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Simplified indexes for the seismic assessment of masonry buildings: International database and validation

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ABSTRACT

Heritage masonry buildings are particularly vulnerable to earthquakes because they are deteriorated and damaged, they were built with materials with low resistance, they are heavy and the connections between the various structural components are often insufficient. The present work details a simplified method of seismic assessment of large span masonry structures that was applied to a database of 44 monuments in Italy, Portugal and Spain, providing lower bound formulas for different simplified geometrical indexes. Subsequently, the proposed thresholds are validated with data from the 2010–2011 Canterbury earthquakes, which includes 48 stone and clay brick masonry churches. Finally, fragility curves that can be used to estimate the damage as a function of the peak ground acceleration (PGA) are also provided.

1. Introduction

A disaster is an event caused by nature or man that causes great physical damage, destruction or loss of life, or a drastic change in the natural environment. Danger is the level of threat to life, property or environment, but it is important to understand that danger is not correlated to damage, and that disasters are the result of poor risk management.

Risk management involves, first, the perception and communication of risk to society. It is then essential to have proper tools for assessment and diagnosis, but also to define a set of possible solutions, and their costs, to implement a risk mitigation strategy. Over the past 30 years, economic losses due to disasters have increased tenfold, while earthquakes caused 80,000 deaths/year in the last decade, see Fig. 1. Studies indicate that investment in mitigation provides society an average of four times the amount invested [11]. In addition to savings to society, the US Federal Treasury can redirect an average of 3.65 times the money spent on mitigation resulting from disaster relief costs and tax losses avoided. This result was published in December 2005 in a report prepared by the Multi-hazard Mitigation Council of the National Institute of Building Sciences, called "Natural Hazard Mitigation Saves" [24]. The report was the culmination of a 3-year, Congressionally-mandated independent study. Another interesting example is given by the World Bank [32] and United Nations where a study about retrofitting of buildings to increase earthquake resiliency provides a cost-benefit ratio of up to eight, for a discount rate of 5%. Sanghi [28], on the presentation of the same study, provides a benefit-cost ratio of 4.6 for earthquakes, based in Istanbul, and stressed the obvious fact that the world population exposed to earthquakes will rise dramatically from 2000 to 2050. As mitigation of the seismic risk in the existing built heritage implies a large investment, it is necessary to set priorities and consider an extended period of time to get communities physically, socially and economically resilient.

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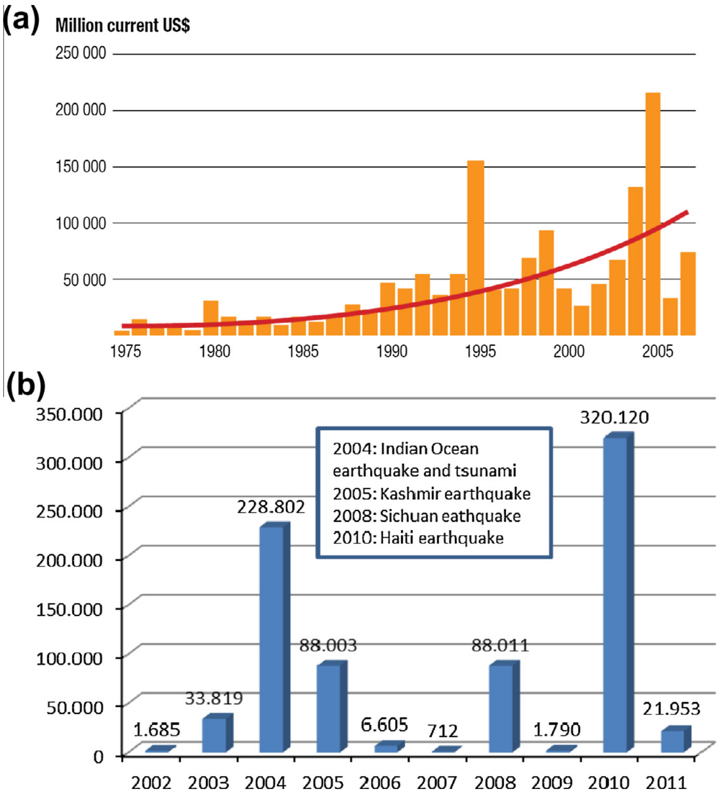

Fig. 1. Effects of disasters: (a) economic losses associated with natural disasters [31], (b) number of deaths in the last 10 years [30].

Recognizing that it is not possible to accept a full loss but it is also impossible to ensure the absence of any damage when an extreme event occurs, it is important to be prepared for disasters and for subsequent retrieval. Many existing buildings are highly vulnerable because they are deteriorated and damaged, they were built with materials with low resistance, they are heavy and the connections between the various structural components are often insufficient. The required approach is known, being necessary to: (i) characterize the existing built heritage; (ii) perform simplified analysis at the territorial level to estimate the vulnerability and risk of this heritage; (iii) in cases identified with higher risk in the previous step, perform detailed analyzes to confirm the vulnerability and risk; (iv) define a plan with long-term intervention measures and their costs, taking into account the observed risk; (v) implement the plan, with periodic reviews of time and costs, considering the economic constraints and the costs incurred in actual interventions. It is also true that a strategy like this requires political and societal commitment to become reality.

As masonry is one of the most used materials of the built heritage, this paper aims at providing a simple and fast screening tool at territorial level for a first safety assessment of masonry structures. In case of urban areas, and in spite of their diversity, a common matrix can usually be established for the seismic areas, more structural than technological. This built heritage consists typically of low height buildings (up to three stories), moderate spans (maximum of 4 or 5 m) and large thickness of the walls (less than 1/7 of the height) [14]. This paper is however focused in churches, given: (a) their intrinsic greater structural vulnerability due to open plan, greater height to width ratio and, often, the presence of thrusting horizontal structures from vaulted ceilings and timber roofs; (b) the ample geometry survey drawings and documentation available. Moreover, in earthquake prone countries, churches and monuments have already been subjected to earthquakes, and sometimes survived them, meaning that these structures are historical testimonies and they represent full-scale testing data. This fact permits to discuss and, generally, to accept that these ancient structures have been adjusted to local seismicity. The simplified method of analysis for large span heritage buildings introduced in [18] is applied here to a database of 44 monuments in Italy, Portugal and Spain, providing lower bound formulas for six different simplified geometrical indexes. The first three indices are associated with in-plane effects and they mainly refer to the ideal case of ordinary masonry structures, whose seismic response is related to the model of equivalent frame behavior. In particular, the accuracy of a given index depends on the conditions of structural regularity (typical approach for reinforced concrete structures and steel structures): regularity in plan and height, rigid decks, small number of floors, good quality of the links (connections, curbs or chains, lintels). The result of these indices, however, highly depends on the box-like behavior of the building and hence on the possibility to actually achieve a global response. This condition is very difficult to achieve in masonry structures such as monumental churches, for which the non-linearity and geometrical out-of-plane effects (local out-of-plane mechanisms) frequently prevail. These effects are partly addressed here through the out-of-plane indices.