasco Building.

The key findings of the study are listed as follows:

- For a scenario where densely packed fuel (in cartons) is stored in a compartment, fire can be more severe for a structure as higher temperature are obtained during the fire and the duration of fire would also be longer compared to loosely stored (stacked) fuel because of much slower burning rate, however, it might not trigger the spread of the fire.
- If the fuel is loosely stored (stacked) resulting the fuel height reaching close to the ceiling, the fire tends to spread to adjacent rooms, and it can travel even the compartments are separated by fire barrier provided the false ceilings present is continuous.
- The height of the fuel has a great influence on fire propagation in both vertical and horizontal directions. For Case 1 fuel distribution, the fire was able to propagate in both directions as the height of the fuel bed was higher compared to Case 2 that promoted the fire propagation in both directions.
- The vertical spread of fire to upper floors is governed by HRR (flame height, oscillatory motion) and the height of fuel load.
- The horizontal spread of fire is greatly influenced by the breakage of the false ceiling, location of the openings and the presence of partition walls.
- Fuel in the Plasco Building was most likely to be stored as a combination of both cases.
- Due to multiple ignition points and multiple flashovers, the fire had reached upper floors and led to the collapse of the Plasco building in three hours.

While there are several models to simulate the effect of a fire, such as the standard temperature-time curves, parametric fire model, and travelling fire models, their validity remains debatable. To date, the most realistic approach to simulate real fires is through computational fluid dynamics. To get a realistic thermal load for structural analysis, computer modelling is necessary whilst considering the factors explained in this paper. To obtain the fire scenario for the entire building, the complete model of the Plasco Building can be simulated using the fire behaviour and load distribution information obtained from this paper. As data for the Plasco Building is quite scarce, this study helps to move a step forward to investigate the collapse of the building.

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