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Urban Infrastructure Resilience to Fire Disaster: An Overview

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Abstract

Fire disasters are a serious threat to the functionality of the built environment, in particular in densely populated urban areas where city infrastructure systems are under strain. Yet, fire safety issues are still mostly considered at the level of individual elements or buildings, disregarding the global risk for systems' functionality. In line with the current efforts toward ensuring more resilient cities, this paper presents an overview of urban infrastructure resilience to fire disaster. The definitions of resilience and the quantitative frameworks established for other hazards such as earthquakes are reviewed. Then, the specificities of structural fire engineering are presented and it is shown how resilience frameworks could be applied to fire hazard. Finally, the paper identifies areas where further research efforts are needed.

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Keywords: urban resilience; disaster mitigation; fire hazard; critical infrastructure; literature review; risk management;

1. Introduction

The concept of disaster resilience has gained increasing attention over the past years. With urban population growing at a record pace, city infrastructure systems are under strain and disruptions due to hazardous events need to be minimized. For a society, this calls for the necessity to develop mitigation plans, be prepared, be able to withstand, and to rapidly recover from such disruptions. Among man-made disasters and natural hazards, fire is a serious threat

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to the functionality of the built environment and can severely damage different infrastructures (e.g. bridges, buildings, etc.), disturbing a city's ability to deliver a proper service to the community. Despite its importance, fire safety issues are still mostly considered at the level of individual elements, disregarding possible cascading effects and global impact on the system functionality. In this context, this paper aims at reviewing the applications of resilience framework to other types of hazards and at presenting an overview of urban infrastructure resilience to fire disaster.

2. Resilience framework

The concept of resilience has been evolving in the past few years. Ayyub [1] provides a comprehensive review of existing definitions for the term resilience in the literature:

- In the U.S. Presidential Policy Directive [2] on Critical Infrastructure Security and Resilience, the term resilience means "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions."
- The U.S. National Research Council [3] defined resilience as the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events as a consistent definition with U.S. governmental agency definitions.
- Bruneau et al. [4] investigated a conceptual framework for seismic resilience that is also useful for a coordinated research effort, and listed characteristics of resilience to include robustness, redundancy, resourcefulness, and rapidity.

The most current resilience framework, as it applies to the context of community performance in case of a disturbance, is shown in Fig. 1.

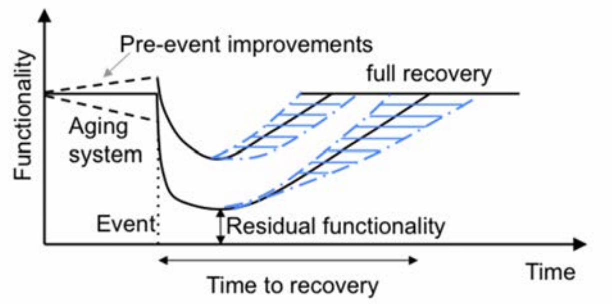

Fig. 1. Resilience framework adopted from [4]-[6].

The figure shows that with time, the community may maintain the level of functionality, enhance the level by improving the status of different components/systems, or experience a decline in functionality due to aging. A sudden shock to the community (such as an earthquake, hurricane, man-made disaster, etc.) causes a sudden drop in the operability of the systems in the community. Resilience is related to the residual level of functionality after the event and to the restoration time to return to normal operation. At times, during restoration and repairs, the community may return to a functionality level higher than that of prior to the disturbance.

3. Implementation of resilience framework for hazards other than fire

Community resilience to disaster has been primarily investigated for events that significantly affect wide areas and test the community on a large scale, e.g. earthquakes, tsunamis or flooding. In earthquake engineering, ensuring residual functionality and rapid recovery is now recognized as an essential objective in addition to limiting fatalities and direct damage to buildings and infrastructures. This was exemplified by the full recover and rebuilding of the area struck by the L'Aquila earthquake in 2009 [7]. In this context, many research works have been conducted to quantify the seismic resilience of communities. For instance, Cimellaro et al. [8] provided a framework for quantitative definition of resilience using an analytical function that can fit both technical and organizational issues. The methodology was applied to two health care facilities. Franchin and Cavalieri [9] presented a novel metric of network-based resilience that focuses on the evolution of efficiency of communication between citizens during the reallocation of displaced population after the event. Similar issues are investigated as regards to flooding, e.g. Harrald [10] developed models and measures to predict and compare the resilience of coastal communities' subject to potential catastrophic coastal flooding.

At a more localized scale, Quiel et al. [11] tackled resilience with respect to blast loading. He proposed a framework that focuses solely on the amount and severity of damage inflicted by a hazard event, so that it is accessible to structural engineers in practice, assuming then that resilience can be inferred by correlating the amount of required recovery to the extent of damage.

Ensuring resilience to various disasters has thus become a major goal for structural engineers. It is useful to adopt a common definition and general framework for resilience independently of the hazard considered. However, in-depth analyses leading to development of recommendations and reformulation of design codes demand consideration of the specificities of each type of hazard.

4. Specificities of structural fire engineering

The resilience framework requires evaluating the direct consequence of the disaster, which in the case of fire engineering is the performance of the structure against fire hazard. Three problems have to be solved when modelling the behaviour of a structure subjected to fire: 1) fire development, yielding the gas temperature evolution in the vicinity of the structure; 2) heat transfer process, yielding the temperatures in the structural elements; and 3) thermo-mechanical response, yielding the behaviour of the structural system, i.e. stresses, deflections etc. A brief review of the three problems in the fire engineering practice is reported here below.

In a prescriptive approach, the fire development is defined by nominal temperature-time curves, such as the ISO 834 heating curve [12]. Conversely, in a performance-based approach, the models aim at deriving physics-based thermal actions to capture more closely the real situation. Different modelling strategies are available depending on the problem features. In buildings, compartment fire models can be adopted under certain assumptions. These include the simplified parametric temperature-time curves of EN1991-1-2 [12] or the more advanced zone models, which are based on the differential equations for energy and mass balance. When flashover is unlikely to occur, for instance in large open spaces, localized fire models such as the Hasemi model should be preferred. Finally, computational fluid dynamics models may be employed to analyse specific and/or complex configurations. Performance-based models have the advantage of modelling the full fire development including the cooling phase until burnout.

The heat transfer process considers conduction through the structural member cross sections and convection and radiation at the boundaries between the members and the environment. Simplified finite difference method (i.e. lumped mass) are available for members and materials for which the thermal gradient through the section is negligible (e.g. slender steel profile). For concrete material, the lumped mass method can also be utilized but the cross section must be divided into separate zones. Tabulated values have been derived for cross sections subjected to standard or equivalent fire curves. For all fire regimes, material types and irregular geometries, advanced methods such as the finite element (FE) method can be utilized.

The fire load causes the material temperature to change, which creates changes in the material stress-strain curves as well as internal forces due to thermal elongation. The thermo-mechanical response can be estimated in structural member, system or community level approaches. The most traditional member level approach is to use standard fire resistance ratings to quantify the behaviour of isolated structural members during fire. In a system approach, the interactions of members within the structure are considered. The community level approach aims at considering different types of structures and evaluating the overall resilience to fire hazard [13]-[14]. Simple calculation models have been proposed to assess performance of isolated members, however, due to high nonlinearities in material and geometry, advanced numerical methods are required for studying fire performance of structural systems.

Given the high level of uncertainties in parameters involved in analysing structures in fire (such as fire load or materials properties), the research community has moved towards probabilistic frameworks to estimate the probability of structural failure. For example, Guo and Jeffers [15] provided a comparison between the first/second order reliability methods and Monte Carlo approach for a protected steel member under fire. In addition, the probability of occurrence of the fire must be evaluated for potential fire locations. When quantifying robustness of the structural system to a given fire scenario, the structural damage state and the intensity of the hazard must be defined [16]. Yet, there is no consensus in the literature and this question remains critical for the overall resilience assessment of structures.

5. Resilience to fire hazard

A recent study by NRC [17] has highlighted the vulnerability of critical infrastructures, such as border crossing bridges and tunnels, or government buildings, to extreme fires. To improve resilience, the study notably recommends incorporating property protection of critical infrastructures within the fire safety requirements, in addition to the current objectives of life safety. The role of first responders during and after fire should also be further studied to improve their safety and train them to reduce the fire damage, which would allow reducing the recovery time after a fire event.

Infrastructure resilience to fire can be evaluated based on a three-stage analysis of the infrastructure resistive, absorptive and restorative capacities [18]. First, the resistant capacity in the context of fire disaster reflects the capability to prevent the occurrence of fire and to limit the initial damage should a fire occur. Risk management methods still need to be developed to identify the most effective measures to increase the resistant capacity of an infrastructure. Examples of measures include the limitation of fire load, the use of active fire protection systems (sprinklers), or application of passive protection (insulation) to key structural elements. Second, the absorptive capacity focuses on cascading effects and damage propagation in the system. The aim is to limit the maximum impact of the fire in order to maintain the largest possible level of residual functionality (Fig. 1). This can be achieved through robust structural design to fire, which allows to limit the contribution of indirect risk to the total risk [16]. Third, the restorative capacity is linked to the time to recovery after fire (Fig. 1). Resilient systems have the ability to be repaired quickly and efficiently. In case of infrastructure subjected to fire, an example of key issue is the assessment of the damage level and residual load-bearing capacity after fire. This assessment impacts the repair decisions and hence the time to restore functionality. Recent research has explored this question [19] but additional efforts are required to facilitate efficient and swift reinstatement of functionality after fire.

6. Conclusions

The paper presents an overview on urban community resilience to disasters. Fire disaster in an urban infrastructure could have devastating effects to the community. To access the resilience against fire, a framework inspired by other major hazards that affect wide areas such as earthquake is recommended. The framework should be based on resistive, absorptive and restorative capacities to enhance the infrastructure resilience by minimising the impact of the fire on residual functionality and length of recovery. The key issue is to provide a framework that is capable of quantitatively estimating the system resilience by relying on engineering parameters that can be used in the design process by practitioners.

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