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Unreinforced and confined masonry buildings in seismic regions: Validation of macro-element models and cost analysis

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ABSTRACT

Modern design of buildings requires accounting for sustainability aspects using a life-cycle perspective, but also the early design phase where earthquake actions have a significant influence concerning the structural design. Recently, the seismic evaluation of masonry buildings using macro-element modeling approaches became popular, by applying performance-based assessment procedures through nonlinear static (pushover) analysis methodologies. This work addresses the validation for these approaches referring to two full-scale masonry structures tested under quasi-static lateral loading and almost unknown in the literature. The experimental behavior of tested unreinforced masonry (URM) and confined masonry (CM) structures is compared against the pushover response of the corresponding computational models. Then, referring to typical housing in southern Europe and its usual design with a reinforced concrete (RC) structure, the validated assessment tools are employed to evaluate the earthquake-resistant possibilities of URM and CM solutions, namely in terms of maximum applicable ground accelerations. The masonry solutions are also compared in terms of construction costs against the RC typology. The considered analysis tools present a good agreement when predicting, satisfactorily, the experimental test behavior, thus being able to be used in performance-based design. With respect to the studied housing, the predicted pushover responses for the masonry structures denote capacity to resist earthquakes adequately. These structures allow also a significant cost reduction (up to 25%) against the RC, thus appearing to be competing alternatives.

1. Introduction

The building sector has a large influence in the economy, totalizing about 10% of the GDP in European countries. Moreover, people live most of their lives inside buildings, while housing has a major weight in the budget of families and of the banking system. Low-to-medium rise buildings (up to 3 storeys) are the more frequent typology for housing, requiring then particular attention in developing sustainable solutions for construction. The adopted structural solution represents itself an important initial investment for housing and is the focus of the present paper.

Buildings need to provide for welfare, health and safety of occupants. The occurrence of strong earthquakes in the Euro-Med region, see Fig. 1, even in moderate seismicity zones (e.g., the 2011 Lorca earthquake in Spain), highlighted the consequences of poorly designed earthquake resistance structures regarding: damages, injured people, deaths, post-earthquake traumas and reconstruction costs. It is known that earthquakes can take place all over the world causing large losses. The seismic action needs then to be adequately considered in the design of buildings, as addressed in recent methodologies and codes for seismic safety assessment of structures, e.g. [1–3].

There is an important challenge to be addressed today, which is combining sustainability and earthquake resistance. Cost-effective structural solutions can present higher vulnerability to earthquakes, as is typically the case of unreinforced masonry (URM) when compared to reinforced concrete (RC), which became the dominant structural solution in many countries, even for small houses in low seismicity regions. Still, in many cases and taking into account the seismic performance, URM or confined masonry (CM) structural solutions can be alternatively used for low-rise buildings.

The sustainability concept is often applied in the fields of construction economy or green building as whole, with less consideration of the adopted structural typology, also in terms of

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earthquake resistance. Framed RC structures, given their prevalence, are commonly assumed as reference for sustainable building design. However, the optimization of the building performance in general (economy, safety, durability, etc.) calls for a broad approach to sustainability, which needs to account necessarily for the structural typology.

This study addresses the design of masonry building structures, focusing on the seismic assessment, but economy aspects in construction are also discussed. Different tools for seismic assessment and design of masonry buildings are presented and validated against experimental results obtained from tests on full-scale structures. A validation of recently proposed macro-element approaches for URM structures is made through a comparison with experimental results. Furthermore, the study includes an experimental validation of a new modeling approach recently adopted for CM buildings. The performed benchmarking allows to extend significantly the application domain for the studied modeling approaches.

Afterward, by applying these tools in the performance-based seismic assessment of a typical dwelling in Europe, URM and CM structural solutions are evaluated and compared against the solution in RC. Referring to typical single family housing in southern Europe and its usual design with a RC structure, the validated assessment tools are employed to evaluate the earthquake-resistant possibilities of URM and CM solutions showing that the corresponding structures appearing to be competing alternatives to RC structures. This is an aspect of considerable relevance also concerning sustainability in construction.

2. Macro-element models for masonry

Masonry structures present specific and diverse bond typologies, for which several modeling approaches have been adopted. In the academic-research field the modeling of masonry buildings has been applied using two different scales, namely the micro- and macro-element approaches, see Lourenço [4]. Engineering applications of these academic-based approaches can be found e.g. in [5,6], but they remain confined to a rather small number of experts. The concept of using structural component models designated by macro-element modeling for masonry structures was introduced in the 1970s by Tomaževič [7] and applied to perform seismic assessment. This concept is the one addressed next, given the easy implementation of material laws and of the formulation of structural equilibrium. The adopted structural component discretization largely reduces the number of degrees-of-freedom in relation to the traditional micro- or macro-modeling approaches, allowing for more resource- and time-efficient computations and making them attractive to practitioners. In the following, the available models are briefly described and validated, for unreinforced and confined masonry.

2.1. Models for unreinforced masonry (URM)

Recently, and mainly in Italy, several user-friendly computer codes based on macro-elements have been developed for assessing the seismic safety of URM buildings. Marques and Lourenço [8] benchmarked the ANDILWall/SAM II [9], the TreMuri [10] and the 3DMacro [11] software codes, and provided the basic description of the macro-element formulation and assemblage used in these methods. Briefly, SAM II and TreMuri are based on frame-type modeling by using one-dimensional macro-elements, while the 3DMacro is based on a discretization with two-dimensional discrete elements, as shown in Fig. 2.

Frame-type approaches are based in the discretization of the structure into piers and spandrels, which are connected by rigid nodes hence creating an equivalent frame. Assemblage and solution for this approach can be implemented similarly to framed structures, by applying conventional methods of structural mechanics. However, these methods present limitations concerning the simulation of the interaction between macro-elements through rigid nodes, and the modeling of the cracked condition of panels, which is lumped at middle/end parts of the element. These aspects are improved when considering the two-dimensional approach in 3DMacro by using a set of non-linear

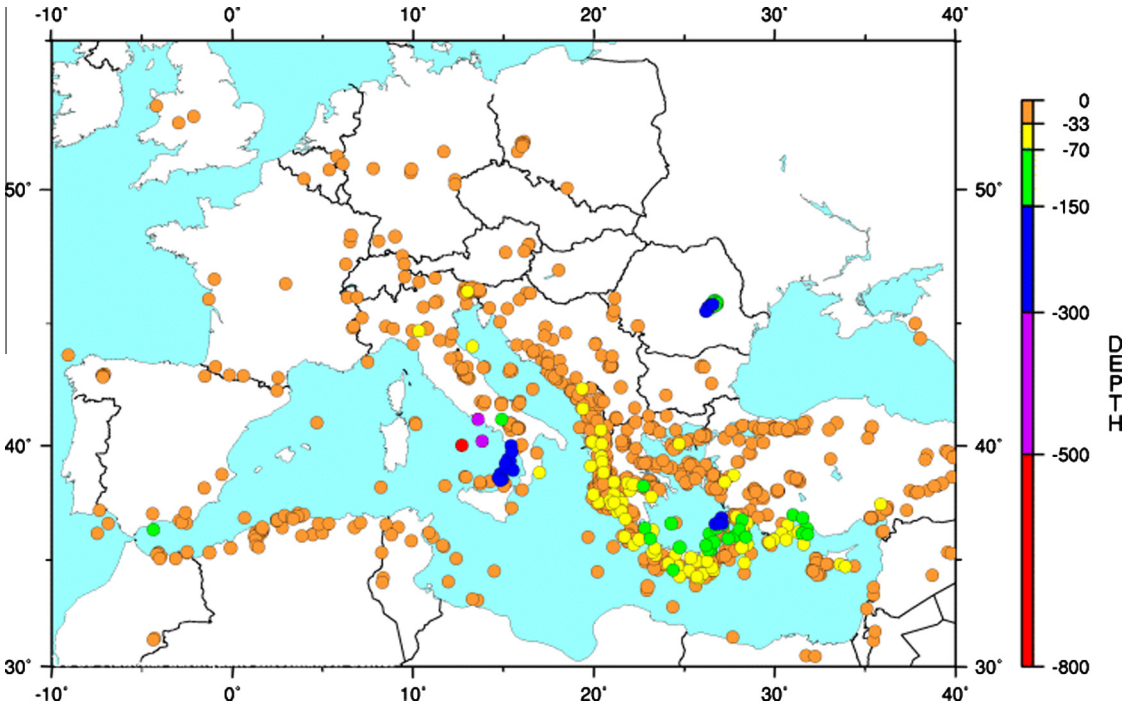

Fig. 1. Earthquakes in Europe with magnitude greater than 5 in the period 1973–2006. *Source:* U.S. National Earthquake Information Center.