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Fire modelling framework for investigating tall building fire: A case study of the Plasco Building

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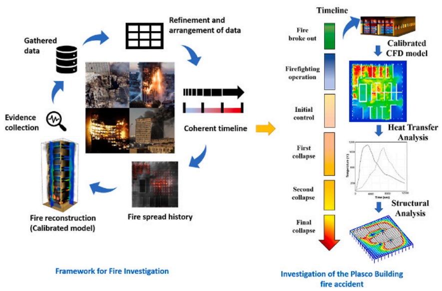
GRAPHICAL ABSTRACT



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ABSTRACT

Fire can damage structures severely and even cause the building collapse. Structural and fire engineers must carry out a comprehensive forensic investigation of major structural failures in the same rigorous and meticulous manner the airline industry investigates air crashes. The forensic assessment should identify the cause, fire spread scenario, fire behaviour patterns from its growth to decay, de-compartmentation, the performance of fire protection systems, and firefighting management. Using the available tools and data, the current paper proposes a methodology to reconstruct the fire for the forensic assessment of tall buildings. This is done by first organising

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Life safety
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observed data into a coherent timeline and presenting the actual fire spread obtained from the visual evidence. The total fire spread within the building is estimated based on fire dynamics principles and observed fire scenes that can be verified with a calibrated CFD model. The collapse of the Plasco Building is assessed by employing the proposed framework. The rise in construction of the tall buildings increases the risk of the occupants' safety from the fire induced structural failure or collapse. The framework presented in this paper can guide engineers to improve the building resilience designs and reduce the fire accidents related risks.

1. Introduction

Each year more than 490,000 structural fires are reported only in the USA [1], out of which an average of 14,500 fires per year occur in tall (or high-rise) buildings [2]. Fighting tall building fires presents a serious challenge because of accessibility issues for firefighters and for occupants' evacuation. Therefore, high-rise structures are usually expected to resist burnout with tolerable structural damage. As a result, the total collapse or severe damage of structures such as three towers of the World Trade Centre (WTC) in New York in 2001 [3,4], the Windsor Tower in Madrid in 2005 [5], the Plasco Building in Tehran in 2017 [6], and the Grenfell Tower in London in 2017 [7,8] are not common and require to be investigated. Although buildings constructed according to modern codes [9,10] are expected to be equipped with high levels of fire protection measures, many existing high-rise buildings built in the past suffer from poor fire safety design and protection measures.

Conventional fire investigations are generally associated with determining the *cause and origin* (determination of the origin of the fire and its cause) of the fire [11,12]. The methodologies for fire investigation are well-documented in many textbooks [11] and standards such as NFPA 921 [12]. These documents have established scientific procedures that provide guidance on how to collect evidence and organise it for use in the legal process, along with proposing a rational hypothesis [12] based on the principles of fire dynamics [13–15], thermochemical decomposition of combustibles [11], and ignition theories [16]. Therefore, while reconstructing the fire event, conventional methodologies primarily focus on fire growth and its effects on the materials stored within the fire compartment. Furthermore, these conventional fire investigations generally apply for small common compartment (or localised) fires, whereas the fire phenomenon in tall buildings is quite different such as travelling nature of fire in the large open floor plan, stack effect, vertical spread and so on. It is imperative to capture and analyse actual structural fire events when they occur because full-scale experiments such as those done at Cardington [17], travelling fire tests [18], and those at a lesser scale currently ongoing at NIST can represent only a fraction of the possible sequence of events leading to fire-induced structural collapse [19,20].

Assessment of structural damage may be done if it is deemed that the structure is economically repairable and reusable. This is unlikely to be the case where partial or total collapse has occurred and in such cases, no investigation or analysis to determine the reasons for the structural collapse are usually part of the conventional fire investigation methodologies. Nevertheless, when the tragic events of WTC occurred in 2001, and three towers (Tower 1, 2, and 7) collapsed after the impact of two airplanes on buildings 1 and 2 of the WTC [3,4], NIST conducted a detailed investigation of the collapse [3,4], and so did several independent researchers [21–25], given the enormous significance of those collapses. WTC Tower 7 became the first tall steel-framed structure to collapse entirely due to uncontrolled fire originating from the collapse debris of WTC Tower 1 [3].

Torero [26] proposed a technique for fire reconstruction, where scientific understanding may be used to determine the fire history and the structural response corresponding to a unique fire scenario. He summarised four key aspects when conducting a forensic assessment of a building after a fire: (1) fire growth; (2) fire protection system (if installed its performance needs to be assessed); (3) egress analysis (no direct impact on fire but human casualties are directly connected); and (4) structural analysis (failure of compartmentation, fire proofing, etc.).

The most comprehensive study to reconstruct the collapse of the WTC was conducted by NIST [4]. A massive amount of data (images and testimonies) was collected to define the sequence of events. However, it failed to track the specific events of fire spread within the building to reconstruct a conclusive fire timeline.

Over the last two decades, the most common approach to reconstruct the structural behaviour is to model all three components of the fire incident, namely: defining the fire, heat transfer to structural boundary, and structural response [26,27]. While defining a fire, generally, empirical or analytical idealised models such as standard fires, ISO curves, are used [28]. Though a great deal of information can be generated to understand the structural response to fire from these models, they are unable to reconstruct the actual fire events, especially for the large fire scenarios such as the collapse of the WTC towers (New York, 2001) [3,21], Windsor Tower (Madrid, 2005) [29], and Plasco Building (Tehran, 2017) [6,30].

The uniqueness of the structural system of a building combined with specific fire scenarios may lead to unique forms of structural failure, which may require a comprehensive study of the actual fire spread. From the several studies on the fire spread history in the WTC towers, distinct fire scenarios were identified, where fire travelled along with the open-floor plates and are being referred to as the "travelling fires" [31,32]. No definitive methodology currently exists that can be used to provide sufficient information about the progress and spread of fire and its impact on the structure in order to reconstruct the fire history for a comprehensive fire-investigation of tall buildings. The methodologies used for the WTC investigations were improvised during the analysis, and eventually, the timeline for fire spread was not considered conclusive [4,26]. The fire that occurred in the Grenfell Tower [33] is still under investigation, and no detailed study that represents the fire spread history in the building is carried out, so far [7,8,34,35]. Similar can be seen for recent fires which lead to failure or partial collapse of the structures [36,37].

In the current paper, a framework is proposed that utilises all available evidence in the form of images, testimonies, videos, and other sources of information as previously used by NIST [4]. The proposed framework can be used to reconstruct the fire history for complex fire scenarios and develop a methodology to perform a comprehensive forensic fire investigation, including structural failure and collapse. The framework allows the establishment of a coherent fire spread history based on visual evidence and testimonies associated with the fire spread behaviour and structural changes within the building during the fire incident. This methodology can be applied to any fire accident in tall buildings such as the Grenfell Tower, where the structure was severely damaged and not safe to use. The fire scenario that led to the collapse of the Plasco Building is reconstructed, and a well-defined sequence of events is presented to establish a rational fire timeline in conjunction with structural damage that occurred in the building during the event.

2. Fire investigation of tall buildings

Investigation of failure or collapse of a structure as a result of a fire should be as meticulous as for the plane crashes where sometimes it may be necessary to even scour the ocean floor to fetch the black box and even investigate the condition of simple nuts and bolts [38,39]. This kind of precision is warranted while reconstructing the fire in order to correctly determine the reasons for structural failure or collapse and avoid them in the future. Engineers have always learned more from failure than from success, so it is a missed opportunity if a comprehensive fire investigation does not follow a major fire-induced structural failure. Babrauskas [40] also argued that the detailed investigation of a fire accident is on the major neglected areas in the fire safety engineering. Recently, there have been a good number of fire incidents where structures have completely collapsed or failed due to fire [3,4,6,41,42]. Unfortunately, major fires occur from time to time such as; Plasco Building in 2017 where the whole structure collapsed, killing around 22 people including sixteen emergency responders.

The foremost step for any fire investigation is the collection of evidence to reconstruct the fire. The primary objective of a forensic investigation of structural failure in fire is generally to understand the structural response to different fire scenarios. The knowledge of many key parameters is required to create a rational and justifiable fire history to develop a fire timeline based on critical events during the fire [43]. These key parameters include the ignition source and origin of fire, nature of combustibles and fire load, fuel distribution, the architectural design of the building, nature of the partitions and compartment walls, ventilation conditions, and so on. Fire growth is a complex combustion and heat transfer phenomenon [13–15].

Over the last two decades, Computational Fluid Dynamics (CFD) has emerged as a strong tool for modelling fire behaviour in both forensic and design applications [44]. CFD tools are capable of computing the spatial and temporal resolution of temperatures and chemical species, which can be easily implemented to construct a rational timeline. However, inherent uncertainties are involved with numerical models of fire, mainly because of the uncertainties associated with the parameters needed to characterise the fire such as fuel load and its distribution, ventilation conditions that vary throughout the fire, and so on.

Many researchers have reported CFD simulations are highly sensitive to numerous parameters (even some parameters that are well defined) which may result in fire behaviour predictions that are not representative of the fires that had occurred in reality [45]. This paper examines how to overcome this uncertainty in the case of forensic studies. This can be done by first organising observed data into a coherent timeline, and then using the timeline as a reference for the calibration process of CFD models. The calibration process has to ensure that realistic temperature predictions are generated while still conforming to the observed travel path and timeline of the fire. Finally, this process is demonstrated for the Plasco Building, which provides an interesting case study that demonstrates complex fire behaviour due to the building's architecture and fuel load.

2.1. Fire signatures

When fire initiates, there are changes in the environment, such as the production of heat, smoke and char etc., which are referred to as fire signatures [46]. When the fire grows and travels, it leaves observable traces behind that can be used to investigate the fire, such as burnt or unburnt fuel, char on the walls, smoke traces and deformation of structural elements due to heat. These fire signatures can be interpreted in a reasonable manner. Spatial and temporal details of fire signatures can provide a great deal of information for reconstructing the fire. Detailed videos of any fire incident uncover many aspects which may reveal the dynamics of the growth of fire within the building [11]. However, it is nearly impossible to have this level of information from a fire incident, such as video footage of the whole incident or images of each critical event within the building. Close circuit television cameras (CCTV) can provide the initial details of the fire if it initiated in a monitored zone. Generally, not all buildings are equipped with CCTV, and even if CCTV is installed, it may get burned down in a large fire or get covered by the smoke layer in the upper part of the compartment where CCTV is generally installed [47]. However, it is possible to reconstruct the fire even by collecting information from different resources such as available images, videos, witnesses' testimonies, etc. In this study, a framework is proposed to facilitate systematic reconstruction of any fire incident and will henceforth be referred to as *'Fire Investigation of Tall buildings'* (FITB).

2.2. Framework for fire investigation of tall building

A framework to reconstruct the fire as part of a forensic investigation of the structural failure or collapse of tall buildings is presented in this section. A simple but robust approach is proposed based on tracing the fire signatures (smoke and flame) from the visual evidence. Fig. 1 shows a flowchart of the proposed framework. The essential components of a fire investigation are creating a coherent timeline of the critical events and determining the rational fire spread history. A robust and reliable timeline helps to ascertain the fire spread between subsequent incidents by narrowing down the uncertainties. The FITB framework, as proposed here, is explained as below.

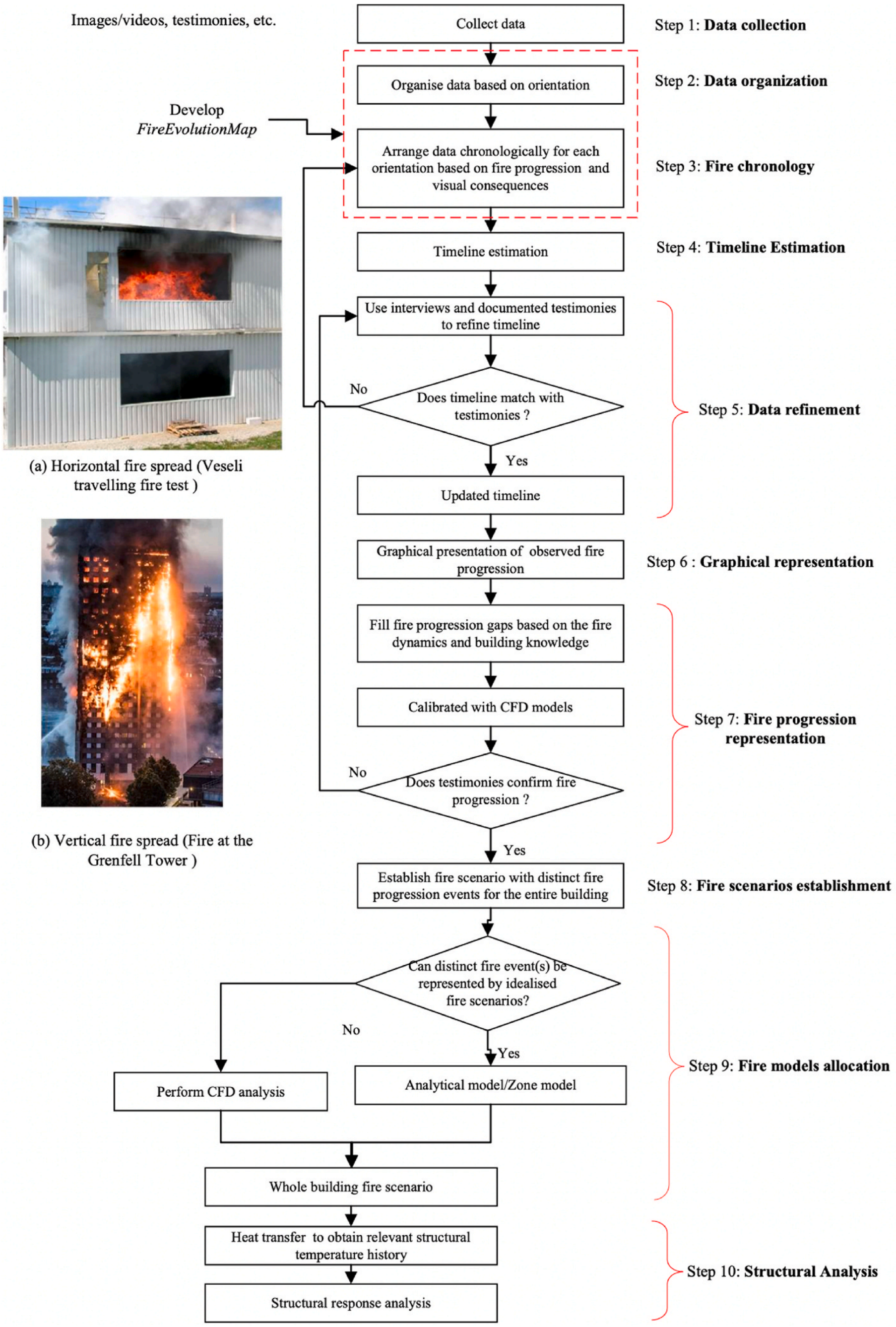

Fig. 1. Framework for forensic fire investigation.

1. **Date collection:** All available information related to fire incident must be collected (represented as step 1 in Fig. 1), such as photographs, video footage, reports from the fire department (if available), interviews of the first responders, testimonies, initial reports from news agencies, etc. Images and videos can be collected from security footage (CCTVs), satellite images, social networks, newspaper articles, and other reliable resources. Metadata of the captured images and videos from the original resources (if available) can provide the exact timing information.
2. **Data organisation:** Once sufficient visual evidence (images and videos) had been gathered (at least a few images that represent the fire signatures from all sides of the building exterior), the images showing the exterior of the building are organised according to building elevation direction (step 2 in Fig. 1), e.g., put all images of the north face in a row and similarly for other sides. It is highly unlikely that any images from the interior of the fire compartment will be available for a complex fire incident. However, if available, a similar exercise can be performed for the building interior.

3. **Fire chronology:** The history of the fire is now analysed by looking at the fire signatures. From the images, it is straightforward to determine if the fire had already traversed a particular location (or not) by spotting the smoke or flame (fire signatures). All images and frames from the videos for each orientation can be easily arranged chronologically based on the fire progression and visual consequences such as visible flame and smoke signature on the walls that tell a story of smoke and fire movement. Each row shows the progressive spread of fire. A matrix of photographs called '*FireEvolutionMap'* is generated, where each row shows the images corresponding to building orientation and columns represent the spread of fire progression in time on each face. A time interval for each image is assigned in the subsequent steps (Step 4 and Step 5).
4. **Timeline estimation:** Now, according to initial reports, testimonies, and news articles, an estimated timeline can be set up that could indicate the time of key events such as time of ignition, fire alarm activation, initiation of the fire protection system, the arrival of first responders, initialisation and effectiveness firefighting operation, the collapse of structural elements (if any), etc [48]. An approximate time interval can be allocated to each image as each image would represent an instance between two key events. If the number of images is limited, this exercise can be done on the wall like a '*detective wall*', however for a large number of images, any spreadsheet program can be used.
5. **Data refinement:** Interviews and testimonies of firefighters and witnesses, and documentaries (if any) should be carefully examined for discovering any key events that may have occurred inside the building such as multiple local collapses within the building (loss of compartmentation due to collapse of partition walls, damage to false ceilings), fire spread within the building and through false ceiling cavities and openings, firefighter interventions and its effect, the effectiveness of the fire protection system (step 5 in Fig. 1), and so on. If the key events established in Step 4 match with the firefighters' statements and other such documented evidence, one may continue to the next step. Otherwise, the timeline can be refined based on firefighters' statements and/or any other more detailed means of information (testimonies, related documents, detailed reports from the fire service department).
6. **Graphical representation:** Once a coherent fire timeline is established, the fire progression and architectural changes can be represented graphically on the plan and elevation drawings for all floors, as shown in Fig. 1 as step 6. Flames and architectural changes visible in the *FireEvolutionMap* can be presented for each floor according to fire's *known* location between or during specific key events. *FireEvolutionMap* of the Plasco Building fire appears in later sections.

7. **Fire progression estimation:** Once all available evidence of the fire spread is illustrated graphically on the plans of each floor, a possible history of fire progression can be established. There might be some missing information while representing the progression of the fire. The gaps in the estimated fire progression can be filled based on the fire dynamics and building knowledge extracted from various sources, such as firefighters' interviews, documented evidence, and/or testimonies. These sources can yield a great deal of useful information such as fuel load, fuel type, and its distribution, which could enable the presentation of the probable fire spread history in a justifiable and rational manner. The estimated fire progression history can further be verified by calibrating the CFD models +with the *known* locations of the fire. This whole process of filling in the missing information to obtain a reasonable fire timeline and verification with CFD is shown as step 7 in Fig. 1.
8. **Fire scenarios establishment**: Once a reasonable fire timeline is established, various local fire scenarios which are representing the distinct fire progression events at the different part of the building would be established. The global fire scenario for the entire building can be obtained by combining all local fire scenarios.
9. **Fire models allocation:** The local fire scenarios for distinct fire progression events, which are established in the previous steps, can now be used to determine the structural fire response. If the fire behaviour can be represented using idealised fire scenarios at certain building locations, it might be reasonable to use analytical models or zone fire models to represent these local fire scenarios. However, for the fire scenarios where the fire may have "travelled" across floors and between floors, with non-uniform fuel distribution, CFD models are the most appropriate choice to obtain the temporal and spatial resolution of temperature and species concentration [26]. This step allocates fire models to the whole building fire scenario, as shown in Fig. 1.
10. **Structural analysis:** The output data from the CFD or any other model from step 9 (Fig. 1) is firstly used to perform the heat transfer to obtain the temperature history for the structural members. This time-temperature history can be used as a thermal boundary condition to analyse the structural response to fire. A reconstruction of fire-induced structural failure may now be possible to be determined. This step completes the original objective of the proposed FITB fire investigation framework and enables meaningful conclusions to be drawn regarding tall building fire safety that could lead to improved designs of structural fire safety and fire resistance systems.

2.3. Estimation of fire spread

In constructing an estimated fire spread history, the *known* locations of fire from the images help to fill in the gaps and reveal the *missing* travelling path of the fire between two key events. However, to establish the fire trajectory accurately, it is critical to understand the behaviour of the fire inside the building. Fire behaviour is highly complex depending upon a number of factors, from ventilation conditions to the type of fuel present and its distribution in the building. Based on the previous experimental studies, reports from accidental fires for relatively large spaces, and a basic understanding of the fire dynamics, the gaps in the fire spread history can be determined, which later can be verified from testimonies and CFD modelling. The fire behaviour observed in experimental studies and some infamous fire accidents are studied, which may be instructive in establishing a rational fire timeline for tall buildings. In terms of fire spread and burning location, ventilation played a vital role even for fuel-controlled fires in large compartments [49,50]. There are various fire scenarios that can lead to the horizontal (Fig. 1a) and vertical (Fig. 1b) fire spread as observed in many large-scale experiments and fire accidents [3,4,14,17,42,51–54]. In a high-rise building, the fire could travel vertically to higher floors either through windows or through vertical openings such as stairways or elevator shafts, façade or failure of sealing material used for closing the floor-to-floor penetration. The observed phenomenon such as buoyancy, stack effect (due to pressure difference through their height), adherence of the fire to the exterior walls, can be used to trace the fire.

3. Fire in Plasco Building

3.1. Accident overview

In 1962, when the Plasco Building was constructed, it was the tallest and one of the most iconic buildings in Tehran, Iran. Almost 60 m tall building had a steel frame structure. Fig. 2 shows the plan view of the Plasco Building. The Plasco Building had two parts, one on the north side of the building, a five-story shopping mall, and on the south side of the building, there was a 16-story tower. The exterior of the building had cemented walls at the eastern and western sides, and the northern and southern sides of the building were covered with steel braces as façade and wall panels (ceramic tiles) [6].

The 16-storey Plasco Building was collapsed in a fire incident that occurred on January 19, 2017. An accidental fire was caused by an electrical short circuit on the 10th floor of the north-western side of the building, as shown in Fig. 2 [6]. The fire travelled rapidly in the vertical direction and reached the upper floors in the early stages of the fire. No automatic sprinkler system was installed in the building. Although when the Plasco Building was constructed, it complied with the design codes of that period, however, comparing with the current codes of practices internationally, it violated many mandatory requirements as shown in Table 1 (comparison is done with the most widely accepted NFPA Life Safety Code [55] for demonstration purpose only). The type and amount of the combustibles, architectural design, lack of efficient firefighting systems, and many other factors made the fire grow rapidly, which eventually might lead to the collapse of the building. There are a few tall buildings that were collapsed merely due to uncontrolled fire [3]. It is vital to understand how fire spreads in a tall building that can lead to its collapse or any structural failure.

In a study, Ahmadi et al. [6] presented a critical sequence of events that led to the collapse of the Plasco Building. However, they did not provide any explanation about the fuel load, fuel distribution, fire spread, and trajectory of the fire. The effects of these factors are critical and must be recognised while conducting a forensic investigation for structural failure in a fire. In the current paper, the proposed framework (FITB) is used to investigate the fire spread and the collapse of the Plasco Building, and finally set up a coherent fire timeline of the key events. Fig. 3 shows the *FireEvolutionMap* of the Plasco fire incident. Section 4 discusses the fire spread presented in the *FireEvolutionMap*.

3.2. Timeline of key events

The key events, which are essential to analyse the fire spread for a forensic assessment, can be determined from the sufficient evidence and testimonies as it implicitly provides the details of the fire growth, travel path of the fire, cause of augmentation or decay of the fire, and so on, as discussed in Section 2.2.

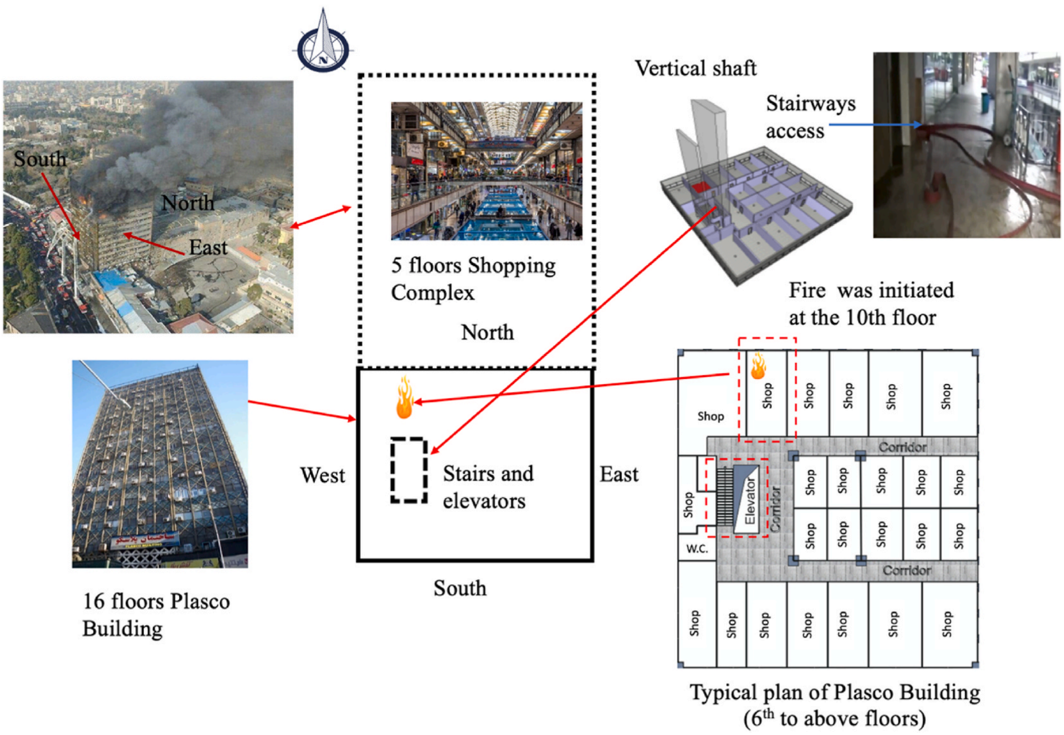

Fig. 2. Details of plasco building.

Table 1
Some of the violations of the Plasco Building with the current codes of practice.

Fire protection and life safety requirement	Plasco Building	Current life safety code [55]
Supervised sprinkler system	Not present	Required
Standpipe system	Present but not operational	Required
Fire Alarm system with voice/ alarm communication	Not present	Required
Means of egress	Only one	Minimum two means of egress are required
Smoke proof exit enclosure	Not present	Required
Change in occupancy	Change from regular business occupancy to mixed occupancy (mercantile, mall, storage facility) without any approval	Allowed, if the new occupancy type complies with the latest building and life safety codes (required approval)

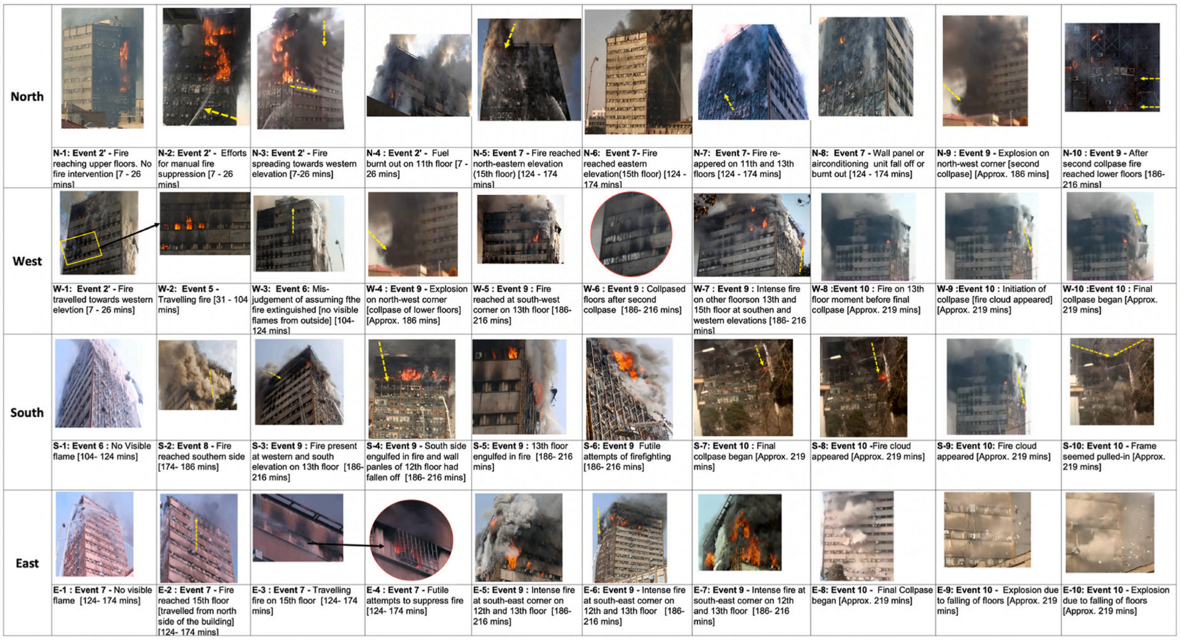

Fig. 3. A concise *FireEvolutionMap* of the Plasco Building accident (High Resolution Images can be downloaded from https://github.com/aatif85/ForensicPlasco.

In this section, an estimated timeline for the collapse of the Plasco Building is set up based on visual evidence, interviews, and testimonies (Section 4). The proposed timeline suggested few modifications to the sequence of events presented by Ahmadi et al. [6] and explained each event with rational justification based on available data, principles of fire dynamic, and structural fire response. A timeline of critical events is illustrated in Fig. 4. An approximate time interval between subsequent key events is allocated. The nomenclature of the key events is given based on the major incident during the specific time interval.

Event 1: Ignition of fire - around 7:56 a.m. The exact time of the ignition was difficult to report. Before calling the Fire Services Department (FSD), security personnel attempted to put off the fire (Section 4.2). The fire was reported to the FSD between 7:56 to 7:58. It can be summed up that the fire started a few minutes before FSD was informed. This event is the starting point of the timeline (Fig. 4).

Event 2: Arrival of Emergency Responder Team - between 8:00 a.m. - 8:01 a.m. Due to the proximity of the FSD (around 350 m [6]), it took nearly 3–4 min to reach the Plasco Building after the fire was reported (See Fig. 4).

Event 3: Pre-firefighting operation - between 8:01 a.m. - 8:22 a.m. This event was one of the most crucial events in terms of fire growth. Once the first responders arrived at the Plasco Building, the pre-firefighting activities such as connecting multiple hoses, erecting ladders took more than 20 min for the firefighters to reach the 10th floor. Due to a considerable long delay in initiating the firefighting operation, the fire reached the upper floors during the early stages of the fire (Fig. 3 [N-1and N-2] and Section 4.3).

Event 4: Beginning of firefighting operation- 8:22 a.m. - 8:25 a.m. It took around 20–25 min to begin manual firefighting after the arrival of the first responders. During this time interval, the fire could be seen at the 10th to 15th floors in the north-western side of the building (Fig. 3[N-2 and N-3]). The beginning of the firefighting operation event is shown as Event 4 on the timeline (see Fig. 4). It is worth noting that during the Event 2 to Event 4 of the timeline ('arrival of the first responders' to 'beginning of the firefighting operation') there was no intervention in the growth and spread of the fire during this period, therefore these events are presented as (E2′) in Fig. 3.

Event 5: Progress of fire and firefighting operation - 8:25 a.m. - 9:40 a.m. During event 5, the firefighting operation was in progress on the 10th and 11th floors, which was continued for more than an hour, and the fire was growing at the 10th, 11th and upper floors.

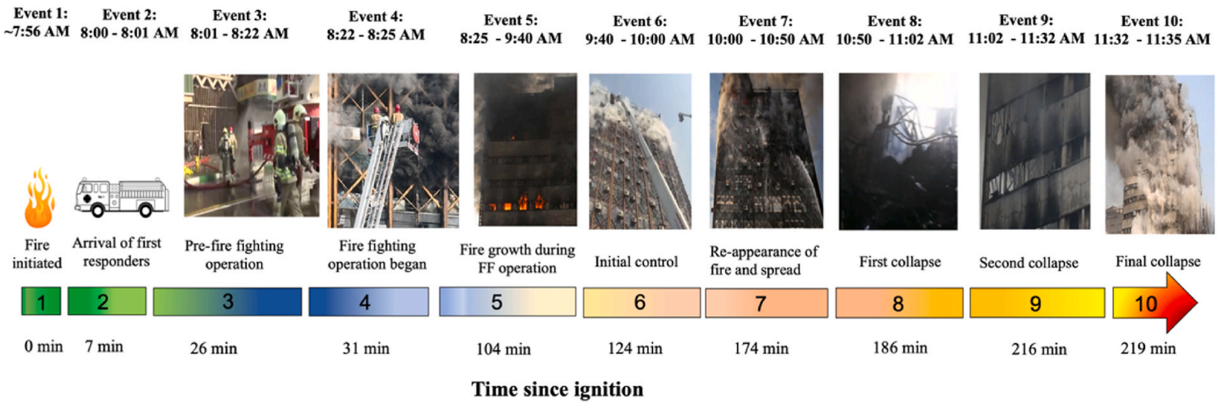

Fig. 4. Timeline of the critical events.

Event 6: Initial control -9:40 a.m. – 10:00 a.m. Around 9:40 a.m., it appeared that the firefighting operation was successful (Fig. 3 [W-3, and S-1]) [6,56]. Due to the presence of high moisture content in the smoke (white smoke), it was assumed that the fire had been extinguished. It is worth noting that the firefighting operation was never performed on the 12th to upper floors, and the elevator monitors were effective to the flames across the perimeter only.

Event 7: Re-appearance of fire -10:00AM – 10:50 a.m. From outside the building, it was assumed that the fire was extinguished. However, in such scenarios where the fire was spreading for more than 2 h, it is not unusual that the fire re-ignited due to its presence at different parts of the building or never extinguished on upper floors. The firefighters tried to suppress the re-ignition of the flames on the 10th and 11th floors before they advanced towards the 12th floor. During this period, the fire could be seen to travel at the western and the eastern side of the building (Fig. 3 [N-5, N-6, E−2, E3, and E4]) at the 12th and upper floors.

Event 8: First collapse -10:50a.m – 11:02 a.m. While the firefighters were seeking to proceed towards the 12th floor, the first collapse occurred between 10:50 a.m. to 10:54 a.m. A significant portion of the 11th floor had fallen over the 10th floor at the north side of the building (Sections 4.2 and 4.3).

An uncontrollable spread of the fire on the 15th floor was observed (Fig. 3 [S-2]), and the fire reached the south side of the building during this event (Event 8 in Fig. 4).

Event 9: Second collapse -11:02AM – 11:32 a.m. Due to prolonged heating for more than 3 h (around 186 min since ignition) at the north side of the building, the floors lost their capacity to withstand existing loads, and almost all the floors below the 13th floor at the north side failed and collapsed around 11:02 a.m. (Fig. 3 [N-9, W-5, W-6, and W-7], and Section 4.2). The fire was travelling in both directions (south-west and south-east). It converged at the south-east corner (Fig. 3 [E−5, E−6, and E−7]), where intense heat was generated. The front portion of the north face was completely burnt out which completely exposed the north side (Fig. 3 [W-6]). This event is associated with the second collapse and represented in the timeline as such. After the second collapse, the fire appeared inside the building on lower floors due to the collapse of the upper floors.

Event 10: Final Collapse -11:33AM – 11:35 a.m. By this time (around 216 min since ignition), the fire became more intense, and the heat was generating at a tremendous rate at the south-eastern corner of the building (Fig. 3 [E−7 and S-6]). While reconstructing the thermal environment of WTC 1, 2, and 7, Gann et al. [57] observed HRR of 1 GW at the corner in CFD simulation.

It appeared that the upper floors started to fall instantly on the lower floors due to prolonged heating and progressive collapse of the entire structure started (Fig. 3 [W-8 to W-10, S7 to S-10, and E−8 to E−10] and Section 4.3). It is observed in visual evidence that this progressive collapse was triggered due to the increased slenderness of steel columns because of the removal of lateral support that was provided by the floor slab. Due to the very high slenderness of columns and extreme reduction in the material properties, the peripheral structural frame could not sustain any load. It started to collapse, and within a moment, all south side seemed to be pulled in as a result of buckling of extremely high slender peripheral columns, and in a flash of moments whole structure of the Plasco Building crumbled to the ground [6,58]. The observed collapse mechanism needs verification by conducting a structural analysis of the building.

4. Source of information

As discussed in Section 2.2, considerable information is required for the reconstruction of the fire and forensic assessment of structural failure. Using the FITB framework, it is possible to determine the fire history from the available resources for the Plasco Building, such as images, videos, reports, testimonies from the firefighters and witnesses, published papers [6,56,59–61], and generate a coherent timeline. The information gathered from various resources is discussed in subsequent subsections.

4.1. Photographs

Images and videos were collected from various sources such as official reports, news articles, *google* images, and so on [62–65]. Images can tell a story about the fire spread that can be interpreted based on the principles of fire dynamics. The fire was observed on many floors at all sides of the Plasco Building. As discussed in Section 2.2, firstly, all gathered images were organised according to the building elevation direction (A detailed description of the fire spread in each direction is explained in supplement 3). Images of the particular direction are re-arranged according to the spread of the fire to determine the fire trajectory. In this section, the most probable fire spread in all building elevation directions is discussed individually by interpreting the information obtained from all sets of visual evidence.

4.2. Firefighters interview and testimonies

A series of interviews, conducted by the new agencies and from a documentary, *Panjshanbeh Suri* (Thursday Fireworks) that was screened in December 2017 [66], explained some aspects of the collapse of the Plasco Building that need to be discussed. Significant information can be gathered from such resources, which is very crucial to understand the fire spread and consequent collapse of the Plasco Building. The interviews of the firemen who were inside the building during the fire incident are gathered and presented here. Firefighters can provide the most valuable and critical information such as fuel load and its distribution, the travel path of the fire, failures of structural components, removal of walls (de-compartmentation) and ceilings, actual ventilation condition and other relevant information that is critical to understand the fire behaviour.

To produce a precise and coherent timeline, it is critical to document the *"testimonies"* of the firefighters inside the building while the building was engulfed in the fire. In the current paper, most of the excerpts from the interviews are taken from the documentary and interviews published in reports. The original interviews are in Persian, which is translated into English and illustrated here. Some of the relevant information is gathered from these resources are discussed in subsequent paragraphs.

Fire Department started to receive calls around 7:56–7:58 a.m. about the fire in the Plasco Building. Fire department confirmed this information; according to them they had started to receive calls around 4–5 min to 8 a.m. According to the testimonies of some callers, the flames were already coming out of the windows of the 10th floor of the building. Even the nearest fire office was very close to the Plasco Building (around 350 m) [6]. By the time when firefighters were approaching the building, a large amount of black sooty smoke was visible from a distance. It was the first indication of the great extent of the fire. As per firefighters' interviews, when they had arrived at the building around 8:02 a.m., the fire was quite large and could be seen from reaching the upper floors through the windows as illustrated in Fig. 3(N-1 and N-2). A security personnel tried to extinguish the fire using the fire-extinguisher when the fire broke out at the inventory of a shop near the north-west corner. Unfortunately, the fire-extinguisher was empty, and it caused some delay to inform the fire department and provided more time for the fire to spread. The non-functional standpipe system in the building exacerbated the situation, and the fire was growing intensively during this time interval. It took approximately 3–4 min for the first responder to arrive at the building since the fire was reported. These initial decisions during a fire incident are quite crucial to control a fire in the early stages. In the case of the Plasco Building, the delay in informing the fire department and the non-functional manual firefighting system made the fire uncontrollable in the early stages of the fire.

Initially, the Plasco Building was designed as a commercial centre, although later it consisted of retails shops, clothing workshops, restaurants, and inventories for textile materials. When firefighters reached the 10th floor, the fire was already present in the false ceilings. All the shops seemed identical in terms of fuel arrangement (boxes filled with fabrics or clothes). Moreover, a lot of materials were stored in the stairways as well [62], as shown in Fig. 5.

Fig. 5a shows a typical shop in the Plasco Building. It is worth noting that the cotton/nylon or textile material can burn quite intensively and ignite at much lower temperatures that can make fire intense in a very short interval of time [67]. Firefighters

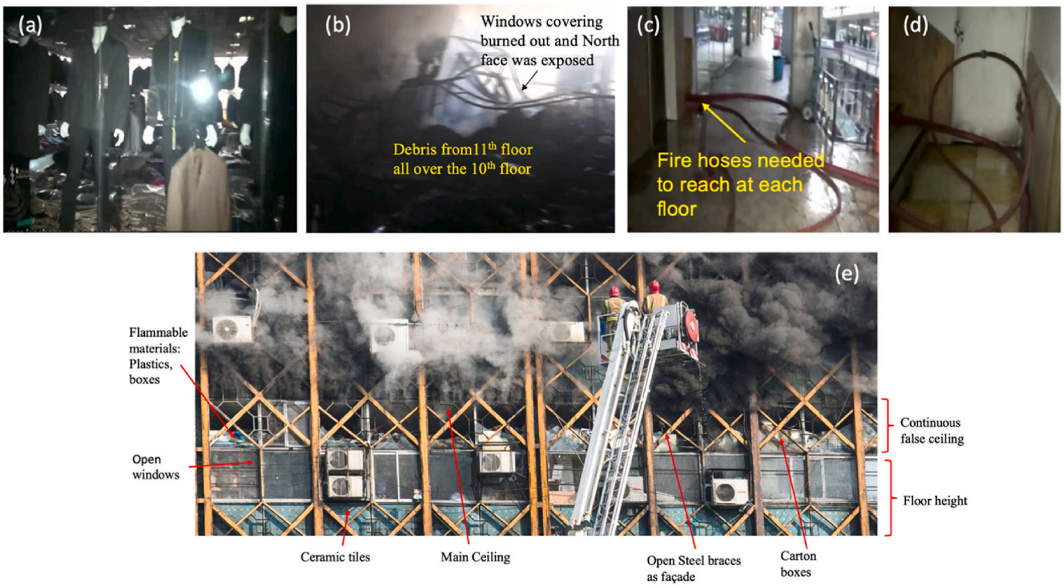

Fig. 5. (a) Typical front part of shops, (b) North side of the 10th floor with debris, and (c) and (d) access to stairways, and (e) Façade and open false ceiling on the north and south face of the building [66].

confirmed that because of the textile as a burning material, smoke was quite dense, and when they wanted to go deeper back to the shops to suppress the fire, there were boxes full of clothes at the backside of almost every shop and reaching to the false ceilings and had a very narrow walkway which was around 1 to 1.5 only. This kind of fuel arrangement made the fire grow rapidly and spread vertically and horizontally in a very short interval of time. Due to the continuous false ceilings and the height of the fuel, the fire rapidly spread horizontally all over the floor plates (Fig. 3[N-3, N-6, W-1, and W-2]).

There are some other factors that affect the fire intensity. For example, there was a considerable delay in starting the manual firefighting operation inside the building. The building architecture and fire location were also responsible for exacerbating the situation. As the fire was initiated at the north side of the building, however, the entrance for firefighters was located at the south side of the building, and there was only one stairway to go up, which was located near the western elevation of the building (Fig. 2). The design of the stairway was not continuous, i.e., on each floor, it was required to walk to reach to the stairway that goes up to the next floor, as shown in Fig. 5c and d (typical design for the stairways in shopping malls). Therefore, multiple hoses were required to be connected. It also increased the travel time of the firefighters to reach the 10th floor. These factors promote the delay of starting a firefighting operation, where the fire was intensifying at each passing moment. Since the arrival of the emergency responders, it took 22–25 min to begin the firefighting operation on the 10th floor. Eventually, when firefighters arrived on the 10th floor, the fire had already become considerably large.

From the initial efforts of the firefighters, the fire was already controlled on the 10th and the 11th floors, and white smoke appeared from all the sides, it was believed that the fire had been extinguished, however fire was present inside the building at upper floors which was reappeared at later fire stages.

When the firefighters were attempting to go to the 12th floor, the first collapse occurred. As per firefighters' testimonies the first collapse *occurred around 10:*54 a.m. *or 10:*55 a.m. In the first collapse, almost 2/3 of the north side of the 11th floor slab (along the width from the north-west corner to north-east) fell on the 10th floor. Fig. 5b shows an image of the interior of the 10th floor after the first collapse, where the collapse debris of the 11th floor can be seen over the 10th floor. At this moment, the north face was completely exposed as façade wall panels had deformed, and ceramic tiles had already fallen off (Figs. 5e and 3 [N-10]). After around 12 min of the first collapse, the second collapse occurred at the north side of the building (Fig. 3[N-9]), when all the floor slabs below the 13th floor on the north side collapsed and fell. During this time interval, at the north side of the building, there was just a steel frame without any lateral support (Figs. 5b and 3[N-10]). Firefighters confirmed that in that second collapse that occurred around 11:02 a.m. almost all floors of the north-side had fallen and whoever was on the way, was already buried. This collapse made almost complete disconnection between the north and the south part of the building. After around 31 min of the second collapse, the final collapse of the building had occurred.

5. Analysis

The methodology described in this paper (Section 2) provides insights for conducting a comprehensive forensic fire investigation and an approach to reconstruct the fire history for any structure that has undergone a fire. For forensic assessment of structural failure, it is essential to determine the fire spread in a building and setting up a conclusive fire timeline.

The most critical factors that lead to a structural collapse in a fire are fire intensity and duration of the fire, which are primarily dependent on the fuel load and the fuel type [68–70]. In section 4, significant information is accumulated from the available data that can describe the critical events involved during the collapse of the Plasco Building. It is apparent from the available images and interviews that due to local flashover and flaring of the fire from windows on the external wall, the horizontal fire spread through the corridors and false ceilings, and the vertical fire spread through the open stairway and vertical shafts of elevator and utilities, the *travelling fire* behaviour was observed. In the recent fire incidents such as the Grenfell Tower, façade played a vital role in vertical spread [7].

In the case of Plasco Building, the façade was composed of open steel braces (Fig. 2 and Section 3), masonry wall and glass windows, so that the facade and the external wall did not contribute to the vertical spread, but the fire flared out from the windows and could spread to upper floors. As discussed in earlier sections, the fuel distribution pattern accelerated the fire spread both horizontally and vertically through the false ceilings, and windows (and shaft), respectively.

To perform comprehensive fire investigation of the Plasco Building, it is crucial to set up a coherent timeline of the critical events during the fire and reconstruct the fire spread history. Subsequent sections discuss the fuel load and critical events that occurred in the Plasco Building.

5.1. Fire load

Fire load is defined as the total quantity of heat released per unit floor area upon complete combustion in a compartment [71] [measured in MJ/m^2]. Fuel load is one of the key parameters to quantify the production of heat during a fire in a compartment. Fuel load also determines the duration of fire [70,71]. The fire load (or fuel load) for a particular occupancy generally lies within a certain range as per codes and standards [28,72]. Nature of the combustible and fuel distribution pattern (piles or stacked) defines the ease of ignition, which in turn dictates the growth rate of the fire [13,14]. Therefore, it is vital to identify the material composition of the fuels stored in a compartment as well as wall and ceiling linings.

In the Plasco Building, most walls and partitions were from mineral and masonry nature. Most linings were also from materials like gypsum plaster, and only in some shops, medium density fibreboards (MDF) were applied on the walls as lining. Therefore, the primary fuel load was the fabrics and clothes, and it can be said that everywhere was filled with piles of these materials without any attention to fire safety management in the building. In some shops, small LNG cylinders were being used for cooking purpose. Bakhtiyari and Jamali [73] tested a sample of typical fabrics taken from some shops in the Plasco Building (five-storey mall shops) with Cone

Calorimeter for an estimation of the fire load in the building (see Table S1 and Fig. S4 in the Supplementary Information). There were more than 580 shops and mercantile units in the Plasco Building, most of them were allocated to production or sale of clothing and related works. This high content of the fabrics and clothing created a high fuel load in the building.

Fig. 5a and e illustrate the condition of typical shops in terms of fuel load. A lot of plastic, carton boxes, and other flammable material can be seen in Fig. 5e The windows were open and made up of thin wire mesh that might provide enough ventilation for the fire to grow and intensify during the whole duration of the fuel burning. Due to the availability of a sufficient amount of oxygen, the fire might never be controlled by ventilation, and it remained in a fuel controlled regime [49,74]. Air conditioning units were also attached near the windows, which were also burnt down, and ceramic tiles also fell off from the building during the fire (Fig. 3[N-10]). In Fig. 5e, it can be seen that the false ceiling was also filled with combustibles. It can be deduced that fire spread rapidly in a horizontal direction because of the open plan and combustible contents in the false ceilings. From the view of the false ceiling in Fig. 5e, it is also evident that the false ceilings were also open to the surroundings, and the fire might have entered inside the false ceiling during the early stages of the fire through windows. The factors such as high fuel load, favourable fuel distribution and ventilation conditions, design of the false ceilings, and open combustible façade, all together made the fire spread rapidly in both horizontal and vertical directions [75].

5.2. *Observed fire spread*

The horizontal and vertical spread of the fire from its origin and all the key events that were discussed in Section 3.1 are represented graphically in Fig. S3 (as suggested in the step 6 in FITB) by arranging the visual evidence (Fig. 3: *FireEvolutionMap* of the collapse of the Plasco Building). Fig. S3 shows the plans and elevations (not to scale) of each floor where the fire broke out and all the floors above it. Elevations from all directions are presented, and fire locations observed from the specific image (*known* fire locations) are illustrated. The *known* fire location observed from the visual evidence is presented as *'yellow flame sign'*.

This exercise is conducted to understand the overall fire spread behaviour and can be used to calibrate the CFD model. Fig. 6 shows the fire spread history of the 13th floor (plan view only). For the description of fire spread history for all floors, refer to supplement material (Section 2 in supplement material).

In Fig. 6b, the available visual data ("*yellow flame*") shows the fire presence only at the western side, and Fig. 6d does not indicate any flames as it was considered that the fire had been suppressed. However, during Event 7 (Fig. 6e), flames appeared along the perimeter, which shows that the fire was not completely suppressed, and it was present at the inner portion of the building. A similar phenomenon was observed for other directions as well. Therefore, it is clear from Fig. 6 that there are some gaps that need to be filled to represent the most possible fire spread. Using the information from interviews and documentary, principles of fire dynamics, knowledge from previous experimental data, and observed fire behaviour in previous fire accidents, these gaps would be filled in the next section.

5.3. *Estimated fire spread*

It is clear from the "*known location*" in Fig. 6 and S3, for a comprehensive investigation, data from the visual evidence of the Plasco Building is quite limited. However, based on the understanding of the fire behaviour, fuel load, fuel distribution, and previous and latest locations of fire, a trajectory of the fire spread inside the building can be easily traced. From "observed" data in Fig. 6 and S3 (Yellow flame), it was noticed that the flames reappeared on the same floor at different locations. The re-appearance of the flames helps to predict the probable direction and the flow pattern of the fire. Fig. 6 shows the most probable estimated trajectory of the fire on the

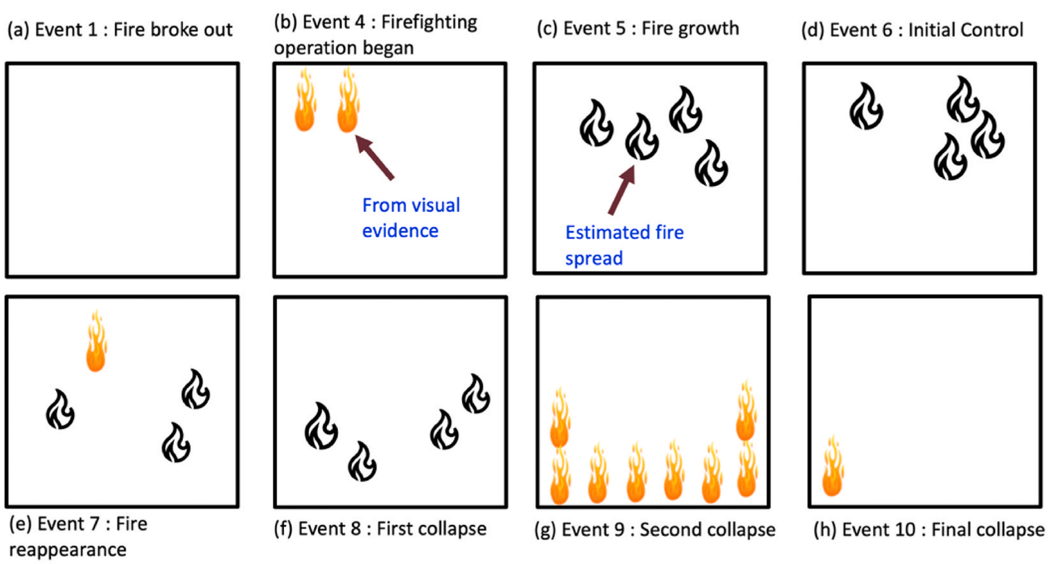

Fig. 6. Observed and estimated fire spread history of 13th floor.

13th floor (Supplement material shows the fire spread history for all fire floors). The most probable *missing* data to complete the fire travelling path to represent the fire spread is shown in *'grey flame sign'* under a box (the most probable regions where the fire might present). During event 1 (E1) and event 2 (E2′), fire spread is the same as fire was spreading vertically or near the north-eastern corner of the building. The fire was visible around the perimeter after Event 6. Thus, the fire must be present somewhere inside the building, both as flaming and smouldering ones, which soon became visible around the perimeter of each floor (Fig. 6e, g, and h). The fire might have been present inside the building throughout the entire duration of burning, though it did not appear from outside for a short period of time.

During Event 9, a tremendous amount of flames can be seen on the 13th floor at the south side of the building (Fig. 6g), but almost no fire or a small number of flames were visible in the previous events since E2'. Based on the fire intensity (due to fuel load) and fire location at Event 9, fire trajectory is approximated that can be rationally justified based on the valid principles of fire dynamics discussed in Section 2, such as pyrolysis, burning of the hot gases in the high ventilated region, adherence of the flames to the exterior of the building and so on. Furthermore, the information gathered in Section 4, such as the fire presence of the false ceilings, initial control of the fire, etc., can facilitate filling the gaps. By applying a similar principle travelling path of the fire on each floor can be illustrated. Now, the full fire spread history is determined, which further can be qualitatively verified from the CFD modelling.

Once the fire trajectory and the fuel load are known, local fire scenarios can be established for the distinct locations in the entire building such as flashover in a compartment or over an entire floor. After establishing the appropriate global fire scenario for the entire building by combining the local fire scenarios at the different parts of the building, structural response analysis can be performed. Finally, a conclusive fire reconstruction of the structural failure of the Plasco Building can be achieved with the calibration of the estimated fire history with the calibrated CFD model.

5.4. Preliminary study

In cases of structural failures, it is also necessary to quantify the correct thermal load to which the structural response is closely linked. The definite location and duration of the fire are two of the most crucial parameters that define the actual thermal gradients within the compartment. The fire models prescribed in current fire codes to analyse the structural performance are limited to certain floor area, and the available analytical fire model cannot be applied to obtain a realistic structural response [76].

The present study provides crucial information about the collapse of the Plasco Building that can be used to perform structural analysis and understand the collapse mechanism. Previous studies of the collapse of the Plasco Building did not consider the realistic fire load [60,61]. Ahmadi et al. [6] provided information of the sequence of the critical events and structural details but no description of fire behaviour and structural response were discussed. Aghakouchak et al. [58] investigated the local and global behaviour of this structure during three stages of partial and global collapse, assuming some specific temperature scenarios in different parts of the building. Behnam [60] used the parametric curve to perform the structural analysis, however, these curves do not represent the real fire and consider uniform fire load throughout the compartment [77]. It is clear from the above analysis in the previous sections that the fire spread was not uniform, and the fire was observed at different locations during each key event. In other studies, Hajiloo et al. [59] and Yarlagadda et al. [61] used the fixed temperature of structural components (800 °C for beams and 400 °C for columns), which is not accurate to represent large fire scenarios because the temperature was not uniform during the whole fire duration.

Due to travelling fire behaviour, for a significant portion of the Plasco Building, it is required to perform a CFD fire modelling. An open-source CFD package developed by NIST -fire dynamics simulator (FDS)- is used to carry out the current fire simulation. The CFD analysis requires detailed input parameters from the information collected in this paper to calibrate the model, such as fuel load, fuel type, fire travel trajectory, and geometrical conditions (open windows, continuous false ceilings, and so on). The calibration process has to ensure realistic thermal boundary conditions for structural analysis. Using the thermal load from the CFD and/or other appropriate idealised models, a realistic fire behaviour of the Plasco Building can be simulated.

5.4.1. Calibrated CFD model

Based on the data obtained in previous sections and estimating the fire spread history, CFD models can be calibrated to further verify the fire spread (Step 7 of FITB). A detailed explanation for the calibrated CFD fire simulations (such as fire simulations for all floors, grid size, mesh sensitivity) based on the current investigation study is presented by Khan et al. [78]. Their study provided a numerical analysis that demonstrated how fire can propagate vertically through an open facade and horizontally (due to the de-compartmentation).

5.4.1.1. Vertical fire spread. Firstly, to verify the vertical fire spread, the northwest corner of the Plasco Building from the 10th to 15th floors was simulated as shown in Fig. 7. The vertical fire spread can be verified with the visual evidence of the Plasco Building (Fig. 7c). This simulation represents the vertical fire spread and calibrates the entrance of the fire to the upper floors. As shown in Fig. 7, once the fire broke out on the 10th floor, it reached the upper floors in the early stages of the fire (confirmed by witnesses' testimonies). Due to the sufficient quantity of air, the fire increases rapidly and releases an extensive amount of heat, making it easier to reach upper floors.

Fig. 7b obtained from the FDS simulation clearly shows that the fire reached upper floors within 30 min since the ignition, as observed in the fire accident. In later stages, the fire was observed spreading horizontally from a similar location (the north-western corner of the building), agreeing with the visual evidence and testimonies. Fig. 7d shows the temperature contour plots and presents the rise in temperature of upper floors. The fire spread on different floors and ignition at different time intervals presents various fire scenarios for the building fires (Step 8 of the FITB). Currently, there is no fire modelling method (other than CFD, which also required simplifications to simulate the fire spread), that can accurately represent the vertical fire spread.

5.4.1.2. Horizontal fire spread. Based on the estimated fire progression history (presented in the previous sub-section and Fig. 6), a CFD model is generated that represents the fire spread on the 13th floor. The top view of the CFD domain of a typical floor is shown in

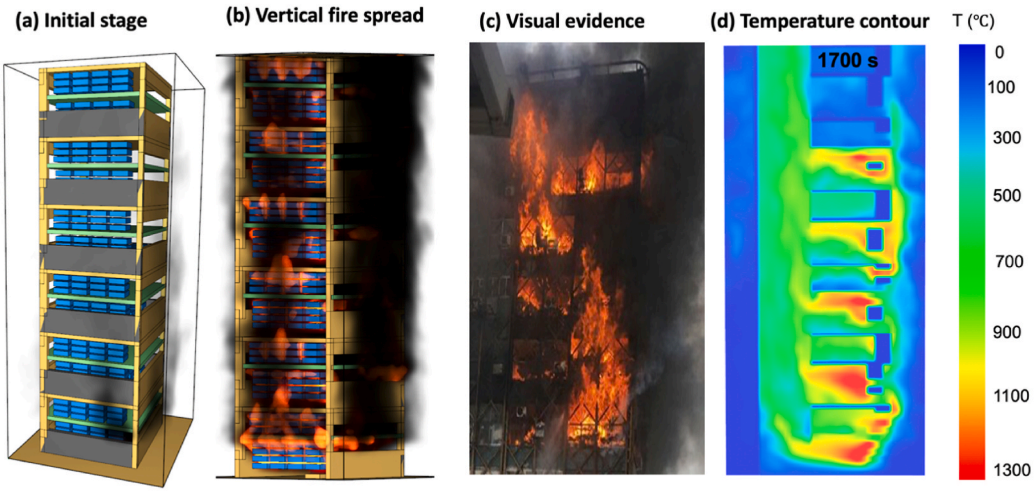

Fig. 7. (a) CFD model of the north-western corner of the Plasco Building (b) Vertical fire spread at 1800 s (c) Visual evidence when the fire reached upper floors (d) Temperature contour plot at 1700s.

Fig. 8a. The room is filled with fuel (nylon is used as fuel for CFD analysis) in a similar manner as generally found in garment shops. Based on the data obtained, such as fuel load, ventilation conditions, and so on. CFD models are calibrated for each floor (calibrated CFD models for all floors can be found in Ref. [78]). Fig. 8a also shows the horizontal fire spread of the fire on the 13th floor. According to firefighters' testimonies, the false ceiling was open to the atmosphere, and fire entered the false ceiling during the early stages of the fire.

In the fire simulation, the fire did not reach the adjacent compartment until the false ceiling was not removed, as shown in Fig. 8a (fire at 850s). The false ceiling failure is controlled by the obstruction removal techniques in FDS. The timing for false ceiling removal is approximated (calibrated) based on the fire spread observed in Fig. 3 and testimonies. The calibrated CFD models represent a reasonable empirical fire spread history that can be further refined based on the requirement of accuracy. Fig. 8b shows the temperature contour plots which represent the travelling behaviour of the fire on the 13th floor.

5.4.2. Heat transfer analysis

It is clear from the CFD results that the temperature distribution for the whole structure is not uniform, where some part of the structure is colder (south-east region in Fig. 8b (fire at 600s and 1800s), and north-west region in the later stages of the fire) and providing restraint to the hotter part of the structure. This kind of non-uniform heating of the structure may result in a complex structural response [79]. Owing to the non-uniform heating within a structural member, thermal gradients get induced in structural elements. The classical curves such as standard fire curves, Eurocode fire models [28] cannot be applied, which are incapable to produce the said effects. Fig. 8b represent the travelling nature of the fire where the fire travelled in all direction. Therefore, the thermal data for the building must be obtained from the calibrated CFD models (Step 9 of FITB: "Allocation of fire models"). The data obtained from the CFD can be transferred to any finite element model to perform the structural analysis and understand the structural response. The authors developed two open-source packages – OpenFIRE – to carry out the structural response analysis in a finite element tool using CFD simulation results [80,81]. One of them does not require any license and is free to download and use [80], and another one requires a licence to present the results using a graphical user interface [81]. The authors explain the methodology to obtain the thermal data from the CFD for carrying out the heat transfer and structural analysis in FEM [80]. The thermal data to carry out the heat transfer analysis can be in the form of gas temperatures, heat fluxes, or adiabatic surface temperatures [76,82].

To capture thermal gradients in all structural components such as slabs, trusses, columns on each floor, many 'AST (Adiabatic Surface Temperature) measuring devices' are installed in the CFD simulations [83]. OpenSees (an open-source FEM tool) is used to carry out heat transfer and thermomechanical analysis [84,85]. To perform a heat-transfer analysis in OpenSees, the material property of carbon steel (for trusses and columns) and concrete (slabs) are taken from Eurocode 3 [10]. The convective heat transfer coefficient of 25 W/m^2K according to the Eurocodes [28] is assumed for fire-exposed surfaces. An emissivity of 0.7 and 0.85 is used according to the Eurocodes for concrete and steel, respectively.

Fig. 8c shows the temperatures obtained at the structural components after the heat transfer analysis in OpenSees for the 13th floor fire at two locations: (a) temperature history near the north-west corner (where the fire first broke out), and (b) temperature history near the south-east corner of the building (where the fire was present just before the final collapse). Once the fire started, the temperature rises rapidly on the north side due to the direct impingement of the flames. While at the south-eastern part of the building, where fire reaches during later stages, initially, the temperatures increase mainly due to hot smoke, which is the reason that the temperature at southeast was much lower during the first 4,000s. The peak temperature on the south-eastern side is observed after 2 h of the fire, while at the north-western corner, the peak temperature was reached within the first hour of the fire. The heat transfer in the concrete slab of 120 mm deep is presented in Fig. 8c. Fig. 8c shows the temperatures on the exposed and unexposed surface to the fire

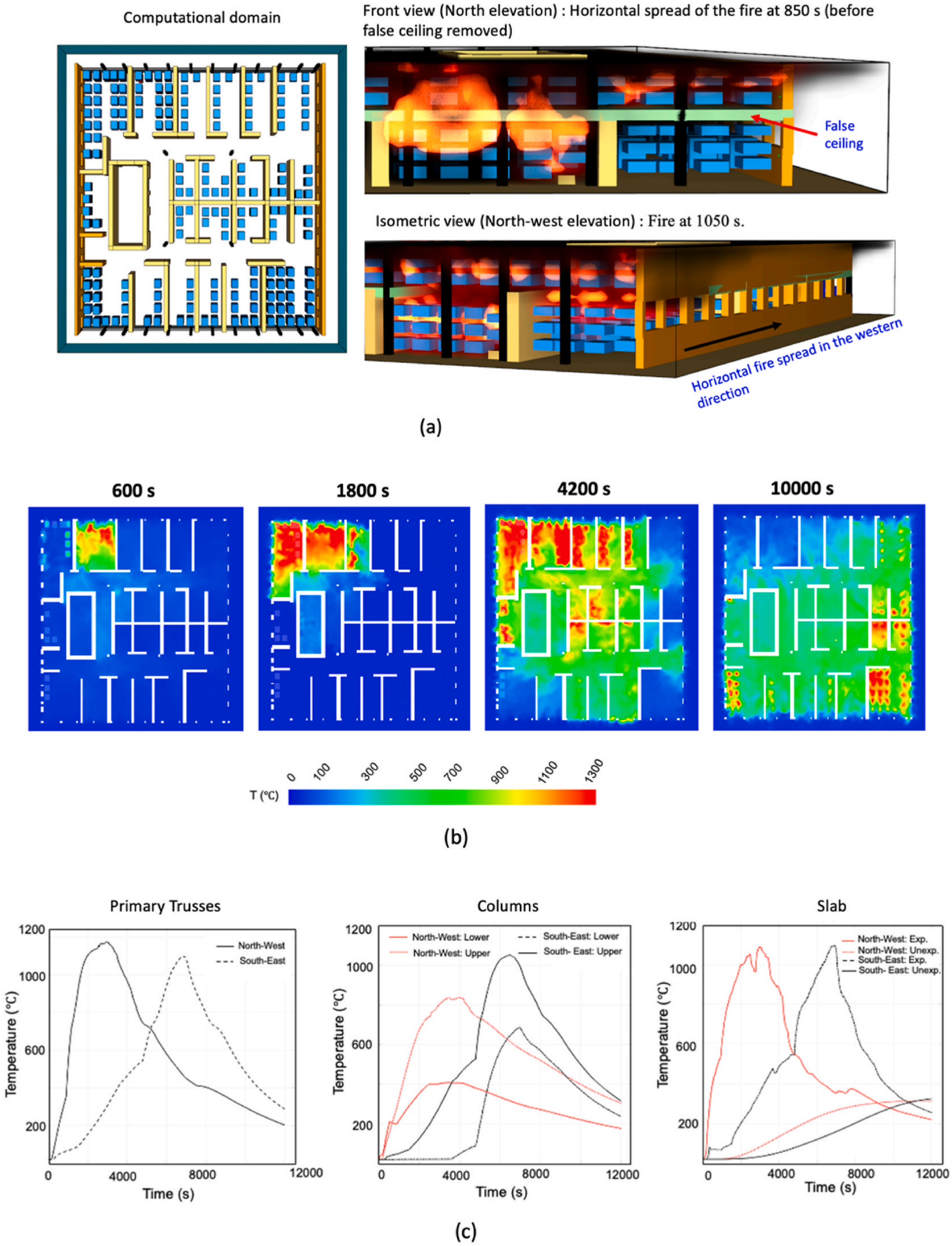

Fig. 8. (a) Computational domain and Horizontal spread of the fire (b) Calibrated CFD model of the 13th floor of the Plasco Building, and (c) Temperatures after heat transfer analysis in FEM.

near the northwest and southeast corners. Due to the lower thermal conductivity of the concrete, the temperature on the unexposed surface starts rising during later stages of the fire. Due to slower conduction heat transfer in concrete, the temperatures on the unexposed surface kept increasing even in the decay stages of the fire. Fig. 8b and c clearly represent the travelling behaviour of fire, which cannot be represented by the traditional approaches such as parametric study or standard fires.

5.4.3. Thermomechanical analysis

Once heat transfer analysis is finished, the temperature output from OpenSees is obtained as loading conditions for structural analysis (Step 10 of FITB). The middleware (OpenFIRE) maps the respected temperature history from the heat transfer analysis to each element of the structural model (beam-column elements are used for truss and columns, and shell elements are used for slabs). The temperature history is applied as a thermal load in the thermo-mechanical model to simulate the nonlinear structural response to fire. In the preliminary analysis, the connections between the roof trusses and the concrete floors are considered rigid in nature. A detailed information including mesh size, type of elements (beam-column, shell, truss elements) for conducting thermomechanical analysis and structural model can be found on [86]. However, in reality, the connection may not be rigid due to the age of the building (more than 50 years old building). The bond between the steel and the concrete would be somewhere between fully rigid to fully detached. In further study, various bonding conditions will be analysed to calibrate the structural behaviour with the structural failure observed in the visual evidence. In the current study, the strength degradation of the steel has been factored by considering the elastic modulus of the steel as a function of temperature, as suggested in Eurocode 3 [10].

Fig. 9a shows the vertical deflections obtained in the slab of 13th floor at different times during the fire. Results show the sagging of the floor area which is exposed to fire. For example, the slab at the north-western corner of the floor experienced a sag when it was exposed to fire while an increase in the vertical deflection has been observed at the opposite corner when fire travelled towards western and eastern directions, as shown in Fig. 9a. Preliminary results are presented in Fig. 9b which shows that due to high temperatures in trusses around the column at the south-east of the floor, the column is pulled in by the sagging trusses, that may cause the failure of this column and trigger the collapse of the entire building (as observed in visual evidence). From Fig. 9, it is clear that a complex thermo-mechanical behaviour under realistic fires is obtained by coupling CFD analysis with FE simulations. To understand the response of complex tall buildings such as the Plasco Building, it is suggested to perform a detailed structural analysis by incorporating complexities such as multiple floor fires and connections. Using the data obtained from this study (realistic boundary condition – thermal data – obtained from calibrated CFD models), a detailed structural analysis will be performed in the future study. The realistic thermal data allows understanding the reasons for the total collapse of the Plasco Building through developing a reasonably comprehensive 3D finite element model of the building. In a further study, the progressive collapse of the building will be simulated with respect to the travelling fire phenomenon as represented by the heat transfer and thermomechanical results presented for 13th floor in this study.

It is clear from this study that with the temperatures obtained from calibrated CFD models and the detailed forensic analysis, a credible structural response to real fire scenarios can be simulated. In the further study, a 3D nonlinear analysis will be performed to

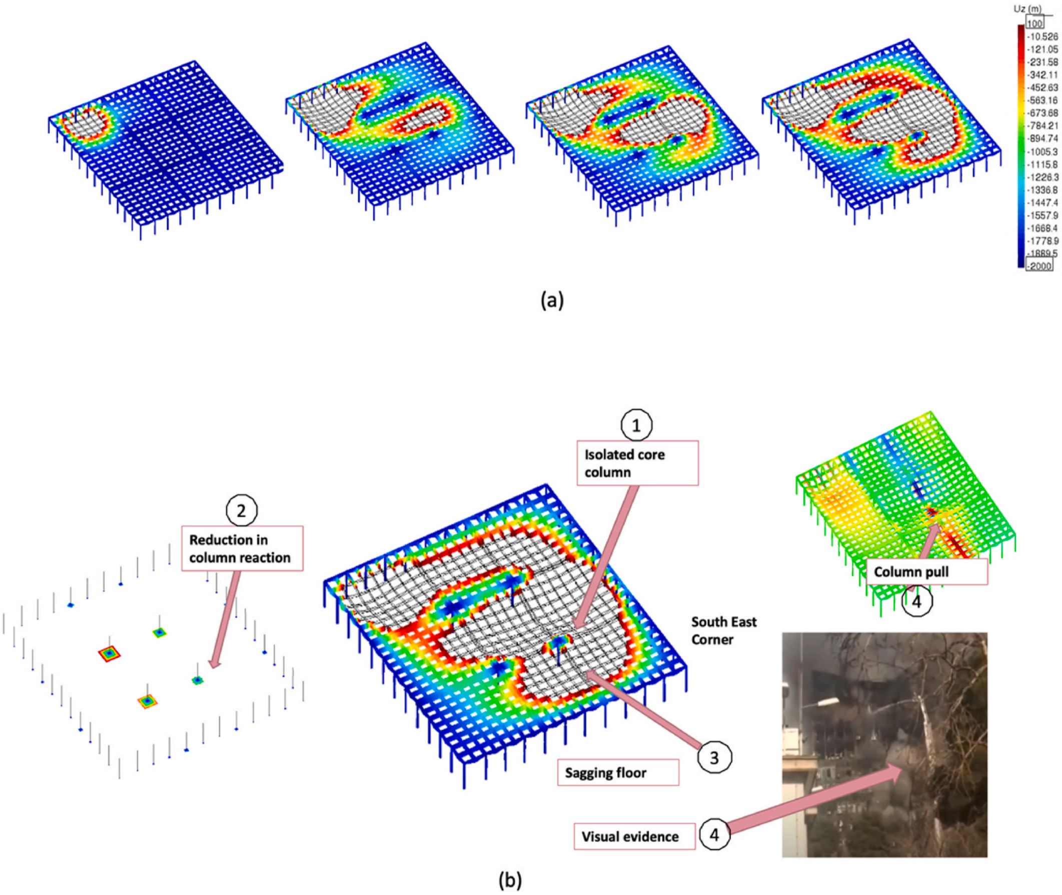

Fig. 9. (a) Thermo-mechanical behaviour of slab in a realistic "travelling fire" (13th floor), and (b) Preliminary results: Triggering of the collapse of the Plasco Building.

understand the local and global collapse of the Plasco Building during the fire. This whole process put forward a well-structured methodology to carry out a detailed forensic investigation of the failure of tall buildings in fires from collecting evidence to detailed structural response analysis. Such detailed studies for building fires are helpful for improving life safety and building safety designs and reducing the risk related to fire accidents.

6. Conclusions

Well-defined methodologies are present for engineers and investigators to investigate accidents such as plane crashes. Such precision is also warranted to investigate the structural collapse or failure due to a fire accident as it may result in a higher number of casualties and huge economic loss. Generally, the conventional methods for fire investigation do not include structural failure or collapse while reconstructing the fire. A simple yet robust fire investigation tool (FITB) is proposed in the present paper that provides a methodology to perform fire investigation of a structure so that improved fire safety design for tall buildings can be achieved and such incidents can be avoided in future. A conclusive and coherent timeline representing critical events during a fire accident can be created using the available images, videos, testimonies, interviews etc.

By calibrating the CFD model, the realistic temporal and spatial resolution of temperatures can be obtained and used to analyse the structural failures. Using the proposed methodology, the fire in the Plasco Building is reconstructed, and a conclusive fire event timeline is created. Events related to the flames and structural damages observed from the visual evidence are presented graphically for each floor of the Plasco Building. The spread of fire is verified with the firefighters' interviews and testimonies. The fire spread behaviour on each floor and across floors is estimated based on the basic understanding of fire dynamics and experimentally observed phenomenon. The estimated fire spread will further be verified using the CFD model. The temperature output from CFD fire model provides a realistic thermal boundary condition to study the collapse mechanism of the Plasco Building. A preliminary study for the collapse behaviour of the Plasco Building is presented using the empirical thermal data obtained from calibrated CFD models. A detailed independent study will be performed for structural analysis by adding more complexities in FE models.

The current framework for forensic fire investigation can provide comprehensive details of a fire incident, including the growth pattern of the fire, fire behaviour, fire load, fuel distribution, fire detection, the performance of fire protection systems, and information about how firefighting operation was carried out. To handle such massive data, this methodology will further be improved by employing artificial-intelligence methods that can automatically arrange the data systematically and produce the most probable fire spread in the building. This whole process allows understanding the response of complex tall buildings to a realistic fire, such as the Plasco Building where complexities are increased due to multiple floor fires, connections, and travelling fire behaviour. The methodology presented in this paper can be helpful to structural fire safety engineers to improve the building fire-safety and life-safety designs.

Authorship contribution statement

Aatif Ali Khan: Conceptualization, Methodology, Software, Data collection, Analysis, Validation, Writing - original draft, Visualization.

Mustesin Ali Khan: Methodology, Software, Writing-review & editing, Visualization.

Ramakanth Veera Venkata Domada: Software, Writing-review & editing, Visualization.

Asif Usmani: Supervision, Conceptualization, Methodology, Writing-review & editing, Project administration, Funding acquisition.

Xinyan Huang: Supervision, Methodology, Writing-review & editing, Analysis.

Saeed Bakhtiyari: Data collection, Methodology.

Masoud Jamali Ashtiani: Data collection, Methodology.

Sadegh Garivani: Data collection, Methodology.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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