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ESTIMATION OF THE COMBINED SEISMIC-FIRE RISK: A CRITICAL REVIEW AND FUTURE RESEARCH AGENDA

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Abstract

The estimation of the combined seismic-fire risk and the optimization of interventions for buildings and infrastructures in the context of metropolitan areas represent a very actual and critical theme. In fact, different forms of hazard can affect structures throughout their existence. The occurrence of a seismic event in areas exposed to various risks or already affected by other phenomena is highly probable, especially in countries characterized by high seismicity. Nevertheless, the seismic safety assessment of existing buildings/infrastructures is commonly carried out considering the seismic action only, generally applied to an analytical model, neglecting the stress-strain state induced by previous phenomena or without considering the cascading effect related to a different hazard, such as a fire induced by the earthquake. The devastating examples throughout history and the high dependency on uncertain factors of urban fires following earthquakes have motivated the proponent research units to study and develop models for estimating the probability of occurrence of this phenomenon, the possible consequences and damage mitigation strategies, starting from the strong expertise of each unit in the seismic and fire fields respectively. Therefore, the paper will focus on the few studies conducted in this field, trying to understand in there is the possibility of extending them to both buildings and infrastructures. In particular, the paper will set the overall methodology for estimating seismic and fire hazard and subsequentially the vulnerability/risk, starting from the definition of the main structural typologies belonging to urban metropolitan areas for both structures and infrastructures. Each class will include infrastructures and buildings sharing common essential features from the point of view of the earthquake and fire resistance. The methodologies will take into account the environment-induced existing damage. In the context of the safety assessment of existing buildings and infrastructures, a pivotal role is played by the possible degradation state of the existing structure, that will be considered in the work. The methodology will be very useful for the classification of building and bridge typology vulnerability against combined seismic and fire risk at metropolitan scale.

Keywords: Fire Risk, Seismic Risk, urban metropolitan areas, fire after earthquake

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1 INTRODUCTION

Fire following earthquake (FFE) is one of the major cascading effects that can occur in seismic affected urban area, indeed despite technological advances, the fire propagation remains a hardly predictable danger [1]. During the history, a lot of fire following earthquake occurred, and in many cases the fires caused more damage than seismic shock. It is possible to indicate the earthquake of San Francisco in 1906, where it was estimated that approximately 80% of the damage in the San Francisco area was caused by post-earthquake fire; about 28.000 buildings were damaged by fire. The earthquake caused structural and non-structural damages: the first damage compromised the integrity of many fire safety systems; non-structural damage hit the major urban lifelines such as water and gas reserves, transport systems, communications and electricity generation and distribution. The Tokyo-Yokohama region was effect by a large earthquake in 1923, which occurred at lunchtime and so many people died because of the fire that broke out while they were cooking; in addition, in the center of Tokyo, a fire occurred in an army clothing store causing the death of 38.000 people. The water system breakdown slowed down the firefighters' intervention, which took nearly two days to extinguish the fires that destroyed about 40% of Tokyo and 90% of the city of Yokohama. In 1931, an earthquake with a magnitude of 7.8 affected New Zealand, in the Napier area. The damage to Napier's water system and the collapse of the Havelock bridge, used to transport the city's water network, made it difficult to tame the fires that interrupted the city's water supplies in no time. Seismic shocks have also damaged electric and gas systems. Three chemists' shops have been identified as the outbreaks and the wind played a fundamental role in the propagation of the city fire. The Niigata earthquake in 1964 had a magnitude of 7.5 and one of the most devastating was the rupture of petrol tanks: the fire spread immediately caused several explosions that fueled the fire until it spread even in the city area. It was one of the worst industrial fires in Japan. The earthquake of Loma Prieta in California caused a lot of fires, caused by the numerous water pipes broken; it was necessary to resort to the use of a fireboat to be able to control the fire.

Therefore, it is clear that the main causes of FFE are linked to short-circuits, abrasions, chemical reactions and other damages caused by shocks to industrial and urban territory; the earthquake can damage not only structures, but also communications, water system and transport networks.

The scenario of fire following earthquake, despite its catastrophic potential, is not yet considered in seismic design. Indeed, the current seismic design provides that ordinary structures are designed to suffer a certain degree of damage during strong earthquakes; to safeguard human lives, the proper ductility of the structure is exploited to collapse and this mechanism causes a vulnerability in the structure when exposed to additional hazards.

All these aspects are studied in literature focusing on the building structure, but a lack of research is evident for the infrastructure like bridges and therefore at urban scale.

Therefore, starting from a critical review, this paper aims to propose a design/verification methodology combined seismic and fire hazards, that is applicable to both building and infrastructure. In particular, a probability-based study considering parameter uncertainties to evaluate the performance of an RC existing structure exposed to seismic actions and fire is conducted. An old RC school building is used as a case study. The idea of this paper consists in assessing the performance of the existing and retrofitted building in terms of both the seismic and fire resistance. It is clear that the seismic retrofit and fire resistance upgrading follow different paths, depending on the specific configuration of the building. A good seismic retrofit does not entail an improving of the fire resistance and vice versa. The goal of the current work is to study the variation of response due to the uncertainties considered in records/fire curves selection, and to carry out the fragility assessment of structures by obtaining fragility curves under the effect of different records/temperature. Moreover, the paper presents a methodology that can be applied to other existing buildings/infrastructures in order to measure the effectiveness of the retrofit operations on seismic and fire resistance performances.

2 CRITICAL REVIEW

In last decades, there has been a growing urban population, with a migration from rural to urban areas. The growing urban population leads to disaster risk being increasingly concentrated in cities. Especially, in low- and middle-income countries, the urban space is structured in a way that accelerates risk inequality, because low-income households are forced to occupy hazard-exposed areas with low land values, with inadequate infrastructure and social protection, as well as high levels of environmental degradation. Therefore, the concept of urban resilience has been developed: the capability of the urban system to prepare, respond, and recover from multi-hazard threats with minimum damage to public safety, economy and security of a given urban area. This definition links with the definition of multi-risk approach, to establish a ranking of different types of risk, considering possible conjoint and cascade effects [2][3].

Motivated by the massive impacts of earthquakes, the seismic risk field has gained popularity. However, little attention has been paid to a potentially highly impacting phenomenon: the interaction between seismic and fire risks. Indeed, historical records have shown that fire ignitions triggered by earthquakes present a significant likelihood of ending up in massively destructive urban fires, as also described in the introduction [4-6]. The devastating examples throughout history [7–9] and the high dependency on uncertain factors of urban fires following earthquakes [10] have motivated the scientific community to develop models for estimating the probability of occurrence of this phenomenon, the possible consequences and damage mitigation strategies [4]. Most models used for estimating post-earthquake fire probability are based on statistical analyses of damage data from recent earthquakes in different countries [11]. A risk management tool is proposed in [12], addressing the issue of the probability of occurrence of post-earthquake fires in historical centres. However, the approach neglects the change of the fire structural vulnerability due to the earthquake-induced structural damages [13]. All the referenced studies refer to fire events in structures, while infrastructures like bridges are not included. Especially in the context of urban environments, fire is a severe hazard to the built infrastructure. Bridge fires are characterized by a high heat release rate, which can result in the temperature rising as high as 1100°C within few minutes. A statistical study conducted by Lee et al. [14] showed that the number of bridges damaged due to fire is significantly more than the number of bridges damaged due to earthquakes. There is also a lack of attention in design codes for bridge fires, which makes the need for the development of performance-based fire design methods. However, designing all bridges for fire is also not appropriate and may increase the project cost substantially. Therefore, bridges at high fire risk are to be identified first. For fire risk assessment of bridges, a framework is required that considers all critical factors affecting the bridge fire risk. Only a few research have been conducted to estimate the bridge fire risk [15]. The level of fire protection required for different bridges can also vary significantly. Therefore, it is required to estimate the correct amount of fire protection for each bridge that is at high fire risk [16].

Therefore, while from the seismic point of view several aspects of the design and verification of buildings and infrastructures have been addressed, a lack of information is evident for the fire aspect both for designing and for seeking more efficient and effective risk mitigation strategies. Miano et al. [17] have shown that a structural intervention for increasing the seismic resistance can have a positive effect also on the fire resistance, changing the whole structural fire vulnerability. This approach should also be extended to infrastructures, with the aim of optimizing structural interventions thus reducing both ambient and economic impacts. Indeed, a very import issue is the amount of resources spent on fire protection, considering that the construction sector dominates the global carbon footprint with a 40% share among all industries. Half of this share is due to the CO_2 embodied in the building elements, and the structural system covers one-third. Fire-protection materials have a major impact on the structural system cost: up to 15% in case of commercial multi storey buildings. Therefore, the optimization of the materials and the structural configuration for maximum seismic and fire performance are crucial to increase both the cost and the environmental efficiencies in the building sector. In this respect, an easy-to-use analytical model could be useful to assess the feasibility and sustainability of building a seismic and fire-resistant structure.

3 CRITICAL ASPECTS FOR BUILDINGS AND INFRASTRUCTURES

This section presents in detail the critical aspects for the estimation of the combined seismic-fire risk, respectively for buildings and infrastructures.

With respect to buildings, the first step is the data on their characteristics acquisition. Particular attention should be dedicated to the buildings' deficiencies and damages. The identification of the data related on both structural (i.e. structural regularity, material properties) and non-structural (i.e. sprinkler systems, ceiling systems and partitions) features that could affect fire and seismic risk. Because in the risk classification of buildings the structural and non-structural elements could affect both vulnerability and hazard definition, the scores assigned to the structural and non-structural features is important to define a unique safety index. The definition of seismic hazard and fire curves for buildings, such as the vulnerability of non-structural elements, such as sprinkler piping systems, ceiling systems and partitions is a focusing point to obtain an accurate estimate of the seismic-fire combined risk. In particular, the non-structural typologies, not only affect the functionality of the buildings but are also of importance in the multi-risk analysis. In fact, the seismic fragility of sprinkler piping system could affect the fire hazard, while the specific features of the ceiling system and partitions installed in the building could modify both fire-vulnerability and seismic losses.

As for the buildings, also for infrastructures a classification of structural schemes and in particular of the types of deck and piers can be of great help in defining the scenarios of damage due to fires below or above the deck when accidents occur and the possible structural consequences, associated with the earthquake. A further possibility that can be investigated is the presence of the gas pipelines below or inside the deck structures, for example when the city's underground utilities are hosted by bridges, as represented below. In fact, the use of the primary infrastructure (bridge) to host the secondary infrastructures (service networks) is becoming widespread. Moreover, the modeling of the single event or the combination of fire-earthquake events depends on the chosen scenarios. Subsequently, the assessment procedure of the hazard can be divided between the case of the accident above or below the bridge from that of the fire induced by the underground services hosted by the infrastructure. In fact, the explosion or fire triggered is profoundly different in the two cases. The fire load curve is therefore related to the type of event as well as the structural consequences and damage are related to the structural type involved.

The influence of structural degradation due to environmental effects or to other hazards [18] on the fire and seismic vulnerability is another aspect to be accounted for. This regards both buildings and infrastructures. Fragility updating procedures can be used to assess the influence of environmental effects on the vulnerability to the single seismic and fire risk and then to the combined risk. The risk assessment can be integrated with data coming from monitoring and from a grading of the state of degradation that can provide a numerical estimate of the modification of the vulnerability. Finally, for both buildings and infrastructures, the optimization of the risk mitigation measurements and choices of the type of retrofit interventions is of paramount importance when dealing with multi-risk analyses. In fact, mitigation strategies that could be obvious to reduce the seismic risk could not be optimal for fire hazard.

4 BRIEF APPLICATION

The case study is a school building. It was built in the '60s in various phases and has a reinforced concrete structural type [19]. The building consists of one level below the ground, two levels above ground and the roof. It should be noted that the first level is placed at about 2.50 m from the foundation floor, measured from the foundation isolated plinths. The other two floors destined to permanent and accidental loads of the classrooms, etc., are about 3.60 m high. The maximum height of the floor, measured at the intrados of the roof ridge, is a about 2.70 m. All floors are of the reinforced concrete slab type with prestressed reinforced concrete and hollow core slab. The building is irregular because, for the first two floors there is an almost L-shaped plan. Instead, the other two floors have a plan approximable to a rectangle. The floor area is around 980 m^2 in the 1st and 2nd floors, while is around 810 m^2 in the 3rd and 4th floors. Figure 1a shows a view of a typical floor of the building.

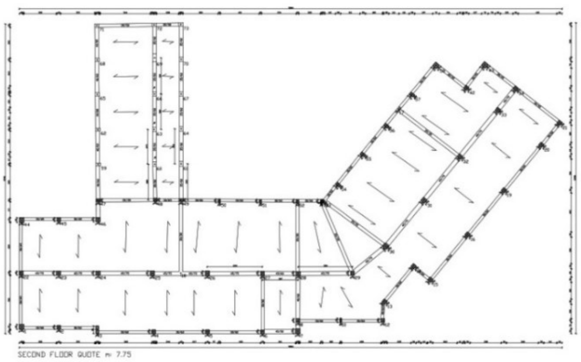


Fig. 1 Typical floor view of the building.

4.1 Proposed methodology

With regards to seismic assessment and retrofit fragility analysis, Cloud Analysis is used [20-24]. Once the ground motion records are applied to the structure, the critical demand over capacity ratio for the selected limit state (DCR_{LS}) is found [25]. This provides a set of values that form the basis for the cloud-method calculations. The statistical properties of the cloud response are calculated through a logarithmic linear regression applied to the response. This is equivalent to fitting a power-law curve to the cloud response in the original (arithmetic) scale. This results in a curve that finds the median drift demand for a given level of acceleration:

$$\eta_{DCR|Sa}(Sa) = a \cdot Sa^b$$
$$\ln(\eta_{DCR|Sa}(Sa)) = \ln(a) + b \cdot \ln(Sa) \quad (1)$$

where ln(a) and b are regression constants. The logarithmic standard deviation $\beta_{DCR|Sa}$ is the root mean sum of the square of the residuals with respect to the regression prediction:

$$\beta_{DCR|Sa} = \sqrt{\frac{\sum(\ln(DCR_i) - \ln(a \cdot S_{a,i}{}^b))^2}{N-2}} \quad (2)$$

where DCR_i and $Sa_{,i}$ are the demand over capacity ratio values and the corresponding Sa for record number i within the cloud response set and N is total number of records. The standard deviation of regression, as introduced in the preceding equation, is presumed to be constant with respect to Sa over the range of Sa in the cloud. Finally, the structural fragility curves based on the Cloud Analysis can be expressed as:

$$P\left(DCR > 1 \middle| S_a\right) = P(\ln DCR > 0 | S_a) =$$
$$1 - \Phi\left(\frac{-\ln \eta_{DCR|S_a}}{\beta_{DCR|S_a}}\right) = \Phi\left(\frac{\ln \eta_{DCR|S_a}}{\beta_{DCR|S_a}}\right) \quad (3)$$

With regards to fire assessment and retrofit fragility analysis, in Italy, the new Code for Fire Safety, in accordance with European codes, defines five safety performance levels (Table S.2-1: Council Directive 1988) depending on the importance of the building:

Level I: no external consequences for structural collapse;

Level II: maintaining the fire resistance requirements for a period of time sufficient for the evacuation of occupants.

Level III: maintaining the fire resistance requirements for the natural fire duration;

Level IV: limited damage of the structure after fire exposure;

Level V: complete serviceability of the structure after fire exposure.

Also here, as described before for the seismic procedures, for each analysis, the corresponding critical demand to capacity ratio (DCR) is adopted as the structural response parameter. The formulation of the DCR_{PL} parameter is based on the cut-set concept, as previously described for the seismic performance evaluation, and accounts always for the first excursion of the performance level (PL).

With reference to the Level 4, C is the component displacement capacity, denoted as ΔC, L4, and identified as the displacement capacity corresponding to the achievement of the value of 1/100 of the length of the components (in this case beams or columns).

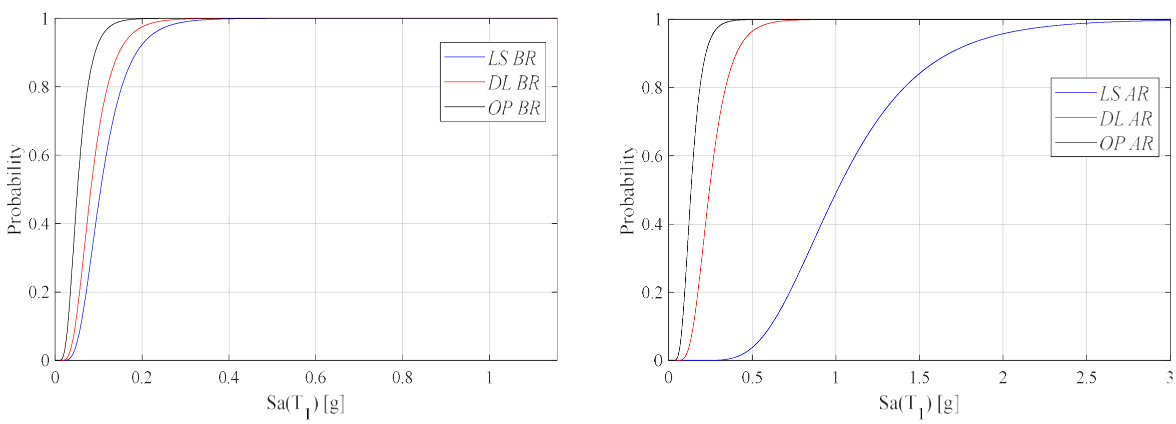
As analysis procedure, multiple stripe analysis (MSA) is chosen [26]. In the MSA procedure, a suite of different buildings (defined by different ventilation factors O) are subjected to increasing fire loads levels. At each level, the statistics of the structural response such as median, logarithmic standard deviation, and probability of collapse can be estimated. The methodology adopted to derive the fragility curves related to fire resistance of the building is originally proposed by Baker [26]. The analysis is conceptually the same of the one used in seismic engineering. It can also be seen as the equivalent of an incremental dynamic analysis (IDA). In fact, since the potential buildings analyzed through the different steps are the same, MSA and IDA are practically the same. In particular, a set of potential buildings with different opening factors (O) is analyzed. These buildings are subjected to increasing fire loads (QF) from a minimum of 100 MJ/m^2 to a maximum of 1750 MJ/m^2, with a time step of 150 MJ/m^2, having a total number of 10 steps. After the application of the retrofit operations on the case study building, these plausible buildings (defined by different ventilation factors O) are regenerated. These retrofitted buildings are subjected to increasing fire loads (QF) from a minimum of 100 MJ/m^2 to a maximum of 1900 MJ/m^2, with a time step of 150 MJ/m^2, having a total number of 11 steps. At each level, the statistics of the structural response such as median, logarithmic standard deviation, and probability of collapse can be estimated. The MSA-based fragility herein is estimated by following the procedure in Baker [26], in which a bi-parametric logarithmic fragility model is fitted through a maximum likelihood method to the fragility function. More, specifically, the two parameters $\eta Q|_{DCRPL=1}$ and $\beta Q|_{DCRPL=1}$ of the Lognormal fragility can be estimated by the maximum likelihood estimates. The likelihood for MSA can be calculated (assuming independent observations) as the product of the likelihood for each stripe:

$$\{\eta_{DCR},\beta_{DCR}\} = \arg\max \left\{ \prod_{i=1}^{N_{stripe}} \binom{N_i}{r_i} \Phi\left(\frac{\ln\left(x_i / \eta_{DCR} \right)}{\beta_{DCR}} \right)^{r_i} \left[1-\Phi\left(\frac{\ln\left(x_i / \eta_{DCR} \right)}{\beta_{DCR}} \right) \right]^{N_i-r_i} \right\} \quad (4)$$

where N_{stripe} is the total number of stripes (fire loads levels); Ni is the number of potential buildings defined by different O factors for stripe i; r_i is the number of potential buildings in stripe i for which $DCR_{PL}>1$.

4.2 Results

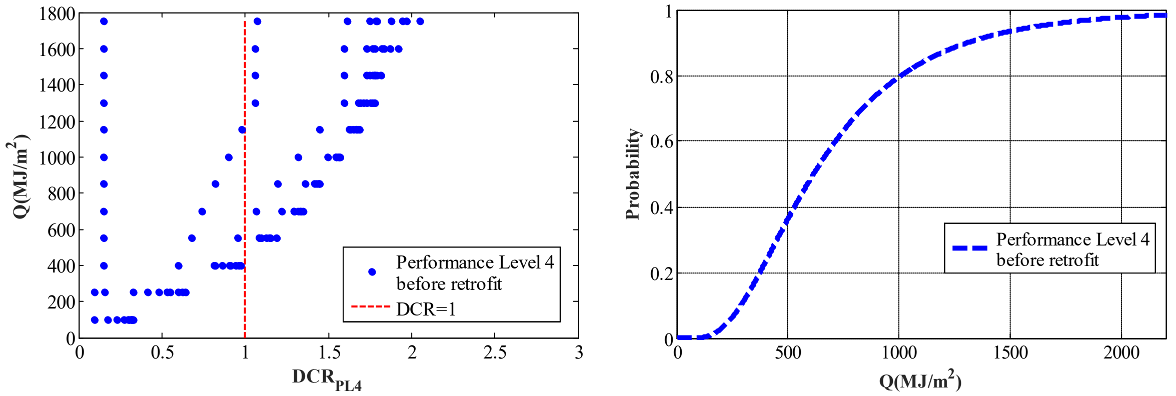
Figures 2 (a,b) show the Cloud Analysis-based fragility curves (based on Equation 3), obtained by employing 30 records for three limit states [18]. The record selection is a very critical issue in the implementation of non linear dynamic analysis procedures. Herein, a set of 30 strong ground-motion records is selected from the NGA-West2 database (see [20] for the details about the criteria for record selection) in order to implement Cloud Analysis. This suite of records covers a wide range of magnitudes between 5.6 and 7.2, and closest distance-to-ruptured area (R_{RUP}) up to around 40 km. Only one of the two horizontal components of each record is considered. The records are free field or measured on the ground level. The Cloud Analysis-based Fragility curves are shown with the following colours: i) black for the Operational (OP) Limit State ; ii) red for the Damage Limitation (DL) Limit State; iii) black for the Life Safety (LS) Limit State. In Figure 2a, the curves are related to the before retrofit (BR). Figure 2b, instead, represents the after retrofit (AR) condition. More details about limit states, modeling and retrofit option are given in Miano et al. 2020.



(a) (b)

Figure 2: (a) Fragility curves for OP, DL and LS limit state before retrofit; (b) Fragility curves for OP, DL and LS limit state after retrofit.

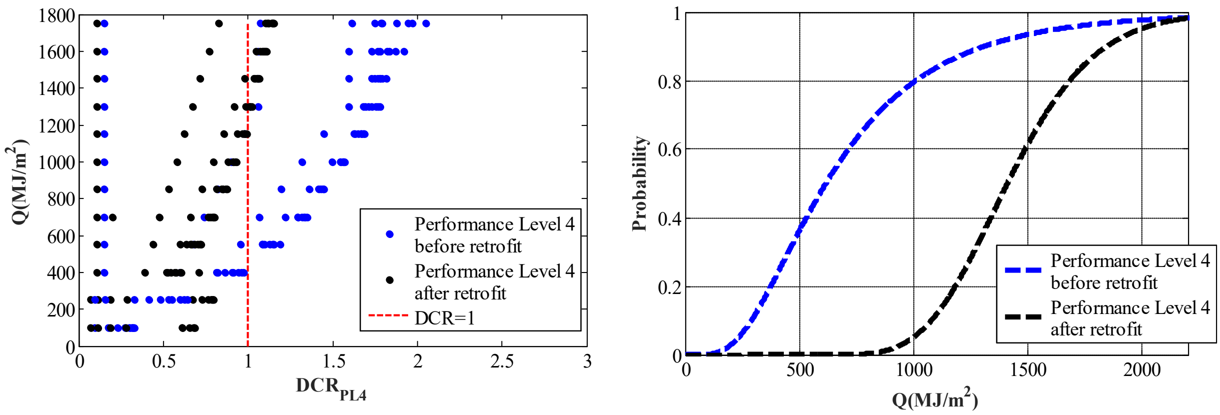
Figure 3a shows MSA raw data (Q-DCR_{PL}) for which the analyses are performed up to QF amplitudes where at least a consistent part of the potential (with different O factors) buildings cause exceedance of the PL. Figure 3b illustrates the MSA-based fragility curve obtained by method of “Baker 2015”.



(a) (b)

Figure 3: a) MSA results before retrofit operations for PL 4; b) Fragility curve before retrofit operations for PL 4.

Figure 4a shows MSA raw data (Q-DCR_{PL}) for which the analyses are performed up to Q amplitudes where at least a part of the potential (with different O factors) retrofitted buildings cause exceedance of the PL. Figure 4b illustrates the MSA-based fragility curve obtained by method of "Baker 2015" before and after retrofit for the PL 4.



(a) (b)

Figure 4: a) MSA results before and after retrofit operations for PL 4; b) Fragility curves before and after retrofit operations for PL 4.

5 CONCLUSIONS

The estimation of the combined seismic-fire risk and the optimization of interventions for buildings and infrastructures in the context of metropolitan areas represent a very actual and critical theme. In fact, different forms of hazard can affect structures throughout their existence. The occurrence of a seismic event in areas exposed to various risks or already affected by other phenomena is highly probable, especially in countries characterized by high seismicity. Nevertheless, the seismic safety assessment of existing buildings/infrastructures is commonly carried out considering the seismic action only, generally applied to an analytical model, neglecting the stress-strain state induced by previous phenomena or without considering the cascading effect related to a different hazard, such as a fire induced by the earthquake. Therefore, starting from a critical review, this paper aimed to propose a design/verification methodology combined seismic and fire hazards, that is applicable to both building and infrastructure. In particular, a probability-based study considering parameter uncertainties to evaluate the performance of an RC existing structure exposed to seismic actions and fire is presented. It is shown that the seismic retrofit and fire resistance upgrading follow different paths, depending on the specific configuration of the building. However, a good seismic retrofit does not entail an improving of the fire resistance and vice versa. The work studied the variation of response due to the uncertainties considered in records/fire curves selection, and to carry out the fragility assessment of structures by obtaining fragility curves under the effect of different records/temperature. Moreover, the paper presented a methodology that can be applied to other existing buildings/infrastructures in order to measure the effectiveness of the retrofit operations on seismic and fire resistance performances.

REFERENCES

[1] Lesbo C. (2018) Fire Following Earthquake, PhD. Thesis, Department of Architecture and Design Architecture for Sustainable Project, Politecnico di Torino

[2] Coaffee, J. (2008), "Risk, resilience, and environmentally sustainable cities", Energy Policy, Vol. 36 No. 12, p. 4635.

[3] United Nations Office for Disaster Risk Reduction(2009), Global Assessment Report on Disaster Risk Reduction: Risk and Poverty in a Changing Climate, Geneva, available at: www.preventionweb.net/gar

[4] Della Corte G., Landolfo R., Mazzolani F.M.(2003). Post-earthquake fire resistance of moment resisting steel frames. Fire Safety Journal, 38, 593-612, https://doi.org/10.1016/S0379-7112(03)00047-X.

[5] C. Scawthorn, Fire following earthquake, Fire Saf. Sci. 1 (1986) 971–979, https://doi.org/10.3801/IAFSS.FSS.1-971.

[6] J.C. Schencking, The Great Kanto Earthquake and the culture of catastrophe and reconstruction in 1920s Japan, J. Jpn. Stud. 34 (2) (2008) 295–331, https://doi.org/10.1353/jjs.0.0021.

[7] K. Himoto, Comparative analysis of post-earthquake fires in Japan from 1995 to 2017, Fire Technol. 55 (3) (2019) 935–961, https://doi.org/10.1007/s10694-018- 00813-5.

[8] N. Elhami Khorasani, M.E.M. Garlock, Overview of fire following earthquake:historical events and community responses, Int. J. Disaster Resil. Built Environ. 8(2) (2017) 158–174, https://doi.org/10.1108/IJDRBE-02-2015-0005.

[9] M. Kobayashi, "Urban post-earthquake fires in Japan, Proc. U.S.-Japan Work. Urban Earthq. Hazards Reduct. (1985) 121–133.

[10] T. Nishino, T. Tanaka, A. Hokugo, An evaluation method for the urban post-earthquake fire risk considering multiple scenarios of fire spread and evacuation, Fire Saf. J. 54 (Nov. 2012) 167–180, https://doi.org/10.1016/j. firesaf.2012.06.002.

[11] M.R. Zolfaghari, E. Peyghaleh, G. Nasirzadeh, Fire following earthquake,intra-structure ignition modeling, J. Fire Sci. 27 (1) (2009) 45–79, https://doi.org/10.1177/0734904108094516.

[12] P. B. Julià T. M. Ferreira, H. Rodrigues, Post-earthquake fire risk assessment of historic urban areas: A scenario-based analysis applied to the Historic City Centre of Leiria, Portugal, International Journal of Disaster Risk Reduction 60 (2021) 102287, https://doi.org/10.1016/j.ijdrr.2021.102287

[13] S. Li, R.A. Davidson, Parametric study of urban fire spread using an urban fire simulation model with fire department suppression, Fire Saf. J. 61 (Oct 2013) 217–225, https://doi.org/10.1016/j.firesaf.2013.09.017.

[14] Lee GC, Mohan SB, Huang C, Fard BN. A study of US bridge failures (1980-2012).

[15] M.Z. Naser, V.K.R. Kodur , (2015) A probabilistic assessment for classification of bridges against fire hazard, Fire SafetyJournal76(2015)65–73, http://dx.doi.org/10.1016/j.firesaf.2015.06.001

[16] Garlock M, Paya-Zaforteza I, Kodur V, Gu L. Fire hazard in bridges: Review, assessment and repair strategies. Eng Struct 2012;35:89–98. https://doi.org/10.1016/j.engstruct.2011.11.002.

[17] Miano, A., de Silva, D., Compagnone, A., Chiumiento, G. (2020), Probabilistic seismic and fire assessment of an existing reinforced concrete building and retrofit design. Structural Engineering and Mechanics, Vol. 74, Num. 4, p. 481-494. DOI: http://dx.doi.org/10.12989/sem.2020.74.4.481.

[18] Miano, A, Mele, A, Prota, A (2022). Fragility curves for different classes of existing RC buildings under ground differential settlements. Engineering Structures, 257, 114077.

[19] Miano, A., & Chiumiento, G. (2020). Case study on seismic retrofit and cost assessment for a school building. Structural Engineering and Mechanics, An Int'l Journal, 73(1), 53-64.

[20] Jalayer, F., De Risi, R., & Manfredi, G. (2015). Bayesian Cloud Analysis: efficient structural fragility assessment using linear regression. Bulletin of Earthquake Engineering, 13, 1183-1203.

[21] Jalayer, F., Ebrahimian, H., Miano, A., Manfredi, G., & Sezen, H. (2017). Analytical fragility assessment using unscaled ground motion records. Earthquake Engineering & Structural Dynamics, 46(15), 2639-2663.

[22] Miano, A., Sezen, H., Jalayer, F., & Prota, A. (2017, June). Performance based comparison of different retrofit methods for reinforced concrete structures. In Proceedings of the 6th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2017).

[23] Jalayer, F., Ebrahimian, H., & Miano, A. (2020). Intensity-based demand and capacity factor design: A visual format for safety checking. Earthquake Spectra, 36(4), 1952-1975.

[24] Jalayer, F., Ebrahimian, H., & Miano, A. (2021). Record-to-record variability and code-compatible seismic safety-checking with limited number of records. Bulletin of Earthquake Engineering, 19(15), 6361-6396.

[25] Jalayer, F., Franchin P., and Pinto P., (2007), "A scalar damage measure for seismic reliability analysis of RC frames", Earthq Eng Struct Dyn, 36(13): 2059-2079. https://doi.org/10.1002/eqe.704.

[26] Baker J.W., (2015), "Efficient analytical fragility function fitting using dynamic structural analy" , Earthq Spectra, 31(1):579 - 599. https://doi.org/10.1193/021113EQS025M.