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Towards a "behavioural design" approach for seismic risk reduction strategies of buildings and their environment

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A B S T R A C T

Earthquake safety paradigms in urban scenarios can be represented by the following: buildings response to ground shaking; possibility to evacuate urban areas; rescuers' assistance to evacuating pedestrians after reaching assembly points in the urban fabric. The first element is widely investigated and involves studies on buildings vulnerability and site hazard. Last two issues are strongly influenced by urban scenarios modifications due to the earthquake and human behaviours during both event and evacuation. Consequently, understanding how people behave in similar conditions becomes an essential issue in order to properly evaluate the urban risk assessment, efficiently organize evacuation procedures and plan interventions (on critical buildings, infrastructures). Hence, this paper firstly offers an overview of current literature on human behaviour in earthquake so far as urban scenario safety is concerned. Critical factors that determine individuals' response performances focus on human behaviours and environmental modifications due to the earthquake. The study underlines how some of the assumptions about the existing paradigms seem to be not consistent with the knowledge set out in the literature: individuals' behaviours are generally neglected while proposing risk-reduction strategies (management, interventions on buildings), and these strategies are supposed to directly induce correct emergency behaviours on people. On the contrary, a successful approach should combine traditional evaluations with innovative analyses on human behaviours and man–environment interactions in earthquake conditions: hence, this paper finally suggests a "behavioural design" approach. Following fire safety engineering criteria, simulation models would be used for evaluating the exposure parameter and check operative strategies for interferences reduction in emergency conditions.

1. Introduction

Knowing and defining human behaviours in emergency conditions are basic problems in the safety assessment process. The analysis of the "human" factor in relation to critical scenarios (D'Orazio et al., 2014b; Kobes et al., 2010) represents one of the bases for proposals about interventions on buildings and emergency management strategies. The "human" factor effect becomes the fundamental issue when the built environment suffers modifications due to the occurring disastrous event and people have to strictly interact with the scenario in order to reach safe conditions (such as in case of evacuation). Hence, a joint man–environment investigation approach is needed, for example, in fire (Kobes et al., 2010; Proulx, 2002) and earthquake (Akason et al., 2006; Alexander, 1990; D'Orazio et al., 2014b; Kosaka, 1996; Prati et al., 2013) emergencies. An interesting similarity can be performed between fire and earthquake evacuation and the related approaches to the design of risk-reduction strategies.

Fire evacuation is mainly performed during the event, or rather while the fire is spreading inside the building. Human behaviours are influenced by fire propagation stages and environmental modifications (e.g.: reaction-to-fire of building materials, smoke productions) (Kobes et al., 2010; Proulx, 2008). In general terms, the environment where people move is "dynamic" because of the propagation of the event and its effects. The possibility to escape from a building during a fire is a consequence of decisions carried out by occupants in relation to the surrounding environment (Kobes et al., 2010): in general terms, building planning and design actions should be oriented to a minimization of the total evacuation time. Studies focused on human behaviours in a fire and also provided a quantification of motion and wayfinding activities (Kobes et al., 2010; Proulx, 2002; Shi et al., 2009). The fire safety engineering (Borg and Njå, 2013; Kobes et al., 2010; Korhonen and Hostikka, 2010) approach considers these behavioural issues as fundamental for the correct building design. Recent national

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and international regulations positively adopted researchers' works outlines (BSI, 2004; Confederation of Fire Protection Associations Europe, 2009; Ministry of Interior (Italy), 2015). At the same time, design tools have been recently developed in order to consider these phenomena and then to properly help the architects during the design phase (Borg and Njå, 2013; Korhonen and Hostikka, 2010; Ronchi and Nilsson, 2013; Zheng et al., 2009).

Similarly, earthquake safety paradigms are strictly influenced by man–environmental interactions, especially in urban scenarios. Earthquake evacuation is generally performed after the main shake itself (and so during the immediate aftermath). Although the environment where people move can be considered less dynamic than the one of a fire (because of the kind of emergency), the surrounding damaged scenario highly influences evacuating individuals while they are gaining a safe condition (Alexander, 1990; D'Orazio et al., 2014b; Yang et al., 2011). Thus, "behavioural aspects" in earthquake should be considered while dealing with individuals' safety level and related risk-reduction strategies.

According to previous works and to the synthetic representation of Eq. (1), the earthquake risk R at urban scale (Ambraseys, 1983; Villagràn De León, 2006) can be determined by the site hazard H (Klügel, 2008), the buildings vulnerability V (Calvi et al., 2006) and the exposed elements E (Mouroux and Brun, 2006; Villagràn De León, 2006):

$$R = R(H, V, E) \quad (1)$$

This definition links the three essential issues which have to be inquired (D'Orazio et al., 2014b). The site introduces the possible earthquake characteristics through its related hazard (Klügel, 2008). The urban layout is composed by built areas, public spaces (streets and squares) and infrastructures that can suffer from a certain damage level in function of the earthquake magnitude (Federal Emergency Management Agency, 2009a; Grünthal, 1998; Mouroux and Brun, 2006). The "human presences" in the scenario must be considered in terms of both inhabitants' number and inhabitants' response to the event (Alexander, 2012; D'Orazio et al., 2014b). At the same time, people choices are influenced by the earthquake magnitude itself and to environment modifications due to the earthquake (e.g.: ruins and debris formation) (Bernardini et al., 2016; Grünthal, 1998; Prati et al., 2012; Quagliarini et al., 2016; Rao et al., 2011). In fact, on the one side, they could be trapped or injured for buildings damages and collapses. On the other side, their possibility to reach safe places and meeting points could be compromised, and rescuers actions could not be really efficient. These statements clearly show how the earthquake safety paradigms can be influenced by three linked main key factors:

- The buildings response to ground shaking, as function of buildings vulnerability and earthquake magnitude (or ground acceleration) (Grünthal, 1998; Hill and Rossetto, 2008; Lagomarsino and Giovinazzi, 2006).
- Possibility to evacuate urban areas, as function of buildings and infrastructures damage and pedestrians' flows along the evacuation paths (Amini Hosseini et al., 2014; Mishima et al., 2014; Quagliarini et al., 2016; Truong et al., 2013).
- Rescuers' assistance to evacuating pedestrians after reaching assembly areas in the urban fabric, as function of emergency management procedures, real pedestrians' evacuation process, and the scenario damages (Amini Hosseini et al., 2014; D'Orazio et al., 2014a; Italian technical commission for seismic micro-zoning, 2014).

Contrary to what is observed in the fire safety field, a limited number of studies deal with human behaviours in earthquake conditions (Alexander, 1990; Bernardini et al., 2016; D'Orazio et al., 2014b; Kosaka, 1996; Prati et al., 2013; Prati et al., 2012), and only few of them success in providing tools or rules that could be effectively useful for management actions and planning interventions on buildings and urban scenarios (such as behavioural schemes (Alexander, 1990; D'Orazio et al., 2014b; Murakami and Durkin, 1988), motion quantities (Bernardini et al., 2016; D'Orazio et al., 2014b; Hori, 2011) and simulation models (D'Orazio et al., 2014a; Hori, 2011; Okaya and Takahashi, 2013; Osaragi et al., 2014; Shimura and Yamamoto, 2014; Truong et al., 2013)).

Current regulations and best practices about earthquake risk assessment, interventions on buildings at urban scale and emergency management planning generally overlook the "human" factor significance. In this way, they seem to follow a deterministic and schematic point of view. It is supposed that building layout and wayfinding systems can directly induce individuals' behavioural uses. Hence, interventions on buildings and emergency management strategies could be enough for reducing people risk, because occupants would surely behave in "the correct way" (e.g.: using right emergency procedures and paths). For instance, while building construction solutions focus on the vulnerability of the built element as itself, current guidelines mainly limit the definition of evacuation layout elements (mainly routes, assembly points and evacuation sites) to the following: rough geometric aspects (e.g.: ratio between outdoor spaces dimensions and facing buildings heights (Italian technical commission for seismic micro-zoning, 2014); distance of refuge places from buildings and between adjacent assembly points (Sapountzaki, 2002)); avoiding (or limiting) secondary hazards and cascade effects (Bureau of Urban Development – Tokyo Metropolitan Government, 2010; Federal Emergency Management Agency, 1996; Italian technical commission for seismic micro-zoning, 2014) (including earthquake-induced fire spread at urban scale); estimating post-earthquake debris quantities (Federal Emergency Management Agency and National Institute of Buildings Science, 2003). These approaches ignore (or, at least, widely underestimate) people's response to earthquake and evacuation choices, as well as excessively simplify criteria for path (total or partial) blockage (e.g.: by using simple geometrical criteria).

Nevertheless, earthquake risk-reduction strategies would really take advantages of behavioural aspects, as for the fire safety case. Understanding how individuals act in these emergency conditions would allow to develop integrated "risk maps" combing traditional and innovative evaluations: evaluations related to traditional parameters and results of behavioural analyses should be easily combined in order to offer suggestions about operative strategies for planning risk reduction strategies, and evaluating community resilience aspects (Ainuddin and Routray, 2012; Alexander, 2012; Amini Hosseini et al., 2014; Cutter et al., 2008; D'Orazio et al., 2014b). A similar approach is urgently needed in urban historical city centres and high population density areas, where the man–environment interactions are particularly strong, and the related general high-risk level and focused interventions could be planned in order to concentrate capitals on strategic elements in the urban factory.

Starting from this point of view, this paper tries to outline a new methodology for assessing risk at urban scale and designing risk-reduction strategies. The method considers human behaviours and response in case of earthquake, and man–environment interactions during the emergency phase as fundamental elements for developing effective risk-reduction strategies. For this reason, the proposed approach is called "behavioural design".

The "human" factor analysis is offered involving both quantitative and qualitative aspects of human behaviours in earthquake. For this reason, methods about how to investigate and organize human behaviours are firstly provided. Secondly, human behaviours are summarized by evidencing the main gaps for the