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

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A B S T R A C T

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, totaling 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
element probably provides a more accurate approximation. According to Cappi et al. [14], the damage in the walls was typically by diagonal cracking and was initiated in the center spandrel (Fig. 7b).

The predicted sequence for the wall deformed shape and damage is summarized in Fig. 8, for every model and in correspondence with wall displacement levels of 7.5 mm (yielding), 18.5 mm (end of the first yielding stage) and ultimate displacement (strength loss of 20%). A wider sequence for the wall predicted behavior is presented in Marques [21]. The known experimental results describing the wall deformed shape and damage are limited, but according to Cappi et al. [14] the wall response incorporates wall-and frame-type behavior patterns. Due to the wall-type behavior, the overturning action generates tension in the left piers and compression in the right piers, while the spandrels are essentially subjected to shear. Due to the frame-type behavior, the four bottom-to-top columns are subjected to similar moments, while the cross members are compressed and bent.

Concerning the deformed shape, the SAM II and 3Muri models provide a similar trend by deforming linearly along the height. On the other hand, the TreMuri and 3DMacro models present an identical first level mechanism. In terms of damage the same groups are identified, with the first group (SAM II and 3Muri) presenting initial damage mostly by flexure, even if some panels fail latter by shear, and the second group (TreMuri and 3DMacro) presenting shear damage in selected panels (e.g. the lower pier on the wall right), associated with rocking of piers at the first level on the wall left. In the experimental test, the earliest damage was due to shear on the intermediate horizontal cross member, and which resulted seriously damaged at the end of the test. Damage to this member is identified by all the models.

The model grouping in terms of the predicted response seems to be associated to the assumptions adopted by the models, as the first group considers one-dimensional elements with a bilinear response, while the second considers a bi-dimensional domain for the material constitutive law. From the experimental and analytical results presented in Cappi et al. [14], namely the identified diagonal shear damage for the central spandrel and a stronger deformed shape at the first level, it seems that the second model group better agrees with the experimental response. For this reason, Fig. 8c and d is assumed to represent the best approximation to the experimental damage.

2.2. Models for confined masonry (CM)

CM is a particular case of masonry structures, even if it presents some similarity with reinforced concrete (RC) structures due to the presence of a frame. CM is characterized by casting of the RC ele-
ments only after the masonry works, which provides a good connection between the confining elements and the masonry panels due to the combination of bond effects, shrinkage of the RC elements and the fact that the vertical dead load is transferred to the walls. The interaction behavior between the confining elements and masonry through the existing interface is a specific aspect that needs to be considered in the response of CM walls under lateral loading. Some models have been implemented for CM structures based on a wide-column approach, e.g. [22,23], considering the interaction behavior between the confining elements and the masonry implicitly in the wall shear response.

Micro-modeling strategies can also be used, namely based in the finite element method, to model explicitly the concrete-masonry interface, e.g. Calderini et al. [24]. Alternatively, a discrete element approach is also applicable, such as that idealized by Caliò et al. [25] originally for URM and which has been extended in the 3DMacro software [11] to model RC/steel/masonry mixed structures. This last approach uses an interface (constituted by nonlinear springs) between the masonry panels (Fig. 9a), which in the case of two neighboring CM panels is interposed by a frame modeled through nonlinear beam finite elements with concentrated plasticity (Fig. 9b). For the beam elements and in agreement to a given type of interaction (axial, flexural or axial-flexural), the corresponding hinges are considered according to the respective $N-M_x-M_y$ domain (such as in Fig. 9c). This approach has already been used for the simulation of a CM structure built in southern Italy after the 1908 Messina earthquake [26].

![Figure 12](image12.png)  
Fig. 12. Experimental against predicted damage in the South wall for three drift levels.

![Figure 13](image13.png)  
Fig. 13. Comparison of the predicted envelopes in 3DMacro against the experimental response. (For interpretation of color in this figure, the reader is referred to the web version of this article.)
4. Conclusions

The present work offers a contribution regarding the design and construction of cost-effective buildings in seismic regions. For this purpose, the tools available for the seismic design of unreinforced and confined masonry buildings are presented and validated against experimental evidence. With reference to an actual case of a single family housing, simulations are carried to assess its earthquake-resistant capabilities and an evaluation of the construction costs of masonry solutions is made in comparing with the usual RC frame structure.

In general and referring to the validation of experimental tests, the analysis tools available allowed a satisfactory prediction of the capacity curve from the pushover analysis, namely in terms of initial stiffness, base shear strength and displacement capacity, thus being accurate to use in performance-based design. Furthermore, the software codes allow simulating the specificities of real masonry building configurations.

Using a typical house in the southern Europe as case study, structural masonry solutions allowed ensuring seismic safety up to large ground acceleration levels, namely 0.15g and 0.20g for URM and CM structures, respectively. Furthermore, these solutions allow a cost reduction of the structure respectively of 24% and 16% when considering the RC structure as reference. For the URM structure, it was demonstrated that a very conservative design is obtained using the force-based method specified in EC8 [1], due to the consideration of very conservative values for the behavior factor.

The simulation of the real dynamic behavior of a masonry building is a very complex task. In order to simplify, the validation of the presented macro-element models against experimental results and also its application to a typical building allows to obtain an approach to the pushover response of the studied structures, which is assumed to provide a representative indication of the seismic behavior, particularly regarding the application of seismic codes.

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References


