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REVIEW

Post-earthquake fire risk and loss assessment in urban areas

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Abstract
Post-earthquake fire (PEF) poses a significant threat to urban structures and may contribute to the collapse of seismically damaged buildings as well as result in catastrophic human casualties and loss of properties. There is some attention of the researchers to further study the impact of PEF risk in urban buildings and its socio-economical aspects on urban life. However, the nature of such phenomenon has not yet been fully understood in depth and many aspects are still unknown. In this paper, a review of the state-of-the-art of the previous PEF events, PEF risk estimation, fire ignition models and probabilistic loss assessment are presented. This work aims to present the main observations regarding the PEF events in history and give a review of the studies that were developed to better understand the PEF phenomenon. It is also presented some mitigation measures that could be helpful to reduce or prevent post-earthquake fires.

Keywords Post-earthquake fire · Historical data · Earthquake damage · Risk assessment · Loss assessment

Introduction

Post-earthquake fires can have a tremendous effect on built urban areas and can result in a chain of events that may incur serious financial and social adversities [1]. According to historical data, it has been observed that fires caused by earthquakes have previously brought massive damage. Examples of such devastating events include the major earthquake in San Francisco in 1906 and the Great Kanto earthquake in 1923.

At 05:12 on Wednesday, 18 April 1906, San Francisco was struck by an earthquake with a magnitude of 7.9 M_w [2–17]. This earthquake was the most devastating in US history and the largest urban fire in history to that time. It is still the largest urban fire in US history and has only been exceeded by the fires that followed the 1923 Tokyo earthquake [8, 11]. After the earthquake, there were reported 52 ignitions which quickly grew into conflagrations that burned for 3 days [3, 8, 10]. The fire causes were mainly related to the fracturing of internal electrical wiring, lit kerosene lamps and gas lights, and boiler fires in factories [5]. The earthquake and subsequent fires destroyed more than 28,000 buildings amounting to a burnt area of 12.2 km^2 and at least 3000 people were killed [12–14]. Some estimates attribute 80–85% of the damage due to the fire rather than the earthquake [8, 12, 14]. The property loss was estimated to be higher than \$500 million (in 1906 dollars) [8, 13]. In San Francisco alone more than 200,000 out of the approximately 400,000 residents were displaced [12, 13]. The primary reasons for the fire spread were related to the damage to structures, wind, failure of the local distribution pipe system, and hampered fire department response [8, 10].

The fire department and the firefighting activities were disrupted due to the lack of regular means of communication and the absence of water in the burning district [5, 6]. The fire alarm receiving office was destroyed and the telephone system failed over a wide area leading to many unsuccessful attempts to send alarms [6]. There were over 23,200 breaks in service lines that were between 15 and 100 mm in diameter which were a major source of loss of pressure and water [8]. Collapsed structures and fallen rubble often prevented firemen from closing valves on distribution mains to decrease pressure and water losses [8]. The pipe damage disrupted the water supplies to the sprinkler systems [5, 6]. It was observed that while the weather was relatively hot and dry, the main factor leading

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to conflagration was the failure of the water system [11]. The overall buildings in San Francisco performed well in the earthquake of 1906, if it was not for the fire damage, most of the earthquake-damaged buildings could have been repaired and reused [14].

The Kanto earthquake occurred at 11:58 on September 1, 1923, and the main shock had a magnitude of 7.9 M_w [18–20]. The epicentre was located just offshore, 80 km off Sagami Bay at 139.5 E 35.1 N [11, 18]. The earthquake caused 277 outbreaks of fire and 133 of these fires spread [5, 6, 11]. Tokyo burned for nearly 40 h and about 40% of the city was destroyed. About 90% of Yokohama was destroyed by the earthquake and fire [5, 19]. The fire occurred before lunchtime and the noontime meals were being prepared, which was an important factor regarding the ignition source. There were numerous small charcoal braziers lit, a large number of heating units and cooking stoves. Some reported ignition sources were related to chemical fires that occurred at medical and pharmaceutical colleges, educational establishments, apothecaries, soap factories and dental clinics [5, 18]. The earthquake caused not only large-scale collapse and destruction but also a tsunami in many coastal areas, along with enormous conflagrations in Tokyo and Yokohama [20]. The tsunami (4–6 m in height) impacted the Boso and Miura peninsulas and destroyed 868 houses. It was acknowledged that Tokyo had a major conflagration hazard due to the presence of wood buildings and the dense urban aggregation. At the time of the earthquake, the meteorological conditions were especially adverse due to a recent dry period and nearby typhoons, with hot dry winds (around 26 °C) of approximately 12.5 m/s. The winds reached a maximum of 21 m/s at 23:00 that evening [6, 11]. The consequence of these aspects was a major conflagration with rapid fire spread that burned for several days which destroyed approximately 447,000 houses over an area of 38.3 km^2 [11, 21]. There was damage in a fire station that prevented the use of equipment and some fire vehicles. The access was blocked due to collapsed buildings, and damaged roads and bridges. There was a complete water failure which contributed to substantial fire spread [6]. There was a significant impact on the public water supplies, with complete water supply failure due to broken underground water pipes, massive leaks and hydrants destroyed by flames. The firefighters, with these limited supplies, fought the fires for 46 h continuously and succeeded in subduing outbreaks at 23 places, but over 100 firefighters were injured and 22 were burnt to death. The spread of the post-earthquake fire was enhanced due to the water supply failure [5, 11]. The Kanto earthquake was one of the most destructive events of the twentieth century causing 140,000 fatalities (more than 91,000 victims were killed by fire) and destroying Yokohama and substantial parts of Tokyo [21–24]. The high number of victims caused by the fire occurred because the citizens were surrounded by multiple fires and the streets for evacuation were blocked due to the fast spread of the fire [21].

At the time, there was no effective tool for early sign detection and the government and people of Japan did not have a specific plan to respond to the earthquake [23]. These two examples show the tremendous impact that post-earthquake fires can have on the built environment, where the damage caused by fires can be more severe than the damage caused by the earthquake itself. However, most codes and standards disregard the significance of PEF in the design stage [25].

It is of the utmost importance to develop PEF models which are essentially categorized into two groups. One group is related to models which estimate the local level of PEF concentrated on ignition. A second group is related to models that predict the global level of PEF including fire spread and suppression [26]. Moreover, to better analyze the fire risk impacts on urban buildings, other aspects such as fire safety equipment, fire department response and amount of fire spread are taken into consideration in the research studies. There is also the development of multi-hazard design methodologies, ignition analysis and PEF collapse performance which aim to understand the PEF effects on structures. However, post-earthquake fire remains a significant problem to be addressed and it involves many situational and sequential features.

Post-earthquake fire in the built urban areas

Post-earthquake fire events

There is much historical evidence that confirms the possible appearance of fires in a built urban environment after a major earthquake [5]. The losses of life and property after post-earthquake fires can be devastating. The post-earthquake fire events are complex and involve several factors, such as structural damage caused by the earthquake, ignitions caused by different sources, management of the firefighting resources and impacts on the lifelines (water, electricity, gas, communication, and transportation). Each one of these factors has a set of specific characteristics that can influence the other factors. It is crucial to understand each one of these main factors to have a comprehensive understanding of post-earthquake fire events. Studying past earthquakes that caused fires is essential to understand these factors, how they impact each other and the consequences that can arise from them. Furthermore, it is a way to observe the main problems that can occur and consequently can help in the development of mitigation actions that can prevent the consequences of such catastrophic events.

To better understand the post-earthquake fire phenomenon there was developed a database of earthquakes that caused at least one ignition. The database, which is presented in Table 1, has 49 earthquakes and the information gathered is the date, location, magnitude, intensity of the earthquake and number of ignitions caused by the earthquake [21, 27–43]. This type of information is valuable and when analyzed can provide some insights regarding the main characteristics of the post-earthquake fires in the built environment. From the database, the highest magnitude observed was 9.2 M_w and the lowest was 4.9 M_w. Regarding the higher intensities observed in the earthquakes, it was observed that the highest intensity was IX and the lowest intensity was VI. The lower values can suggest a threshold regarding the magnitude and/or intensity for the likely appearance of post-earthquake ignitions. It is important to mention that each earthquake led to a unique scenario and the information gathered serves to give a global idea of the post-earthquake fire phenomenon and does not predict future scenarios. The Great East Japan earthquake in 2011 caused 348 ignitions and was the earthquake with the highest number of ignitions. These high numbers of ignitions were caused by the earthquake and the tsunami that was originated from the earthquake. The tsunami induced ignitions were included with the knowledge that the characteristics of tsunami-induced fires are different from the characteristics of earthquake induced fires. It was considered that for this type of global analysis, this type of distinction does not pose a significant problem. In Fig. 1 is represented the number of earthquakes in each country that generated at least one ignition. The earthquakes that caused at least one ignition occurred in 10 different countries. From the 49 earthquakes in the database, 20 were in USA, 19 in Japan, 2 in Chile and Turkey, and 1 in Italy, New Zealand, North Macedonia, Nicaragua, Mexico, and the Philippines. Almost 80% of the earthquakes that caused at least one ignition occurred in the USA and Japan. In Fig. 2 is represented the total number of post-earthquake ignitions that occurred in each country. Beyond being the countries that had the higher number of earthquakes that caused at least one ignition, the USA and Japan were also the countries that had a higher number of post-earthquake ignitions. The combined analysis of Figs. 1 and 2 clearly shows that the countries more impacted by post-earthquake fires are the USA and Japan.

With the information presented in Table 1 is possible to develop some correlations to try to understand how the different data relate to one another. These correlations are presented from Figs. 3, 4, 5, 6. In Fig. 3 represents the relation between the magnitude of an earthquake and the number of post-earthquake ignitions. With the gathered information, it is not possible to establish that earthquakes with higher magnitudes lead to a higher number of ignitions since there are examples of earthquakes in the database that have a higher magnitude but have a relatively lower number of ignitions. Furthermore, there are other examples of high-magnitude earthquakes that are not in the database that did not cause any ignitions. These aspects indicate that establishing a relation between the magnitude and number of ignitions is not optimal. Nevertheless, something is interesting when analysing only the earthquakes that generated 100 or more ignitions, where it is observed that earthquakes with higher magnitudes tend to lead to more ignitions. It is not possible to establish that an earthquake with a high magnitude leads to a high number of ignitions (even because the ignitions are dependent on several other criteria) but perhaps it is possible to identify that the appearance of a high number of ignitions corresponds to an earthquake with a high magnitude. Instead of considering the relation between the magnitude and the number of ignitions, a different approach could be considering the relation between the earthquake intensity and the number of ignitions. In Fig. 4 represents the relation between the maximum intensity of an earthquake and the number of post-earthquake ignitions. The earthquakes presented in the database have a maximum intensity between VI and IX. It is observed that earthquakes with a maximum intensity of VI did not cause more than 50 ignitions, which it is not the same for higher maximum intensities. Perhaps establishing a relation between the maximum intensity and the number of ignitions is a better approach, but this aspect it is not observed in Fig. 4. It is necessary to have more data to be able to draw meaningful conclusions in this regard. Another aspect that can be studied is how is the evolution over time of the magnitude of an earthquake and the number of ignitions caused by an earthquake.

In Fig. 5 represents the relation between the magnitude of an earthquake and the number of post-earthquake ignitions over time, where, with the data gathered, it is not possible to establish a meaningful relation. Instead of evaluating over the years, another approach can be an analysis concerning the time of the day that the earthquake occurred, and the number of ignitions caused by the earthquake. In Fig. 4 represents the relation between the hour of the day that the earthquake occurred and the number of post-earthquake ignitions. It is observed that most of the earthquakes that caused a significant number of ignitions happened during the earlier hours of the morning and during lunch hours, which seems to indicate that there are times of the day in which the appearance of ignitions is more probable to happen. This observation is reasonable since the earlier hours of the day and lunchtime are the occasions when meals are being prepared and there is significant activity in the kitchens. This is the place where more probably can appear ignitions related to open flames and gas leaks which are common causes of post-earthquake fires. This aspect could also be reasonably expected at dinner time hours but that is not observed in Fig. 6.

The relatively small database combined with a few earthquakes in the database that happened at dinner time can

Table 1 List of earthquake events with post-earthquake fires

Year	Month	Day and time	Country	Event	Magnitude (M_w)	Max. intensity	Ignitions
1906	Apr.	18 (05:12)	USA	San Francisco	7.9	IX	50–52
1908	Dec.	28 (05:20)	Italy	Messina	7.1	VII	Multiple
1923	Sept.	01 (11:58)	Japan	Tokyo/Yokohama	7.9	VIII	277
1931	Feb.	03 (10:47)	New Zealand	Hawkes Bay	7.4	VII	+ 10
1933	Mar.	10 (17:54)	USA	Long Beach	6.4	VIII	15
1948	Jun.	28 (16:13)	Japan	Fukui Prefecture	6.8	VII	24
1952	Jul.	21 (04:52)	USA	Bakersfield	7.5	IX	1
1957	Mar.	22 (11:44)	USA	San Francisco	5.7	VI	1
1963	Jul.	26 (05:17)	North Macedonia	Skopje	6.0	VIII	2
1964	Mar.	27 (17:36)	USA	Anchorage	9.2	VIII	7
1964	Jun.	16 (13:01)	Japan	Niigata	7.6	VII	9
1965	Apr.	29 (08:28)	USA	Puget Sound	6.7	VII	1
1969	Oct.	01 (21:56)	USA	Santa Rosa	5.6	VI	2
1971	Feb.	09 (06:00)	USA	San Fernando	6.6	IX	116
1972	Dec.	23 (00:29)	Nicaragua	Managua	6.3	VIII	4–5
1979	Oct.	15 (16:16)	USA	El Centro	6.4	IX	1
1983	May	02 (16:42)	USA	Coalinga	6.2	VIII	4
1984	Apr.	24 (13:15)	USA	Morgan Hill	6.2	VIII	6
1985	Sept.	19 (07:17)	Mexico	Michoacan-Guerrero	8.0	VII	200
1986	Jul.	08 (02:20)	USA	North Palm Springs	6.0	VII	2
1987	Oct.	01 (07:42)	USA	Whittier Narrows	5.9	VIII	132
1989	Oct.	17 (17:04)	USA	Loma Prieta	7.1	IX	41
1993	Jul.	12 (22:17)	Japan	Hokkaido Nansei-oki	7.7	VII	Multiple
1994	Jan.	17 (04:30)	USA	Northridge	6.7	IX	110
1995	Jan.	17 (05:46)	Japan	Hyogo-ken Nambu	6.9	IX	293
1999	Aug.	17 (03:01)	Turkey	İzmit	7.4	IX	3
2000	Sept.	03 (01:36)	USA	Napa	4.9	VII	1
2001	Feb.	28 (10:54)	USA	Seattle, WA	6.8	VII	1
2001	Mar.	24 (15:28)	Japan	Geiyo	6.8	VII	4
2003	May	26 (18:24)	Japan	Miyagi	7.0	VII	4
2003	Jul.	26 (00:13)	Japan	Northern Miyagi	5.5	VIII	2
2003	Sept.	26 (04:50)	Japan	Tokachi-oki	8.2	IX	4
2003	Dec.	22 (11:15)	USA	Cambria	6.5	IX	1
2004	Oct.	23 (17:56)	Japan	Niigata-Chuetsu	6.6	VIII	9
2005	Mar.	20 (10:53)	Japan	Fukuoka	6.6	VII	2
2007	Jul.	16 (10:13)	Japan	Niigata-Chuetsu-oki	6.6	VIII	3
2008	Jun.	14 (08:43)	Japan	Iwate-Miyagi	6.9	VIII	4
2008	Jul.	24 (00:26)	Japan	Northern Iwate	6.8	VII	2
2009	Aug.	11 (05:07)	Japan	Suruga-wan	6.2	VI	3
2010	Feb.	27 (03:34)	Chile	Maule	8.8	VIII	A few major
2011	Mar.	11 (14:46)	Japan	Great East-Japan	9.0	VIII	348
2014	Apr.	01 (20:46)	Chile	Iquique	8.2	VIII	3
2014	Aug.	24 (03:20)	USA	South Napa	6.0	VIII	6
2016	Apr.	16 (01:25)	Japan	Kumamoto	7.0	IX	15
2016	Dec.	28 (21:38)	Japan	Northern Ibaraki	5.9	VII	1
2019	Jul.	05 (20:19)	USA	Ridgecrest	7.1	IX	Multiple
2019	Oct.	16 (19:37)	Philippines	Cotabato	6.4	VIII	1
2021	Feb.	13 (23:07)	Japan	Fukushima	7.1	VIII	Small fires
2023	Feb.	06 (04:17)	Turkey-Syria	Turkey-Syria	7.18	IX	1

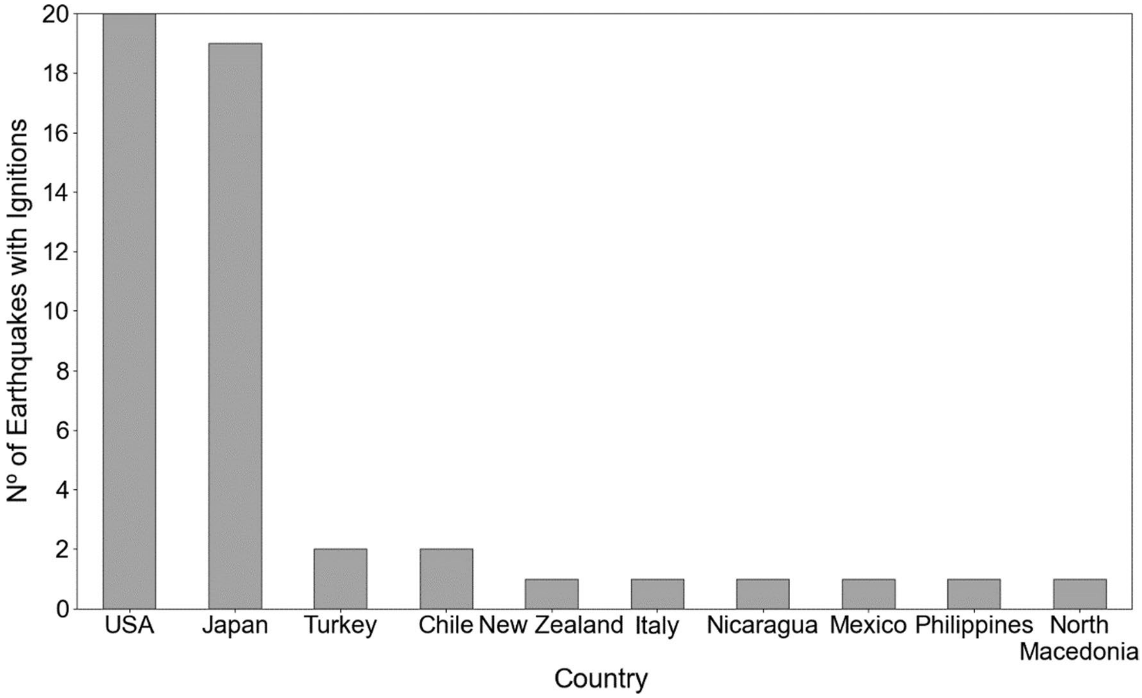

Fig. 1 Number of earthquakes in each country that generated ignitions

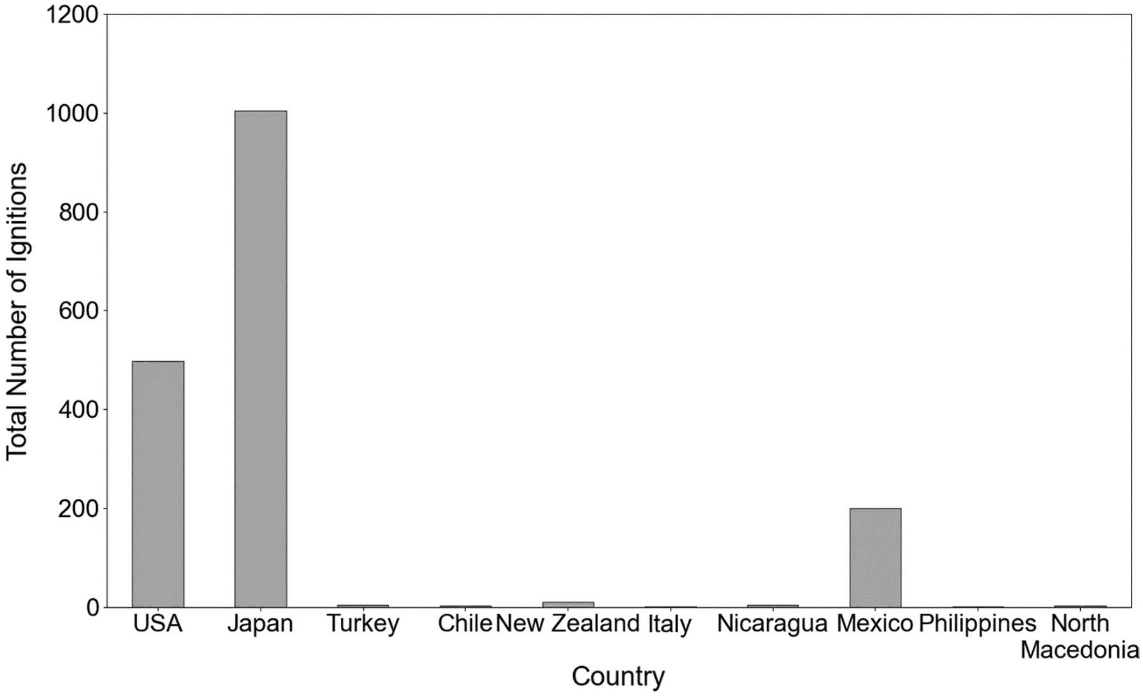

Fig. 2 Total number of post-earthquake ignitions in each country

in a certain way account for this absent observation. This situation highlights the limitations of performing meaningful observations based on the developed database and emphasizes the importance of improving the database to be able to obtain more significant conclusions. Nevertheless, it gives a global idea of the post-earthquake fire phenomenon.

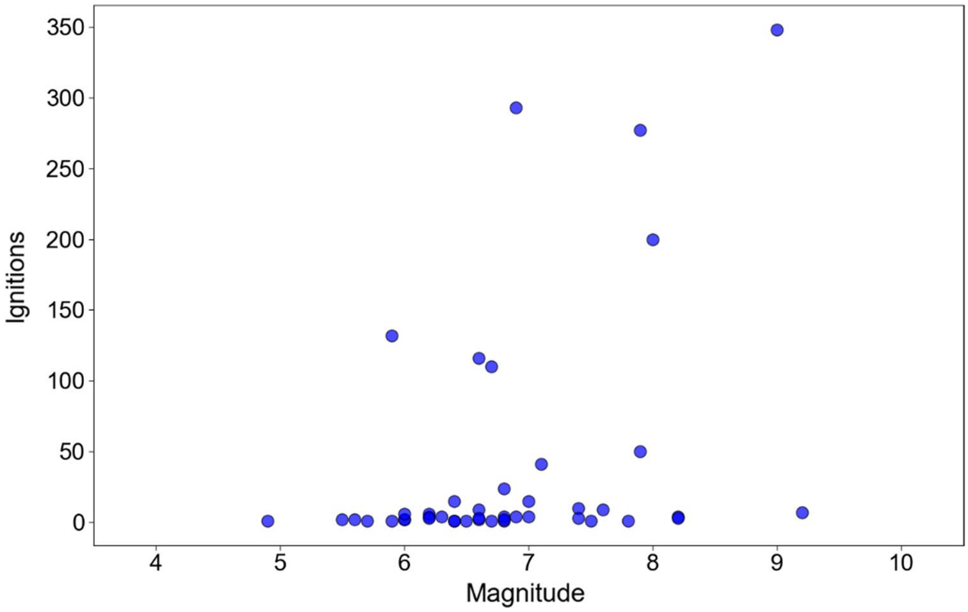

Fig. 3 Relation between the magnitude of an earthquake and the number of post-earthquake ignitions

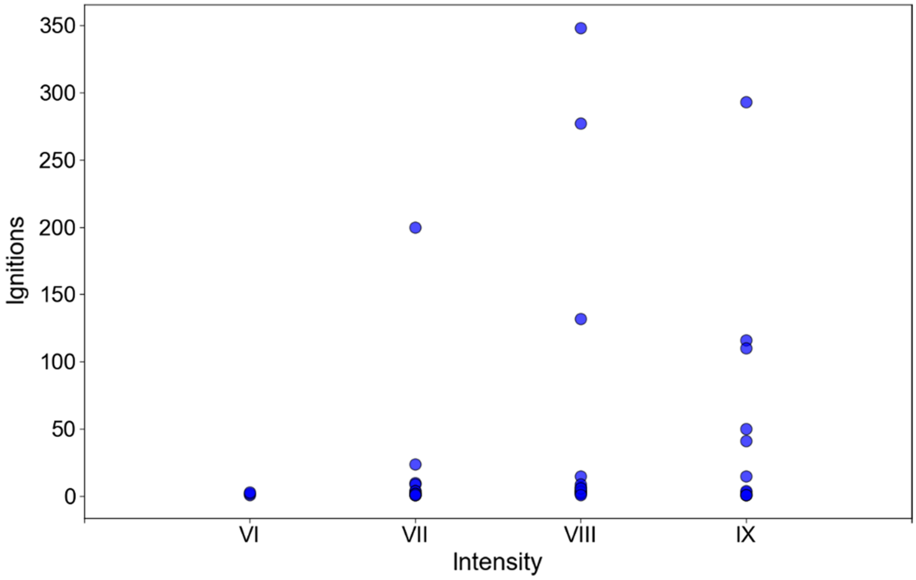

Fig. 4 Relation between the maximum intensity of an earthquake and the number of post-earthquake ignitions

Main observations from post-earthquake fire events

There are several aspects that are commonly observed in post-earthquake fire events that are mainly related with damage in the structures, the origin of the ignitions, firefighting response and the damage in the lifelines. Earthquakes can cause damages in the active and passive fire protection systems and this aspect can lead to undetected ignitions or to a delay in the discovery of ignitions. Consequently, these ignitions can grow into major fires that can prove to be a bigger challenge regarding combat and extinguishment [5, 6]. The main causes of fires after an earthquake are related with gas, electricity, open flames and hot surfaces [21, 33, 44]. Electric power is a significant ignition source, where damaged distribution lines and power circuits in damaged houses are common causes of fire. In addition, even without significant structural damage, collapsed light fixtures and items falling on electric stoves can also be ignition sources [11].

After an earthquake, the restoration of utilities, such as, gas and electricity can lead to delayed ignitions. This aspect can happen hours or even days following the initial disaster [7, 29]. A comparative study of post-earthquake fires in Japan between 1995 and 2017 indicated that ignitions related to electric power are increasing in comparison with earlier earthquakes. It was observed that 70% of the ignitions ensued within a day from the time of the earthquake and that the average time needed for the engines to discharge water increased by 8–25 times when compared to the scenario of

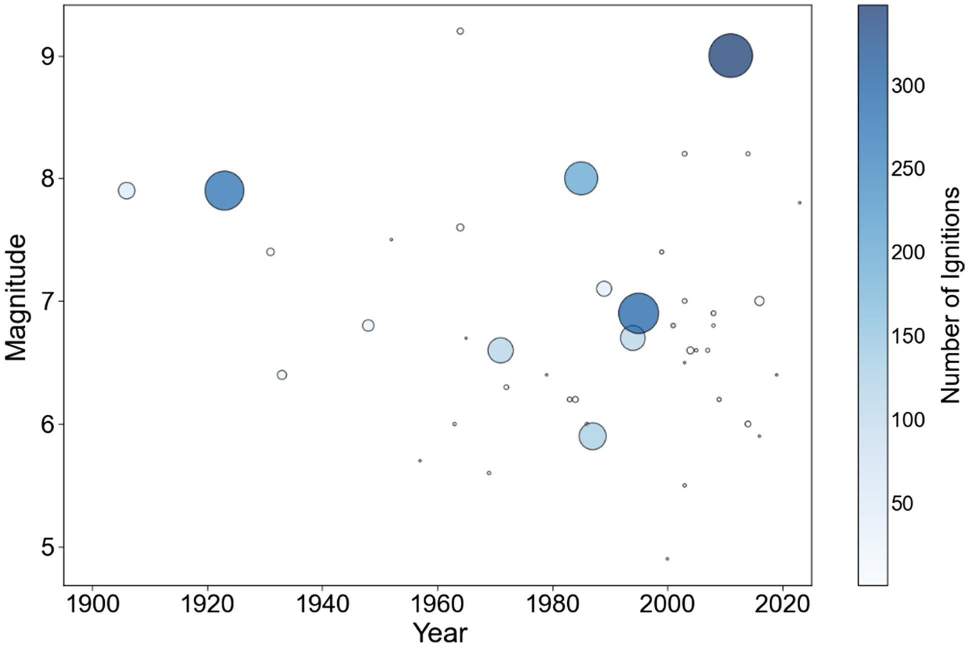

Fig. 5 Relation between the magnitude of an earthquake and the number of post-earthquake ignitions over time

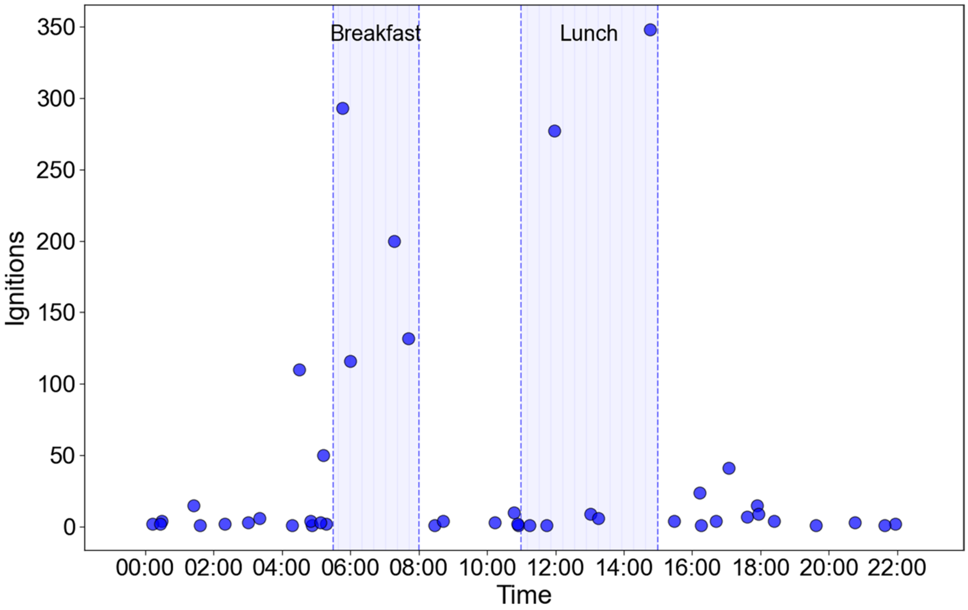

Fig. 6 Relation between the hour of the day that the earthquake occurred and the number of post-earthquake ignitions

ordinary fires [21]. The damage to lifelines, such as electricity, gas, water supply, communication systems and transportation can change a moderately damaging earthquake into a conflagration with severe consequences [7]. Electric power is crucially important for other lifelines, where the power loss is directly linked with a reduced serviceability of telecommunications, transportation, wastewater facilities and water supplies [32]. After major earthquakes, it was observed breaks in water supply systems which led to loss of pressure and inadequate water for firefighting activities, industrial operations, and daily life activities [40, 45, 46]. The areas more commonly to be without water are areas with poor soils and in fault rupture zones. Areas that depend on pumps that do not have backup power are also likely to lose water pressure [11]. After an earthquake it is common to have disruption of communications with an increase of telephone use and/or a reduced telecommunication and data-processing capabilities [29, 47, 48]. This inadequate communication capacity can enhance the difficulty in identifying the number and location of fires as well as finding the best solutions for a given emergency [7, 47].

Successful firefighting of post-earthquake fires depends on the ability of the firefighting teams to respond and to arrive to the location of the fire in a timely manner, to allocate the necessary resources and to mobilize adequate solutions. Roadway and bridge failures, traffic congestion or roadway closures caused by debris will slow down the firefighting activities [11]. It's important to note that the mentioned aspects do not encompass all the primary issues of every earthquake that has led to fires. However, it has been observed that these aspects are common in several earthquake incidents. Nonetheless, comprehending all these aspects is crucial to better prepare for the event of a major earthquake.

Post-earthquake fire risk analysis

The concept of risk in engineering is used to assess an event in which several losses occur due to the uncertainty in the associated factors. With regards to PEF, since the area of fire in urban environment changes with time, the amount of the damage, namely the number of burned buildings and fatalities, increases with time.

There are studies where computational models were developed regarding evaluation methods for urban post-earthquake fire risk. These computational models can incorporate the real conditions of an urban area and the influence of several countermeasures as parameters. The effectiveness of a countermeasure can be evaluated with the development of scenarios before and after the implementation of that countermeasure. The uncertain factors that are determining to urban fire and evacuation include weather, firefighting in preliminary stages, structural damages, fire fatality, initial evacuee locations and obstruction of roads. The city of Kyoto in Japan was selected to be studied for the PEF risk assessment and eight types of inland earthquakes of different active faults in Kyoto were considered in order to quantify the countermeasures that improve the fire resistance of the buildings. In specific, 200 fire scenarios were attributed for each of the eight earthquakes. The simulation results illustrated that method which was introduced could assess the effectiveness of countermeasures in consideration the damage uncertainty by post-earthquake fires even though its reliability is unclear. The results also indicated that this method could be a useful tool for disaster prevention [49].

In another study, the PEF risk was investigated taking into consideration the spreading time of fires by conducting the spreading fires analysis with all the buildings as the fire origins in the target area. Traditionally, macro-simulation and micro-simulations are selected to study the fire spread; however, in this research, a new methodology of PEF risk assessments that is not affected by the assigned origins of fires was presented. The spreading fire analysis is an important procedure for the risk estimation of post-earthquake fires. With regards to fire spread analysis, an analytical model has been created by petri net for a target urban area to conduct fire risk assessment.

The effectiveness of the proposed method has been validated and verified by a numerical investigation. It was observed that the risk degree is not impacted by the assigned origins fires even though the spreading fire analysis is carried out. This methodology showed that it is possible to express the degree of risk in more detail by conducting a spreading fire analysis [50]. In a research project, the PEF hazard analysis in low rise wooden buildings in Japan is investigated and a methodology for fire spread is expressed which essentially relies on region-specific empirical relationships. The fire spread model in this study incorporates aspects such as building density and properties, wind velocity and fire-fighting response and deterioration of this response with increasing seismic intensity. The input parameters of the model including cumulative distribution function of wind velocity are considered in the analysis stages. It was observed that the methodology outcomes were in a favorable agreement with some previous earthquakes such as Kanto and Fukui. The proposed methodology also delivers a reasonable guideline for the PEF risk assessment. Furthermore, it was learned the PEF spreading is generally less problematic than direct structural damage caused by shaking but that fire losses can exceed shaking losses under specific seismic conditions [51]. Older PEF spread models used an empirical approach that considered that the built environment is comprised of equally spaced, equal-sized square buildings, and that the fire spreads in an elliptical shape [52, 53].

In newer studies, it was developed a physics-based model for PEF spread that consider the damage to buildings components caused by seismic motion and heating by fire [54–57]. In this model, urban fire is assumed as a group of multiple, fire involved buildings. The fire spread dynamics in an urban area are predicted by simulating the fire behaviors of individual buildings under the influence of adjacent fire-involved buildings. This new approach has several advantages when considering that the built environment is less homogenous than what was considered, and the typical elliptical shape of the fire does not stay the same when it comes to different fuel loads, suppression efforts and other fires. The physics-based models are usually more appropriate across regions and times, and better supported in theory which can lead to better estimates of fire spread [52].

There are studies where the PEF analysis is based on GIS (Geographic Information System) [58–61]. A software system called GisFFE was developed to perform the dynamic simulation of PEF by means of GIS [60]. Three stages of PEF represented in sub-models in the software. There is a model for ignition after an earthquake, a fire-spread model in urban region and a fire suppression model after an earthquake. The first step of the PEF simulation in the software is related to the estimation of the spatial and temporal distribution of ignitions after a large earthquake. The extent and distribution of the ignitions caused by earthquakes have a unique serial behavior and it is analyzed in terms of spatial and temporal modelling of ignition. The second step corresponds to the mechanisms of urban fire spread which can be implemented for either fire spread for a single building or a group of buildings. The fire development and spread for a single building depends on several factors, such as spatial distribution of fuels, room configurations (ventilation conditions and size) and the potential paths for fire spread. For the case of fire spread in a group of buildings, three different mechanisms are expressed which include thermal radiation, thermal plume heating and firebrand spotting. The weather conditions, such as temperature, humidity, rain and wind can have a significant impact on the fire spread and their effects are considered in the software [62].

The fire spread simulation is implemented by means of defining weather conditions for each hour of the total simulation time. After this, there is the definition of the fire stage of the ignited building with the elapse of simulation time and the calculation of the corresponding temperature and heat release rate. The situation of un-ignited buildings is also monitored during the simulation process and once a new building is ignited, the same procedure is carried out until the end of the simulation time. The validation of the fire-spread model is conducted with the simulation of fire-spread that occurred at a real site, located near a hospital in Kobe city after the 1995 Hanshin earthquake in Japan. The results were compared, and it was observed that both the pattern of fire spread, and the number fire buildings are similar. This indicates the reliability of using the software in the simulation of urban mass fire spread. The third and final step of the PEF simulation is related to the fire suppression and relates to the firefighting activities, that starts from the fire discovery and ends with overall control over the fire. The post-earthquake firefighting activities depend on five steps, which are the fire discovery, fire report, fire response, arrival of the fire brigade and fire control where the time is the main element to measure all the steps [62].

There are studies representing hypothetical scenarios where all these steps were performed. Three important results can be obtained from the development of such studies. The first one is related with the statistical spatial and temporal distribution of ignitions, which can serve as a tool to help reveal the potential risk regions and periods of ignitions for a certain city. The second one is related to the assessment of the total burnt areas, which can help the evaluation of the losses caused by PEF. Finally, the third one is related with the statistical results of firefighting time and fire duration time, which can be helpful information for the rescue teams [62]. All these results can be very helpful to identify the main aspects to improve to be able to minimize the impacts of PEF in the urban environment.

Ignition probability and modelling

The earlier post-earthquake fire ignition (PEFI) model was developed according to statistical analyses on PEF damage information from earthquakes in Japan [63]. Later, other PEFI model that was developed was based on earthquake information between 1906 and 1989. This model defined the number of PEFIs per 1000 singles family equivalent dwellings as a linear function of the modified Mercalli intensity. After this, there was the development of the Multi-Hazard Loss Estimation Methodology Earthquake Model (Hazus-MH). This model was based on 30 PEFI data sets from major metropolitan areas caused by 10 earthquakes that occurred between 1906 and 1989. This model estimates the number of ignitions as a quadratic function of PGA.

These types of models are developed based on reduced available earthquake information and cannot predict the PEFI risk for areas with insufficient earthquake records since such records are necessary to estimate the PEFI parameters. To be able to circumvent this aspect there are the studies, for instance, of Farshadmanesh et al. and Zolfaghari et al. which can assess the number of post-earthquake ignitions without the data of past cases of post-earthquake fires [26, 63, 65].

The studies of Farshadmanesh et al. examine the relation between normal condition ignition risk, peak ground acceleration, and PEFI risk to predict post-earthquake ignition events. In this new model, the PEFI is developed as a higher normal condition risk and can be used in regions with moderate to high seismicity with limited PEFI information [26]. Furthermore, there are also studies regarding PEF ignitions in residential buildings. These consist of analytical models for quantifying the vulnerabilities of the residential buildings to PEF by estimating the failure of ignition sources upon a probable seismic event. The study considers the likelihood of ignition occurrence during normal conditions as a baseline and then adjusts the baseline using some parameters to capture spatial characteristics, ignitability, and potential seismic intensity of the study area. In this study, the source of the ignition model is supposed to be caused by malfunction of failure of household appliances or equipment. However, the interference and misbehaviour of the occupant with respect to such appliances are also one of the other factors that may lead to a PEF ignition which has also been included in the study. Other important aspects to consider in PEF ignition evaluation were the acceleration sensitive ignition sources (given a Peak Ground Acceleration (PGA) in its formulation) and drift-sensitive ignition sources. In this case the conditional probability of PEF values is associated with inter-story drift of structure during an earthquake. The conclusion remarks of the study stated that it is crucial to identify the dominant ignition sources and the probability of each ignition source. Moreover, it was indicated that the vulnerability of residential buildings due to PEF could be approximated by means of the probability of normal condition ignition which is evaluated and considered for as an input for the established model. The model allows the identification of common ignition sources. This is an aspect that can be very helpful to planners regarding urban planning and to local code authorities for the investigation of the impact of fire prevention equipment [64].

The studies of Zolfaghari et al. propose analytical approaches towards the estimation of intra-structure PEFI. The models of these studies provide logical relationships between intra-structure PEFI, various buildings components and earthquake ground motions. The model convolutes many controlling factors and their associated uncertainties to estimate the probability of ignition in a certain building. This analytical tool is designed in a open-source GIS platform which allows a strong spatial analyses and effective capabilities of visualization [63, 65].

Recent studies provide new PEFI model that use historical PEF data and a probabilistic formulation. This model provides the probability of ignition of individual buildings and at census tract scale. The model relates probability of ignition in a census tract to PGA, population density, and total building square footage in a census tract. Then, the probability of ignition in a census tract is related to probability of ignition of individual buildings in the census tract based on the building construction type (noncombustible, mobile home and wood). It can be used to identify areas of a community with high risk of PEFI and can also provide a breakdown of ignitions in different building types. The model was validated against historical PEF events and demonstrated good agreement with the historical data [66]. These types of models are helpful because allow the identification of areas of high risk of ignitions, which permits a better management of resources and the development of adequate mitigation measures.

Post-earthquake fire loss assessment

One of the other major consequences of fire effects on urban areas is undoubtedly the economic losses due to the fire spread and destruction of buildings. In countries such as Japan, New Zealand and the USA, since post-earthquake fires have always been a determining factor in property losses and civilian casualties, many studies have been carried out. In a study developed in New Zealand, the PEF damages to urban buildings has been evaluated for three locations which included Wellington City, Napier/Hastings and Dunedin. These areas are in an active seismic region with different levels of hazard probability occurrence (low, medium, high). Among these cities, Napier/Hastings is of special significance because the PEF was the major reason of damages during Hawke's Bay earthquake in 1931. In this study, first the earthquaking shaking losses were estimated and it was followed by the losses due to PEF. The definition of ignition and mean ignition rate depends on the shaking intensity amount. Furthermore, there is a relationship between the shaking intensity increase and the decrease in Fire Service control of fire spreads. In this investigation, for the sake of modelling goals, a scenario was assumed in which the fire can destroy the building of origin, resulting in the loss of $ 300,000 but however, it is assumed that the fire will not spread towards the other buildings. For determining fire losses, a random distribution of ignitions is implemented among the urban buildings and the corresponding losses are summed afterwards. Factors such as wind speed could tremendously make the situation more complicated as the wind is able to carry sparks and burning brands over considerable distances. The results of the investigation stated that for any given return period, the PEF losses in Wellington were 5 times higher than those for Napier/Hastings. It was also observed that the losses for Wellington, Napier/Hastings and Dunedin were, respectively, $24.6 billion, $ 10.1 billion and $ 12.4 billion. The method proved to be very promising for the probabilistic evaluation of PEF losses, even though some areas of uncertainties remain [67].

There is a study developed in the Montreal region regarding the post-earthquake fire risk evaluation and the identification of opportunities to reduce the risk [68]. In this study there were developed three scenario events, a magnitude 6.5 event centered downtown Montreal and magnitude 7 events to the Northwest and Southwest of Montreal. These scenarios caused very strong ground motions in the study area and result in hundreds of fires and hundreds of breaks in the water distribution system. Accounting for water system damage, fire department response, weather conditions, the growth and final burnt area of fires are estimated to result in losses between $10 billion and 30 billion. These are median estimates and there are results of smaller probabilities of greater or less damage [68].

Other similar studies regarding fire loss estimation were also performed on the city of Vancouver in British Columbia province. To evaluate the post-earthquake fire risk and identify solutions to reduce the risk there were five scenarios developed that investigated the number of fires and the amount of fire spread that those scenarios would generate. Two scenarios correspond to distant events, a 9.0 M_w Cascadia Subduction Zone (CSZ) event and a 7.3 M_w event on Vancouver Island (Leech River-Devil's Mountain or LRDM). Three scenarios correspond to relatively nearby events, a deep in-slab 6.8 M_w event on the subducting Juan de Fuca Plate (JDF), a 6.5 M_w shallow crustal event centered on the city of New Westminster (NWM), and a 7.3 M_w event in the Georgia Strait (GS) just to the west of the city of Vancouver. There were developed 100 trials for each scenario to account for uncertainty. The estimation of the corresponding mean losses in each of the scenarios was carried out afterwards. For each scenario there were 1000 realizations developed. The 9.0 M_w CSZ earthquake scenario resulted in, on average for the 1000 realizations, about 15 ignitions and the mean loss for this event was $162 million. The 7.3 M_w LRDM earthquake scenario resulted in a small number of ignitions that did not develop to large fires and the mean loss for this event is negligible. The 6.8 M_w JDF earthquake scenario resulted in about 106 ignitions with 31 of these becoming large fires, mainly due to the lack of water for firefighting. The mean loss for this event was $7.4 billion. The 6.5 M_w NWM earthquake scenario resulted in about 100 ignitions with about half of these becoming large fires also due to the lack of water for firefighting. The mean loss for this event was $10.9 billion. The 7.3 M_w GS earthquake scenario resulted in over 200 ignitions with about 50 of these becoming large fires, mainly related with lack of water for firefighting, and limited number of firefighters and apparatus. The study proposed some ideas for PEF risk mitigation which included the Fire Department improvements in modern and advanced equipment to tackle fire spread. Additionally, it was also recommended that building standards consider the sprinkling system for some of the existing old and low-rise buildings [69].

These types of studies indicate the tremendous impact of a post-earthquake fire scenario in the built environment and can help in the identification of the procedures that can be developed to reduce the risk of fire damage.

Mitigation measures for post-earthquake fire

Introduction

The prevention of major post-earthquake fires depends on excellent requirements regarding earthquake resistance, fire protection, and the guarantee that both active and passive fire protection systems remain functional after a severe earthquake [6, 24, 70]. There are distinct priorities for buildings owners, territorial authorities, and fire services regarding the damage mitigation of post-earthquake fires.

Building owners

Concerning the building owners, it is beneficial to control the fuel and ignition sources by providing lateral restraint, provide handheld firefighting equipment and training and guarantee seismic resistance of water supplies. It is also important to prevent the spread of fire and smoke with passive fire protection systems, ensure seismic resistance of the smoke control systems. It is also recommended the assessment of the seismic performance of fire protection systems, which should be improved if necessary [6].

The communities should develop an integrated response capability and disaster preparedness and should be constantly cautious in sustaining that capability when faced with urban growth and the normal deterioration of the infrastructures [8]. People should be instructed to deal with post-earthquake fires while in the initial stage, using portable hose equipment or any portable fire suppression equipment. Building resident should ensure that all fire-stop doors are closed and should turn off electricity, gas and fuel-burning heaters [5]. The strengthening of the volunteer fire groups, and their additional training improved the efforts of the public in firefighting activities. This type of approach gives attention to the improvement of the public ability to manage disasters by providing training and equipment. Increasing the capability of people instead of increasing the resources available to the fire departments to assist in firefighting activities and rescue possibly results in a significant increase in the overall ability of society to deal with disasters. There should be provided equipment (e.g., fire extinguishers) for the public in areas of high fire risk. An example of this approach is observed in the Shirahige fire station in Japan, where there are 350 volunteer staff which have 4 h training once a month [5, 71]. The reliability of sprinkler systems and automatic fire alarm after an earthquake should be increased by providing appropriate seismic resistance to sprinkler components, pipework, cabinets and panels [5]. The sprinkler system's dependence on the town main water supplies should be reduced by providing on-site stored water and diesel engine pumps [5].

Local Policies

Concerning the territorial authorities, it is beneficial to strengthen underground and aboveground water pipes and services, verify seismic restraints of fire protection equipment and create emergency response plans for vital lifeline services. It is also important to develop strategies for a controlled reinstatement of electricity and gas after an earthquake. Fire-resistant urban environments with control of claddings and vegetation can also be considered. It is also beneficial to develop studies on the engineering lifelines to identify strategies that are expected to increase the survivability of metropolitan areas against fire [6].

There should be an increase in the availability of firefighting water after a major earthquake. This aspect can be achieved with structural improvements in the water systems, such as, the replacement of cast iron and asbestos cement pipes with ductile pipe systems, the implementation of flexible connections and the strengthening of joints and pipes. The establishment of alternative sources of water for firefighting activities in high-risk areas is also an important strategy that should be considered [5]. The shutoff valves should be inspected regularly and the valves that malfunction should be replaced. This aspect will allow to isolate segments of the system after an earthquake, quickly dewater and repair. New constructions and repairs should be made with seismically resistant elements. In the case of buried segmented pipelines, this can be achieved with joint details that allow considerable compression, extension and rotation without failure. Another solution can be the use of shorter pipe segment lengths near elbows, T's, valve boxes, etc. This solution produces more joints per unit of length at those critical areas, and consequently improves the capability to accommodate seismic deformation without failure. The repair items should be stored in earthquake-resistant buildings or in an open yard to facilitate rapid repair after an earthquake [45].

The restoration of gas and electricity can lead to ignitions, which can occur hours to days after the initial disaster. It is important to carefully consider this problematic before the restoration of these utilities [7, 29, 71]. There should be a joint effort between the gas and electricity utilities, emergency rescue and fire service during the restoration of electricity and gas to avoid new ignitions [5, 7]. It could be beneficial to consider how and when should some areas be reconnected, ensure that there are individuals present in every structure before the restoration and that there are standby fire units in place in the area and at the time of the restoration of gas and electricity [7, 29, 71].

It is possible to significantly reduce the post-earthquake fire problem if the gas industry develops a system to install automatic shut-off valves or redesigns meters with seismic shutoffs, particularly in densely built areas. It should be mentioned that the industry in Japan applied these systems proactively after the 1995 Kobe earthquake [2]. An electric shutoff switch that activates during an earthquake would disable a local electric system and allow a certain location to be inspected before the local electric system is re-energised [5]. After a major earthquake, probable large amounts of rubble should be organized to prevent possible ignitions. The piles of rubble should be frequently broken down and should not be kept in a pile for a long period of time. It should also be separated into types based on the tendency to ferment and the ones with higher tendency to ferment should be disposed first. If there is no immediate strategy for the disposal of the rubble, there should be made available on the site fire-fighting equipment. The installation of pipes in piles of rubble could be helpful to release heat and the insertion of thermocouples into the pipes could be useful for the monitoring of the internal temperatures and generated gases [72, 73]. Concerning the fire services, it is beneficial to preserve operational preparedness for a major earthquake, guarantee earthquake resistance of command facilities and fire stations, and plan for alternative water supplies in the likely scenario of street mains failure after an earthquake [6].

The preparation of an emergency response plan is crucial and should include the description of the emergency headquarters, alternative emergency headquarters, line of command, alternative line of command, the purchase of emergency communication devices (i.e., hand-held radios), etc. [45]. There should be an increase in the capabilities for assessing and reporting post-earthquake fire incidents. Utilizing unmanned aerial vehicles (UAVs) for reconnaissance and using cell phone text messaging to report incidents to an emergency portal should be developed and put into practice [2]. Emergency service operations should not rely completely on computers without reliable backup power and there should be frequent development of exercises with computers "down" [29].

The Emergency officials and the public should be aware of the probable lower than ordinary telephone response after a major earthquake and should be prepared to use different communication methods. Emergency officials should have automatic damage reconnaissance plans to be able to adequately allocate resources. The plans can be, for instance, block-by-block "windshield surveys" or aerial reconnaissance. The public should know the location of the nearest fire stations. There can be an improvement in the relations and coordination between the emergency officials and the media personnel. The media's legitimate requirements for information can be burdensome, especially for public information officers not experienced in large-scale disasters. The low-flying aircraft employed by the media has been a worrisome problem for fire officials in past disasters. The media can provide beneficial assistance to emergency operations if there is adequate planning and cooperation. For instance, a rapid aerial damage reconnaissance could be in part accomplished by the media aircraft, which are experienced in aerial reconnaissance and are equipped with video [29].

Post-earthquake fire mitigation activities

The post-earthquake fire mitigation activities can be developed according to two different time perspectives, short-term mitigation actions and a medium-term planning process. The short-term mitigation actions are related, for instance, to the seismic restraint of vulnerable and heavy equipment, such as stoves, tanks, heating units and boilers in industrial, commercial and apartment buildings. The responsibility of the owner for these aspects should be emphasized in the case of new structures. Other short-term mitigation actions are related to the installation of flexible connections for electricity, gas and water mains in regions of high seismicity. These connections should be installed at points of entry into new and retrofitted buildings and at key network junctions.

It is also important the development of integrated processes for the post-earthquake shutting off and restoration of gas and electricity services [5, 74]. Regarding the medium-term planning process, there should be developed a multi-agency at the regional level which can focus on strategies for addressing the post-earthquake fire. The participating agencies should consist of the fire service, civil defence and emergency management agencies, utility organizations (electricity, gas, and water) and research and hazard information contributors. The focus of the agencies should be to ascertain the level of post-earthquake fire risk in the region and if the risk is significant, there should be identified additional measures (medium-term risk reduction measures) beyond the short–term measures mentioned earlier [74]. There are certain areas with considerable potential for post-earthquake conflagrations due to the climatic conditions, landscape, terrain, and building. These areas should be identified in pre-earthquake planning and adequate preparations should be made to minimize the potential for conflagrations [5].

Concluding remarks

Several aspects should be studied to fully comprehend the complex phenomenon of PEF in the built environment. This review article provides insights regarding the historical data of PEF events and summarizes the main conclusions of studies regarding PEF risk analysis, ignition probability and modelling, and PEF loss estimation. It also provided mitigation measures that can be implemented to reduce the risk of PEF in the built environment.

From the work developed, a database of earthquakes that generated at least one ignition was presented and it was observed that the minimum magnitude of the earthquake was 4.9 M_w and the lower intensity was VI. The earthquake with the highest number of ignitions was the Great East Japan Earthquake in 2011 with 348 ignitions. It was also observed that the countries with a higher number of post-earthquake fire events are the USA and Japan. The main and most common observations regarding PEF events are related to the damage in the structures, the origin of the ignitions, the firefighting response, and the damage in the lifelines. Understanding these aspects is crucial to minimize the impact of PEF events.

Some studies related to PEF risk analysis, ignition probability and modelling, and PEF loss estimation were presented and summarized. These studies show an evolution and improvement in the approach and methodologies for the modelling of the PEF in the built environment and indicate that there is still room for new developments regarding several components necessary for PEF analysis.

The works developed regarding the PEF loss estimation clearly show the significant economic losses that such a catastrophic event can have in society. These losses can be reduced with the application of some specific mitigation actions. The mitigation actions should be studied and analyzed to identify the best solutions for a given location. The PEF phenomenon is very complex and involves several different components, from the behavior of the lifelines to the behaviour of the structures, and from the application of mitigation measures to the response of the firefighters and first responders. These different components can be related to one another, and it is important to understand these relationships for the effective development of mitigation measures to reduce PEF risk and losses.

Historically, the two countries with higher impacts regarding PEF are the USA and Japan. Other countries suffered impacts but not as much as these two countries. This does not mean that only these countries should apply measures to prevent and minimize such catastrophic consequences. PEF phenomenon should be adequately analyzed and studied in countries that have seismic concerns and that can be affected by strong earthquakes. It was observed that the appearance of fires after an earthquake can depend on several factors. One can imagine a scenario of two identical earthquakes happening at different hours of the day or on different days of the year having significantly different consequences regarding the fire damage. Although the historical data is valuable to better understand what can happen in the future regarding PEF, it does not serve as a forecast. Some PEF studies should be developed in earthquake-prone countries. These studies can help in the identification of possible problems regarding PEF and then identify and adopt adequate measures to prevent and minimize the consequences.

Finally, it is worth emphasizing that many questions are still open in the field post-earthquake-fire. The significance of this work lies in its comprehensive exploration of various dimensions related to PEF in the built environment. By investigating historical data on PEF events, the paper sheds light on the magnitude and intensity thresholds associated with ignitions, emphasizing the need for nuanced analysis. The work emphasizes the interconnectedness of various components in understanding PEF, from lifeline behaviour to structural responses and firefighting measures. By emphasizing the complexity of the PEF phenomenon and the diverse factors influencing its occurrence, the article urges a proactive and informed approach to minimize the potentially catastrophic consequences of post-earthquake fires globally.

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