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Modeling the Collapse of the Plasco Building Part I: Reconstruction of Fire

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ABSTRACT

In recent years, fires in tall buildings have become more frequent, which costs billions of dollars each year and the loss of many human lives. The façade fire in the Grenfell tower made the structure uninhabitable, and the collapse of the three World Trade Center (WTC) towers is the total structural failure caused by fire. Despite such events, no well-defined methodology exists to reconstruct both fire and structural behaviors and carry out the forensic investigation of a building fire. This Part-I paper collects the evidence of the Plasco Building fire and generates a coherent timeline to reconstruct the fire processes. The vertical and horizontal fire spread of the building is reconstructed using Computational Fluid Dynamics (CFD) fire modeling and calibrated against the evidence library. The spatial-temporal temperature history from the fire modeling provides realistic fire scenarios to simulate the structural response. The fire simulation results are used as boundary conditions to be transferred to a finite element analysis tool for a detailed structural analysis to determine the likely collapse mechanism of the Plasco Building in Part-II. The methodology presented in this paper to reconstruct the fire can also guide the *structural fire safety engineers* to improve the building fire-safety and life-safety strategies.

Keywords: *building fire safety; high-rise buildings; fire investigation; fire modeling; structure failure*

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1. Introduction

Fires in tall buildings have become more frequent in the last few decades (White *et al.* 2013; Ahrens 2016; Bonner and Rein 2018). According to a survey carried out by National Fire Protection Association (NFPA), it was found that the U.S. fire department responds to almost 40 tall building fires every day (Ahrens 2016). Building structures may sustain severe damages or even collapse during a fire accident. The three towers of WTC (2001) in New York, the Plasco Building (2017) in Tehran, the Grenfell Tower (2017) in London are few examples where fire led to the collapse or severe damage of the entire structure. **Fig. 1** shows some of the major fire accidents of tall buildings that occurred in the past. Fire safety of tall buildings is a major challenge especially evacuating the occupants before the building environment becomes untenable. While investigating the plane crashes, the airline industry may even scour the ocean floor to find the black box and examine the condition of nuts and bolts (Bibel 2008; Porter 2020); structural and fire engineers must carry out the forensic investigation of major structural failures in the same rigorous and meticulous manner. Such detailed investigations can lead 'structural fire safety engineering' to improved structural fire safety and life safety designs.

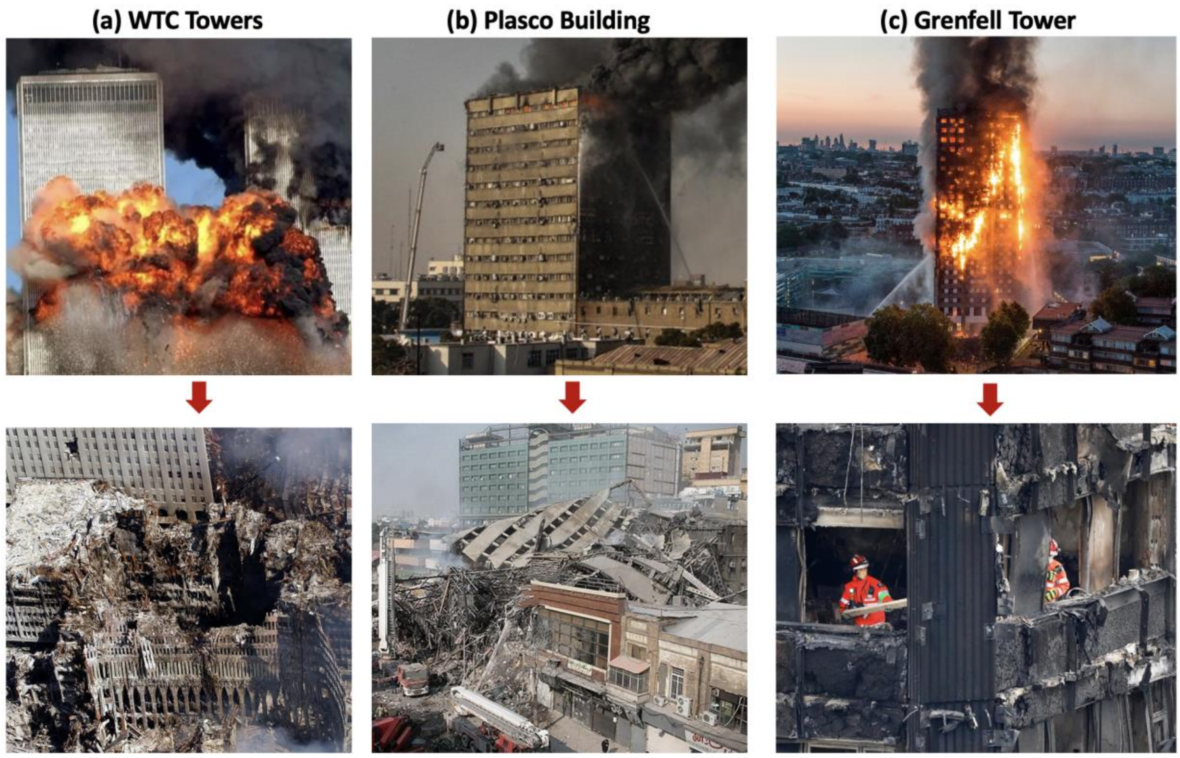

Fig. 1. Tall building fires (a) WTC towers in 2001 during the fire (credit: Getty) and collapse debris of WTC 1, 5 and 6 (credit: Mate Eric J. Tilford), (b) the Plasco Building under fire and the collapse of the Plasco Building (credit: Amin Khosroshahi), (c) the Grenfell Tower fire in 2017 and the structure after the fire (credit: Getty).

Traditional fire investigations are generally associated with discovering the '*cause and origin'* of the fire (DeHaan and Icove 2012; NFPA 921: Guide for Fire and Explosion Investigations 2017), which explains how to collect evidence and organize it for use in the legal process. These methodologies do not include assessment of structural failure or collapse of the building. Nevertheless, after the tragic event of the WTC towers, National Institute of Standards and Technology (NIST) conducted a detailed forensic study for the collapse of WTC Towers 1, 2, and 7 (NIST 2005, 2008). However, these methodologies were ad-hoc and were improvised during the investigation (Torero 2011). It is essential to reconstruct the fire based on observed empirical fire scenarios to develop a rational hypothesis for the fire accident. Current methodologies cannot provide sufficient information about the spread of fire and its impact on the structure to reconstruct the fire history for a comprehensive fire investigation of tall buildings. The Grenfell Tower (Schulz *et al.* 2020) is still under investigation, and so far, no detailed analysis has been performed to reconstruct the fire in that building (Bisby 2018; Torero 2018).

The well-documented methodologies for fire investigation in textbooks (DeHaan and Icove 2012) and NFPA 921 (NFPA 921: Guide for Fire and Explosion Investigations 2017) provide scientific procedures that mainly focus on fire growth and its effects on the materials stored within the fire compartment. Torero (2011) recommended a technique to determine the fire history and the structural response of a building that has undergone fire. His method focuses on fire growth, effectiveness and assessment of fire protection systems, egress analysis for human safety, and structure analysis to determine the de-compartmentation and failure of fireproofing.

A robust forensic fire investigation of an accident may require a great deal of information, such as identifying the cause, fuel load and its distribution, fire patterns from its growth to decay, de-compartmentation, the performance of fire protection systems, location, and source of fire ignition. It is practically impossible to have all information, especially when all fuels have burnt out. However, considerable information can be gathered from the visual evidence, witnesses, firefighter's interviews who were present at the scene during the fire, initial reports. Such information for the Plasco Building accident is collected to reconstruct the fire.

The available literature on the collapse of the Plasco Building does not provide detailed information on the fire spread history that can be used to reconstruct the fire to carry out detailed structure analysis (Yarlagadda *et al.* 2018; Behnam 2019). In a recent study, assuming specific temperatures at different locations of the building, Aghakouchak *et al.* (2021) investigated the local and global collapses of the Plasco Building. An article from Ahmadi *et al.* (2020) provides some information about the sequence of the critical events and structural details; however, no description of the fire and structural response were discussed. To perform structural analysis of the building, Behnam (2019) used the parametric curve, but these curves do not represent the real fire scenarios in modern buildings where floor plans can be larger than prescribed in the codes (Bisby *et al.* 2013; Khan, Usmani, *et al.* 2021). Assuming fixed temperatures over the entire building (800℃ for beams and 400℃ for columns), Hajiloo *et al.* (2017) and Yarlagadda *et al.* (2018) conducted structural analysis, which is not accurate to represent large fire scenarios as the temperatures were not uniform during the whole fire duration. The fire phenomena in tall buildings are quite different, such as the traveling nature of fire may be observed due to the large open floor plan, stack effect, vertical spread, and so on, which idealized fire curves cannot represent. Therefore, it is imperative to reconstruct the fire and carry out a rational investigation of the structural response and damage.

So far, there is no specific methodology available to reconstruct the fire development of a fire accident in tall buildings, and there have been no dedicated efforts paid to analyze the failure of the Plasco Building based on realistic fire temperatures. The prime objective of this study is to reconstruct the fire development in the Plasco Building based on the evidence collected from various resources and by numerical fire modeling using computational fluid dynamics (CFD). The necessary information of the Plasco Building, such as building architecture, ventilation condition, fire timeline – organized by collecting visual evidence, reports, and testimonies (Part I), as illustrated in **Fig. 2**. Then, heat transfer analysis is performed using a heat transfer tool in a finite element model (FEM) – OpenSEES – using the temperature data from the calibrated fire model. The data obtained from the CFD simulations in this paper will be transposed as structural boundary conditions for a detailed structural analysis of the Plasco Building (Part II).

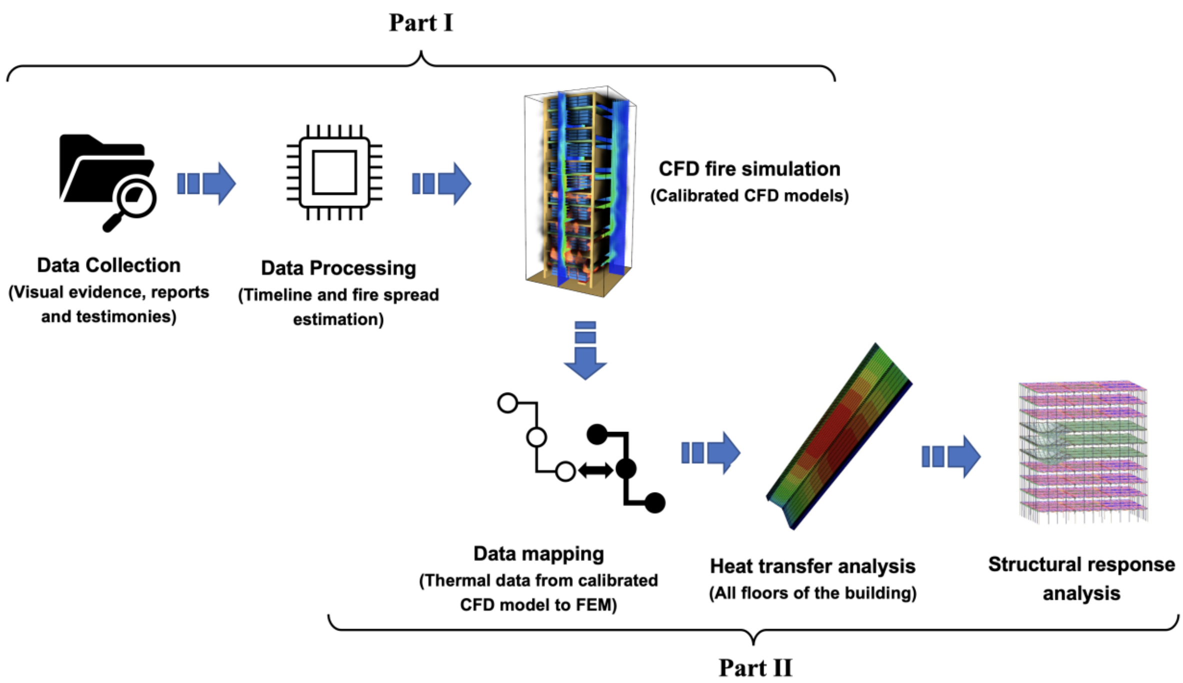

Fig. 2. Flow diagram of the detailed building simulation for the forensic investigation of a structure fire and the scope of this work.

As discussed, previous studies (Yarlagadda *et al.* 2018; Behnam 2019; Aghakouchak *et al.* 2021) that represent the structural collapse mechanism did not consider the real fire scenarios. With the temperatures obtained from calibrated models and the detailed forensic analysis, a reasonable structural response to real fire scenarios can be simulated. The Part II of this work will perform the 3D nonlinear analysis to understand the local and global collapse of the Plasco Building during the fire.

This whole process will 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 structural response.

2. Fire accident of the Plasco Building

2.1. Overview of the accident

The Plasco Building was the tallest building in Tehran when it was constructed in 1962. There was no fire safety strategy for the building such as evacuation plan, although it followed design codes of that period. No fire protection coating was provided to any structural components or the verticals shaft containing the staircase (TFSD 2017; Ahmadi *et al.* 2020; Aghakouchak *et al.* 2021). The Plasco Building consisted of two parts, a five-story shopping mall on the north side and a 16-story tower on the south side of the building. The building's eastern and western sides were cemented, and the northern and southern sides of the building were covered with steel braces as façade and ceramic tiles (Ahmadi *et al.* 2020). A fire broke out on 19 January 2017 at the north-western corner of the 10th floor of the 16-story Plasco Building, which led to the collapse of the building. Due to the rapid vertical fire spread, the fire reached the upper floors in the early stages of the fire. In the building, there was no automatic sprinkler system installed (which was not a mandatory requirement at the time of construction), and the standpipe was not operational. **Fig. 3(a)** shows north and south parts of building.

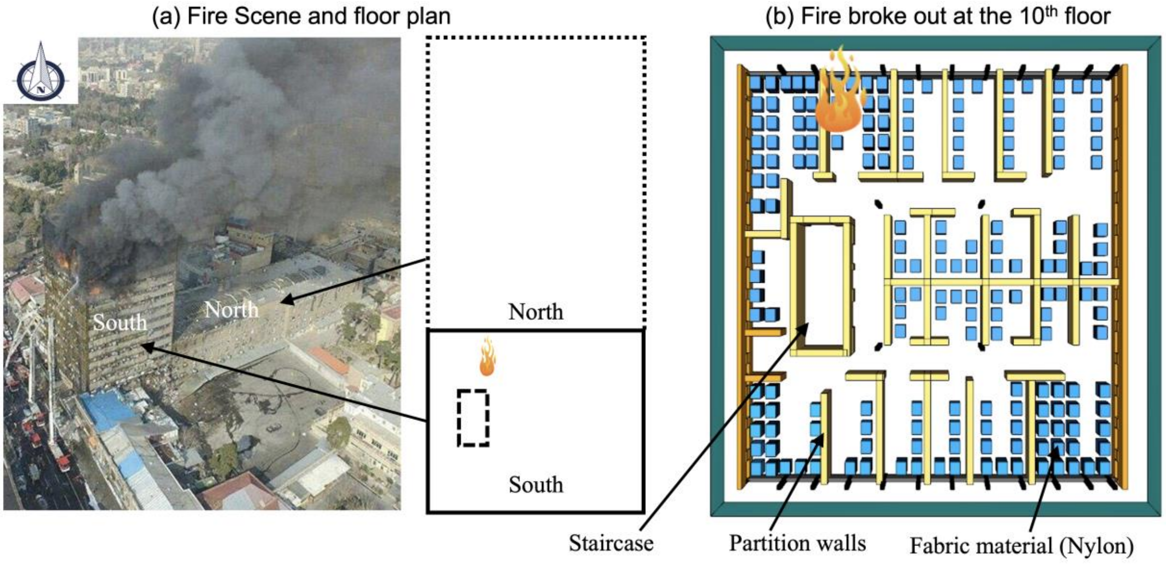

Fig. 3. Detail of the Plasco Building and computational domain ($34\times36\times4$ m^3) of a typical floor plan.

2.2. Forensic evidence of the accident

The principal activity after a fire accident is the collection of evidence to determine the cause and origin of the fire and develop a rational hypothesis. In terms of investigating the structural failure due to fire, unfortunately, there is no well-documented methodology present either in codes and standards or in any textbooks, as discussed earlier. For a detailed forensic analysis of a structural failure in a fire and to develop a rational failure hypothesis, reconstruction of a fire should be based on the realistic fire spread history. By collecting sufficient evidence, an estimated fire spread history and a fire timeline can be generated to reconstruct the fire. The timeline is generated based on the data collected from various resources such as detailed reports from Tehran Fire Safety Department (TFSD), published articles, interviews of firefighters, documentary, and so on. It allows to estimate an approximate time interval between two critical events as presented in the timeline and Fig.4 (Ferdowsizadeh 2017; TFSD 2017; Ahmadi *et al.* 2020). The following sections explain how the fire that led to the collapse of the Plasco Building is reconstructed.

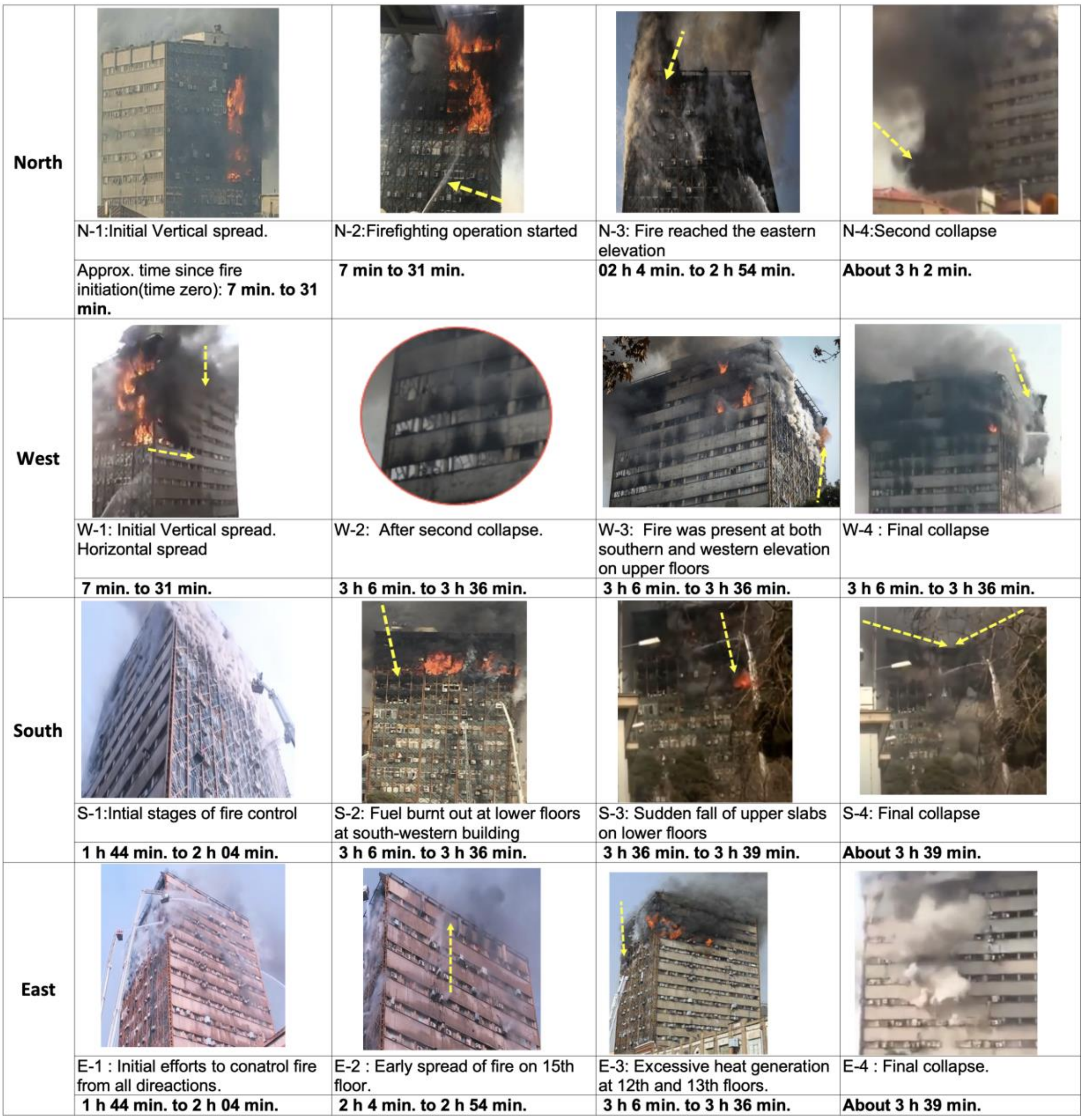

Fig. 4. A concise version of *FireEvolutionMap* of the Plasco Building fire accident.

2.2.1. Fire Evolution Map

The visual evidence – images and frames from the available video footage – are arranged chronologically based on the fire progression and observable consequences such as visible flame, smoke signatures on the walls, and initial collapses. Each row shows the progressive spread of fire in a particular direction. This arrangement of the visual evidence is termed as '*FireEvolutionMap,*' representing the spread of fire progression in time on each face. A concise version of the *FireEvolutionMap* of the Plasco Building is shown in **Fig. 4**, representing the spread of fire in all directions on each floor. *FireEvolutionMap* helps to determine the fire spread in each direction and developing a coherent timeline. By utilizing *FireEvolutionMap* in each direction, the fire spread on each floor is estimated that can be used to build and calibrate the CFD models of the Plasco Building. A detailed version of the *FireEvolutionMap* is included in the **Supplementary Material**.

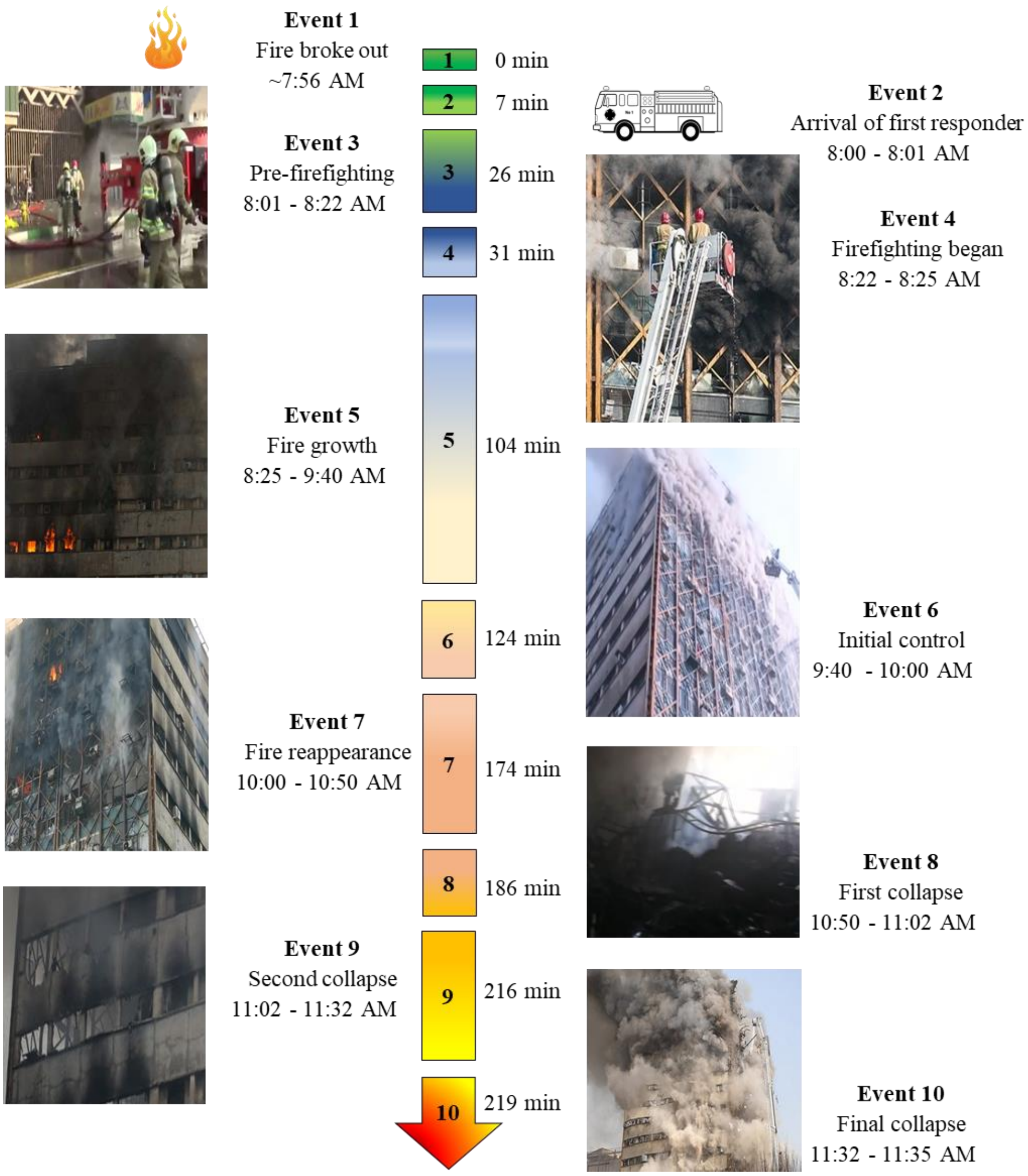

Fig. 5. Timeline of the critical events in the fire and collapse of Plasco Building.

2.2.2. Timeline of the fire accident

While carrying out a forensic investigation to determine an accident's fire history, a coherent fire timeline is the most crucial part of understanding the fire spread and failure or collapse of a structure due to the fire. The sufficient visual evidence, testimonies, and available initial reports can implicitly provide the details of the fire growth, the travel path of the fire, cause of augmentation or decay of the fire, effectiveness of firefighting operation. Based on evidence that is depicted in *FireEvolutionMap*, interviews, and a documentary (Ferdowsizadeh 2017), an estimated timeline for the collapse of the Plasco Building is set up. A timeline of critical events from fire initiation to the final collapse of the Plasco Building is illustrated in **Fig. 5**. An approximate time interval is allocated between two key events based on the available data. Each image in *FireEvolutionMap* would represent an instance between two critical events (approximate time allocation in **Fig. 5**). The timeline is further refined with the firefighters' interviews who were present at the scene during the accident. The critical events such as the arrival of the emergency responder to the first, second, and third (final) collapse are also included in the timeline. As the timeline defines the time interval between two events, it helps in generating rational CFD models while arranging the fuel over the floor and providing the control devices to remove (or deactivate) the false ceilings or windows.

3. Calibration of the Plasco Building fire

Over the last few decades, the capabilities of the CFD fire modeling have been used extensively, particularly for modeling smoke movement in the fire-safety performance-based design (PBD). However, even the most advanced fire models in use today use simplifications of gas-phase combustion reactions and typically do not explicitly include pyrolysis and phase-change processes of solid fuels. Most fire simulations are also highly sensitive to specific parameters, and the modeling results can significantly deviate from the realistic fire events (Rein *et al.* 2009). The user must have sufficient knowledge and understanding of the limitations and uncertainties involved in the CFD fire modeling and obtain as much information as possible about the fire-spread phenomena within the building to reconstruct a realistic fire scenario. To obtain an accurate simulation for the fire of the Plasco fire accident, Fire Dynamics Simulator (FDS) 6.7 (McGrattan *et al.* 2016) – developed by NIST - is used in this study.

The FDS (McGrattan *et al.* 2016) is the most widely used CFD fire modeling software globally for fire engineering design and fire safety research. FDS implements the Large Eddy Simulation (LES) turbulent model to solve the airflow and smoke transport in the fire. The LES model resolves the energy and momentum of large eddies, while ignores eddies smaller than the mesh size. Therefore, no grid independency test is performed in LES, but the analysis's sensitivity to the mesh size is evaluated. A few methods are suggested to estimate the reasonable cell size for the practical problem of the fire plumes. The mesh resolution can be evaluated by determining the characteristic plume length scale (D^*), which depends on the heat release rate (HRR) (Ma and Quintiere 2003; Merci and Beji 2016). In the current study, the cell size was chosen that represents a reasonable fire spread at a lower computational cost. For a more accurate fire spread for any fire accident, a finer mesh may be required. After carefully performing a few numerical tests in this study, the cell size of 0.2 m is used in all fire simulations. **Fig. 3(b)** illustrates the typical floor plan as a computational domain (34×36×4 m^3) used for the CFD fire modeling.

In the Plasco Building, the floor plan of the floors above the 6th floor was typically designed for multiple shops of garment where a high volume of fabric material was stored on the premises. Thus, the fuel type was similar from the floor of fire origin to the upper floors. Therefore, nylon is chosen as a representative combustible (fuel) in the CFD fire modeling, and material properties were assigned according to Society of Fire Protection Engineering (SFPE) Handbook (SFPE 2016). The ignition temperature of the fuel surface (230 °C in the case of nylon) was set for its ignition to simulate the fire spread. To simulate the fire spread, the 'surface ignition method' is utilized. It is a valid approximation to model fire spread in a building, especially when the ignition of the fuel in the adjacent compartments needs to be simulated. Several researchers used this method to represent the traveling-fire experiments (Dai *et al.* 2020) as well. FDS includes few other methods to simulate the fire spread. One is the 'prescribed spread rate model,' where flame spread is controlled by prescribed spread rate, although it is computationally inexpensive; however, in the current case (fire spread in the Plasco Building where compartments are separated by walls) this method is not feasible. In another method, the 'in-depth pyrolysis model,' solid degradation is calculated using the Arrhenius equation. Due to the complex chemistry and heterogeneity of real fuels in fires, this method is very difficult to apply, and it is computationally more expensive than the other two (Merci and Beji 2016). Therefore, in terms of the computational cost, accuracy, and possible fire scenarios in the Plasco Building, the 'surface ignition method' is the most appropriate method for the current study.

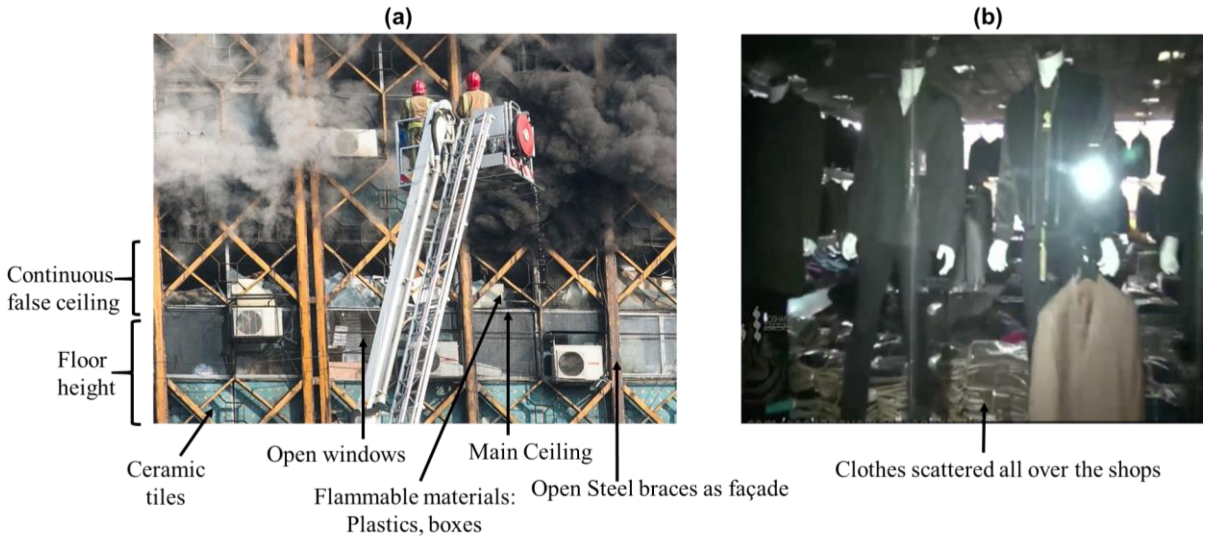

Fig. 6. (a) Detail of the front view of a floor and false ceiling, (b) typical shop in the Plasco Building.

3.1. Effects of fuel distribution on fire spread

Generally, the codes and standards recommend fire load as the major criteria to estimate the fire risk for an occupancy, which is usually defined in statistical terms (EN-1992-1-1 2011; NFPA 2020).

Though the Plasco Building was constructed as a commercial center, the quantity of fuel kept changing throughout the building's life span. The specific fuel load of the building before the fire is unclear, but it is known that whole floors were filled with fabrics (**Fig. 6**). It is necessary to learn how fire can travel vertically and horizontally, as the fire spread is affected by the fuel distribution. For a qualitative understanding of the effects of fuel distribution on fire spread, two cases of the same fuel load density are considered, i.e., Case 1: Fuel is stacked over each other and has air gaps (rack type storage), and Case 2: Fuel is stored in large carton boxes.

3.1.1. Modeling fire spread to the adjacent compartment

Fig. 7 shows the geometry used in the CFD simulation to verify the spread of fire to adjacent rooms for both fuel distribution cases. For Case 1 (**Fig. 7b**), the fire reaches the ceilings and almost all fuel in the compartment is burning without spreading in the next compartment. After removing the false ceiling in the simulation (**Fig. 7c**), the fire reaches the adjacent compartment, and the top surface of the fuel is ignited. Having continuous false ceilings (no separation between the compartment over the false ceiling) as shown in **Fig. 7a** is quite common even in modern buildings. The Plasco Building also had a continuous and open false ceiling (**Fig. 6a**)(Ferdowsizadeh 2017). On the other hand, the flame height for Case 2 (**Fig. 7d**) is not large enough to reach the adjacent room, even after the removal of the false ceiling; it might be mainly due to lower HRR (Pchelintsev *et al.* 1997) because the air gaps increase the HRR (SFPE 2016), and comparatively lower height of the fuel. These simulations represent that the failure of the false ceilings would accelerate the fire propagation, and the height of fuel may play a critical role in determining the ignition of the fuel in the adjacent room.

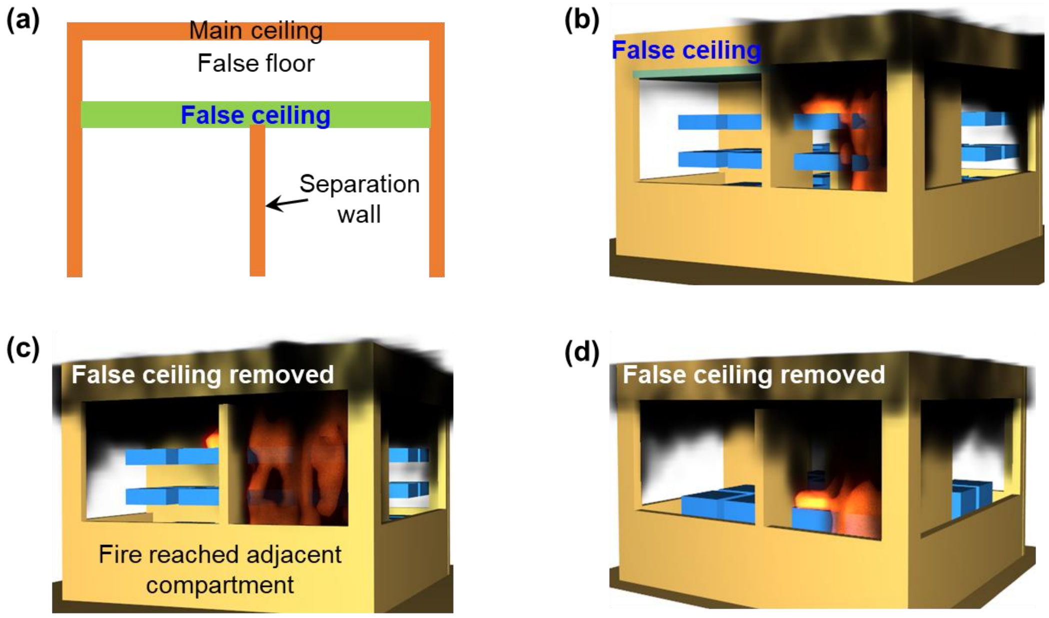

Fig. 7. The modeled fire spread in an adjacent compartment, where Case 1: Fuel is stacked over each other and has air gaps (rack type storage), and Case 2: Fuel is stored in large carton boxes. (a) an example of the open false ceiling between two compartments (b) fire in the compartment before false ceiling removed (c) fire reached adjacent compartment (d) fire in a compartment for Case 2 fuel distribution.

3.1.2. Vertical fire spread

For analyzing the vertical spread of fire qualitatively, a two-floor building (one room at each floor) is simulated for both fuel distribution cases. Each room of 7 × 7m^2 floor area and 3m high was generated in FDS, as shown in **Fig. 8**. For Case 1, it can be seen in **Fig. 8a** that once the fire starts, it grew, and flames can be seen coming out through windows and reaching the upper floor. However, for Case 2, the fire did not reach the upper floor (**Fig. 8b**). This is attributed to the fact that the flames are not high enough to reach the ceiling or enter through openings. According to Hasemi's fire model for localized fire, flame height depends on HRR and the diameter of the fire (Hasemi *et al.* 1996). As discussed, the HRR would be lower for densely packed fuel (SFPE 2016).

From the above CFD simulations, it can be deduced that the fuel distribution greatly influences the rate of fire spread both in horizontal and vertical fire spread. According to the testimonies of firefighters, in the Plasco Building, the fuel was stored near the windows and reached the height of the false ceiling (Ferdowsizadeh 2017). It may be one of the main reasons for the rapid growth of the fire and the vertical spread.

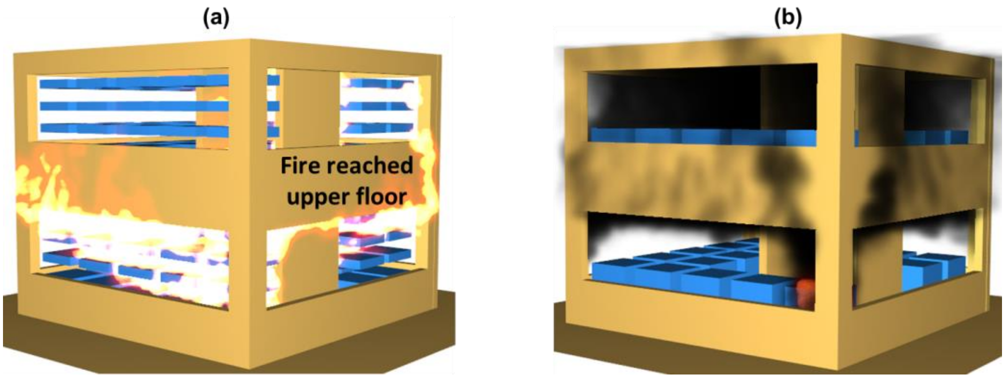

Fig. 8. Demonstration of vertical fire spread (a) For Case 1, fire reached upper floors) (b) For Case 2, fire remained at lower floors

3.2. Vertical fire spread in the Plasco Building

In the Plasco Building, windows were present all around the perimeter of the building, which provides enough fresh air to come in to support the continuous burning. These favorable conditions led to the collapse of the Plasco Building in three hours (Ahmadi *et al*. 2020). In the case of the WTC 7 (NIST 2008), it took seven hours after the fire broke out. As each building is unique, the collapse mechanism of both buildings cannot be compared due to difference in thier size, fire spread behavior, fire protection ratings and so on. To understand the collapse mechanism of each building, an independent study with comprehensive forensic investigation must be carried out. To further verify the fire spread through openings to the upper floors in the Plasco Building, a CFD simulation was performed. The northwest corner of the Plasco Building from the 10th to 15th floors was simulated. This vertical fire spread can be verified with the photographic evidence of the Plasco Building (**Fig. 9**). This simulation represents the vertical fire spread and calibrates the entrance of the fire to upper floors.

An FDS model for the 10th to 15th floors at the north-western corner is shown in **Fig. 9a**. A burner is placed near the corner of the 10th floor (lowest floor in the FDS model) of the building to initiate the fire (burner was stopped after 60 s). As the fuel (fabrics) was present at the end of each shop until the false ceiling height (2.1m), and the fire was observed in the false ceiling as well (**Fig. 6a**). Therefore, in the fire model, fuel is placed up to the height of the false ceilings and in the false ceiling. Clothes were stacked either in racks or large boxes. Therefore, some gaps are provided between pile of clothes.

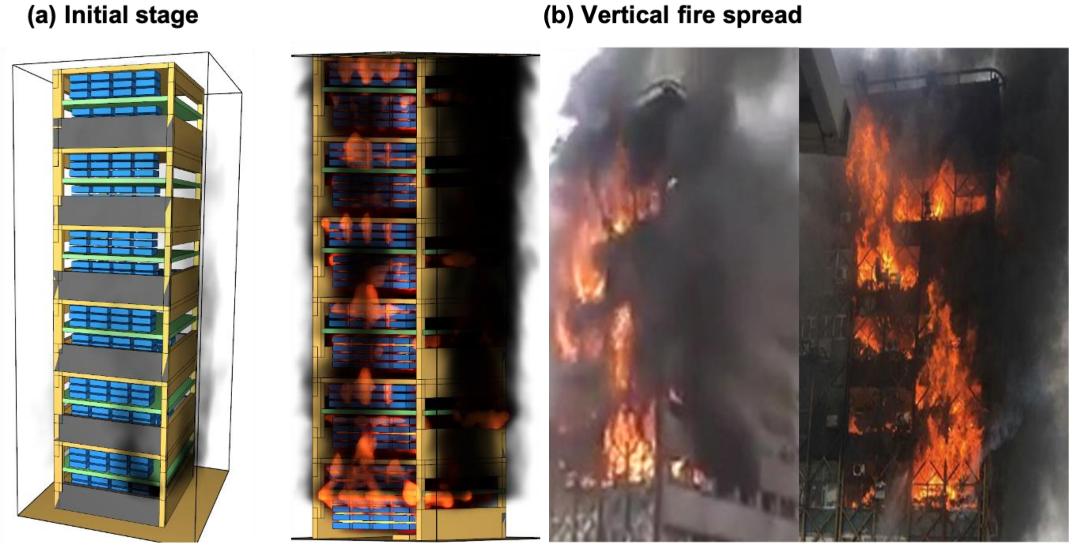

Fig. 9. Fire simulation (at 1,900 s) and images from fire accident for vertical fire spread, (a) initial stage, where walls of north and south sides were still present, and (b) vertical upward fire spread.

As shown in **Fig. 9**, once the fire broke out on the 10th floor, it reached the upper floors in the early stages of the fire. The fuel on the upper floors and adjacent compartments ignited as soon as the temperature of the surface reached its ignition temperature. 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. The false ceiling was open to the air and the windows' covering were made of simple wire mesh on the north side and south side of the building (**Fig. 6a**). In **Figs. 9b**, in FDS simulation, fire can be seen reaching upper floors as observed in the fire accident. Within 30 minutes, the fire had already reached the top floor before the firefighting operation began (Ferdowsizadeh 2017; Ahmadi *et al.* 2020). The façade behind the steel bracing had completely disappeared at some of the floors, and ceramic tiles attached to the façade had fallen off, so these were removed from the simulations from each floor progressively using the obstruction removal technique in FDS. Control devices' (controlling to remove or deactivate an obstruction in fire simulation) timing is set up based on the visual evidence and repetitive simulations to calibrate the vertical fire spread. This simulation represents that fire had reached the upper floors during the early stages of the fire and began spreading horizontally from a similar location (north-western corner of the building), agreeing with the visual evidence and testimonies. The combination of the visual evidence and fire simulation (**Fig. 9**) provides two important pieces of information, i.e., (1) the fire reached the upper floors during the early stages of the fire (before any firefighting operation began), and (2) the fire initiation location was similar at each floor. It justifies simulating fire only for few floors to calibrate the model and obtain realistic thermal data for all floors.

Fig. 10 shows the velocity vectors of the hot gases and incoming air. As shown in **Figs. 9** and **10,** due to the openings at the north side of the building, fire reached the top floor. The large openings (sufficient ventilation) allowed to draw a high volume of fresh air to enter continuously inside the building and kept the fire in the fuel-controlled regime (Torero, Majdalani, Cecilia, *et al.* 2014). The higher velocity of incoming and outgoing gases makes the rapid replacement of the hot gases with the fresh air inside the compartment; eventually, a faster burning rate of the fuel is observed (SFPE 2016).

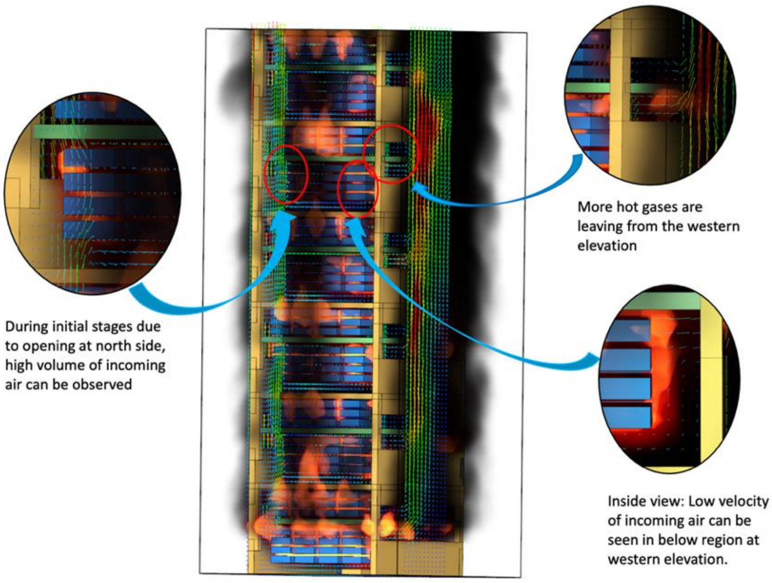

Fig. 10. Fire at upper floors

In the Plasco Building, according to the witnesses, the fire could be seen coming outside the windows and reach the upper floors in the early stages of the fire (Ferdowsizadeh 2017). Some of the witnesses stated that the flames could be seen near the stairway due to the vertical shaft, which was in the proximity of shops (**Fig. 3**). It creates a few hypotheses, such as whether the fire reached upper floors through shaft or openings or a combination of both. In the FDS simulation, the temperature and velocity of hot gases are recorded to observe this phenomenon.

Fig. 11 shows the temperature and velocity contour plots at the center of the compartment. Flames can be seen going upward from the vertical opening (vertical shaft containing the staircase). Though high-temperature gases can be observed inside the vertical opening, it could not ignite fuel on upper floors. The vertical fire spread is mainly from to the windows (or openings), as shown from the rise of temperature near the windows' openings of each floor (**Figs. 11a**). In the vertical shaft, the high velocity of gases is also observed from the simulation (**Fig. 11b**). Due to the buoyancy stack effect, hot gases travel upward.

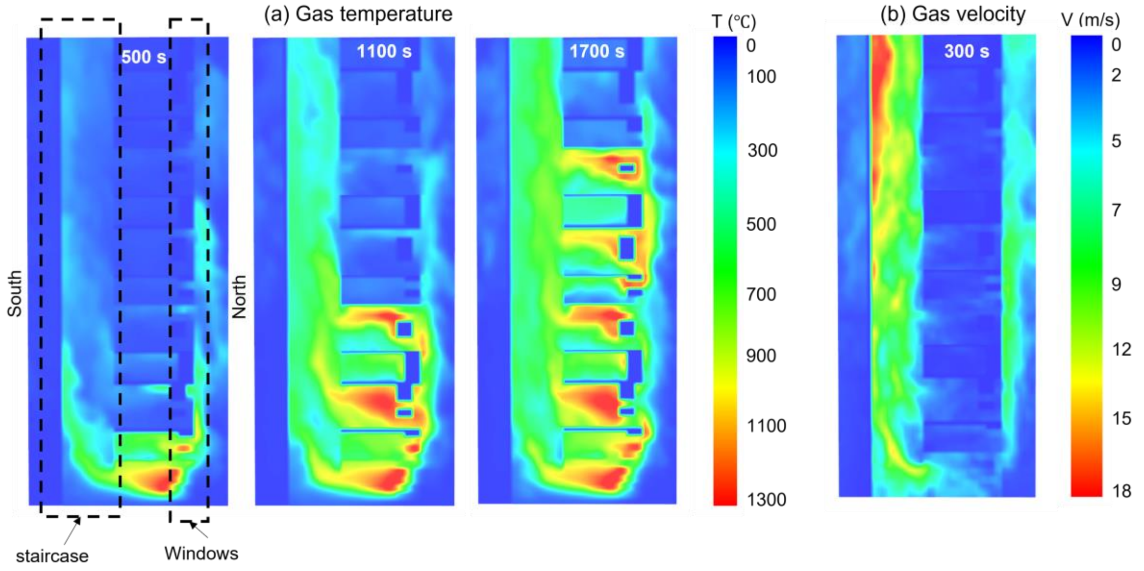

Fig. 11. Sectional view from eastern elevation (a) Temperature and (b) velocity contour plots for vertical fire and smoke spread from windows and vertical shaft, where fuel was burning at the 10th floor (500 s); fire reached at the 12th floor (1100 s); fire reached at the 14th floor (1700 s); and high-speed hot gases reached the top floor through vertical shaft at early stage.

There were openings around the perimeter (**Fig. 6a**) so that the fire might enter upper floors through the opening first. According to the fire department, before reaching the building, they could see the fire coming out of the windows (Ferdowsizadeh 2017). Based on this hypothesis, the fire simulation of few upper floors (13th, 15th) would be done separately, and the fire would be initiated near the windows at the north-western corner of each floor (as discussed earlier). This exercise allows to simulate different floors for different timing such as the 10th, 11th, and 14th floors fire duration was much shorter than the other floors due to the firefighting operation, which significantly reduces the computational cost.

3.3. Horizontal fire spread in the Plasco Building

In large open floor plan spaces, fire tends to travel across the floor plates with localized burning, which process is often termed as the "traveling fire." While reviewing the classical work of Kawagoe and Sekine (1963), Thomas and Heselden (1962), and Harmathy (1976), Torero *et al*. (2014) concluded that fire in large open spaces with sufficient ventilation should be considered as fuel-controlled. In the Plasco Building, windows covering either burnt out or fell off during the fire, which kept the fire in the fuel-controlled regime. Moreover, the false ceiling was open to the atmosphere, and fire entered the false ceiling during the early stages of the fire (**Figs. 9, 10,** and **11**). Generally, fire can reach the adjacent compartments through windows and false ceiling, or due to de-compartmentation (failure of walls). Fire could reach either from the gaps in the false ceiling or complete failure of the false ceiling due to extensive heat. In an fire accident that occurred in the Stardust nightclub, Ireland (1981), once the false ceiling collapsed, the fire reached the ballroom from the alcove. There were 48 fatalities, and another 200 people were injured in this fire (Malholtra and Hinkley 1981).

According to the emergency responders, in the Plasco Building the fire reached the adjacent compartments through a false ceiling (Ferdowsizadeh 2017). Fuel distribution in the Plasco Building played a vital role in the spreading of the fire (**Section 3.1**). From the visual evidence, it was found that fabrics type of fuel was scattered all over the shops on the entire floors. **Fig. 6b** shows the typical shop which was present in the Plasco Building (Ferdowsizadeh 2017). The fuel distribution pattern and a large quantity of fuel support the rapid growth and spread of the fire in the Plasco Building.

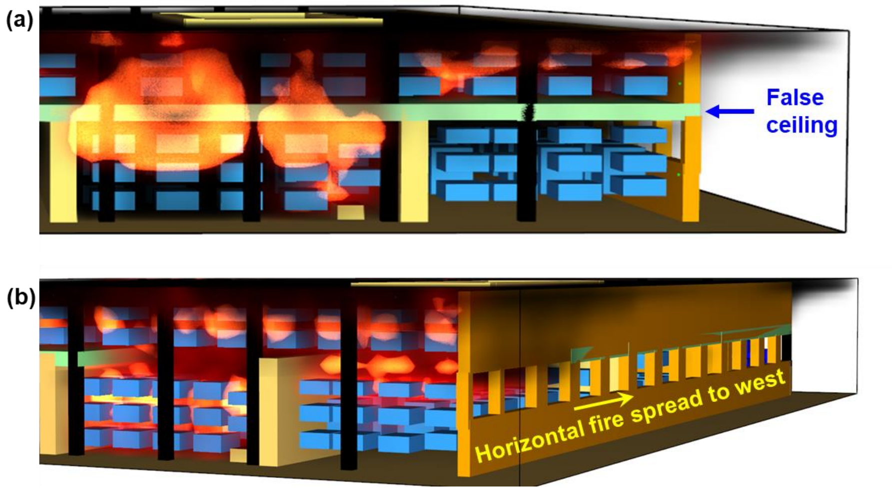

Fig. 12. Typical horizontal spread of the fire on each floor of the Plasco Building; (a) Fire at 850 s (before false ceiling removed), (b) Fire at 1050 s.

An FDS model is generated to represent the spread of the fire on each floor (**Fig. 12**). The top view of the CFD domain of a typical floor is shown in **Fig. 3**. The fire was initiated near the room adjacent to the room at the north-western corner. The fire location was verified with the visual evidence of the early stages of the fire (**Fig. 4**), and interviews of firefighters and security personnel who tried to extinguish the fire once it broke out. The room is filled with fuel (nylon) in a similar manner as generally found in garment shops. The fuel was present in the false ceilings as well (**Fig. 6a**). Once the fire broke out, due to the fuel's height, the fire reached the false ceilings during the early stages of the fire (verified by firefighters (Ferdowsizadeh 2017)). In the fire simulation, the fire did not reach the adjacent compartment until the false ceiling was removed, as shown in **Fig. 12a**. The fire reached the adjacent compartment (at the north-western corner) once the false ceiling was removed from the simulation after 900 s (**Fig. 12b**). The ceiling failure is controlled by the obstruction removal techniques in FDS. The timing is approximated (calibrated) based on the fire spread observed from **Fig. 4** (*FireEvolutionMap)* and **Supplement Material**. Once the flames reached the adjacent compartment, the fire traveled along the western elevation of the building, and the fire started to become larger. It is worth noting that the actual firefighting operation inside the building was carried out on the 10th and 11th floors only (as there was no active fire protection system was available in the Plasco Building). The attempt of controlling fire from the exterior using elevated monitors (fire monitors installed on aerial ladders) turned out to be futile. The firefighting operation on upper floors (floors over the 11th floor) was only from the elevated monitors. After a brief period, the fire was observed almost inside all upper floors. The calibrated model represents a reasonable horizontal fire spread in the Plasco Building.

3.4. Calibration of fire on the fire floors

The fire was observed only on the 10th and all upper floors before the second collapse (collapse of all floors at two-third of the building's north side) (**Figs. 4** and **5**). After the second collapse, the collapsed slabs brought the fire to the lower floors as well. Within 30-35 minutes after the second collapse (**Fig. 5**), the whole building collapsed (final collapse); therefore, the calibration process for the fire is not carried out for lower floors. It can be assumed that the collapse of the lower floors was mainly due to the increment of the dead load due to the failure of the upper floors. It was observed from the visual evidence and witnesses' reports that the fire did not spread on the entire floor of the 10th and 11th floors, mainly due to the initial efforts of the firefighters. Due to the first and second collapses, firefighters could not reach the 12th floor or above. In terms of the 14th floor, after initial rapid growth, not much fire was observed on the 14th floor. It might be due to the firefighting operation, or the fire was not able to penetrate in adjacent compartments. The fire on the 10th and 11th floors were confined to the north-western region of the building. Therefore, in FDS, fire is calibrated for the 10th floor that can also represent the fire on the 11th and 14th floors.

Similarly, the observed flames on the 12th and 13th floors were similar except in the south-western region, where the fire was more intense on the 13th floor. For fire representation, only the 13th floor can be used. However, to obtain the realistic boundary conditions for structural analysis, the fire on the 12th floor is also calibrated. The fire spread rate on the 15th floor was much higher than the other floors. During the early stages of the fire, the fire was observed near the north-eastern corner and along the eastern elevation (**Fig. 4**). Therefore, the fire on the 15th floor is also simulated for calibration. **Fig. 13** shows some of the images from the visual evidence and simulation results of FDS models for few floors.

On the 10th floor, the fire was initiated near the north side of the building, and not much fire was observed other than the north-western side of the building. Due to high fuel content, it lasts more than one hour before it was contained by the firefighters. In the FDS model, only fuel was placed in the two compartments (shops) at the northwest corner. All fuel is allowed to burn in the fire simulation (90 min simulation), and no fire suppression was simulated. According to the firefighters, when they reached near the fire's location on the 10th floor, the fire already covered the north-western region and could be observed in the false ceilings of the 10th floor. In **Fig. 13**, on the 10th floor, both vertical and horizontal fire spread can be seen in an adjacent compartment qualitatively matching incident images.

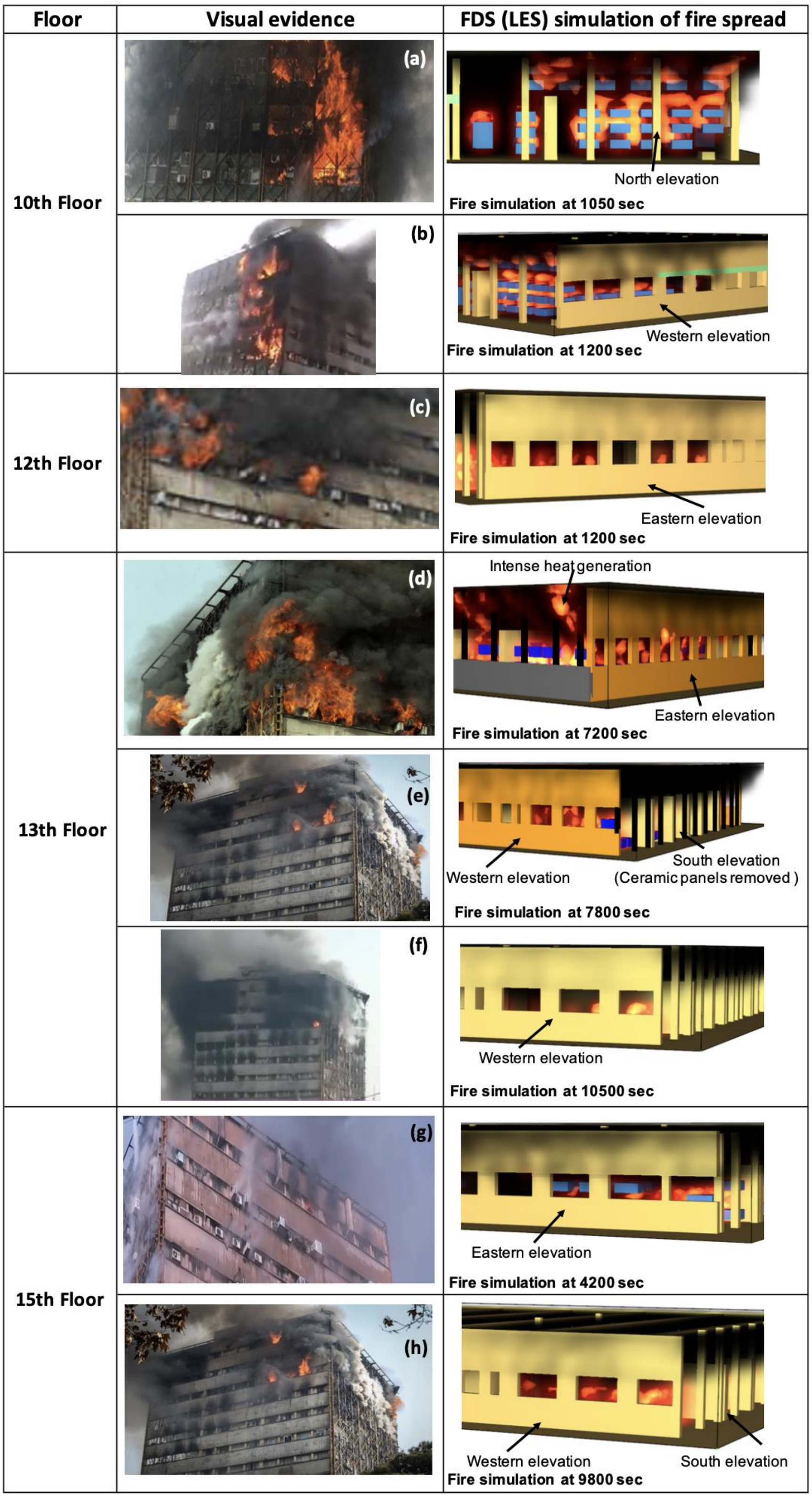

Fig. 13. Calibrated model for few fire floors. (a) fire in false ceilings and upper floors, (b) fire spread along the western elevation, (c) fire at elevation elvation of the 12th floor, (d) flames coming out of the 13th floor at the southeast corner, (e) fire at southeast and south-west corners, (f) fire at the south-west corner before the final collapse, (g) fire at the eastern elevation of the 15th floor, and (h) fire at the south-west corner when all the fuel at south-eastern region burnt out.

While calibrating the fire for the 13th floor, the fuel was placed all over the floor except near the north-eastern region, as no fire or smoke signatures were observed in that region of the building. A few assumptions can explain it, such as (a) due to the fire suppression process from outside, (b) or fire was not able to penetrate through the adjacent compartment boundaries, (c) or not enough fuel present on the false ceiling of the 13th floor. This method of fire calibration is because FDS allows materials to burn when their surfaces' temperature reaches ignition temperature; however, in reality, fuel combustion chemistry is quite complex. Although FDS also has a complex chemistry model representing the pyrolysis process, which includes more reactions, the multi-chemistry method has many assumptions and is computationally much more expensive, as discussed earlier. Therefore, the adopted model (placing the amount of fuel that allowed to match the fire spread with the evidence) is reasonable and computationally inexpensive for calibration.

The images from the simulation and fire incident show that when the fire reached the south-eastern corner of the 13th floor, the fire became very intense. The production of an enormous amount of heat was due to the merging of the fire from eastern and southern sides of the building. The simulation also reproduces flames visible at the southeast corner. During this period, the flames can be seen at the western elevation of the 13th floor as observed from visual evidence. Similarly, while calibrating the fire on the 15th floor, using the control devices, the fire was allowed to penetrate into adjacent compartments through the failure of the false ceilings. In **Fig. 13**, the fire can be seen at the eastern elevation both in fire simulation and the image from the accident during the early spread of the fire. Furthermore, **Fig. 13** also shows the fire at the west elevation when the fuel at the south elevation was already burnt out.

Given the uncertainties associated with a such a complex building fire, it is highly unlikely that the exact fire spread can be simulated through full-scale experimental study, let alone fire simulation. Especially, it becomes much more complex when there is no precise information of various features that can affect the fire spread, such as fuel location and its distribution, failure of compartmentation and false ceilings, change in ventilation condition due to failure of windows, gaps, or openings that can allow the fire to spread, and so on. However, the method presented here is to calibrate the fire, based on the detailed and careful forensic investigation, which allows a reconstruction of the fire.

4. Coupling of CFD and FEM

The fire curves presented in internationally recognized standards and codes are mainly applicable for small compartments. These fire models were proposed several decades ago and largely depended on empirical or semi-empirical relationships. There have been some attempts to put forward more realistic idealized fire models, for example, "traveling fires" for large open plan floor plates (Stern-Gottfried and Rein 2012; Rackauskaite *et al.* 2015; Dai *et al.* 2020). However, these models are crude and require more validation studies. The true response of complex structures to real fires cannot be determined using the prevalent idealized fire models. A CFD-based fire modeling tool can produce a realistic and high-fidelity fire scenario.

Before performing the structural analysis of a building, it is necessary to perform heat transfer analysis using the gas temperatures that reach the structure boundary. Therefore, it is required to transfer realistic data from FDS to any finite element tool to carry out heat transfer analysis. The temperatures in the form of adiabatic surface temperature (AST) are calculated from the calibrated FDS model. The concept of AST was introduced by Wickstrom (Wickström *et al.* 2007; Wickström 2008) to produce rational boundary conditions for conducting a heat transfer analysis. AST can be considered effective fluid phase temperatures, including both heat transfer modes – radiation and convection heat transfer. It is worth noting that AST is calculated based on some assumptions such as unit configuration factor and unit emissivity, which are reasonable when the structural surface is engulfed in smoke as in the Plasco Building. The data transfer from the CFD model to FEM is not straightforward, especially due to spatial and temporal discretization in fluid and solid domains.

After conducting the fire simulation, the output data needs to be transferred to the heat transfer (H.T.) model using a suitable coupling technique. A middleware is developed to transfer the data from FDS to OpenSEES (Khan *et al.*, 2021). The middleware is also open source and can be downloaded from (OpenFIRE 2021). It makes the whole process streamline from CFD simulation in FDS, heat transfer, and structural analysis in the F.E. tool.

4.1. Heat transfer analysis and future study

To capture thermal gradients at all structural components such as slabs, trusses, columns on each floor, many 'AST measuring devices' are installed in the FDS simulations. On trusses and slabs, devices are installed every 2m, while on each column, two devices are installed. The number of devices is sufficient to obtain the thermal gradients on each structural component along their length. However, while performing structural analysis, it may be required to get more refined data, then more devices might be needed. 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. The convective heat transfer coefficient of 25 W/m^{2}K according to the Eurocodes for (EN-1994-1-2 2005) is assumed for fire-exposed surfaces. An emissivity of 0.7 and 0.85 are used in accordance with the Eurocodes for steel and concrete, respectively.

Fig. 14a shows the temperatures obtained after the heat transfer analysis in OpenSEES for the 15th floor's fire at two locations: (a) temperature history that represents the temperatures at the truss near the north-east corner (where the fire broke out), and (b) temperature history that represents the truss temperatures near the south-west 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 impinging of the flames. While at the south-eastern part of the building, where fire reaches during later stages, initially, the temperatures increase due to hot smoke, which is the reason that the temperature at southeast was much lower during the first 4,000 s. The peak temperature at the south-eastern side is observed after two hours of the fire, while at the north-western corner, the peak temperature was reached within the first hour of the fire. The temperatures fell quite rapidly at the south side of the building, which can be explained as HRR becomes much higher in the later stages of the fire, and due to very high HRR, all fuel is burnt out rapidly.

Fig. 14b shows the temperature at the two columns at the northwest and southeast corners. Temperatures are measured at 1.2m and 2.8 m from the bottom of each column. The peak temperatures at the lower part of each column are almost half of the temperatures reached on the upper part of the column. It is mainly due to the hot gases reaches the upper portion of the compartment. The traveling nature of the fire can be seen in columns' cases as well.

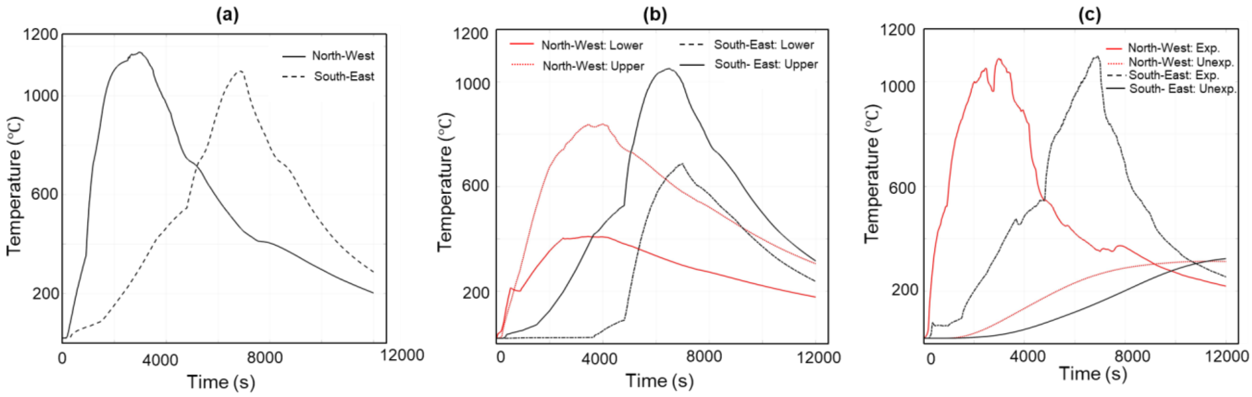

Fig. 14. Temperatures after heat transfer in FEM (a) Trusses (b) Columns (c) Slabs.

The heat transfer on the concrete slab of 120 mm deep is presented in **Fig. 14c**. **Fig. 14c** shows the temperatures on the exposed and unexposed surface to the fire near the northwest and southeast corners. The trend of temperature on the exposed surface is similar to the trusses. 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 stage of the fire.

In Part II of this study, the heat transfer analysis of the whole structural frame of the Plasco Building (fire floors) will be performed. Once heat transfer analysis is finished, the temperature output from OpenSEES is obtained as boundary conditions for structural analysis. The middleware maps the respected temperature history from the heat transfer analysis to each element of the structural model. The temperature history will then be applied as a thermal load in the thermo-mechanical model to simulate the nonlinear structural response to fire. **Fig. 15** shows the OpenSEES structural model, including trusses, columns, and slabs.

The realistic thermal data allows understanding the reasons for the total collapse of the Plasco Building through subjecting a reasonably comprehensive 3D finite element model of the building. In the further study, the progressive collapse of the building will be simulated with respect to the traveling fire phenomenon as represented by the heat transfer results (**Section 4.1**).

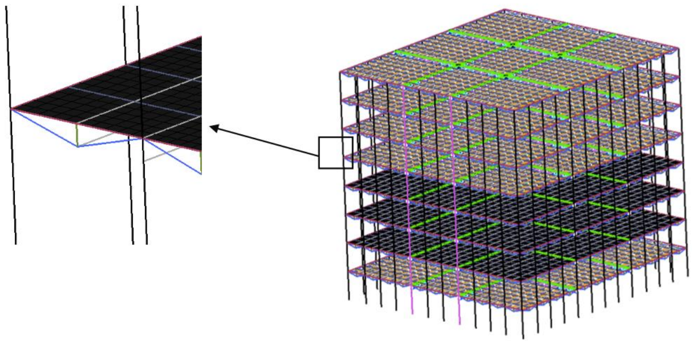

Fig. 15. Visualization of OpenSEES model with composite slab modelled (three floors only).

5. Conclusions

In a fire accident, structures do fail and sometimes collapse as well. Each year, in addition to the loss of lives, fire accidents cost a significant percentage of the world's total Gross Domestic Product (GDP). This paper uses the available evidence such as images, video footage, interviews, and reports to reconstruct the Plasco Building's fire. The information gathered from the evidence facilitates the development of a conclusive timeline from fire initiation to the total collapse of the building. The fire timeline helps to estimate the spread of the fire between two key events, which in turn allows allocating the approximate timing to each visual evidence. Using CFD modeling, the fire-spread history of different floors created from the visual evidence is calibrated. The fire simulation qualitatively matches with the visual evidence.

This paper also explains how the fuel distribution in the Plasco building affected the vertical and horizontal spread of the fire. Simulation shows that fire was able to reach all upper floors of the building in the early stages of the fire due to the height of the fuel and ventilation conditions. The fire simulation also demonstrates that the false ceilings' failure supports the fire to reach the adjacent compartments.

The data obtained from the CFD simulation is transferred to the F.E. tool to perform the heat transferer analysis. The temperatures on the surface of the structural components, namely trusses, columns, and slabs, depict the traveling behavior of the fire in the Plasco Building. Heat transfer analysis of the whole structure provides realistic boundary conditions to attain structural response to a real fire. The detailed structural analysis of the Plasco Building based on the thermal data obtained in this paper will be carried out in Part II of this study. The whole process, from collecting the evidence to the structural response analysis, provides a novel methodology to carry out the forensic investigation of tall buildings' fires, which can guide the s*tructural and fire engineers* to improved structural fire safety and life safety designs.

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