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Resilience assessment of complex urban systems to natural disasters: A new literature review

Katarina Rus, Vojko Kilar, David Koren*

University of Ljubljana, Faculty of Architecture, Zoisova cesta 12, SI – 1000 Ljubljana, Slovenia

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ABSTRACT

In parallel with the observed greater frequency of natural disasters worldwide, there has been an ever-increasing interest in urban resilience and its assessment. Experience obtained in recent extreme events (in particular, earthquakes and floods) has revealed that both the level of preparedness and the response of affected cities were insufficiently high, whereas the recovery process was long and expensive. For this reason improved pre-disaster mitigation actions, as well as smart and strategic urban planning in threatened areas (e.g. in earthquake-prone regions), is essential. For this purpose, a comprehensive review of the existing literature has been performed in relation to the holistic assessment of urban system resilience to natural disasters, with an emphasis on the effect of earthquakes. The main goal of the review was to try to determine how to best assess the resilience of urban systems as a whole, taking into account all of their components, i.e. both the physical components (i.e. of buildings, infrastructure, and open spaces) and the social components (i.e. of the community), as well as the dynamic interactions between them. Besides considering the commonly measured indicators (e.g. determination of the scope of actual structural damage caused by an earthquake), the paper tries to extend the discussion to some indicators which are not so commonly taken into account, by applying a quantitative resilience assessment approach. Based on the results of the described new literature review, a preliminary concept which could be used to assess the seismic resilience of complex urban systems, taking into account all urban components which have been identified as having an important impact on the latter, is presented. This concept consists of three different parts: (i) a probabilistic fragility analysis for each individual physical element (i.e. a building or an infrastructure element), (ii) a composite index methodology for the measurement of community disaster resilience, and (iii) a complex network approach (graph theory) for the assessment of the resilience of urban systems as a whole. Since, in the existing literature, there is a lack of consideration of urban open space, which can have a significant role in the recovery process, it is suggested that, in future research of seismic resilience assessment, such open space should be taken into account, and that an in-depth study of possible recovery strategies be performed.

1. Introduction

In recent decades the frequency of occurrence of natural disasters, and the extent of their devastating impacts, both economic and to humankind, have, according to [1–3], shown almost exponential growth. These facts can be mostly attributed to poor urbanization strategies, and the worsening effects of climate change. Worldwide, between 2006 and 2015, natural disasters, on average, annually affected approximately 224 million people, killing almost 70,000 of them, and simultaneously causing more than US$ 135 billion in damage [4]. As the present trends of population growth and urbanization continue, it can be expected that more and more people will be exposed and that assets will be more concentrated in risk-prone areas. Today, more than half of the world's population lives in cities, and it is expected that, by 2050, up to 75% will do so [5,6]. This means that there is an ever-increasing need for special attention to be paid to risk mitigation and the adaptation of urban systems.

As a result of the above-mentioned threats, the notions of urban resilience and resilient cities have recently raised interest among both practitioners and researchers. The term 'resilience' is derived from the Latin word 'resiliere', which means "to bounce back" [7,8]. With its roots in physics and mathematics, the concept was originally used to indicate the capability of a material or system to return into balance after being displaced [9]. Holling [10] used the term resilience to describe the capacity of a natural ecosystem. He defined ecological resilience as the persistence of relationships within a system and a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist. Later the term

* Corresponding author.
E-mail address: david.koren@fa.uni-lj.si (D. Koren).

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resilience was more widely applied to other scientific fields (ecology, materials science, social science, economics and engineering), and today it is still evolving. Thus, during the last few years several interpretations of resilience have been proposed, depending on different scientific approaches and the fields involved. Researchers and theorists dealing with resilience try to find answers to the fundamental questions: resilience for whom, what, when, where and why [11,12]. In the literature two dominant theoretical perspectives have been identified: socio-ecological and engineering. While the socio-ecological perspective considers resilience as a process-oriented phenomenon (a dynamic concept), the engineering perspective views resilience as a result-oriented concept (a static premise). Based on this aspect, the engineering approach understands the term resilience as bouncing back to the same (stable) condition before an adverse event, whereas the socio-ecological approach denotes adaptive resilience, such as how to respond to, recover from, and adapt to new conditions. As such, an ecological approach allows the existence of different equilibrium conditions achievable by the system after potential disruptions [3]. According to the study by Asadzadeh et al. [12], the theoretical background of disaster resilience measures can be distinguished based on their semantic completeness (why resilience), measurement focus (resilience for when), and operationalized domain (resilience of what):

- The semantic completeness of disaster resilience frameworks is characterized by a distinction between their attitudes toward the term resilience (a static or result-oriented vs. dynamic or process-oriented concept);
- The measurement focus of resilience frameworks can be classified into: (i) measuring the recovery and stability of communities by focusing on the return time and efficiency of characteristics (*engineering resilience*), (ii) capturing the persistence (robustness) level of communities by focusing on buffering capacity, withstanding shocks, and maintaining functions (*ecological resilience*), and (iii) measuring adaptive capacity, as well as learning, and transformability (*socio-ecological resilience*), which enable communities to respond successfully to, recover from, and adapt to new conditions;
- The operationalized domain of disaster resilience measurement frameworks endeavour to measure either (i) the characteristics of systems (evaluation of the unique quantities of some attributes in communities without any evaluation of quality that makes them different from others) or (ii) the capacities within them (evaluation of quality performance or the ability of systems or community elements).

A general definition of resilience was published by the National Academies Press referring to resilience as "the ability to prepare and plan for, absorb, recover from and more successfully adapt to adverse events" [13,14]. Another definition was proposed by the United Nations: "Resilience is the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner including through the preservation and restoration of its essential basic structures and functions" [2,15,16]. Social resilience is understood as the capacity or ability of a community to anticipate, prepare for, respond to, and recover quickly from the impacts of disaster [16]. One recent engineering-based approach has defined resilience as a system's coping capacity and ability to withstand or adapt to external shocks, along with the effects of pre-disaster preparedness and adaptive response actions that can be quickly taken in the disaster's aftermath in order to recover efficiently and effectively [17,18].

The concept of a "resilient city" combines both of the above-mentioned aspects, i.e. the engineering-based aspect and the socio-ecological-based concept. According to Godschalk [19], a resilient city is a sustainable network of physical systems and human communities, capable of managing extreme events; during disaster this network must be able to survive and function under extreme stress. Bozza et al. [20] defined urban system resilience as the capacity of a complex system, composed of non-homogeneous components interacting and coexisting, to withstand an external stress and bounce back to an equilibrium state or bounce forward to new equilibrium states (improved conditions). Whether bouncing back to a pre-disrupted condition is the most favoured option or not is a matter for debate. The interpretation of resilience as bouncing back as a positive outcome can be identified as "elastic" resilience, whereas the recent approach of resilience implementing uncertainty and adaptation can be defined as "ductile" resilience [3]. In accordance with the mechanical definition of elastic behaviour of a material (the elastic branch in the stress-strain diagram), "elastic" resilience interpretation seeks to regulate a return to the pre-existing equilibrium (the static concept of resilience). Conversely, the "ductile" resilience interpretation – in parallel with the nonlinear behaviour of the material exhibiting large deformations at a certain level of stress – is no longer about returning to the equilibrium or maintaining the status quo, but is seen as a process of on-going self-transformation that can be likened to bouncing forward (the dynamic concept of resilience). According to Chandler and Coaffee [21], the first generation of resilience thinking (i.e. the static concept) could be understood also as a "homeostatic" approach, whereas the second generation of resilience (i.e. the dynamic concept) can be recognized as a "autopoietic" approach. In the latter, bouncing back is not the aim but rather growth and development, through an increased awareness of interconnections and processes.

Based on all of the above-mentioned different approaches and definitions, it is clear that the notion of resilience has a broader meaning than just the capacity to resist an external disturbance. This means that it should therefore be distinguished from the concepts of "resistance", which refer to the force required to displace a system from equilibrium, whereas resilience refers also to the time required for the system to return to equilibrium once displaced [9,22]. The time dimension [2,9,22–24] is essential when considering the concept of resilience as a process before a disaster occurs, at the time of disaster occurrence, and after the disaster (corresponding to the different phases of: preparedness, response, recovery and adaptability). Besides the time scale, also other scales (e.g. spatial and functional) do matter when resilience is discussed. According to Young [25], scales are the levels at which phenomena occur both in space and time. The literature review recently performed by Cerè et al. [3] highlighted a strong contrast between extremely broad analyses (involving broad-scale networks without any particular focus either on buildings or infrastructures) and limited-scale methodologies (e.g. those addressing building-scale or urban-scale resilience in relation to a single typology of disruption). Building an understanding of urban resilience across multiple scales requires an awareness of both spatial diversities in adaptive capacities, and trade-offs in resilience between different scales [24]. It should, however, be noted, that, according to the analysed spatial scale (i.e. the urban macro level), the level of accuracy of an individual component's characterization is, in general, lower than in the case of the analysis of just one element (e.g. a selected building) among the studied urban sub-components. Consequently, the accuracy and applicability of the results strongly depends on and is limited to the considered urban scale. If an assessment of resilience from the holistic perspective is desired, the used resilience indicators should be able to capture the change in resilience at different scales, and should not be limited to individuals, communities or even cities [26].

Because the concept of resilience has been used in various research fields, it has several definitions with different meanings, and different approaches have been proposed for its assessment. In order to obtain a clearer picture and overview of the topic, a more exact review and in-depth analysis of the existing literature is needed. Several such review articles taking into account different resilience research fields and topics have been published. Some of them are focused on community resilience [9,12–14,26–28], whereas others have approached this question from the engineering perspective [3,8,29,30].